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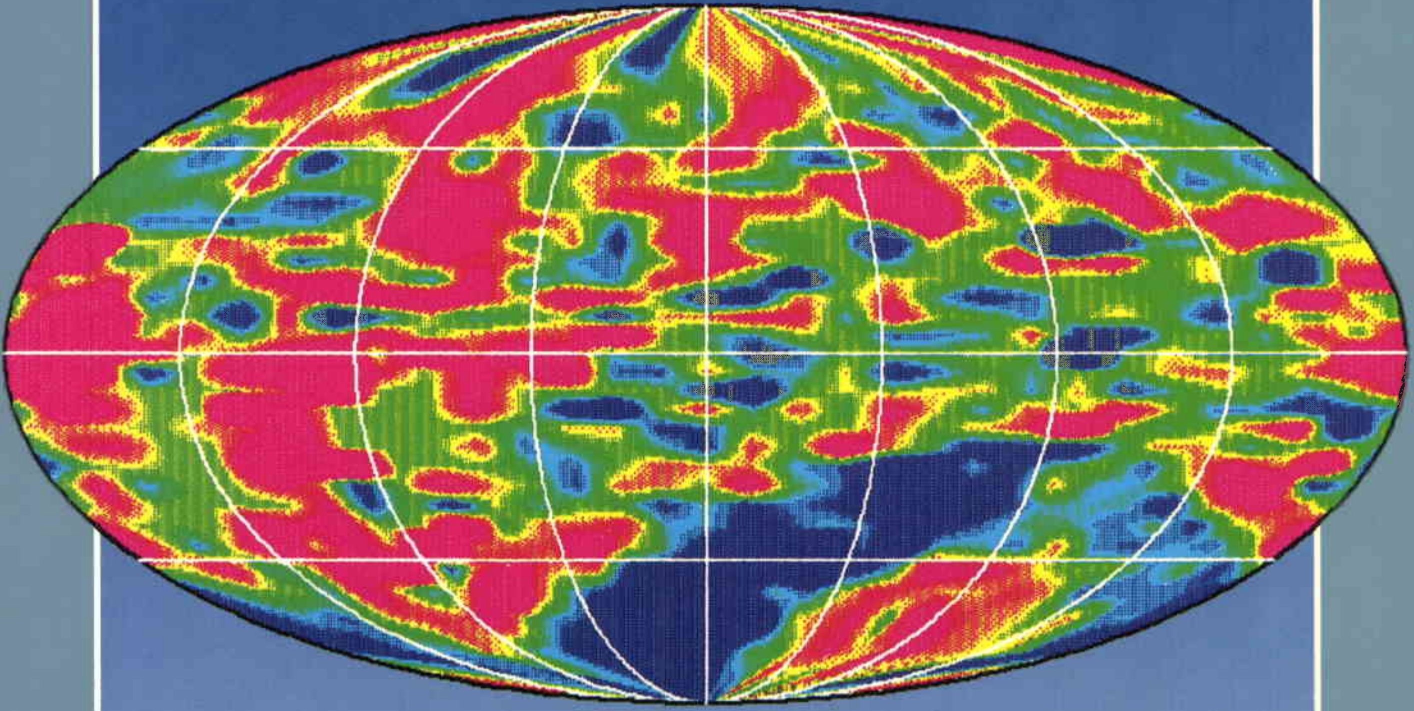

number 69

february 1992

european space agency

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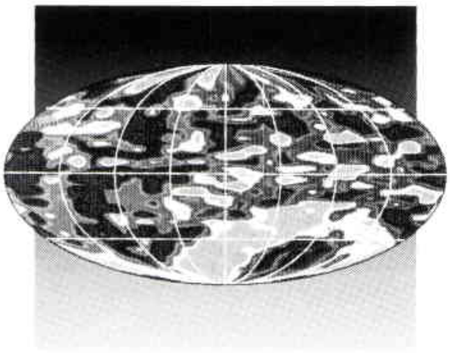

Cover: Comparison of early star positions obtained from Hipparcos with those from previous ground-based observations, the colour-coding representing the discrepancies in 'longitudes'.
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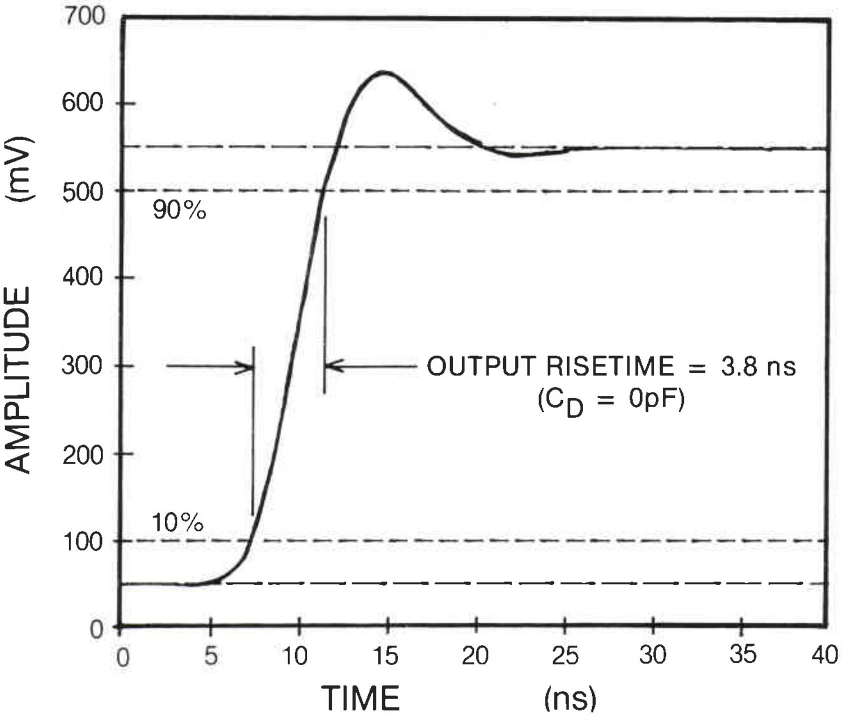

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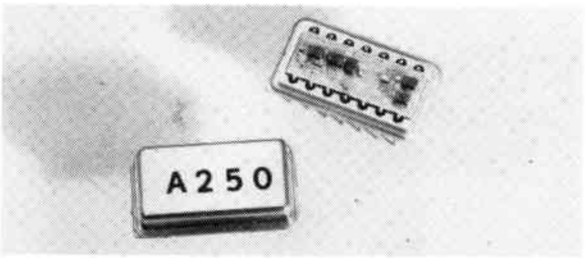

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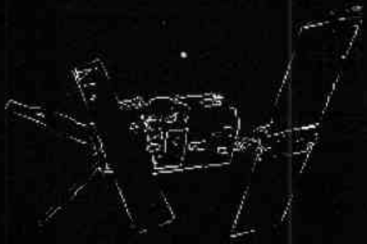

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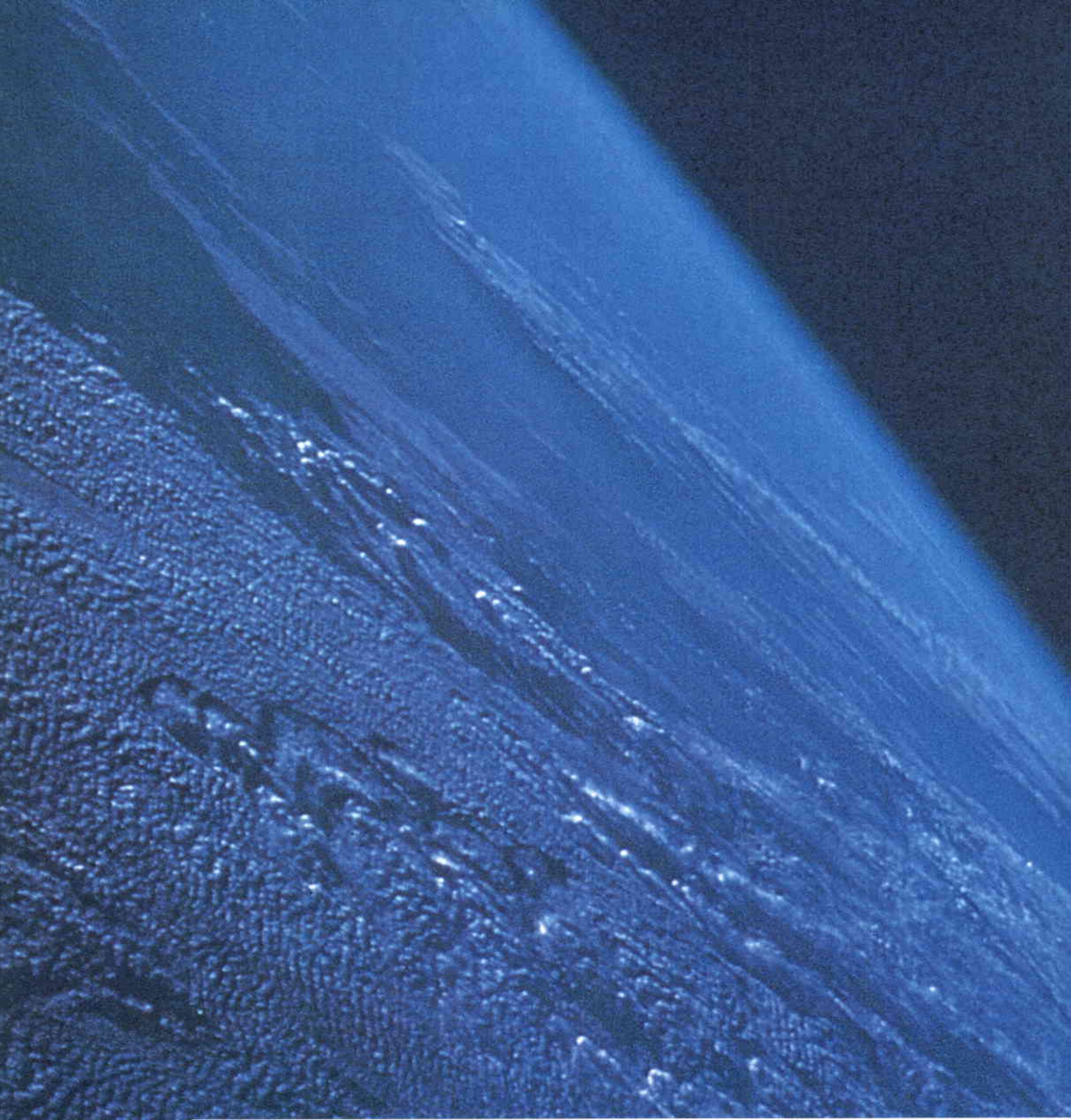

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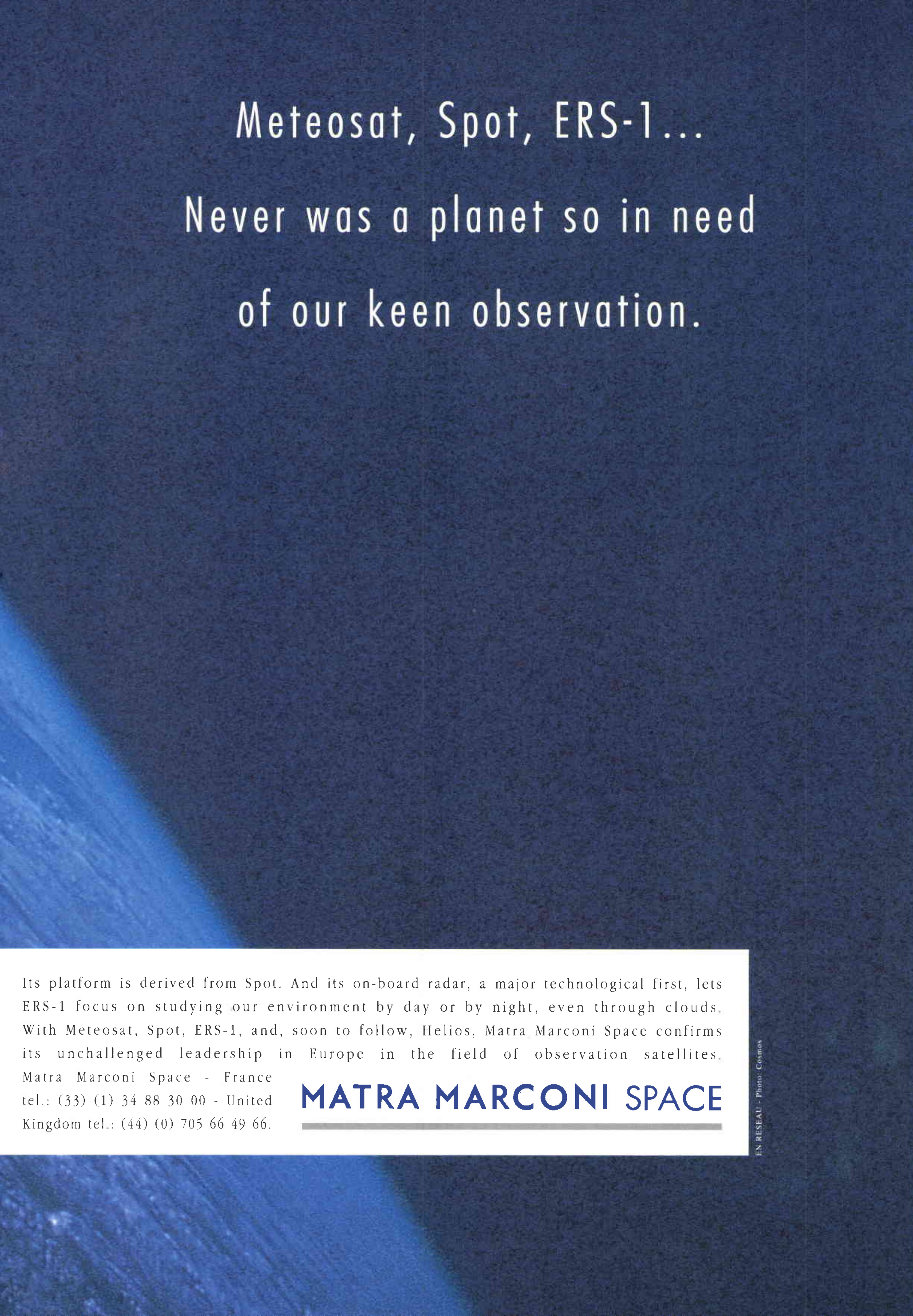
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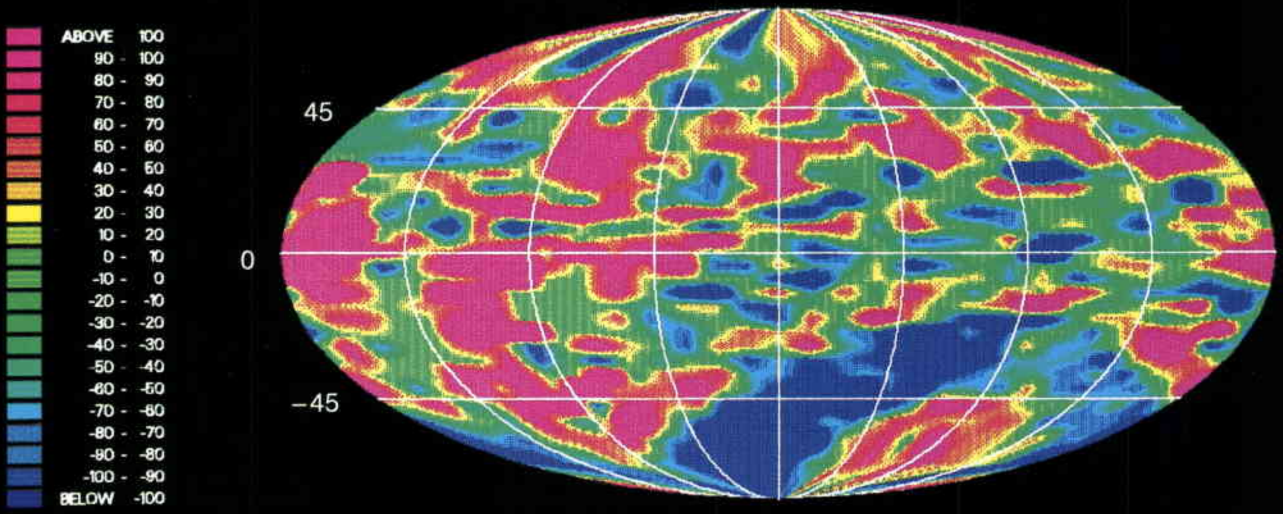

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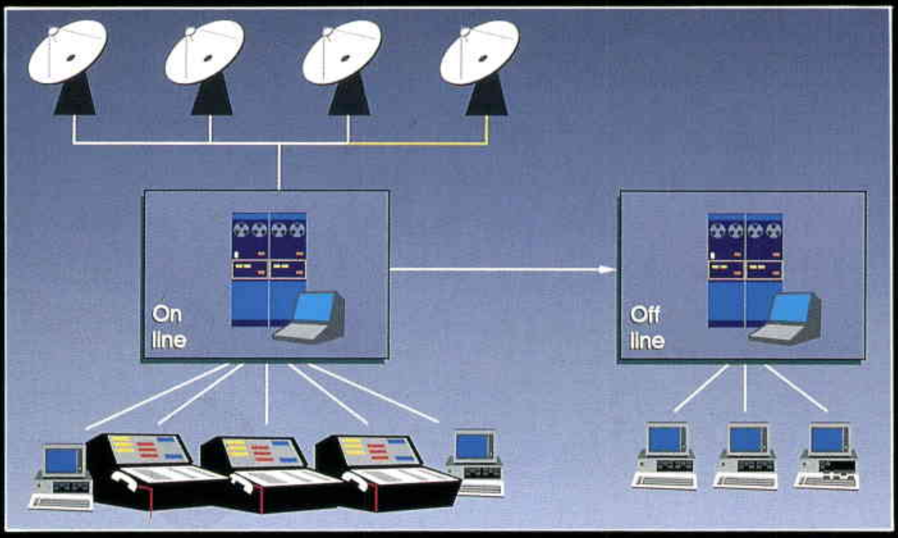
The following six articles summarise the progress of the Hipparcos mission since the satellite's launch on 8 August 1989. The first three cover the activities necessary for the post-launch implementation of the 'revised-orbit' mission, the routine operational activities carried out by ESOC thereafter, and details of the in-orbit performance of Hipparcos' payload. The next three cover the mission's scientific aspects: the observing programme, the data-analysis tasks, and the scientific results emerging from the global analysis of the data.

The Hipparcos project is close to achieving the target accuracies foreseen for the mission and on course to provide the astrometric and astronomical communities with an abundance of fundamental scientific data of unprecedented quality.



Implementation of the Revised Hipparcos Mission at ESOC

J. Van der Ha
Hipparcos Ground Segment Manager, European Space Operations Centre (ESOC), Darmstadt, Germany

Introduction

The Hipparcos satellite was launched during the night of 8 August 1989 by an Ariane-4 vehicle. Because of failure of the satellite's apogee boost motor to fire, Hipparcos did not achieve its intended geostationary orbit. A significant redesign of the mission-operations concept and associated ground-support facilities was immediately started with the objective of achieving the maximum possible scientific return from the so-called 'revised mission'. By the end of November 1989, less than four months after launch, the revised mission implementation was completed to the point where the collection of scientific data from Hipparcos could start.

Following the launch of ESA's astrometry satellite Hipparcos in August 1989, ESOC has been responsible for defining the revised Hipparcos operations concept for the new elliptical orbit, for implementing the necessary facilities associated with this concept, and for preparing for the subsequent revised mission operations.

Investigation of the boost-motor failure

On Thursday 10 August 1989, at about 14.00 h Central European Time, ESOC uplinked the telecommands to initiate the firing of the apogee boost motor which would propel Hipparcos into the geostationary orbit for which it had been designed. No change in satellite velocity was subsequently observed at the ground stations, and so it was evident that the motor firing had not been successful. It took only a few hours to confirm that the uplinked commands were correct, and so the failure was almost certainly on-board, and almost certainly impossible to repair.

During the following weeks, ESOC staff, together with Project and Contractor experts, performed detailed investigations in order to understand what exactly had happened on-board. A reformatting of the telemetry format within a few days after the failure allowed a sampling of the currents in the 'pyrotechnic relay unit' at intervals of 5 ms. From the data downlinked during subsequent motor firing attempts, it was possible to reconstruct the behaviour of the firing relays, which indicated that the fault was somewhere in the pyrotechnics chain.

A total of five apogee-boost-motor firing attempts were made before 25 August 1989 without any success, and the fact that Hipparcos would never be able to reach its intended geostationary orbit had to be acknowledged.

Initial prospects

Immediately after the first firing attempts, investigations were initiated to check the possibility of fulfilling at least part of the mission objectives under the prevailing circumstances. The prospects were not very promising in that the hydrazine fuel available would allow the orbit to be raised by not more than a few hundred kilometres. This, in turn, meant that the satellite would be exposed to the radiation effects of the Van Allen belts during each and every orbital revolution, as indicated in Figure 1. This radiation was expected to degrade the solar arrays to such an extent that there would be insufficient on-board power for Hipparcos to survive the long eclipses (of over 100 min duration) starting in March 1990 (Fig. 2).

The most optimistic outlook at the time was that, if a 'hibernation mode' for the first long eclipse season could be devised, there could be a chance of survival until the next series of eclipses started in mid-1990. By that time, it was feared, the on-board power generation would be so degraded that meaningful scientific data could no longer be collected.

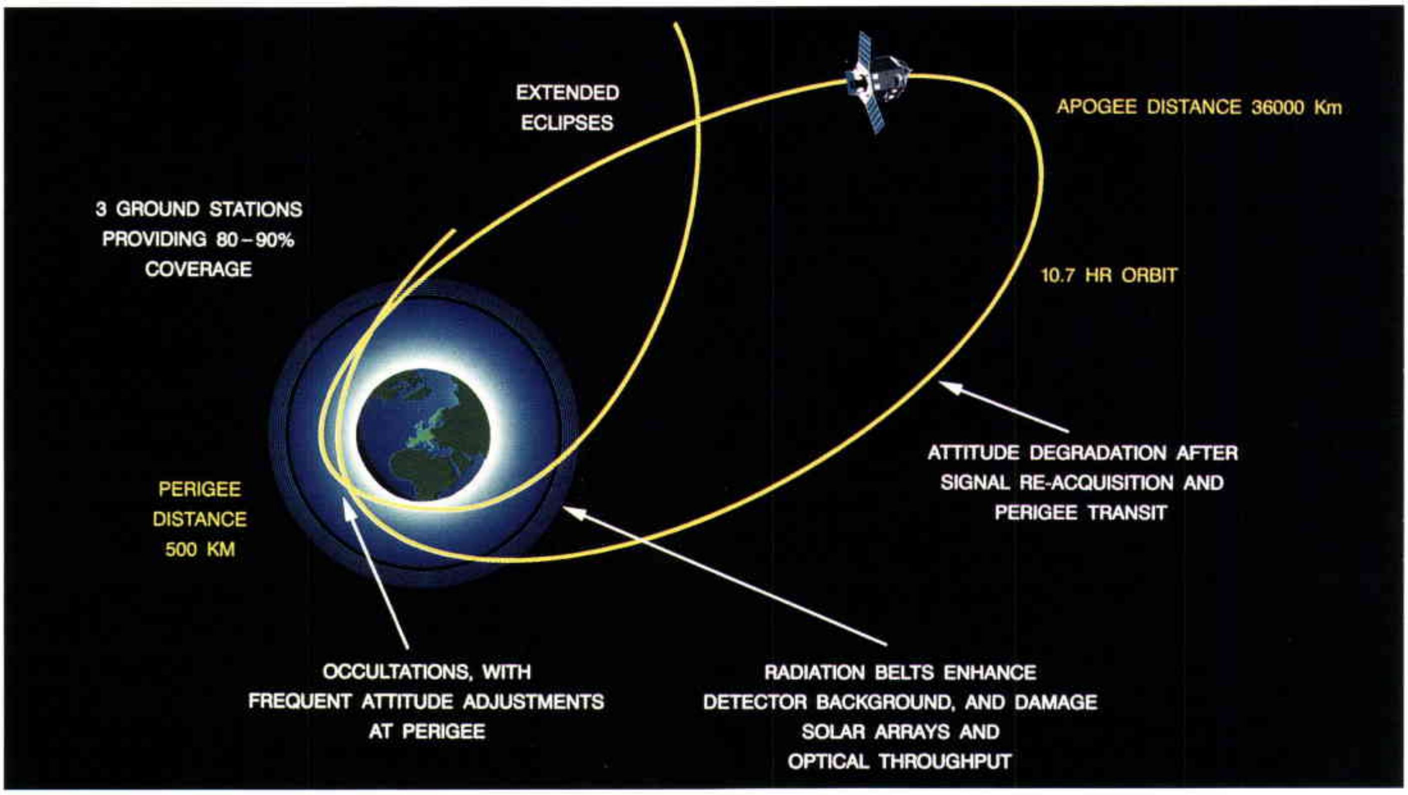


Figure 1. The Hipparcos revised orbit and associated difficulties

Under the latter scenario, the outcome of the mission would be reduced to something between 5 and 10% of the original mission objectives, but this would still represent an achievement that would be hard to accomplish with ground-based astronomical observations. In any case, it was to be hoped that these measurements would still prove useful for validating the Hipparcos mission concept.

Many problems and uncertainties contributed to the general pessimistic mission prospects at the time:

- the limited ground contact via the Hipparcos-dedicated antenna at Odenwald (about 32% of the time) would not be sufficient for significant science data collection;
- the limited station coverage from Odenwald would severely complicate the execution of the operations and endanger the satellite's safety outside the coverage interval; a number of precautions would therefore need to be implemented before the loss of contact (the satellite design was based on essentially full ground-station coverage with occasional interruptions of not longer than 0.5 h);
- the long periods without ground-station contact would necessitate frequent initialisations of the autonomous attitude-determination process from the ground, which would further reduce the time for scientific data collection and would require a larger operations team;
- the intense radiation in the Van Allen belts (crossed about four times a day) would increase the detector background levels, thus complicating the autonomous star detection, and induce a darkening of the payload optics, which in turn would degrade the photometric results;
- the long eclipse periods which would occur in March 1990: the associated power problems were expected to require a special, and still to be designed, 'hibernation mode';
- the occultations caused by the Earth being in the field of view would be significantly longer and more frequent than in the geostationary orbit; this would make the maintenance of the on-board attitude knowledge more difficult;
- the Earth albedo effect would provide a thermal input to the payload in the perigee region, which could lead to significant distortions in the fine modulating grid of the payload;
- the high perturbing torques in the perigee region could introduce attitude-control difficulties.

Mission redesign

A combined effort by ESOC staff and experts from ESTEC and from the satellite Prime Contractor was necessary to address all aspects and potential problems of the revised mission. These teams concentrated on the relevant system, spacecraft, payload and associated operational aspects.

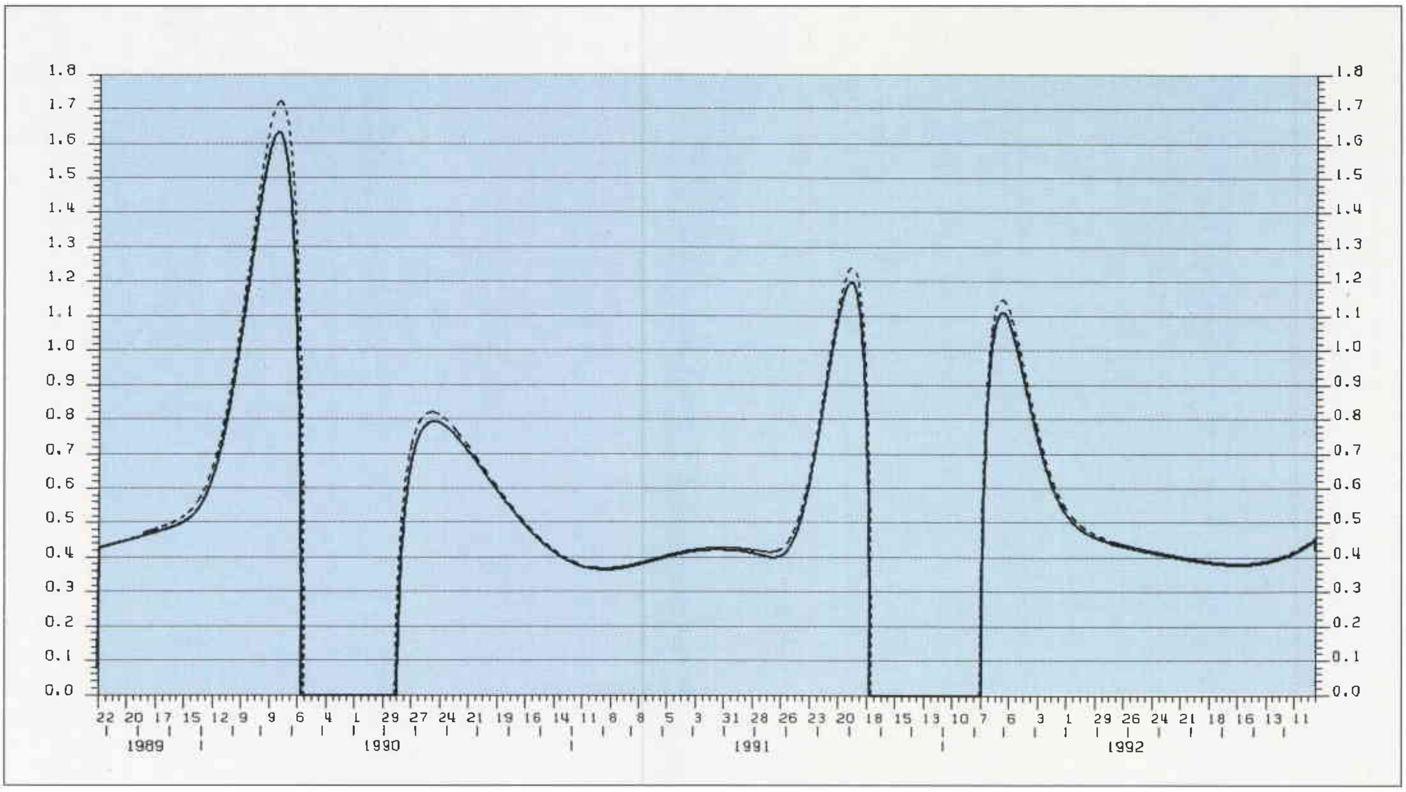


Figure 2. Eclipse duration (hours) during the revised mission

At the same time, the Hipparcos Science Team began investigating the scientific implications of the revised mission. Their simulations indicated clearly that ground-station coverage should be increased to the maximum extent; only with close to full-time station coverage would it be possible to establish a full-sky network of star measurements within a limited mission lifetime using the nominal attitude scanning law and star observation strategy implemented in the on-board software (which would not be easy to modify).

The primary goal of the mission redesign efforts was to recover as much as possible of the original Hipparcos mission objectives. The problems to be addressed were essentially those of a new mission with a few significant differences:

(i) there was little flexibility left in the satellite system design: only limited on-board software modifications were possible within the prevailing practical constraints;

(ii) only narrow margins were available in terms of orbit selection because of fuel constraints;

(iii) finally, each day spent on mission re-definition represented a day of lost scientific mission time.

Some of the most significant mission-design aspects studied at ESOC in the first weeks after the failure were:

- evolution of the geostationary transfer orbit and the satellite attitude orientation for subsequent apogee-boost-motor firing attempts and Sun aspect angle violations;
- redesign of the attitude-acquisition sequence (directly from the attitude required for apogee-boost-motor firing to the Sun-pointing attitude);
- station-coverage predictions for the transfer orbit and potential recovery orbits;
- eclipse and occultation predictions for the potential recovery orbits;
- potential implications of modifying the nominal scan law and the star observation strategy;
- fuel-budget requirements and predictions under the revised orbit and attitude acquisition strategies;
- strategies for covering the long periods without ground contact and a low-density 'programme star file' as a means of survival of the on-board attitude knowledge;
- new attitude-control parameters designed to cope with the high disturbance torques in the perigee region.

At the same time, ESTEC and Contractor experts were evaluating the radiation effects of the Van Allen belts on solar-array and payload degradation. The thermal and power aspects of the new attitude acquisition strategy, and associated risks, were also being assessed and evaluated.

Recovery orbit selection

Immediately following the first apogee-boost-motor failure on 10 August 1989, a team of mission-analysis and flight-dynamics experts started investigating potential recovery orbits. After it was found that 12 h or 8 h orbital periods were not practically feasible, the orbit-selection process concentrated on achieving a perigee altitude above 400 km in order to reduce the influences of air drag and atomic oxygen with, at the same time, a synchronism between the scanning-law period (2 h 8 min) and the orbital period. This was considered beneficial because it would limit the effects of albedo heating on the payload and minimise the duration of payload occultations in the perigee region by a proper tuning of the initial scan angle.


Figure 3. The Goldstone DSS-16 site with its 26 m antenna

Fortunately, a 10 h 40 min orbital period proved to fulfil both criteria, and was within reach with the available fuel resources. The necessary orbit adjustments were performed (after implementation, validation and simulation of the new software and control procedures required) in a series of five manoeuvres during the period 7–18 September 1989.

Ground-station network

The station-coverage predictions did not vary significantly for the various possible orbits, and indicated that Odenwald would have contact with the satellite for not more than about 32% of the time. Adding the Perth and Kourou stations would extend the coverage to about 81% (but even with those extra stations, gaps of the order of 9–11 h would have to be tolerated once every four days).

Preparations were immediately started to bring the Perth station on-line for telecommanding, high-rate telemetry reception and tracking purposes: this involved the installation at Perth of equipment which was used in pre-launch telemetry and telecommand interface tests between the satellite and the Control Centre at ESOC. In addition, dedicated communications lines were ordered from the PTT. Testing of the real-time interfaces with the Control Centre was performed during the first weeks of September 1989. By mid-September, Perth was declared fully operational: contact with the satellite was then available for about 62% of the time.

Subsequently, similar activities were initiated to bring the Kourou Galliot station on-line for high-rate telemetry and telecommanding functions: the necessary equipment was procured or retrieved from other stations. By early November 1989, this station was also able to support all requisite real-time interactions between the satellite and ESOC. The support from Kourou was essential for gaining a better understanding of attitude-control performance in the perigee region, as it was the only station able to provide occasional coverage in this region.

Coverage was further improved later with the assistance of NASA, who offered the Goldstone DSS-16 station in California's Mojave Desert (Fig. 3) for the Hipparcos revised mission. To ensure that the data interfaces with ESOC were the same as for the other stations used for the Hipparcos revised mission, it was necessary to install ESA telemetry, telecommand, and data communications equipment at Goldstone. The equipment was procured by and integrated at ESOC before being transported to Goldstone at the beginning of 1990.

The real-time communications interface with ESOC was quite complex, and it took considerable effort on both ESOC's and NASA's parts, between mid-March and the beginning of May 1990, to get this station operational.

Since the Kourou station's coverage intervals were almost completely contained within those of Goldstone, its support to the revised Hipparcos mission was terminated by mid-1990.

Contact with the satellite was now possible for about 90% of the time and the loss-of-contact periods were limited to no more than 1.5 h. This has eased the operational problems somewhat because the on-board attitude knowledge is less likely to be lost during such small non-coverage periods. However, it should be kept in mind that the complexity of the Hipparcos revised mission operations remains significantly above what would have been considered acceptable during the design phase.

Figure 4 shows the geographical locations of all ground stations that are (were in the case of Kourou) operational during the Hipparcos revised mission. Table 1 summarises the coverage percentages and maximum non-coverage durations for the network configurations used.

Modification of the operations plan

A significant portion of the Hipparcos flight-operations procedures had to be rewritten to take account of the new mission sequences adopted in the acquisition phase: the perigee raise and orbit adjustment manoeuvres; attitude acquisition sequence up to Sun-pointing; and the sequence of events after solar-array deployment. A considerable system-analysis effort involving ESOC, Project and Contractor experts was needed to ensure that the operations were compatible with the satellite's design characteristics.

All operations had to be arranged into sequences that would fit within the interval of ground-station coverage (about 8–10 h for Odenwald). Furthermore, it had to be ensured that before contact was lost, the satellite would be put into a safe configuration that would allow it to survive the long periods without ground contact.

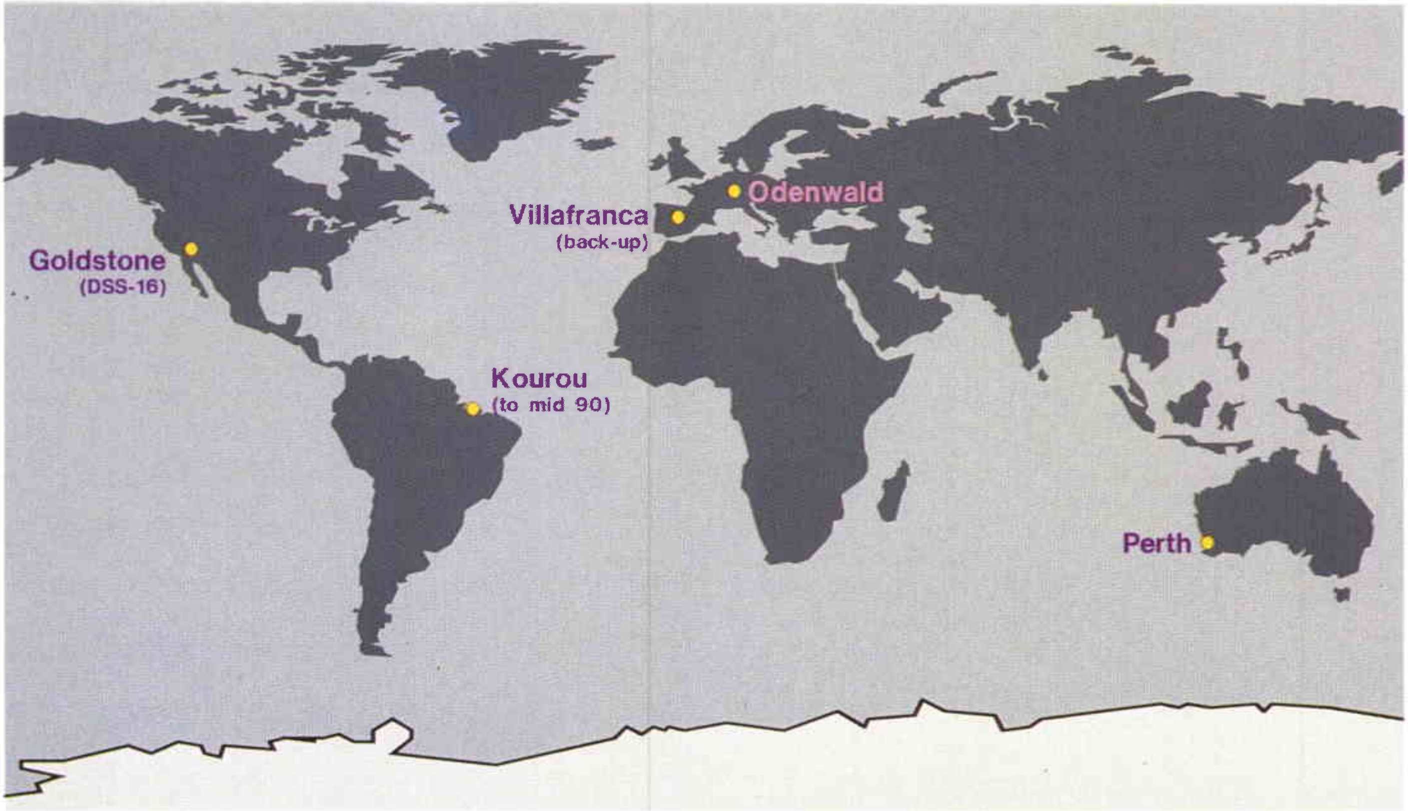
Table 1 — Summary coverage characteristics of network options

Network station(s)*	Coverage percentage	Maximum coverage gap
ODN	32.3	almost 24 h
ODN + PER	61.8	almost 12 h
ODN + PER + KRU	81.1	almost 11 h
ODN + PER + KRU + GDS	93.8	1 h 13 min
ODN + PER + GDS	91.4	1 h 27 min

* ODN = Odenwald PER = Perth KRU = Kourou GDS = Goldstone

The operations were by necessity extremely risky, since the time pressure did not allow full assessments of all possible eventualities or to prepare for potential contingencies. Validation (as far as feasible) of the new procedures was effected via simulations using the ESOC software simulator, often not more than one day prior to a procedure's actual execution. Hence, the flight-control procedures were finalised no more than a few hours before actual operations were conducted.

Figure 4. The ground-station network used to support the revised Hipparcos mission



The failure or back-up mode concept had to be revised as the nominal criterion (using the interval between thruster pulses) was no longer valid because of the high torques on the satellite when in the perigee region. The redesign of the operations for the revised mission had to take into account the following new constraints:

- station contact is frequently interrupted: this results in the need for procedures to ensure spacecraft and payload safety during periods without ground contact;
- eclipse periods last much longer (maximum of 104 min) and their more frequent occurrence demands careful monitoring of the on-board power-generation and associated battery-management functions;
- payload occultation periods occur with higher frequency (up to 28 per day) and have longer durations: this leads to a higher risk of losing the on-board attitude knowledge and requires more frequent support from the ground; also, more telecommand uplinks must be prepared (for payload shutter opening and closing);
- crossing of the Van Allen radiation belts often leads to difficulties in attitude knowledge (re)acquisition and the data collected in these periods are not of sufficient quality to be forwarded to the scientific data-analysis teams.

The operational support of the on-board attitude-determination process is one of the most demanding tasks. Because of the long ground station loss-of-contact periods, and due to the noise in the star-mapper signals induced by the radiation belts, frequent losses of knowledge of spacecraft attitude had to be anticipated. In these instances, ground control must re-establish the on-board attitude knowledge using down-linked star-mapper signals and a star pattern-recognition technique. A new team was recruited and quickly trained to support these unforeseen activities around the clock. In the early days of the revised mission, this particular support was needed after almost every perigee passage.

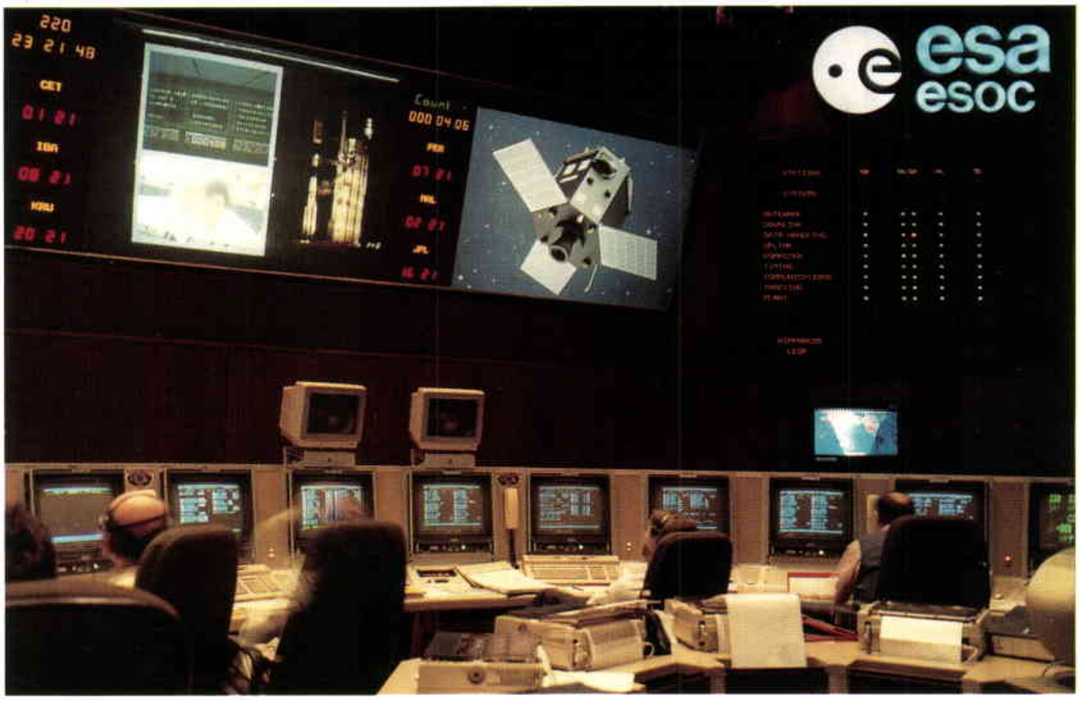


Figure 5. ESOC's Main Control Room

On-ground and on-board software modifications

New on-ground support software was implemented to prepare the manoeuvres required for achieving the recovery orbit, i.e. the perigee-raising and the period-adjustment manoeuvres, and the new attitude-acquisition sequence.

The Hipparcos mission-planning software had to be redesigned and extended to include many more unforeseen events related to the specific characteristics and Van Allen belt passages of the new elliptical orbit:

- ground-station coverage start and end times;
- switching of the on-board torque model in perigee region;
- implementation of a special attitude-control strategy for the perigee region;
- switching of shutters and antennas outside ground-station contact periods;
- calculation of revised eclipse durations;
- prediction of payload-occultation intervals.

Updates to the on-board software were necessary to extend the buffer for time-tagged telecommands, which had now to accommodate the many commands needed during the long periods without ground contact. The memory area for the 'programme star file' was also increased, in order to be able to store a larger number of stars for attitude survival during intervals without ground-station contact.

Initial operations phase

The initial payload switch-on and initialisation of the payload operations were conducted during the last week of September and early October 1989. Unfortunately, the initialisation was severely hampered by extremely high solar activity, with an exceptional solar flare occurring just at the time when the first star-mapper samples were received: it was enough to ensure that no star transits could be observed.

After completion of the attitude scan-law acquisition and the successful calibration of the payload star mapper and main (image dissector tube) detectors, actual scientific data collection was started on 26 November 1989. The initial data recovery rate was about 50%, which meant that 'good' data for scientific data reduction were collected for about 48 h during every four-day period (i.e. the interval after which the ground-station coverage pattern repeats itself).

The computer system installed to support Hipparcos was severely overloaded because of the many additional software tasks required (mainly for ground attitude re-acquisition). It was therefore replaced by a more powerful VAX computer at the beginning of 1990.

By summer 1990, the science-data recovery rate had increased to about 65% with the addition of the Goldstone station and because of further improvements and tuning of the operations support, mainly in the area of initialisation of on-board attitude determination and payload control.

The data-interface definition between ESOC and the scientific Data-Reduction Consortia (FAST, NDAC and TDAC) was also significantly affected by the revised mission. The necessary modifications to the interface were implemented and validated, using real telemetry tapes, in the course of 1990.

Further modifications to the Hipparcos operations concept as a result of on-board anomalies occurring during the 'routine operations' are described in the next article in this Bulletin.

Conclusion

Compared with the initially poor prospects for the Hipparcos mission immediately after the failure of the apogee-boost-motor firing in August 1989, the outcome of the revised mission implementation may be rated as extremely promising. The mission has in fact been recovered very successfully, and there is hope now that the full Hipparcos and Tycho mission objectives may eventually be fulfilled (see the later article in this Bulletin on the scientific expectations).

Figure 6. Members of the Hipparcos Mission Control Team, August 1989

This outlook is even in happy contrast to the expectations at the start of the revised mission in September 1989, when the most optimistic predictions foresaw a useful mission duration of not more than a few months, and the possibilities of constructing a second Hipparcos satellite were even being explored.

Acknowledgement

The successful conclusion to the Hipparcos saga of initial misfortune has been made possible by the dedicated efforts and expert knowledge of those in the ESA Project, Industry and ESOC teams so closely involved in the operations and, last but not least, by the dedication of the many scientific collaborators.

ESOC's Role in Routine Hipparcos Operations

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The routine science data collection phase of the ESA Hipparcos astrometry mission commenced on 1 November 1989, since when the mission has run routinely without major interruption. The activities carried out by ESOC during these last two years of highly successful mission operations have directly contributed to the extraction of the optimum performance from the scientific payload and to the high efficiency of the scientific data collection.

Introduction

Hipparcos was launched on 8 August 1989 by an Ariane-4 vehicle (flight V33). The mission had been designed for a geostationary orbit but, because of the ensuing apogee-boost-motor failure, the spacecraft remained in its geostationary transfer orbit.

A revised mission concept, aimed at minimising changes to the existing mission design and at maximising its scientific output in the prevailing non-nominal situation, was therefore studied and duly implemented. In the course of the mission, however, new problems and difficulties in operating the spacecraft in its revised orbit became apparent. To overcome them, further modifications to both the spacecraft and the ground segment have had to be applied.

Hipparcos is fully controlled by the European Space Operations Centre (ESOC), in Darmstadt, near Frankfurt (D). By employing remote ground stations, all the necessary telecommanding is performed and all the telemetered data is received from the spacecraft at ESOC. This data falls into several categories, including attitude-control, spacecraft-housekeeping and, of course, the scientific data. By monitoring this data (both in real time and off-line), it is possible, through the Hipparcos Dedicated Computer System, HDCS (a complex hardware and software setup), to control and operate the spacecraft in an optimum manner. Of primary importance are spacecraft safety, on-board and on-ground systems maintenance, and effective science data return.

ESOC is also responsible for archiving all spacecraft data, and for pre-processing and distribution of the data to the scientific community. For the Hipparcos project, several scientific teams have been assembled (the Input Catalogue Consortium and three Data Reduction Consortia) to prepare for the scientific observations and to derive the scientific results from the data sent by ESOC.

A detailed (pre-launch) mission description can be found in ESA Special Publication SP-1111. An overall picture of the data distribution and control from the operational point of view, and the satellite nominal scanning law, are shown in Figures 1 and 2, respectively.

Functional structure

ESOC's role throughout the Hipparcos mission has been to ensure that the maximum amount of scientific data of the best possible quality is collected. This implies that not only must the safety of the satellite be ensured, but its efficiency as a scientific production tool must be kept as high as possible at all times.

This was achieved, in part, by setting up a 'mission control team' already several years before the launch. This team had the res-

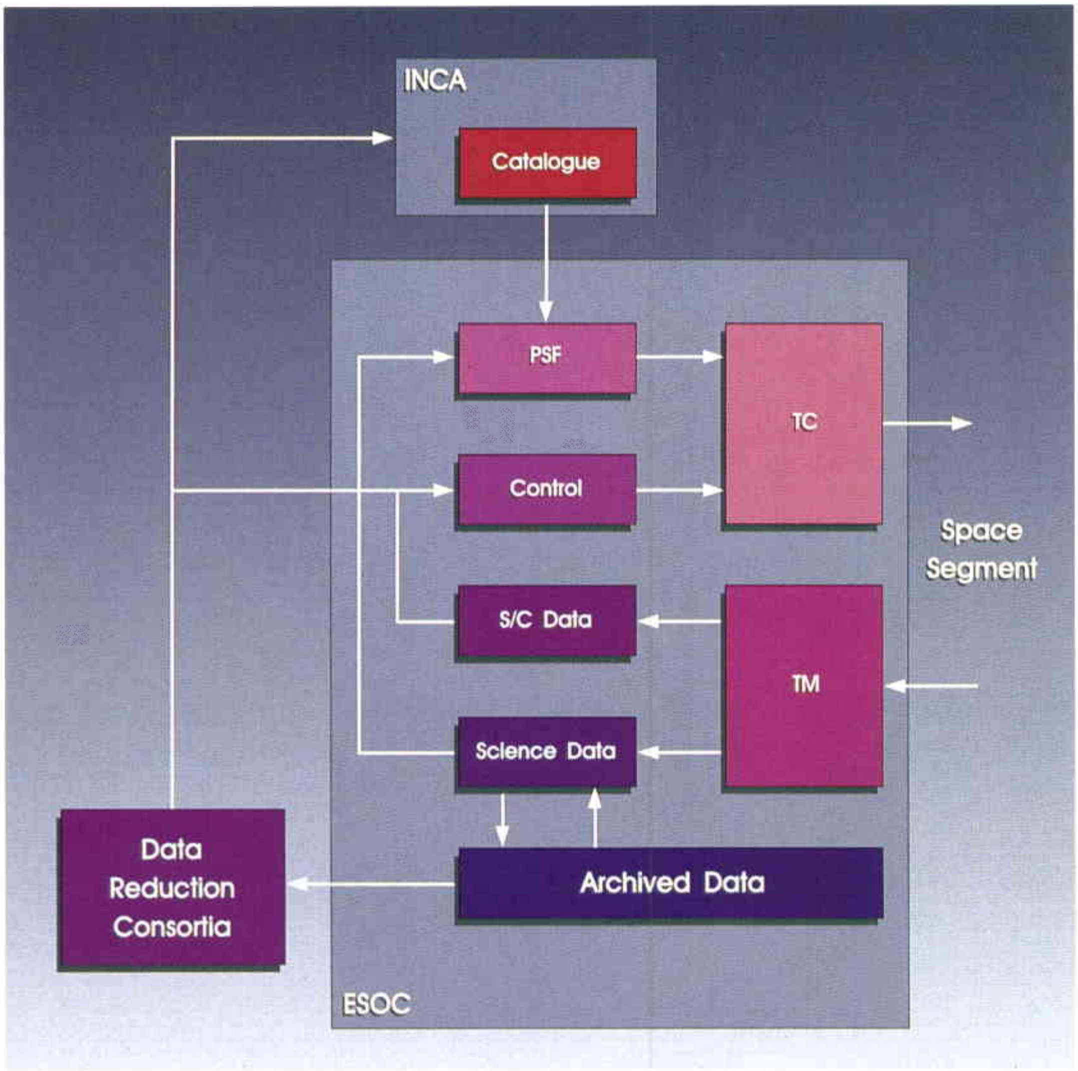


Figure 1. Data distribution and control within the Hipparcos project (PSF is the Programme Star File, while TC and TM refer to telecommands and telemetry, respectively)

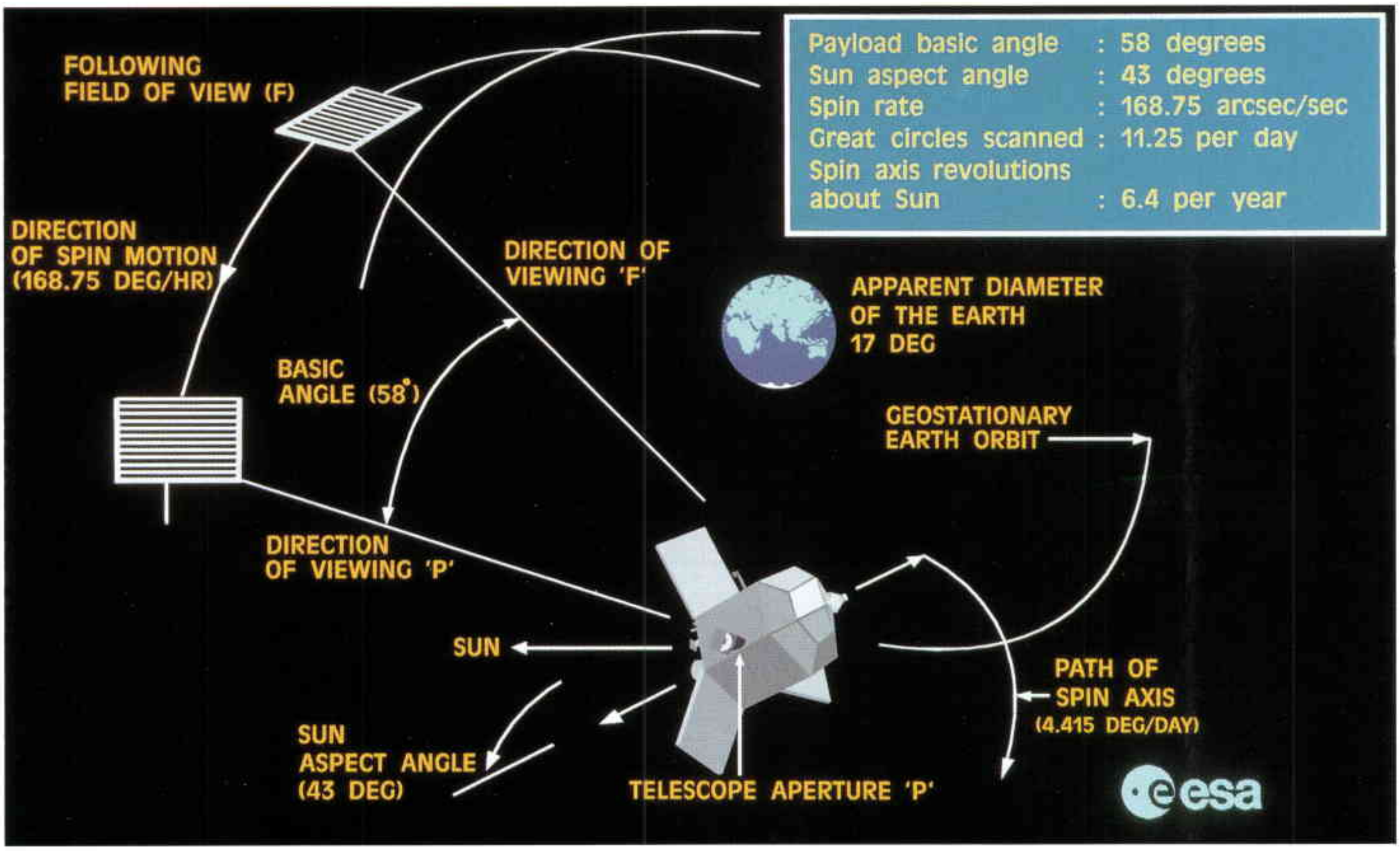


Figure 2. The Hipparcos nominal scanning law

ponsibility for preparing the overall ground segment and appropriate operations plans. To do this, the team organised a ground segment with all the facilities and relevant operational procedures needed to control the satellite and collect the scientific data.

In the current routine operations phase, the ESOC Hipparcos Control Team consists of twenty specialists whose numerous functions can be separated into three main areas:

- The first group, the Spacecraft Control Team, deals with the monitoring and control of the satellite, the creation of the mission plan, the command generation, the management of spacecraft parameters and commands (ground-resident satellite database), the spacecraft performance evaluation and the on-board software updates.
- The second group, the Flight Dynamics Team, deals mainly with the real-time attitude monitoring and correction for the spacecraft, the programme star-file generation, mission plan preparation, orbit determination, payload performance monitoring, payload calibrations, and the Input Catalogue maintenance.
- The third group, the Software Support Team, is responsible for maintaining the software that processes the telemetry and telecommanding in real time. In addition, they perform the data archiving and produce the final tapes which are sent to the Hipparcos Data Reduction Consortia.

In addition to the above, the ESOC infrastructure support guarantees hardware availability, provides ground-station-coverage scheduling, link configurations to the various ground stations and computers, ranging support and other facilities common to all ESOC-controlled satellites.

The operations facilities

Ground-station network

The Hipparcos ground-station network consists of three S-band stations. Two of them belong to the ESA ground-station network (ESTRACK) and are located in Germany (Odenwald) and in Australia (Perth). The third station, located in the USA (Goldstone) and belonging to the NASA Deep-Space Network, was added in the first half of 1990. All ground stations provide full tracking measurement, and satellite data (telemetry) acquisition operations and commanding for the Hipparcos mission. A fourth ground station, located in Spain (Vilspa), serves as a back-up to the Odenwald station.

Operations Control Centre

The Main Control Room is used only during critical mission phases or emergency operations. All routine operations are controlled from the Hipparcos Dedicated Control Room (Fig. 3), which is equipped with three workstations connected to the Hipparcos Dedicated Computer System.

Figure 3. The Hipparcos Dedicated Control Room at ESOC

The Flight Dynamics Room is used during critical mission phases and important manoeuvres. For the Hipparcos mission, the flight-dynamics attitude and payload functions have been transferred to the Hipparcos Dedicated Control Room to ease the operational interface between the control teams.

The Ground Control Room establishes the connections between the relevant ground stations and the Operations Control Centre, as well as the data-line connections between the computer systems.

Computer and software systems

The Hipparcos operational software consists of two separate elements:

- the on-line software, providing support to all activities associated with near-real-time satellite control operations
- the off-line software, which provides support to all non-real-time activities.

The on-line software resides on a VAX 8650 machine, with a VAX 785 as a back-up, while the off-line software runs on a Comparex 8/96 machine. The two computers are interconnected by a high-rate data link, which allows both to be used during some on-line activities, such as programme star-file production and payload calibration and monitoring.

The on-line software supports the following tasks:

- telemetry processing chain
- telecommanding chain
- real-time operator interface
- maintenance of operational databases
- telemetry filing and archiving
- report generation
- ranging support
- on-board computer and control-law electronics monitoring and updating
- real-time attitude monitoring
- ground real-time attitude determination
- payload performance monitoring
- real-time payload calibration.

In addition to the Hipparcos-specific software, a number of general software facilities are implemented in the on-line software system. This general software is called the 'Spacecraft Control and Operating System' (SCOS) and provides standard telemetry processing, workstation displays, reading telemetry data from history files and database editing facilities.

The off-line software system concentrates on:

- off-line telecommand preparation
- on-board software maintenance
- spacecraft performance evaluation
- mission planning support
- programme star-file support
- Input Catalogue maintenance
- payload calibrations and monitoring
- calibration support and analysis
- Data Reduction Consortia tape production.

In addition, orbit determination is performed on the Multi-Satellite Support System (MSSS).

Spacecraft routine operations

The routine operations are characterised by the regular nature of the payload operations, with satellite control and monitoring activities being performed under strict procedural guidelines. Any anomalies detected prompt the implementation of recovery procedures, which are undertaken following pre-established rules. In the event of major contingencies requiring procedural modifications, the Prime Contractor, responsible for the satellite's construction, is called upon for advice.

The Hipparcos spacecraft was, of course, expected to operate from geostationary orbit at longitude 12°W, with continuous science data received by a ground station in the Odenwald in Germany. This not being so, ESOC has to cope with a number of problems in an operational context because of the satellite's elliptical orbit.

Solar-panel degradation

The Van Allen belts are two regions of high-energy particles trapped in the Earth's magnetic field. The inner belt, between 1000 and 4000 km from the Earth's surface, contains mainly high-energy protons, while the outer belt, at between 8000 and 12000 km altitude, contains high-energy electrons. Hipparcos passes through these regions twice per orbit (the orbital period being 10.6 h) and the efficiency of its solar panels is being eroded by the repeated radiation exposure more quickly than if the satellite were in geostationary orbit. The consequence of this process is a potentially shorter lifetime for the mission (Fig. 4).

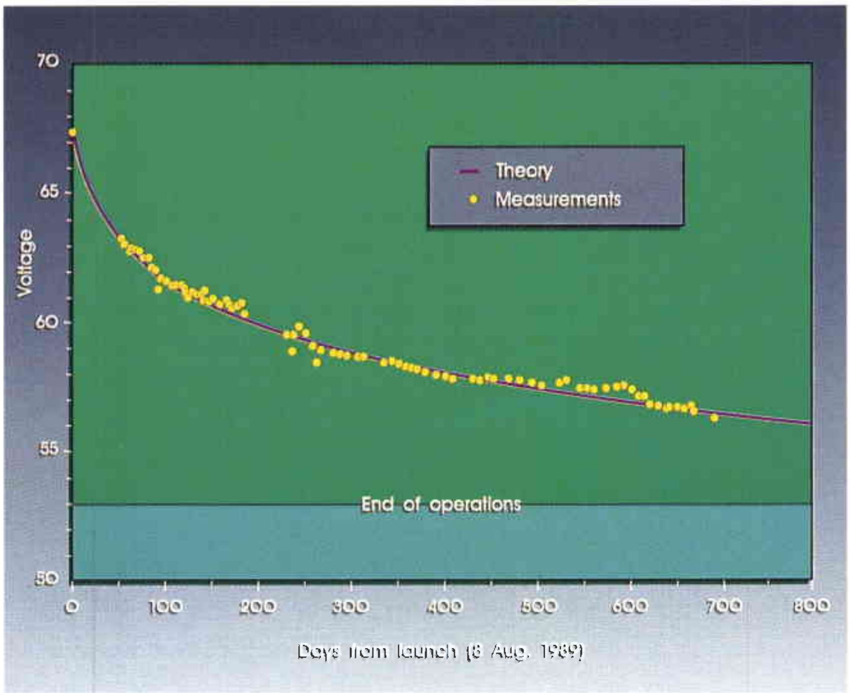


Figure 4. Degradation of the solar arrays. The solid red line represents the theoretical decay in the output voltage; the circles show the in-orbit measurements

Longer eclipses

Coupled with the solar-panel degradation problem is the fact that, in the elliptical orbit, the eclipses of the Sun by the Earth are much longer (up to 100 min) and much more frequent than in the geostationary case. During these eclipses, the spacecraft can only function by drawing power from its batteries. This power-deficit problem is enhanced during the longest of these eclipses, and detailed power budgets and appropriate operational procedures have been prepared to 'hibernate' the spacecraft at times when the batteries cannot supply enough energy to maintain a fully nominal mission throughout the eclipse.

Loss of ground-station coverage

One of the most serious consequences of being in the elliptical orbit is that one ground station is insufficient to track the satellite at all times. At the beginning of the mission, complete operational support was only available for about one third of the time, thus posing major problems in terms of how to manage the satellite outside the visibility periods. These included maintaining its attitude until the next visibility period, and how to protect it, with appropriate subsystem reconfigurations, against such events as eclipses, occultations, perigee passages, and possible on-board failures.

The number of Hipparcos ground stations was quickly increased to three, as described above, but the very lowest part of the orbit is still not trackable from any ground station (Fig. 5).

Higher disturbance torques around perigee

In the intended geostationary orbit, the only significant external disturbance torques acting on the spacecraft were expected to be due to the solar radiation pressure and the constantly spinning gyros. However, close to the perigee of the elliptical orbit, other effects become significant; for example, atmospheric, magnetic and gravity-gradient torques all play a role, depending on the altitude and attitude of the satellite. Their combined effect is to degrade the on-board attitude control, with greatly increased fuel consumption (implying a shorter lifetime, based only on consumables) necessary to correct it, and to degrade the on-ground attitude determination.

Loss of attitude control

Radiation from the Van Allen belts blinds the photomultiplier tubes which sample the star-mapper data: the on-board computer may then not be able to recognise a star signal embedded in the noise. Consequently, close to perigee, where the external torques are greatest, the on-board attitude-determination system does not receive bright-star transit data frequently enough to maintain knowledge of the spacecraft's attitude. Hence, the spacecraft drifts more and more until the intervention of certain on-ground software activities is able to correct the attitude knowledge.

Occultations

Occultations occur when the Earth or the Moon crosses one of the satellite's two fields of view. The payload detectors could be

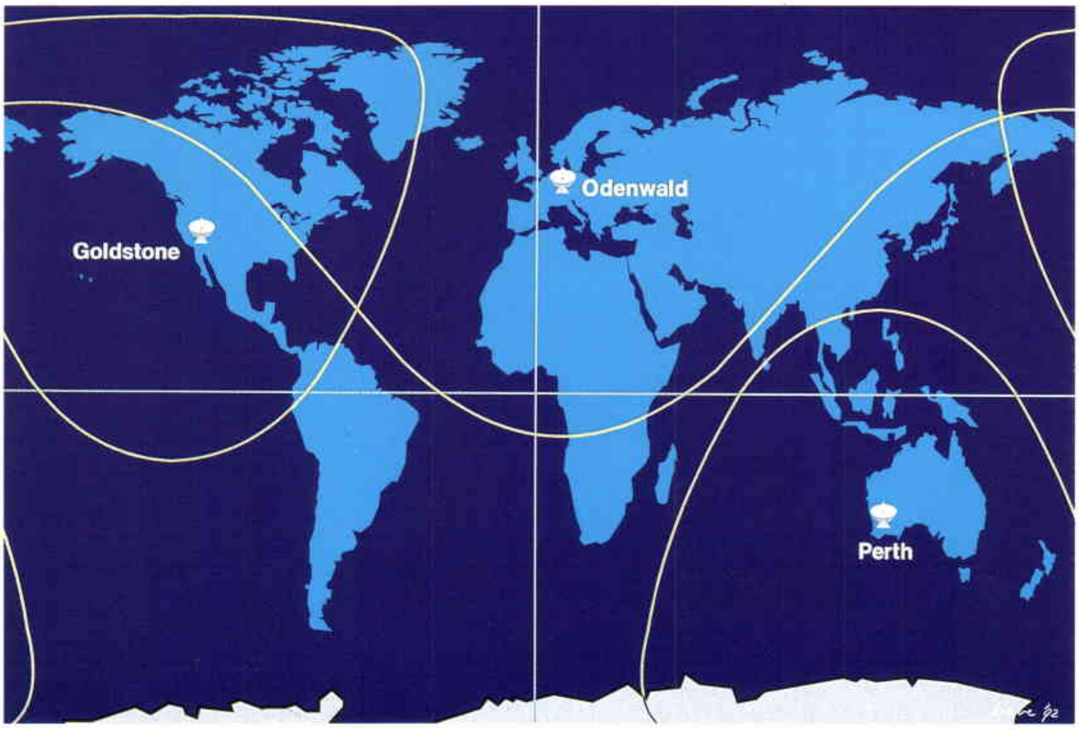


Figure 5. Coverages of the three Hipparcos ground stations: Odenwald (D), Perth (Aus) and Goldstone (USA)

damaged by these events if they were not shielded by shutters, which close at these times. The Earth occultations, like the eclipses, occur more frequently and last longer in the elliptical than in geostationary orbit, again reducing the amount of good science data. Also, when they occur near perigee, they increase the risk of loss of attitude control.

Mission planning

The Hipparcos Mission Plan is regularly generated for a seven-day period starting always five days in advance, using a specifically designed software tool on the off-line system. It includes all orbit and attitude related events, as well as ground-triggered ones (e.g. ground station non-availability).

Because of the changed nature of the orbit, the Mission Plan had to be greatly enhanced in order to support operations. For example, the use of time-tagged commands has been extended in order to perform spacecraft operations outside ground contact, such as the closing and opening of the shutters for occultations, switching between the 'perigee' and 'apogee' attitude controller, and handling the more frequent eclipses.

The generation of a Mission Plan is based on both manual inputs, such as payload calibrations and ground-station availability times, and automatically computed events. Validity checks are performed according to pre-defined rules and any inconsistency is brought to the attention of the operator, who can then modify the inputs.

The output of the Mission Plan tool is therefore a time-ordered sequence of events (ground-station visibility, payload calibrations, antenna-switching, occultations, eclipses and apogee/perigee control parameters changing) which may trigger possible satellite- or ground-segment-related operations.

From this Mission Plan, a chronological telecommand plan is produced automatically using pre-defined command sequences. Conflicts between the command sequences related to different events are resolved automatically according to pre-defined rules. The commands established in this manner are then transferred from the off-line to the on-line computer for uplinking to the satellite at the specified times.

Programme star-file generation and Input Catalogue maintenance

The Input Catalogue is held at ESOC and contains the details of the 120 000 stars and other objects to be addressed in the main observation programme. Many of these stars are also used as guide stars for on-board attitude control.

To hold the complete Catalogue on-board and calculate the individual expected observation times there would impose too much of a computational burden on the on-board computer. The solution is to hold only the expected observation times for the next few hours (typically two to three during normal operations) and refresh this buffer by regular updates from the ground. The off-line computer calculates the various observation parameters needed on-board, including crossing time across the main grid, brightness and observation priority.

Several stars are observable at any given moment and the observation priority determines the length of time for which a star is to be observed as it crosses the grid.

The observation duration is calculated taking into account the brightness of the star (the dimmer the star, the longer the observation), its scientific priority, the number of other programme stars within the field of view competing for the available observing time, and the number of times the star has already been observed during the mission. Because there are long periods without ground-station support, some stars may be under-observed over a particular time interval. Consequently, the relative importance of observing these stars later is increased. In this way, all the stars in the Catalogue should be observed sufficiently to provide uniform accuracies in position, parallax and proper motion, by the end of the mission. The observation-priority parameters are also updated at ESOC, by looking at all the successful observations over the previous 24 h. Results are regularly communicated to the Data Reduction Consortia for cross-checking.

The variable-brightness stars are a special case; to optimise observing time, it is important to be able to predict their apparent brightness. This is done by using brightness ephemerides for the variable stars, provided by Montpellier University. Once the variable stars have been observed by Hipparcos, the data are processed at ESOC and the results are communicated back to Montpellier once per month, to further refine the ephemerides. Periodically, a new version of the latter is sent to ESOC for use in generating the programme star file.

As the Data Reduction Consortia process the science data, more accurate positions have been determined for the Catalogue. These results have been made available to ESOC for use in the programme star file, thereby improving the overall accuracy not only of the instantaneous field-of-view positioning, but also of the real-time attitude-determination performance, which in turn leads to further improvements in overall mission accuracies.

Special programme star files are prepared to support periods of non-coverage by one or other of the ground stations: these so-called 'sparse programme star files' provide up to 2300 guide stars (this number corresponding to the maximum on-board memory available), which enables the attitude-control system to follow the nominal scanning law over periods of up to 12 h without ground contact.

Attitude control and monitoring

Currently, the satellite's on-board real-time attitude-determination system relies on measurements from three gyros and a star mapper. As a result of tuning efforts since the start of the mission, involving ESOC, Matra (the prime spacecraft contractor) and the scientific Data Reduction Consortia, real-time attitude determination is now capable of working to an accuracy of 1–2 arcsec if stars are being successfully identified in the star-mapper processing. If errors build up to over 10 arcsec, however, star measurements can no longer be used for the real-time attitude estimate, which diverges from the real attitude. Currently, this happens after approximately half of all perigee passes, where higher disturbance torques and noise in the star-mapper signal (caused by Van Allen belt radiation) make divergence more likely. Without accurate attitude determination, the transit times of stars across the main grid become indeterminate and little useful science data is obtained.

At these times, ground intervention is required to correct the attitude-determination parameters on-board. A suite of programs called the 'Ground Real-Time Attitude Determination System' is then applied at ESOC. These programs run as a chain, performing various levels of processing in real time as data are received from the spacecraft. The on-ground processing works from the raw gyro and star-mapper data to provide maximum independence from the on-board processing. The raw star-mapper data is filtered to identify stars as the light crosses the two sets of four unevenly spaced slits. The crossing times, brightnesses and colours of the stars can be measured at this stage. By comparing the brightnesses of the measured star transits, it is possible to firstly match the crossings of one star across the two sets of slits, and then to match the pattern of stars observed crossing the vertical slit against the on-ground star catalogue, thus identifying which stars are being observed in real time.

The expected transit times can be calculated and compared against those measured, along with the gyro measurements, to estimate the spacecraft's attitude, rotation rates and gyro rate biases. The entire procedure of star-mapper filtering, star recognition and attitude estimation has to be performed in near-real-time, allowing attitude prediction accurate to within 5 arcsec. Once convergence of the on-ground attitude estimate is achieved, the relevant attitude angles and re-calibrated gyro biases are reset on-board by direct commanding.

In addition to the Ground Real-Time Attitude Determination, software is running continuously to monitor the attitude and the behaviour of the gyros and thrusters. Various alarms are triggered on-board and on the ground should an attitude anomaly occur, such as a failed gyro or jammed thruster. If the spacecraft is visible from one of the ground stations, procedures can be implemented to minimise attitude drift. On-board, there are other safety measures which can be triggered automatically or manually from the ground to protect the satellite if it should start to drift for any reason.

To optimise thruster performance, there is a simple model of the disturbance torques on-board. This is re-calibrated every two weeks at ESOC. Close attention is also paid to the gyro-rate biases, which are crucial for maintaining real-time attitude stability. After perigee, it is often sufficient to reset these values to those before perigee to maintain real-time attitude convergence.

Payload monitoring and calibration

Near-real-time payload monitoring

Software is running continuously on the ground to monitor the validity of the science data obtained. Given that the Data-Reduction Consortia are generally working with data several months old, it is vital that ESOC has some way of verifying in real time that the scientific data being gathered is correct and useful.

Once per minute, therefore, a main-detector and a star-mapper observation are selected from the previous 30 s of observations. The selected stars are processed to estimate their brightnesses and modulation coefficients. The estimated values are compared with the expected values based on the photometric parameters defining the star (brightness and colour) and based on the calibrated response of the telescope and detectors. Reports are generated for each processed observation.

This program has proved very useful for checking that the entire system is performing properly, i.e. good agreement between predicted and estimated brightnesses is only obtained when on-board real-time attitude determination is operating correctly. It is now used routinely in operations for diagnosing whether manual intervention is required from the ground to correct the spacecraft's knowledge of its own attitude.

The results from this very powerful tool are used in other ways. They may be stored and analysed to indicate to the Data-Reduction Consortia when the science data was of good quality, thereby reducing the amount of processing they have to do. The results of the variable-star processing are already producing useful scientific results. Information is also being derived on the photometric properties of the telescope. In particular, the glass is darkening due to radiation exposure. By comparing the measured brightness of the stars against those predicted, a steady decrease is seen, which if averaged can be used to correct the estimates over the lifetime of the mission.

Telescope refocussing

The telescope can be refocussed using a mechanism that allows the grid assembly to be moved with respect to the telescope focal plane. This is necessary to compensate for such effects as moisture release, which slightly alter the focus during the lifetime of the mission. The quality of the focus for any given position of the grid assembly is assessed by ground processing of the main mission data collected for bright stars in the centre of the main grid. As the focus is improved, so the modulation coefficients that define the quality of the observation increase.

The refocussing calibration is performed every week throughout the mission to monitor the best focus position and, when necessary, change it on-board. The motor that changes the focus position does so in steps of 1.38 microns, and the goal is to keep within just one step of the best focus position.

Image dissector tube piloting calibration

The image dissector tube consists of a photomultiplier with an electromagnetic deflection system that allows only one small part of the photocathode to be sampled at any given time. This small 'instantaneous field of view' is circular, with a diameter of 38 arcsec on the grid. For the best scientific observations, however, it needs to be piloted to within a few arcseconds of the star images. It is the requirement to pilot the main detector accurately that demands knowledge in real time, on-board, of the spacecraft attitude. To do this accurately, the following information is needed by the on-board computer:

- a priori position estimate of the star (from the programme star file)
- knowledge of satellite pointing direction (from the real-time attitude determination)
- knowledge of geometric distortions in the optical system
- knowledge of the transformation between grid position and detector piloting currents.

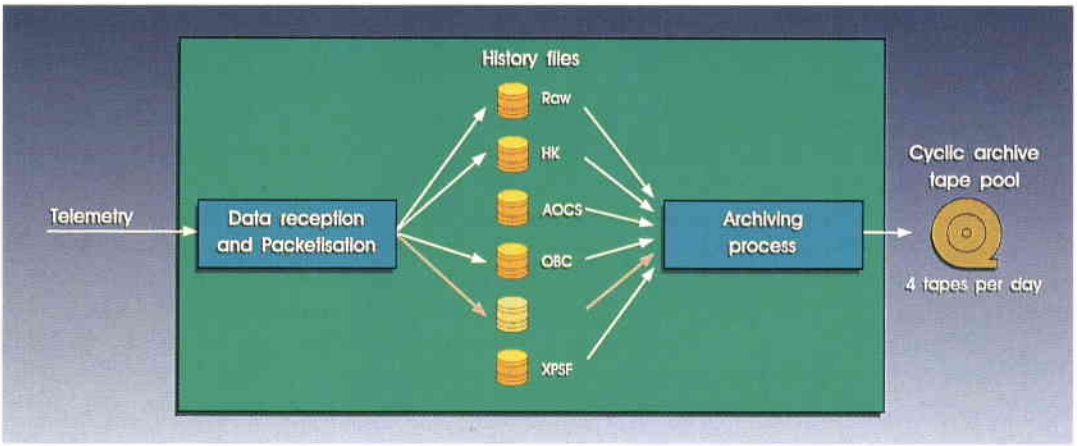
The electrical piloting of the instantaneous field of view to the computed position of the star's image is performed using a 'coil-current calibration matrix' of 11 x 11 points defining a regularly spaced mesh on the grid. The electrical currents needed to pilot to each point in the mesh are known. The coil-current calibration matrix is recalibrated daily and sent to the satellite.

Data archiving and tape production

ESOC archives all data coming from Hipparcos and also takes care of the production and distribution of scientific (Data-Reduction Consortia) tapes to the user community. As a first step, archive tapes are produced on the Hipparcos real-time machine (VAX 8650) every 6 h, without interfering with real-time operations. Each tape contains raw science data, house-keeping parameters, attitude and orbit control telemetry, on-board computer telemetry, and star information. Each tape carries approximately 100 Mbyte of data (Fig. 6).

Two cartridge copies are made from each original archive tape: one goes directly to a back-up store, and the other is used to generate the scientific tapes using the off-line Comparex 8/96 computer. The archive cartridges are read to produce a set of disk files for the derivation of the scientific data streams. At this point, a tape-write task is started to create the final tapes in the agreed

Figure 6. The data-archiving process. The history files consist of raw data, housekeeping (HK) data, attitude and orbit control system (AOCS) data, on-board computer (OBC) data, and the extended programme star file (XPSF)



interface format. This task also adds eclipse, orbit, payload- monitoring, and coil-current calibration-matrix files to the scientific streams. These tapes are then distributed to the scientific consortia: FAST, NDAC, TDAC (Heidelberg) and TDAC (Tübingen). Finally, every week a 'first-look' tape is sent to an institute within the FAST Consortium (at Utrecht) for preliminary analysis of the science data (Fig. 7).

Spacecraft performance evaluation

For long-term performance evaluation studies, the satellite-processed telemetry data and derived parameters (auxiliary data) are regularly transferred from the on-line computer to the off-line machine. There, all the spacecraft data are collected and automatically archived onto cartridges under the control of the Spacecraft Performance Evaluation System (SPES).

The SPES software contains routines to retrieve telemetry data in order to evaluate spacecraft performance over any desired time interval (up to the duration of the entire mission) and includes an on-line query language and graphical representation and report facilities.

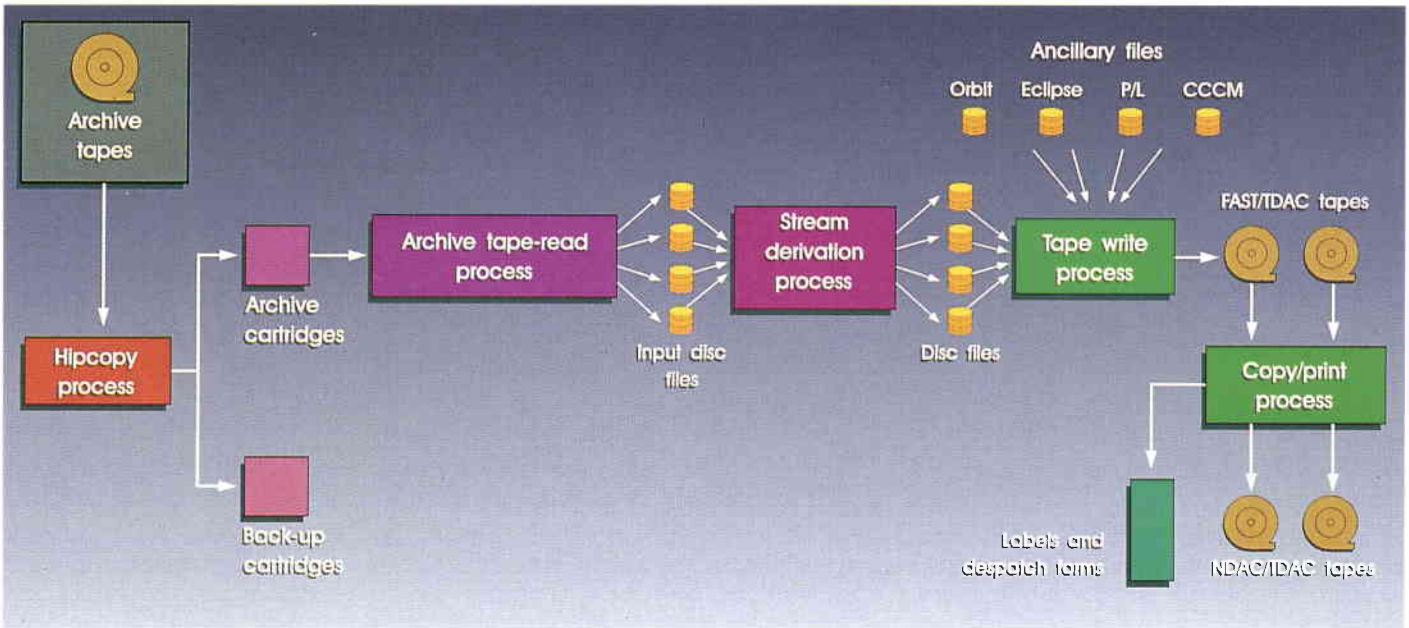
Science data collection

By employing the three ground stations, the spacecraft is visible for 90% of the time, but useful science data cannot be collected during all of this time. Loss of attitude control around perigee, and long occultations, restrict science-data collection to 75% of the duration of visibility. Despite the interruptions, the data gathered is continuous enough for 95% of it to be successfully processed by the Data-Reduction Consortia.

On-board anomalies

The satellite payload and subsystems are generally performing very well, especially considering the fact that Hipparcos is subject both to a very harsh radiation environment, due to the Van Allen radiation belts, and to aerodynamic drag effects at perigee.

Figure 7. Science data tape production. P/L and CCCM data are the payload and coil-current calibration-matrix data, respectively



A total of 57 anomalies have occurred in the first two years of the routine mission, due mainly to 'single-event (radiation) upsets' or hardware problems on-board or on the ground. The radiation-related anomalies are of a recurring nature and are recovered by, for example, reloading the on-board computer, the programme star file, or by resetting the logic of the unit affected. The hardware-related anomalies have occurred primarily in the areas of payload thermal control, the gyros, and the payload remote terminal unit.

Figure 8. The Hipparcos control team in 1991

Conclusion

The Hipparcos mission has now been operational for two years. Despite the harsher orbital environment to which it is exposed and the hardware problems encountered, the satellite remains fully operational.

Early results from the Data-Reduction Consortia indicate that 75% of the collected data can be successfully processed. This implies that the original mission objectives can be realised by the end of 1992 or early 1993. Current gas usage would allow the mission to continue until mid-1994 if no catastrophic failures occur. This would allow a significant increase in the overall accuracies of the Final Catalogue compared even to the nominal mission.

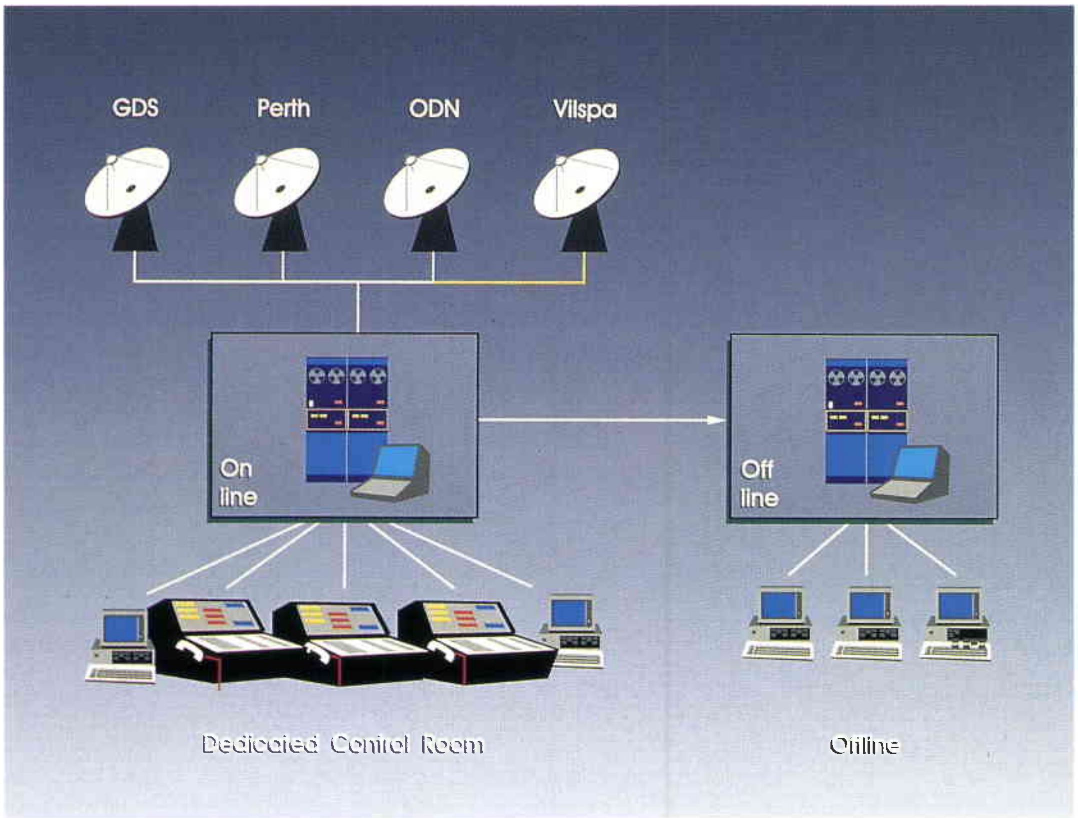
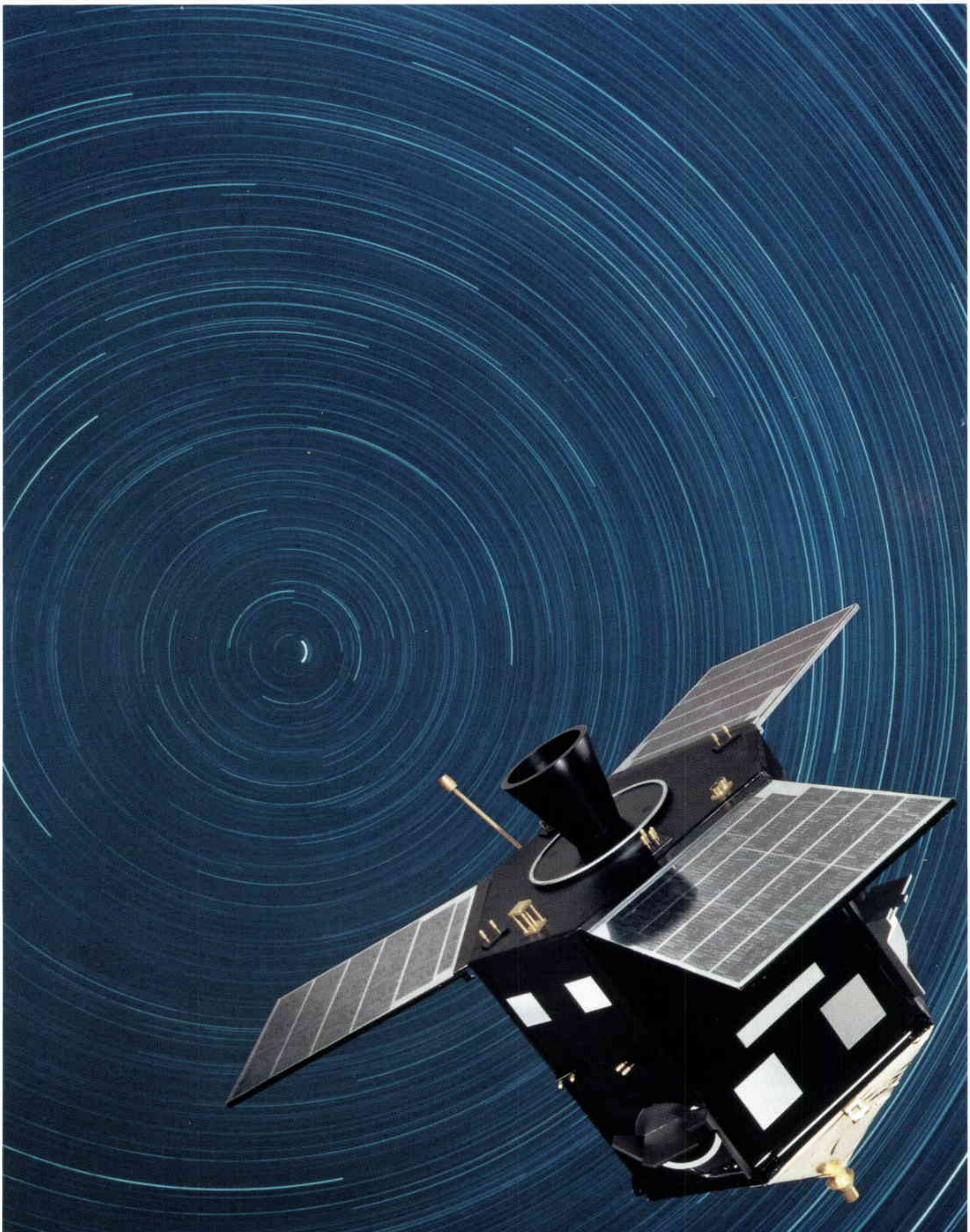


Figure 9. Overview of Hipparcos ground-segment communications



The Hipparcos Payload's In-Orbit Performance

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Introduction

Despite its non-nominal orbit, ESA's Hipparcos astrometry satellite is proving to be an impressively valuable scientific mission, with a data-collection efficiency approaching about 70% of the pre-launch expectations.

The building of the Hipparcos payload was in itself a considerable technical challenge for Matra, the Prime Contractor, who faced unusually stringent requirements in order to achieve the 2 milliarcsec measurement accuracies necessary to satisfy the intended astrometric and astronomical goals.

The in-orbit performance of Hipparcos has been carefully monitored since its launch in August 1989 and the first technical appraisals of the behaviours of some of the satellite's payload components and subsystems are already available.

Two years after launch, detailed technical results regarding the in-orbit behaviours of components and subsystems of the Hipparcos payload are now available, results that will be of considerable value to future optical payload designers. The unexpectedly severe environment encountered by the satellite in its revised orbit has provided extra motivation for the detailed analysis of the data collected.

The payload

The Hipparcos payload is centred around an all-reflective Schmidt telescope, working in the visible part of the electromagnetic spectrum. It has an entrance pupil of 290 mm diameter and a focal length of 1400 mm. A modulating grid is located at the telescope's focal surface. It consists of 2688 parallel slits with a period of 1.208 arcsec, and covers a square field about 0.9°x0.9°. The telescope has two fields of view approximately 58° apart, which are brought together in a common telescope and measurement system by means of a 'beam combiner' mirror located in the entrance pupil.

The modulating grid is re-imaged onto the photocathode of an image dissector tube detector by means of a set of folding mirrors and relay lenses, constituting the 'image dissector tube relay optics'. Two image dissector tube detectors and two relay optics are used in cold redundancy (i.e. the redundant detector is switched off when not in use), selection being performed by means of a switching mirror. The instantaneous field of view of each image dissector tube is nominally circular, with a diameter of about 38 arcsec. The instantaneous field of view can be directed to any point of the 0.9°x0.9° field by varying the currents applied to the deflection coils.

In addition to the primary detection chain (consisting of the modulating grid and the image dissector tube), the payload includes two star mappers (one of which is also used in cold redundancy). The primary function of the star mapper is to provide data allowing the on-board three-axis satellite attitude determination (a task performed by the on-board computer) and the a posteriori determination of the attitude (a task performed by the data-analysis consortia on the ground).

Each star mapper consists of a star-mapper grid located at one side of the main modulating grid, and two photomultipliers,

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measuring the light transmitted by the whole star-mapper grid in two different spectral bands: B_T and V_T. The spectral separation is performed by means of a dichroic beam splitter, which reflects the shorter-wavelength light (the B_T band) onto one photomultiplier and transmits the longer-wavelength light (the V_T band) onto the other. A schematic of the payload layout is shown in Figure 1. (A more complete description of the payload and the scientific mission can be found in ESA Special Publication SP-1111).

Initial results

Detection systems and payload mechanisms

The Hipparcos payload includes two primary (main field) detectors, and four-star mapper detectors, half of which are in operation at any given time. The overall light throughput

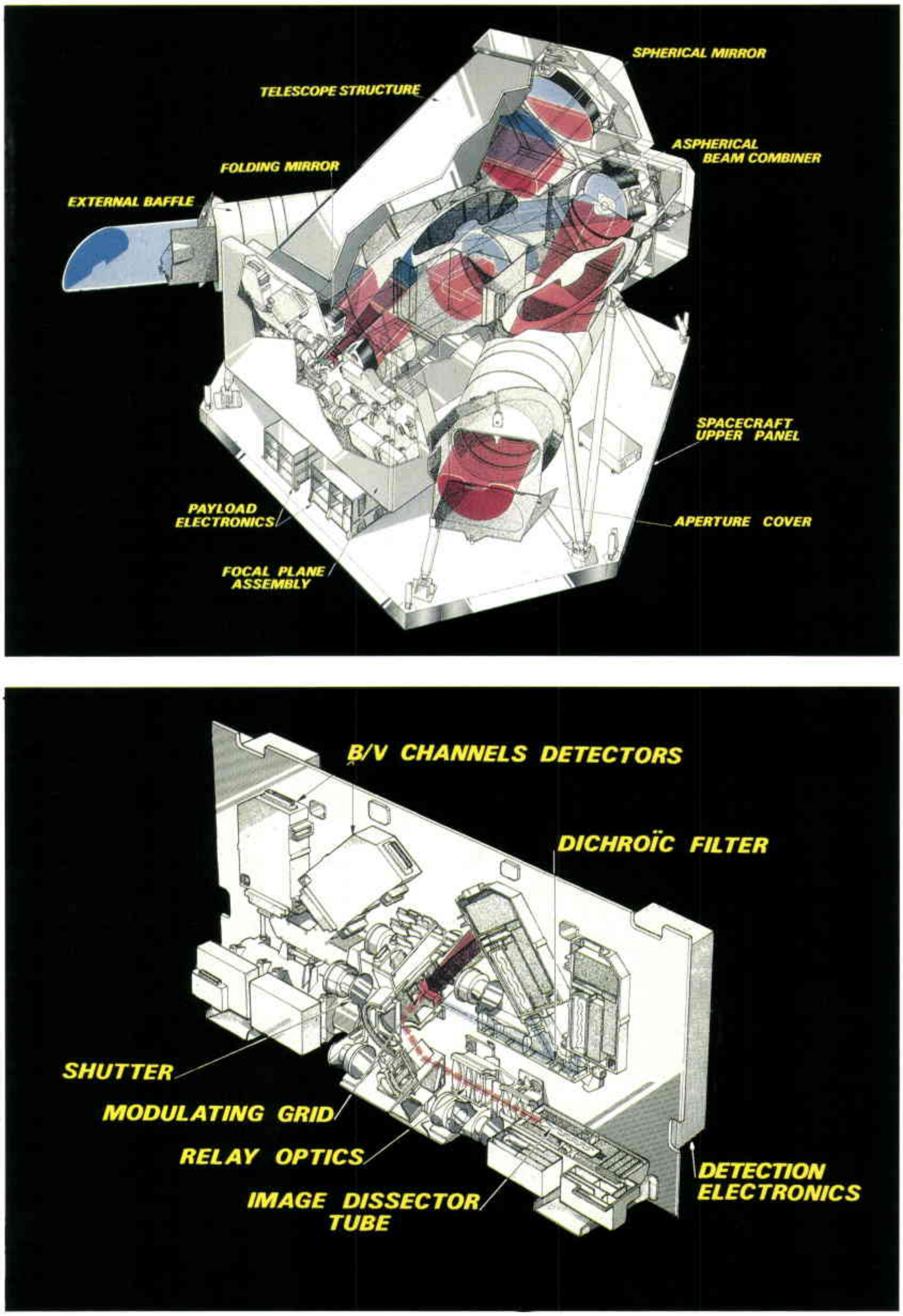


Figure 1.
(a) An overview of the Hipparcos payload showing the two fields of view 58° apart.
(b) A detailed view of the focal-plane assembly, showing the modulating grid, the relay optics, and the detectors

of the payload, including the detector efficiencies, are in good agreement with the pre-launch expectations, and the overall accuracy error budget. All detectors, and all payload mechanisms (including the refocussing mechanism, the detector switching mirrors, and the instrument shutters) have functioned without problem since launch.

Payload thermal control

To ensure relative stability of the optical components within the Hipparcos payload, which is of paramount importance for any instrument devoted to metrology, it was necessary to place very stringent requirements on the temperature stability of the payload structure, the optical elements, and the detectors. Short-term temperature-stability requirements on the mirrors were ±0.05°C.

These requirements have been achieved by proper thermal design of the payload enclosures, where the boundaries have been used to balance internal and external thermal disturbances. Thermal control has been achieved by both passive and active means (even when the payload was in the 'off state'). In-orbit measurements indicate that the short-term stability is well below the thermistor resolution (less than 0.03°C), and that the predictions are comfortably met.

Telescope-structure moisture release

The telescope structure has been designed to maintain the accurate relative positioning of the three telescope mirrors and the units located in the vicinity of the telescope focal plane. The mass, stiffness and stability requirements called for a box-type structure made with carbon-fibre-reinforced plastic skin panels, and stiffeners or carbon-fibre-reinforced plastic shear panels linked by corner profiles and folded edges. By using 12-ply multi-layers, the enclosure panels achieve a high Young's modulus (about 10^5 N/mm^2 and a very low coefficient of thermal expansion (approx. 10^{-7} per °C).

Unfortunately, it is quite impossible to completely 'dry out' a carbon-fibre structure before launch. Water outgassing (moisture release) is followed by a small but non-negligible shrinkage of the structure, which is a well-known effect. The net result is that the telescope focus has to be readjusted regularly using a dedicated mechanism. To minimise this effect during on-ground activities, the payload was continuously kept under a dry-nitrogen flow once the final telescope adjustment had been achieved.

Predictions of the in-orbit focus variation were computed prior to launch based on test sample data (Fig. 2). Careful in-orbit measurements of the depth of modulation of the star signals allows the best-focus position of the complete telescope to be measured and maintained to an accuracy of about 1 micron. Whilst the early post-launch evolution in focus followed the pre-launch predictions rather closely, the movements have been significantly larger over longer time-scales than those expected. This effect can be easily compensated for by making slightly more frequent focussing adjustments for the payload. Meanwhile, the reasons for the greater variation are under investigation, with sensitivity to the severe irradiation environment (due to the lower orbit) being one possibility that has not yet been ruled out.

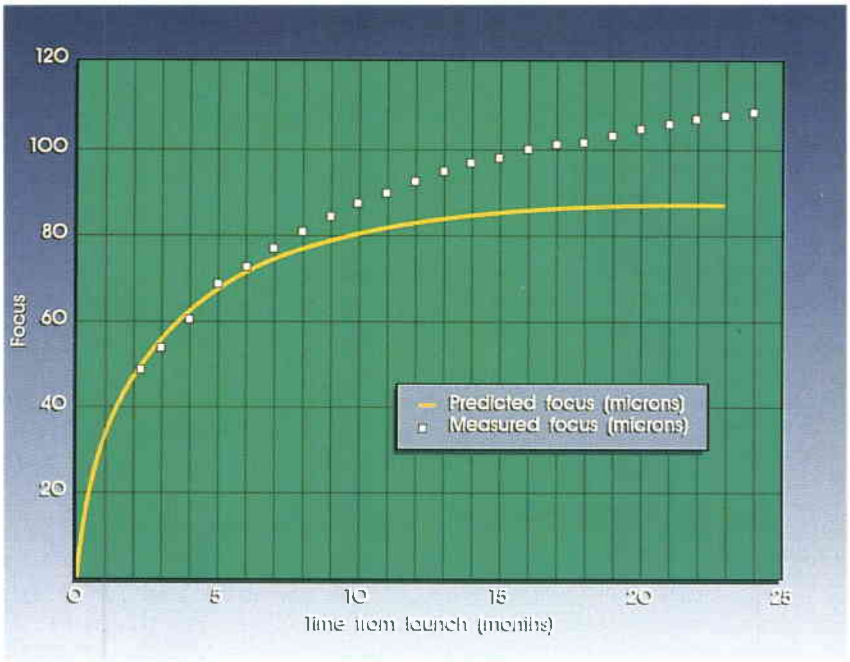


Figure 2. Focus variation (in microns) of the Hipparcos telescope as a function of time. The solid line refers to predicted values, and dots to those measured

Telescope optical performance

Image quality

Although it is not unusual to use Schmidt telescopes in space instrumentation, one of the critical components of the Hipparcos telescope is undoubtedly the 'beam combiner' mirror, which brings the light from the two viewing directions to a common focal surface. This mirror has an aspheric and asymmetrical profile to compensate for the optical aberrations induced by the large spherical mirror. The real challenge for the optical manufacturer was to cut this mirror after polishing, and to bond the two halves with a 29° angle, preserving in the process the extremely high optical quality (approx. 1/60th of a wavelength error on the overall optical surface). A mounting device with three 'pads' was required, and as a consequence the two fields of view are not supported in an identical manner.

Predictions of the in-orbit image quality (under the zero-gravity conditions experienced in orbit) indicated that the star images from the preceding and following fields of view should have a slightly different profile. This effect has been confirmed, and Figure 3 shows the small variations in the modulation factors of the first harmonic of the stellar signals. Interestingly, the modulating grid is not only a suitable device with which to measure star distances, but also a powerful tool for assessing the optical quality of a telescope in space!

Chromaticity effects

Optical simulations also predicted that the mirrors could not be designed and built in a manner that would be completely free from chromatic effects. Thus, with the measuring accuracies required of Hipparcos, it was expected that the measured star positions would be slightly colour-dependent.

Based on extensive interferometric testing under vacuum (but in a 1 g environment), it was possible to conclude that the specification should be met in-orbit (direct chromaticity measurements were not feasible on-ground with the required accuracy). Finally, in-orbit scientific data reduction has subsequently proved that the specification has been met and that the interferometric wave-front error analysis used during assembly and verification was a valid tool for predicting chromaticity effects at the level of about 1 milliarcsec.

Stability of bonded mirrors in space

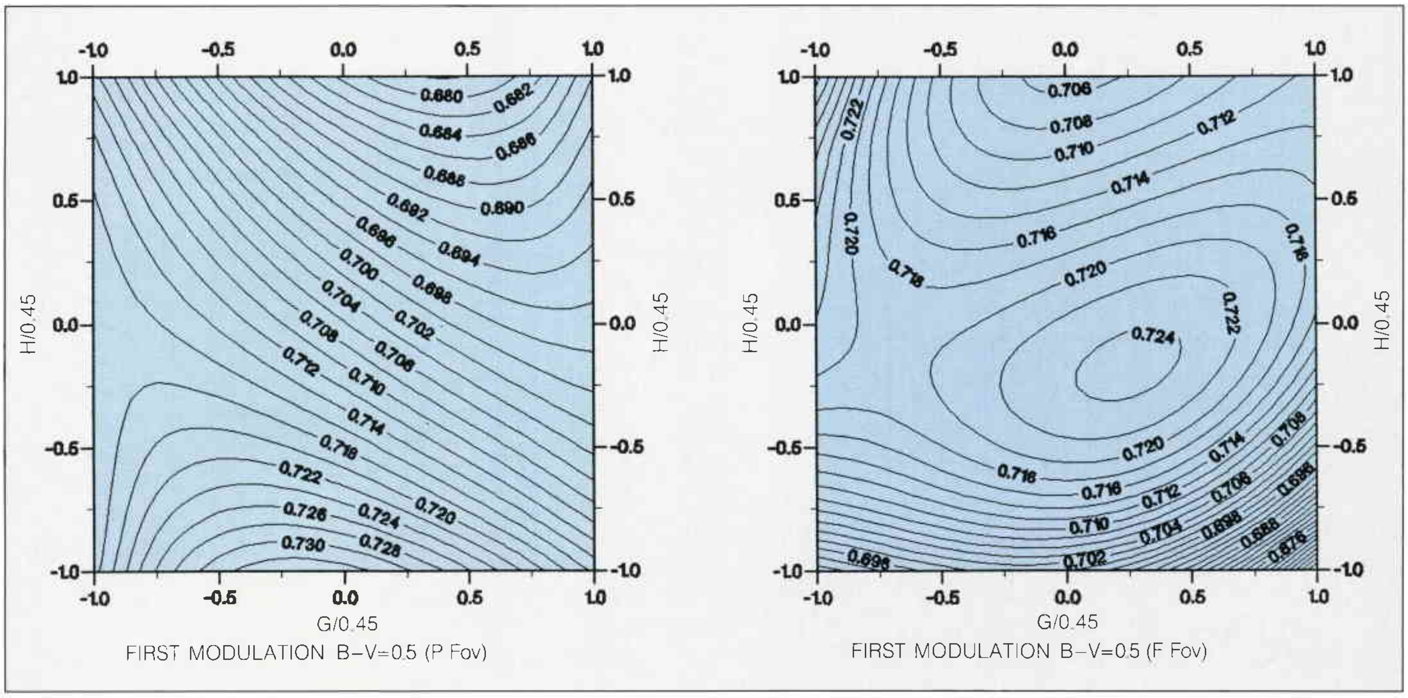
The angular stability of the bonded beam-combiner mirror is another critical parameter of the payload optics. The stability of the angle between the two fields of view (also known as the 'basic angle') was required to be better than 1 milliarcsec over any 2.8 h period. In Figure 4, the long-term variations in this parameter are displayed. The drift in the basic angle, derived from great-circle reductions, is actually better than about 1 milliarcsec per month. There is no doubt that the mirror's mechanical stability is a direct consequence of the good behaviour of the payload structure and the associated thermal control.

Grid performance

The Hipparcos modulating grid, which was deposited by an electron-beam pattern generation technique on the curved focal surface of the telescope, is without question a superb and unique item. A geometrical calibration was performed in the laboratory, prior to its delivery, with an accuracy in the range of 11 nm rms (or 1.5 milliarcsec). There was an almost inevitable caution about having full confidence in the validity of the measurements carried out in the submicron range, but in-orbit calibrations and routine measurements have proved that the grid manufacturing was so accurate that there is no need for a correction table for the main mission.

Particulate contamination

A significant concern during payload integration was the cleanliness of the surrounding environment. No substantial



FIRST MODULATION B–V=0.5 (P Fov)

FIRST MODULATION B–V=0.5 (F Fov)

Figure 3. Variation of the modulation factor M_1 (the first harmonic of the signal generated when the star crosses the grid) over the two fields of view (P Fov and F Fov). Note the steep variation in M_1 in the lower right corner of the right-hand figure due to a small local mirror deformation (such variations are calibrated during the data-analysis process). This type of information is derived as part of the instrument calibration during the data-analysis process, and has been supplied by the FAST Data Reduction Consortium. (Courtesy of F. Mignard)

contamination by dust or particles could be allowed, and the environment was specified to be 'Class 100'. In practice, no contamination problems have been detected by the scientific data-reduction consortia. A few 'cosmetic' defects, which were created during the manufacturing process and which were identified and catalogued during the grid's acceptance, have been confirmed by the data-processing teams. Figure 5 shows an example of the influence of such a defect on the modulated signal.

Degradation of payload efficiency under irradiation

With the revised highly-elliptical orbit, which intercepts the Earth's Van Allen radiation belts twice per day, early concern was expressed about the possible degradation of the payload's efficiency due to irradiation. Indeed, during each such passage, scientific data collection has to be discontinued due to the high background noise generated in the star-mapper detectors by the associated high-energy particles.

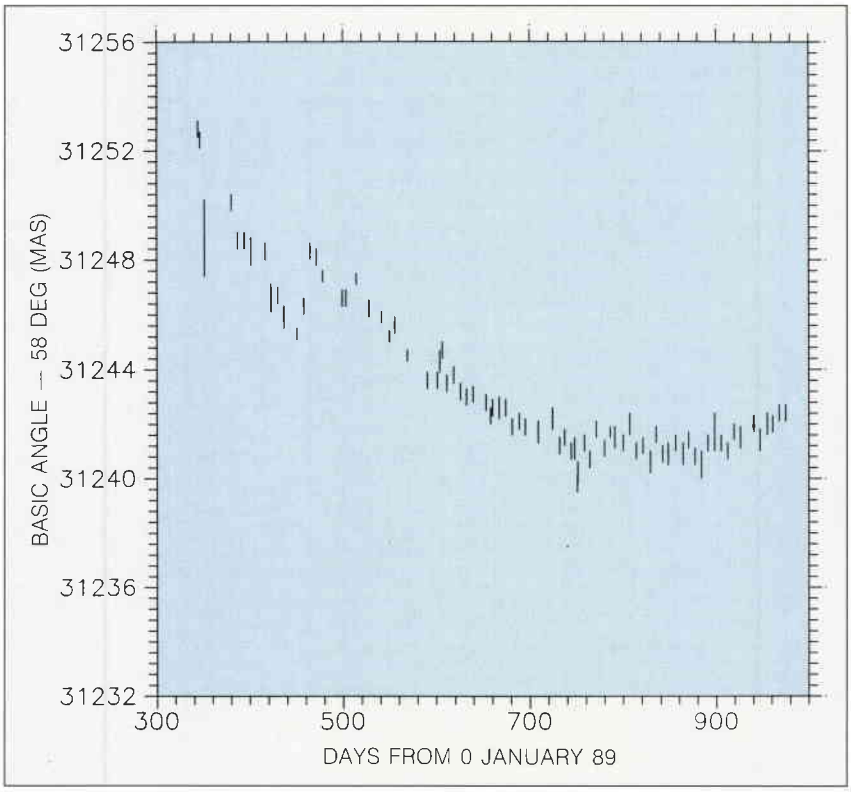
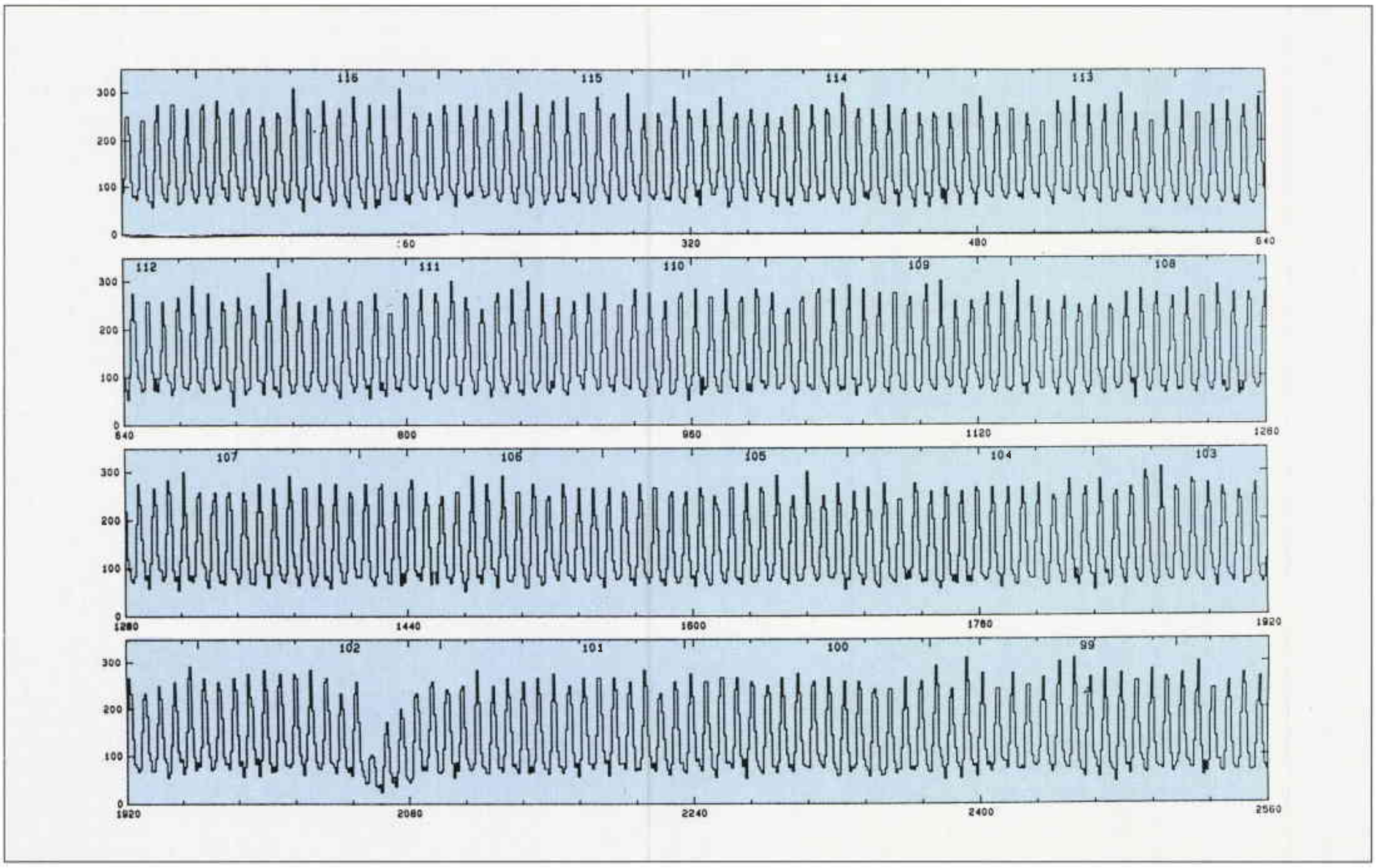


Figure 4. The variations in basic angle (the angle between the two telescope viewing directions) derived from scientific data reduction. A 'jump' due to a switch to the redundant thermal control unit at around day 440 is clearly visible. The long-term behaviour can be explained by small changes in the optical and structural elements (Results from the FAST Data Reduction Consortium, courtesy of H. Schrijver)

Figure 5. Influence of a small 'dust-like' grid defect on the output signal. The figure shows the modulated signal of a star as it passes across the focal plane of the telescope. This signal is regular, except at the location of the known 'defect' at the bottom left of the figure (Results from the FAST Data Reduction Consortium, courtesy of H. Schrijver)



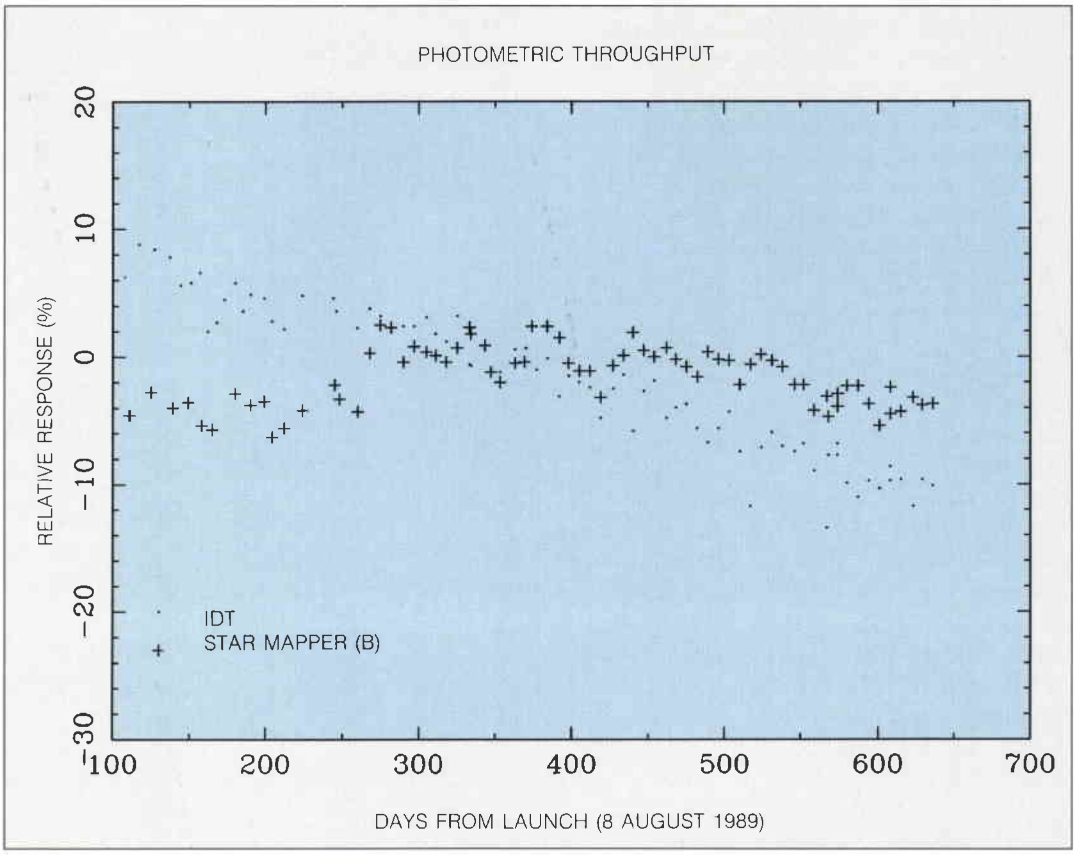


Figure 6. Photometric throughputs of the main detector (image dissector tube) and star-mapper (B) channels

By using some of the reference stars observed by Hipparcos, it is possible to monitor the payload's photometric throughput. Figure 6 shows that the star-mapper channels have remained almost constant, whereas a significant decay in the main detection chain (18% over 2 years) is apparent. The explanation lies in the fact that the radiation shielding for the optics was designed for the geostationary orbit, where the irradiation conditions are quite different to those experienced in the present situation. The star-mapper channels are less sensitive to radiation in that the lenses are made of fused silica and, with star mapper's less-stringent optical imaging requirements, there are fewer or them. The main detector relay lenses, which are more complex, have been manufactured from various (undoped) standard glasses. One may conclude that the loss in optical transmission is due mainly to the 'darkening' of the glass under irradiation. While the effect is clearly measurable, however, it will not significantly degrade the overall scientific return.

Conclusions

Certain new manufacturing concepts have been fully validated by the preliminary results obtained by the Hipparcos payload in-orbit. Despite the unforeseen highly eccentric orbit, the key Hipparcos payload performances are generally well within the pre-launch predictions. This excellent payload behaviour is contributing greatly to the first-class scientific results that are now being generated by the Hipparcos mission.

Scientific Involvement in the Hipparcos Mission

The Hipparcos observing programme is based upon a single, uniquely-defined Input Catalogue. Compiled at the Observatoire de Paris, Meudon, the preparation of this Catalogue has involved the collaboration of a large number of ESA Member-State scientists – both for the detailed assessment of currently-available data, and for the contribution of an extensive compilation of ground-based observations necessary to bring the observing catalogue to the quality necessary for the satellite observations and data analyses. While the INCA Team Leader is responsible for the Input Catalogue compilation as a whole, various 'task leaders' have been responsible for the various subsets of the work. The Consortium includes institutes from Belgium, Denmark, France, Germany, The Netherlands, Spain, Switzerland and the United Kingdom. Thus the Input Catalogue compilation has been a truly collaborative European scientific effort.

The data analysis tasks are similarly substantial, and the entire organisation of the preparation and execution of the work is even more complex. The overall Team Leaders of the three Consortia are assisted by Executive Committees comprising the 'task leaders' responsible for the various disciplines and data-processing stages and, where appropriate, by evaluation or software-maintenance groups. In all cases, the work of each Consortium is 'monitored' by a Steering Committee with representatives from each participating country.

Within the NDAC Consortium, the data analysis is performed in the countries that developed the respective software elements, i.e. in the UK, in Denmark and in Sweden, with the individual participating institutes ultimately responsible for their own software quality, data interfaces, and data management.

Within the FAST Consortium, a different approach has been followed, with the integrated software running within the CNES (Toulouse) computing centre; substantial elements of the integrated software also run within the Consortium's First-Look Facility at SRL (Utrecht). The software elements of the extensive overall scientific data-processing package have been developed within participating institutes in Italy, France, The Netherlands, and Germany. Acceptance tests were run before and after software integration, and the responsible institutes participate closely in the evaluation of results during execution.

The TDAC Consortium relies on some software elements and results of the data processing within NDAC and FAST (for example, the satellite attitude for TDAC is derived by the NDAC Consortium within Denmark, based upon the first analysis steps carried out in the UK; subsequent attitude updates are supplied by the FAST Consortium's main processing chain in France, based upon software developed in Italy). Other critical stages of the TDAC Consortium data processing are carried out at institutes within Germany and France.

The extensive cross-checking of the intermediate data-processing stages is carried out where the expertise and resources permit. Thus, for example, the one-dimensional 'great-circle' results determined by FAST and NDAC in CNES and Copenhagen, respectively, are inter-compared at the Geodetic Institute in Delft, where the relevant FAST software was developed; the precise reconstructed satellite attitude data from both Consortia are inter-compared and evaluated at CSS (Turin), where the software for the first stages of the FAST data treatment was developed and coded. Half a dozen other major inter-comparison exercises are carried out at various institutes. In addition, all the partcipating institutes take responsibility for the proper functioning and critical evaluation of their elements of the overall data-reduction package.

The Hipparcos Science Team, the composition of which has changed slightly during the lifetime of the Hipparcos project, advises ESA on all scientific aspects of the mission, through to the completion of the final Hipparcos Catalogue. It is made up of representatives of the scientific consortia involved in the mission, and presently consists of: P.L. Bernacca, M. Crézé, F. Donati, M. Grenon, M. Grewing, E. Høg, J. Kovalevsky, F. van Leeuwen, L. Lindegren, H. van der Marel, F. Mignard, C.A. Murray, M.A.C. Perryman (Chairman), R.S. Le Poole, H. Schrijver and C. Turon.

The principal participants in the four scientific consortia are listed on the facing page.

Summary of Expected Hipparcos Scientific Results

Number of stars (main mission)	118 000
Typical accuracy of positions (at 9 mag)	2 milliarcsec
Accuracy of parallaxes	2 milliarcsec
Accuracy of annual proper motions	2 milliarcsec
Photometry at each of 100 observations	0.01 mag
Information on binary or multiple systems	
Number of stars (Tycho experiment)	1 000 000
Accuracy in Tycho positions (at B=10.5 mag)	0.03 arcsec
Accuracy in Tycho photometry (B and V)	0.03 mag
Expected Hipparcos Catalogue availability	1995

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The Hipparcos Observing Programme: Preparation of the Input Catalogue

C. Turon
Observatoire de Paris-Meudon, France
Team Leader, INCA Consortium

Two years into the Hipparcos measurement programme is a convenient point at which to reflect on the observing programme of ESA's revolutionary astrometry mission, and to examine the extent to which it has fulfilled its scientific and operational objectives. The comprehensive scientific observing programme, and its complex operational implementation, have passed all post-launch tests supremely well and promise a scientific return unsurpassed in the history of astronomical positional measurements.

Introduction

A substantial effort has been devoted to the preparation of the Hipparcos Input Catalogue. Work on it commenced in 1981, soon after ESA's definitive selection of the mission, and the Input Catalogue has recently been published as ESA SP-1136 on behalf of the INCA Consortium, the group responsible for its compilation. It has been estimated that approximately 200 man-years of effort have been devoted to its production, with the collaboration of some one hundred scientists throughout the ESA Member States and beyond.

The Hipparcos Programme itself is dedicated to the precise measurement, for astrophysical and astrometric reasons, of the positions, distances and spatial motions of the stars in our region of the Galaxy. At the start of the Phase-B industrial activities, it had been foreseen that a Catalogue of some 100 000 pre-selected objects would satisfy the dual purposes demanded of it: first, as the definitive list of high-priority stellar targets to be observed by the satellite during its nominal two and a half year mission; secondly, to be able to use the astronomical targets themselves as the reference for the satellite attitude determination, both during the observations, and subsequently, during the data-reduction process.

Actually, as the launch date drew nearer, the parallel efforts of the data-reduction groups, who were designing their operational software to match the expected satellite data, and who were carrying out detailed simulations of the data-analysis tasks, were able to demonstrate that an enlarged observing programme had only a minimal impact on the eventual positional accuracies. As a result, the final observing list falls just short of 120 000 targets.

Assembling the Input Catalogue

The resulting 'Input Catalogue' was put together on the basis of an 'Invitation for Proposals' distributed by ESA to the worldwide astronomical community. As a result of this call, 214 scientific proposals, containing requests for more than 500 000 targets, were received in 1982 (these proposals are listed, along with a detailed account of the Input Catalogue and its preparation, in ESA SP-1111, Vol. II). The task of assigning scientific priorities, and assembling a unique list of stars for the observing programme, then began.

Various, and usually conflicting, requirements had to be faced in the Input Catalogue's construction. The satellite itself spins slowly across the sky at a constant rate, and the observing time that can be devoted to any one part of the sky is therefore strictly limited: any given area cannot contain too many stars, or too many faint stars. On the other hand, the satellite attitude-control process, and the subsequent stages of the data processing, demanded that there be a reasonably uniform sky density of sufficiently bright stars. Hipparcos actually lies somewhere between a 'survey' mission, where all parts of the sky are scanned in a predetermined manner, and an 'observatory facility', where objects are observed on the basis of their known coordinates and assumed scientific interest (this is also almost true for the Tycho experiment, which surveys the sky with the star mappers as the satellite spins, although a basic list of known stars is also used to facilitate the data analysis).

Pointing the Hipparcos detector to the required target, in the presence of the satellite's spinning motion, also demanded accurate knowledge of the star positions at the time of observation – about 1 second of arc, close to the limits of ground-based positional measurements for such a large number of stars. In addition, allocation of the available observing time to the programme stars present in the telescope's 1 square degree field of view demanded that the magnitudes, or star brightnesses, also be known to a rather good accuracy. All of this information had to be compiled well in advance of the launch.

The assessment of scientific priorities for each of the proposed scientific investigations was one of the first tasks to be undertaken, and it was entrusted to an ad hoc scientific peer review team under the chairmanship of Prof. Adriaan Blaauw. Three meetings of the Selection Committee took place over a period of nearly three years, in between which the INCA Consortium attempted to include the relevant proposed targets into the global observing programme. The progress towards a final observing list was made in an iterative manner, with many of the recommendations being reviewed in the light of simulation results, competing proposals and, in some cases, the comments of the original proposers themselves. The unusual step of requesting the views of the proposers on the recommendations of the peer review group was intentional: there would only be one Hipparcos observing list, and it had to be drawn up with its historical significance in mind!

Achieving order out of confusion

There are large numbers of astronomical catalogues in existence. A given star may figure in only one such catalogue, depending on its brightness, astrophysical nature or astrometric measurement history, or it may be contained in many catalogues, assembled over 50 years or more. Each of the catalogues might reflect a different scientific interest in the star: it could be contained in early 20th century sky-survey measurements, in lists of variable stars or of double stars, in recent programmes of radial velocity measurements, or in any of dozens of other lists scattered throughout the vast astronomical literature. Here the confusion started.

Depending on the scientific interest expressed by a given proposer, the same star could have been proposed under numerous different identifiers, with different information provided on its position or magnitude, depending on the catalogue from which it was selected. For many astronomical studies, a coordinate or magnitude slightly in error might have very little repercussion – it could still be found within the field of view of most ground-based telescopes, albeit with a little searching with the assistance of 'finding charts' by the observer. For Hipparcos, such an error would mean missing the star altogether, or allocating an incorrect observing time to it, or including it twice or more within the observing programme at different locations! The unification of the data received from the proposers, the selection of the best-available positional and photometric data for each star, and the assessment of whether further ground-based observations of the objects would be needed to meet the observational requirements of the satellite, were enormous tasks.

These tasks were eased substantially, but by no means completely, by the existence and convenient access to the SIMBAD stellar database of the Centre de Données Astronomiques de Strasbourg (CDS). From the 500 000 or more candidate targets proposed, the basic list of stars requested was reduced to about 230 000 distinct stars. The incorporation of scientific priorities and the outcome of simulations of the way in which the satellite observations cover the sky, slowly (over the period of the INCA Consortium's work) reduced this number to the final target list of nearly 118 000 objects. Whilst representing just 55% of the total list of targets proposed, this final programme actually contains 94% of the 'priority 1' programmes, as defined by the Selection Committee (Figs. 1 & 2).

This final target list provided a network of stars over the entire sky, some three stars per square degree on average, merging astrometric and astrophysical interests, and balancing scientific, observational and operational considerations. The INCA

Task Leaders within the INCA Consortium

C. Turon (Team Leader), M. Crézé, D. Egret, A. Gómez, M. Grenon, H. Jahreiss, Y. Réquième, A.N. Argue, A. Bec-Borsenberger, J. Dommanget, M.O. Mennessier, J.C. Mermilliod, L. Prévot, F. Arenou, M. Chareton, F. Crifo, D. Morin, B. Nicolet, O. Nys, M. Rousseau, M.A.C. Perryman

The above names represent the involvement of some 100 scientific personnel in the Input Catalogue preparations.

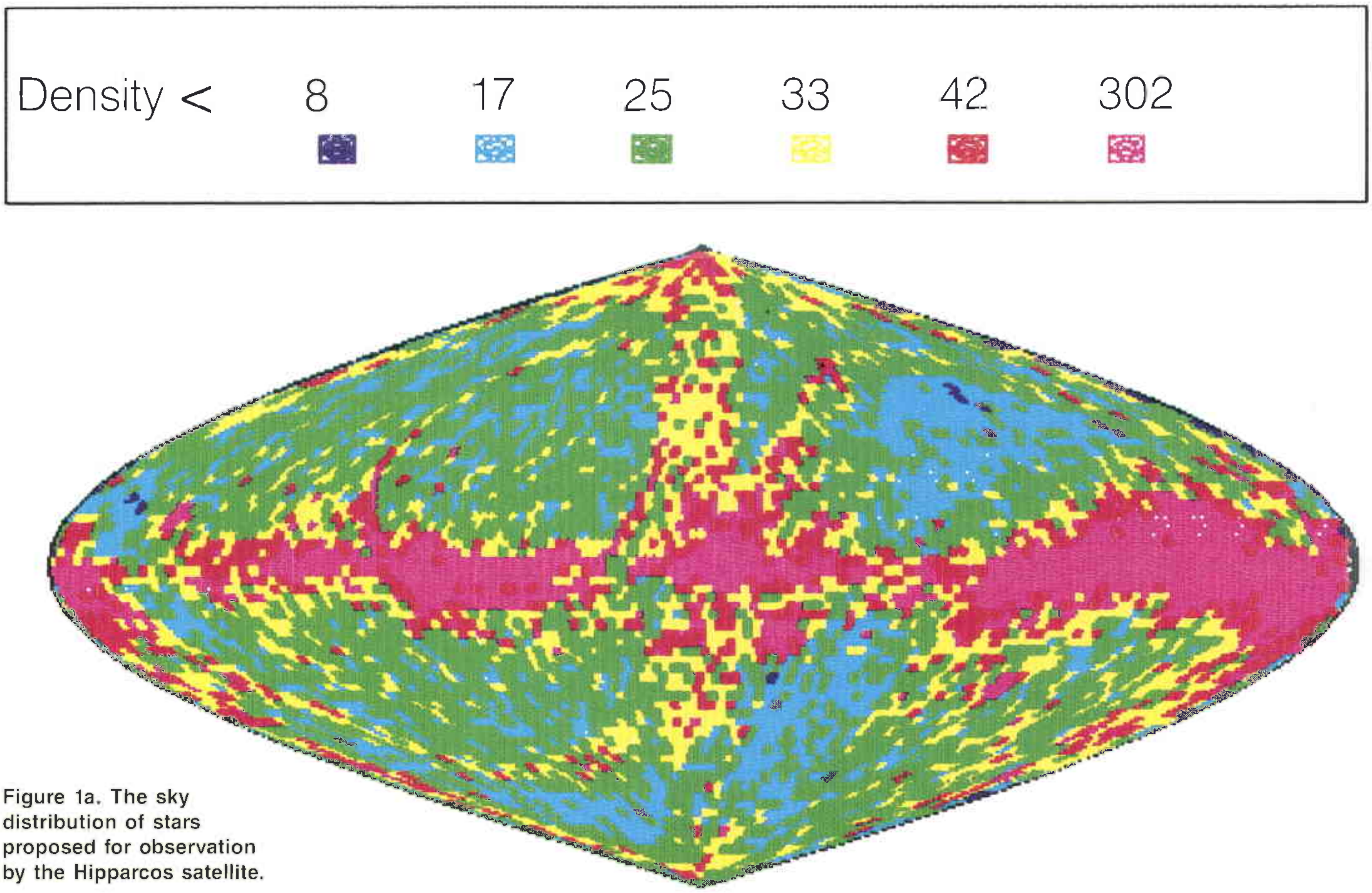

Figure 1a. The sky distribution of stars proposed for observation by the Hipparcos satellite.

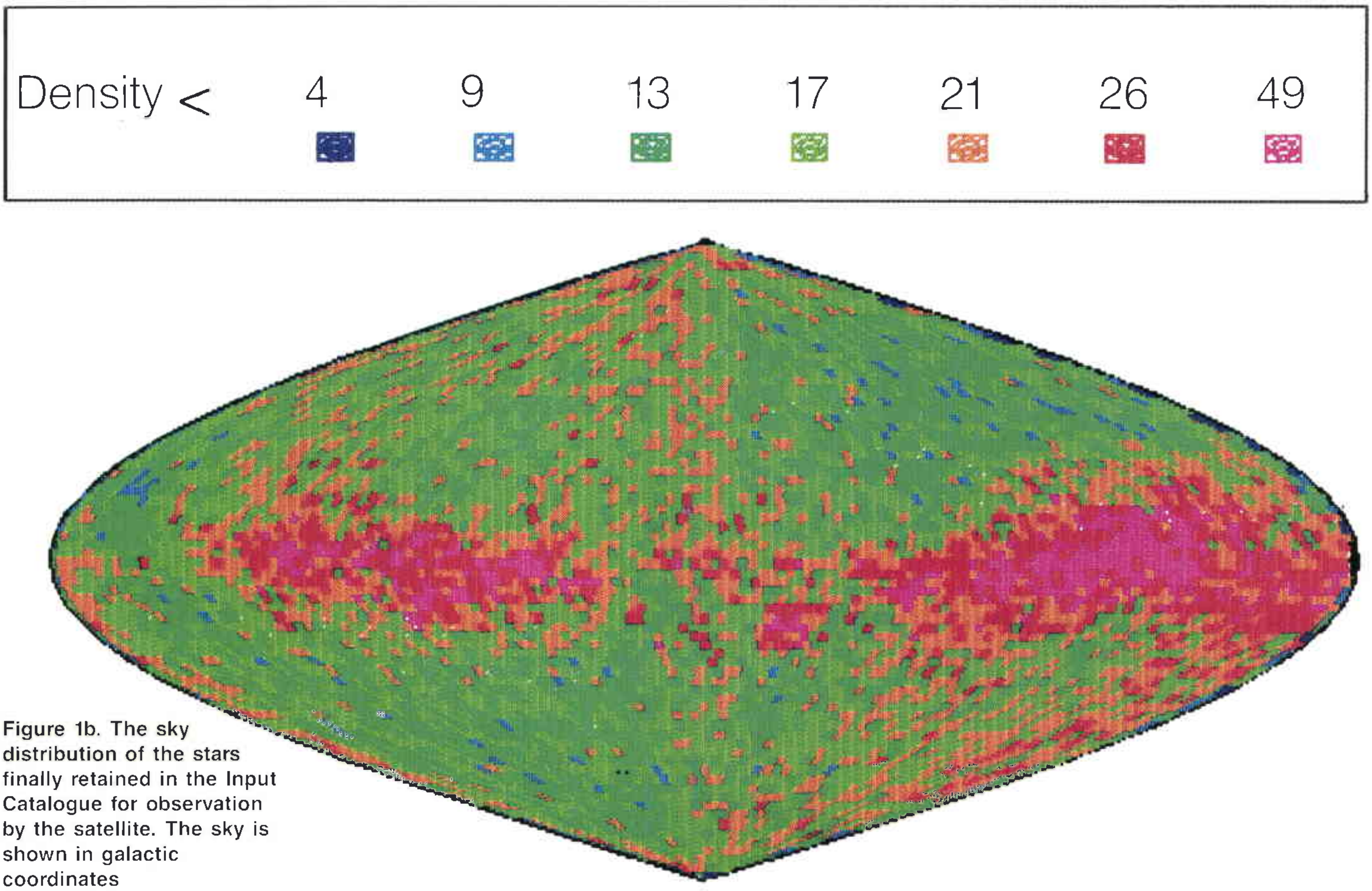

Figure 1b. The sky distribution of the stars finally retained in the Input Catalogue for observation by the satellite. The sky is shown in galactic coordinates
(Courtesy of F. Arenou)

Consortium also proposed observations of astrophysically-interesting candidates where these had been omitted from the entire list of observing proposals. Consequently, the final Input Catalogue ensures a substantial sampling of the most important stellar categories present in the solar neighbourhood. The Consortium also ensured that a list, of 52 000 bright stars, was contained within the observing programme which was complete to well-defined magnitude limits (around 7.3–9 mag, depending on galactic latitude and spectral type of the star), important for statistical studies of the Galaxy and the solar neighbourhood.

The ground-based preparations

Careful astrometric and photometric studies of each star in the observing programme were needed in order to assess whether the available information was sufficient to allow the Hipparcos observations to be made. A massive series of ground-based observations was then embarked upon: measurements of about 100 000 star positions from photographic plates, some 10 000 additional positions from automatic meridian circle observations, 10 000 star magnitudes and colours obtained from multi-colour photoelectric photometry (the particular photoelectric system being chosen according to the star's spectral type in order to be able to derive astrophysically-useful parameters in addition to the star's magnitude). More than 100 000 star colours were computed from spectral types combined with a new model of light extinction within our Galaxy. Not all of these new observations are included directly in the Input Catalogue, although it does contain a substantial body of previously unpublished data.

Special programmes were undertaken to deal with particular, and particularly 'troublesome' (yet scientifically important) objects, such as double and multiple star systems, variable stars, and stars in high-density regions of the sky such as galactic open clusters, and the Large and Small Magellanic Clouds, minor planets or asteroids (48 are contained within the final observing list), and the moons of the major planets Jupiter and Saturn which are observable with Hipparcos.

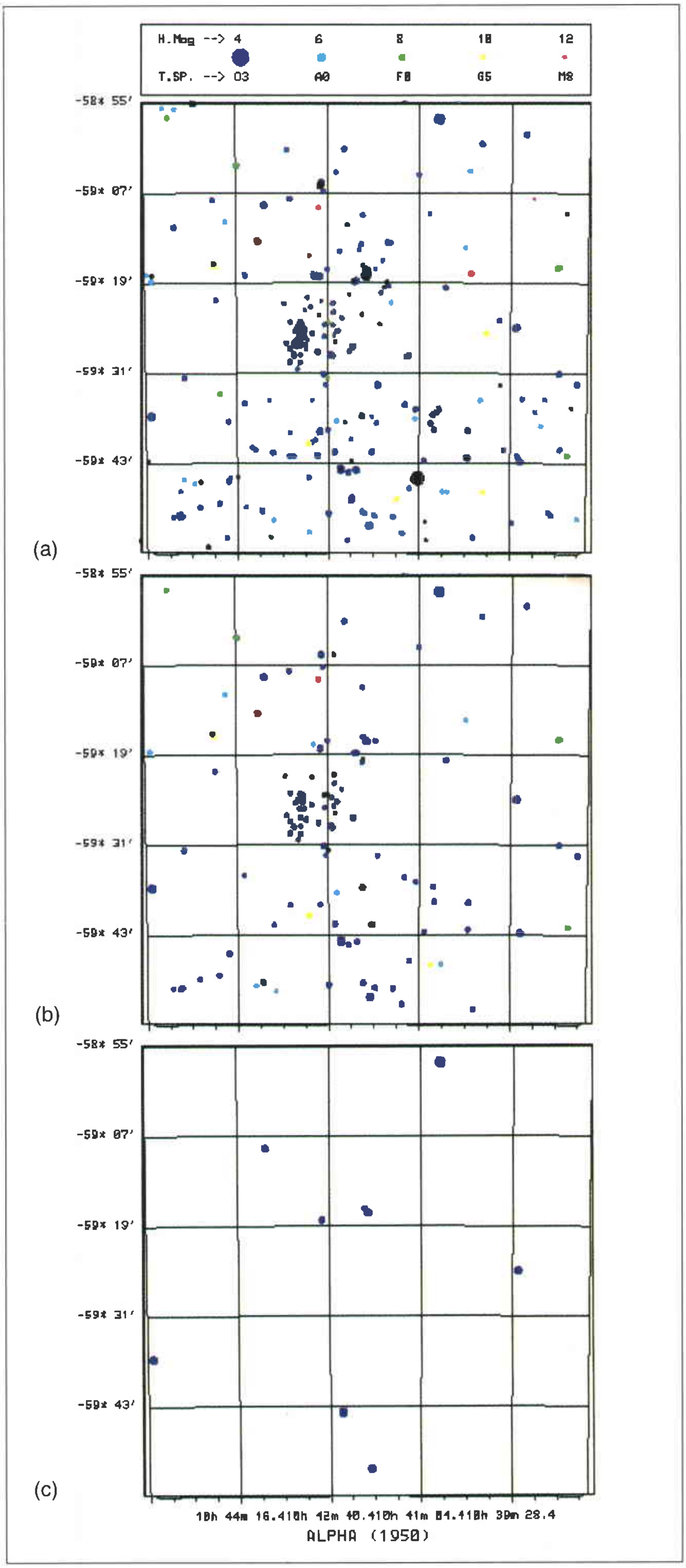

Figure 2. The situation in a very dense area of the sky near Eta Carinae:
(a) all stars from the SIMBAD Database
(b) all proposed stars, and
(c) the stars retained in the Input Catalogue

(Courtesy of F. Arenou)

The effort and attention to detail required to prepare for and match the unique observing capabilities of the Hipparcos mission were formidable. The Input Catalogue was nevertheless delivered to ESA, for interface verifications, and implementation at the ESOC Control Centre, well in time for launch. Prof. Adriann Blaauw, who chaired the scientific selection and in effect has monitored the INCA Consortium's work over the past ten years on behalf of the end-users of the Hipparcos data, has made the comment that:

> *'Few, if any, satellite projects have produced already before launch so many things useful to astronomy as Hipparcos has. I hope nobody will mind if, for a moment, and most disrespectfully, I call Hipparcos the biggest vacuum cleaner astronomers have ever seen'.*

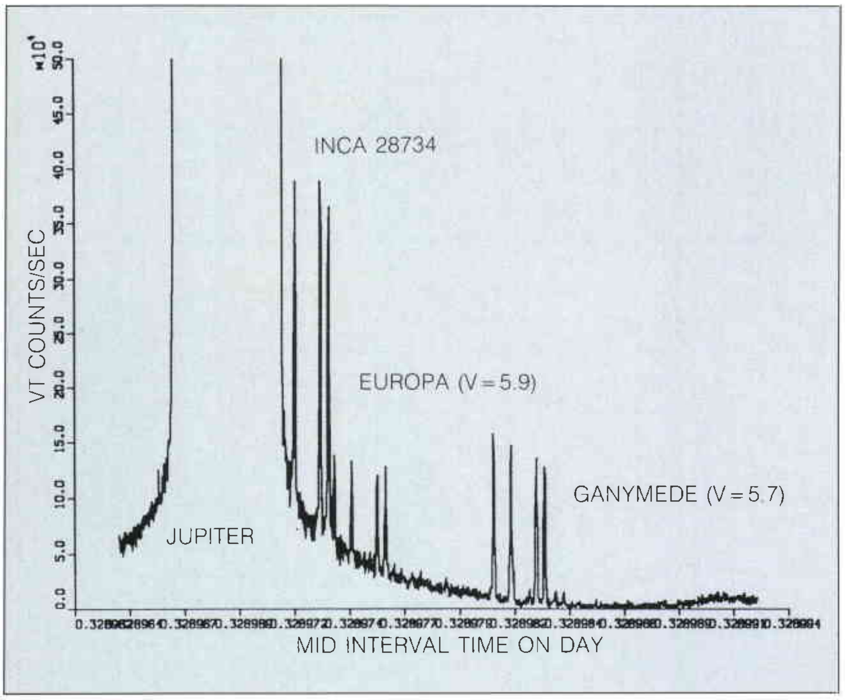

Figure 3. The transit of Jupiter and its moons across the satellite's star mappers

Payload commissioning and the Input Catalogue

The way in which the Hipparcos satellite makes its measurements – relying on those very measurements in order to determine its real-time attitude, and thus point to the area of the sky in which the next objects are to be found, sounds like a circular process almost too good to be true. The problem is compounded further by the telescope's two viewing directions on the sky, separated by about 58°, which are superimposed within the payload onto the same focal surface. Such a complex system is, of course, impossible to test out fully on the ground, and the first measurements were awaited both with excitement and some anxiety.

Once in orbit, when the satellite was set spinning about its axis, and the baffle covers opened to allow star light into the payload's star mappers, the first system tests could begin. Star images were indeed seen, clearly modulated by the star-mapper grid, the signatures of bright stars transiting every few seconds. The first stage of the attitude-measurement routine consisted of matching these transits with those expected from the strip of the sky that the satellite was known to be scanning – a pattern-recognition problem complicated by the two superimposed fields of view. This complex and delicate stage, however, ran smoothly, and the Input Catalogue passed its first tests with distinction. Almost without exception, the 60 000 or so 'reference' stars were seen at their expected locations, within a second of arc or so of their expected positions, and with their correct amplitude in both photometric channels of the star mapper. Thus, not only were catalogue positions good, but their space velocities (needed to estimate the star positions at any time, based on information compiled at another observation time) were too (Fig. 3).

With the star mappers operating, the satellite's attitude is known by the on-board computer to within about 1 arcsec at all times, based upon the transits of bright stars, and the on-board gyroscopic updates about all three satellite axes in between those transits. The main detector on board the Hipparcos satellite has a very small sensitive area, which is about 30 arcsec in diameter, and this can be commanded electronically, by the on-board computer, to point to the star to be observed once the satellite's attitude is known, and once the expected location of the star is available to that computer. The information necessary to point the detector to the candidate star includes its expected time of entry into the detector field of view, and the location in the x–y detector plane at which the star is expected to commence its transit.

All information needed to run the observing programme and, in the process, control the satellite's attitude motion as it scans the sky, is prepared on the ground at ESA's European Space Operations Centre (ESOC) in Darmstadt (D) on the basis of the contents of the Input Catalogue, and using the predicted scanning motion derived from details of the deterministic scanning law.

A subset of the stars, namely those with a large amplitude of variability, cause some of the greatest problems. Their brightnesses (based on past observations from the ground) have to be predicted before uplinking the details of the star observations to the satellite – if the star is very faint at the time of observation, it may need to be allocated more observing time, or dropped altogether from the observing programme for that particular forthcoming observation. Minor planets and the planetary satellites also add their own special complications to this aspect of the regular mission planning and implementation: their current positions need to be determined on the basis of detailed tabulations of their motion within our Solar System. These interfaces were comprehensively verified pre-launch, and all have run smoothly throughout the mission.

Each star takes approximately 20 s to cross Hipparcos' field of view, due to the satellite's spinning motion (it rotates about its spin axis approximately once every 2 h). But in this interval, many other Input Catalogue stars (some six on average in the combined field) are also present. The on-board computer allocates observing time to each star as it transits, based on its brightness, its scientific priority, and the details of the other stars in the same field competing for observing time. The observations are, in practice, interlaced rapidly and repeatedly, in order to compensate for any satellite jitter, so that the star observations are effectively made instantaneously. The data is telemetered to the ground, with real-time signal monitoring being conducted at ESOC, where the data are archived for despatch to the scientific teams responsible for data processing.

The next stage of the verification of the Input Catalogue therefore takes place at ESOC, during the signal monitoring. Only if the star is within a few seconds of arc of its expected location will a signal be seen, and only if the Input Catalogue position and the star brightness predicted for the main detector are good will the signal have the expected modulation signature (created by the grid of opaque and transparent slits at the telescope's focal surface). Since launch, and from the results of some 'quick-look' processing carried out by the data-reduction teams, we now know that for fewer than 100 of the 120 000 programme stars is little modulation seen. For these few stars, this is an indication that the catalogue positions or magnitudes were poor, or in some cases quite simply wrong: for some of these, checks were made on the ground and corrections implemented for Hipparcos' next observations of that part of the sky. Given the inhomogeneous material from which the Input Catalogue was created, the matching was by-and-large excellent, and probably exceeded any reasonable expectations. The Input Catalogue was largely validated, and certainly permitted the Hipparcos satellite to operate, and carry out its scientific measurement programme, in an outstanding manner.

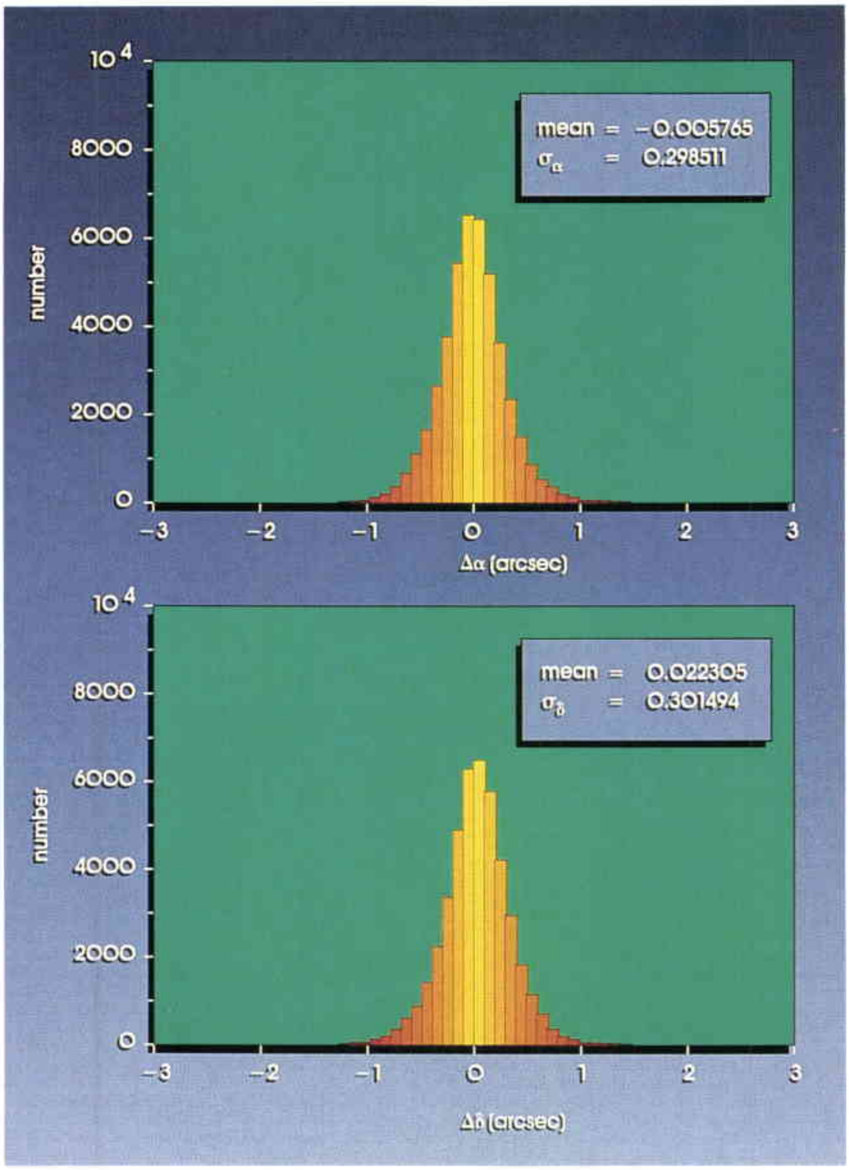

Figure 4. A comparison between the Input-Catalogue positions (in both coordinates on the sky: right ascension and declination) and those obtained from the first few months of satellite observations using the satellite's star mappers. Because the star-mapper observations are of such high precision compared with those obtainable from the ground, these figures show the actual errors on the Input Catalogue positions (the results combine the INCA positions with those derived by the NDAC Consortium, supplied by F. van Leeuwen)

Feedback from the data processing

The ground processing of the Hipparcos data is a huge and complex process, requiring the treatment of some one thousand million bits (1 Gbit) of data per day. Each day, this vast supply of information flows into the mass data-processing tasks running on the ground; it must eventually be processed in its entirety to yield the improved star positions, space motions projected onto the celestial sphere, and distances, which are the goal of the Hipparcos mission. The final stages of the Input Catalogue verification require the Hipparcos results themselves to cross-check, independently, the validity of the star positions compiled on the ground. This can be carried out at two levels: at the relatively coarse level of the star-mapper observations, and later at the level of the main Hipparcos detector observations.

Comparison of Input-Catalogue contents with star-mapper results

The general properties of the Input Catalogue can already be deduced from the results obtained from the star mappers, without waiting for the final, or even intermediate, results from the main data-processing chain (which will ultimately yield results of much higher precision). Within both of the main data-processing teams (the NDAC and FAST Consortia), the on-ground processing of the star-mapper data is an essential first step in refining the real-time knowledge of the satellite's instantaneous attitude. The actual times of the signal transits of a given star across the star-mapper grid, compared with the predicted transit times, provide an estimate of the discrepancy between the predicted position of the programme star and its true position.

Figure 5. Members of the INCA Consortium Executive Committee, January 1988

Thousands of such transits are recorded and processed each day, and the data can be compiled to build up a consistent picture, not only of the satellite attitude to an improved accuracy of about 0.1 arcsec, but also of the star positions to a similar accuracy. Star-mapper information in the two photometric channels provides details of the star's intensity and 'colour', and transit times for the same star with different scan orientations (obtained at different times of the year) yields information about any other nearby companions that the star may have, i.e. whether the star is a member of a double or multiple system. The results from a few months of such star-mapper data processing are shown in Figure 4. These types of results have shown that the Input Catalogue positions are indeed of the quality expected pre-launch: the error distributions are symmetrical, have a width of about 0.3 arcsec, and show no strong variations as a function of position on the sky. This was most encouraging, and indicated that the large-scale regional errors in positional measurements acquired from the ground were not in general above this level of significance. Magnitudes in both star-mapper colours are also found to be in excellent agreement with expectations, and double-star systems that could be clearly identified as such before launch show up in the data processing with the expected properties (separation, magnitude difference and position angle).

Comparison of Input-Catalogue contents with main mission results

It is very early days to describe the results of the main mission processing, and thus to assess the Input Catalogue's performance and features at the level of a few milli-arcseconds; this is part of what the entire Hipparcos mission is all about. However, the first, very provisional results of the 'sphere solutions' from the main mission data processing are just beginning to appear, and some early, again tentative, pictures are beginning to emerge. These are described in the accompanying article on the scientific results.

Conclusion

The Input Catalogue is not perfect. No star catalogue is, and indeed this is the reason why the Hipparcos mission was undertaken in the first place – to improve our knowledge of the star positions. But the Input Catalogue has served as a perfect, albeit highly complex, tool both for operating the Hipparcos satellite with optimum efficiency, and for ensuring that a scientific programme of maximum quality can be undertaken with this unique mission.

Hipparcos Data Reduction — Construction of the Hipparcos Star Catalogue

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The on-ground treatment of the Hipparcos satellite data is the largest and most complex data-analysis problem ever undertaken in the history of astrometry. Assembling a final and highly accurate catalogue of star positions, distances and motions presents a unique problem, both scientifically and from the data-management viewpoint, for the Consortium of European scientific institutes involved in the tasks. The development of the data-analysis techniques guided the development of the satellite design itself. Self-checking procedures, implicit in the satellite measurement and data-analysis techniques, demonstrate that the ultimate astrometric catalogue promised by the Hipparcos mission will shortly become a reality.

Introduction

When in contact with one of the three ground stations, the Hipparcos astrometry satellite returns an uninterrupted flow of data to the ground at a rate of 24 kbit/s. This stream contains data from the primary optical detection system on-board, which measures the relative along-scan separation of programme stars present within the combined fields of view of the Hipparcos telescope, as well as information from the satellite's attitude measurement and control system. The data reductions then consist of re-assembling these data into a system of star positions, distances and spatial motions. In the process of the signal analysis, valuable information on the brightnesses of the 120 000 stars within the main measurement programme, and information on the double or multiple nature of the observed stars, is derived. An auxiliary catalogue (the Tycho Catalogue, which is of lower positional precision but which contains additional photometric information) of perhaps as many as one million more stars is being constructed from the data stream sent down by the satellite's star mappers. The lengthy and complex catalogue construction tasks are now fully under way.

The data-reduction tasks

The goal of the Hipparcos measurements is to determine star positions with an unprecedented accuracy – a factor of a hundred or so times better than realistically achievable from the ground for such a large number of stars. By making these very accurate measurements from space over a period of about three years, and repeating the observations of the same stars at different times and at different 'orientations' on the celestial sphere, the tiny changes in the star positions due to their actual motions through the Galaxy, and the minute shifts in their apparent positions (reflecting their distances; Fig. 1) as the Earth moves around the Sun, can be discerned.

From the very beginning of the Hipparcos project it was evident that the process of building the Star Catalogue from the type of astrometric observations that could be made in space was going to be a difficult, and delicate, task. Indeed, a significant effort was devoted during the Phase-A studies of the mission to identifying the procedures that could be used, assembling the mathematical tools necessary for analysis of the data, and demonstrating (through simulations and mathematical modelling) that the necessary accuracies were achievable.

The problems in devising an overall data-analysis procedure were threefold. First, a method had to be identified which would allow the basically one-dimensional

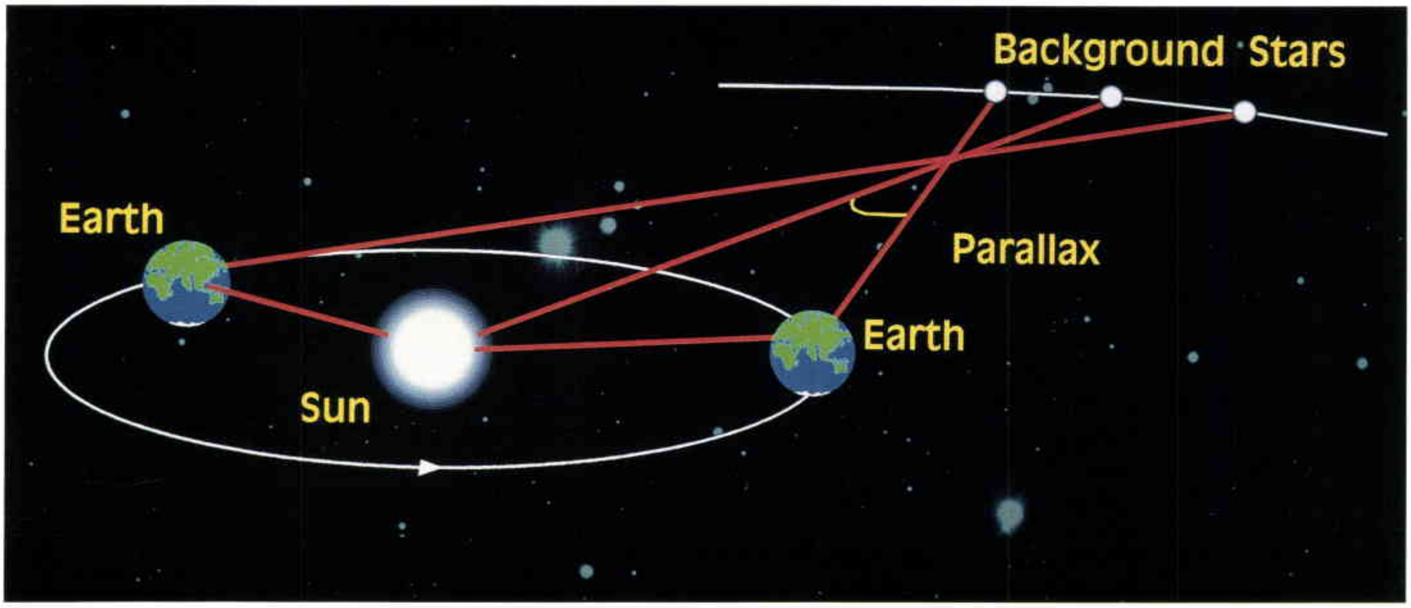

Figure 1. The principle of measuring a star's parallax, or distance. The distance determination relies on the fact that a star's position appears to change with respect to more distant objects as the Earth moves in its annual orbit around the Sun. Thus relative measurements between any pairs of stars on the sky will also change, according to the stars' distances, the time of year, and the direction along which the measurements are projected

measurements foreseen for the Hipparcos satellite to be built up into a catalogue of two-dimensional positions, motions, and distances. Secondly, the method had not only to be possible in theory, but also possible to implement computationally. Thirdly, the data-processing tasks would have to be implemented in a manner that allowed extremely stringent control over any possible sources of error. The effects to be studied were very much at the limits of the possible satellite technology, and errors arising in the measurements or in their processing could, all too easily, propagate through to the final scientific catalogue.

The fact that the first two of these problems could be overcome was demonstrated during the period of the Phase-A study activities. It was shown that the measurements could be combined in three discrete steps, and the method became known as the 'three-step method'; it is described below in greater detail. The adoption of this method also opened the way for comprehensive simulations (during the Phase-B activities) which could assess the accuracy of the final catalogue resulting from various assumptions: such as the telescope size, the number of stars in the observing programme, the mission duration, and many hundreds of other details which could influence the precision with which the data could be gathered, and the manner in which it could ultimately be compiled into the final catalogue.

The complicated nature of the entire data-analysis procedure, combined with the very stringent requirements on the control of errors throughout the measurement and analysis tasks, resulted in an unusual approach being adopted for the reductions. It was agreed by the scientific community who were supporting the Hipparcos mission, and indeed strongly encouraged and endorsed by ESA and its advisory committees, that the entire set of analysis tasks should be carried out by two separate teams of scientists. Working largely independently, but using, of course, the same satellite data, two catalogues would be produced. In effect (although the true situation is much more involved), an inspection of the catalogues produced by each team would lead to a much greater degree of confidence in their final results, and in the manner in which these results had been achieved. The nature of the problem can be put into perspective by noting that the reductions represent the largest data-analysis problem ever undertaken in astrometry, if not in astronomy as a whole.

The measurements and the three-step analysis method

The goals of the Hipparcos mission, and the measurement principle of the satellite and its early performance in orbit, have been described in previous ESA literature (the methods adopted for the data analysis have been described in detail in ESA SP-1111, Vol. III). The satellite consists of a telescope with two viewing directions, separated by about 58° on the sky, and each has a field of view of about 1° square. A total of about six stars (out of the 120 000 stars contained in the overall programme) – an average of three within each field of view – are observed at the same time. The on-board detector measures their relative positions by means of a modulating grid at the telescope's focal surface; star images cross the grid and produce a modulated intensity signal, which is sampled and sent to the ground for analysis. The satellite spins slowly (once

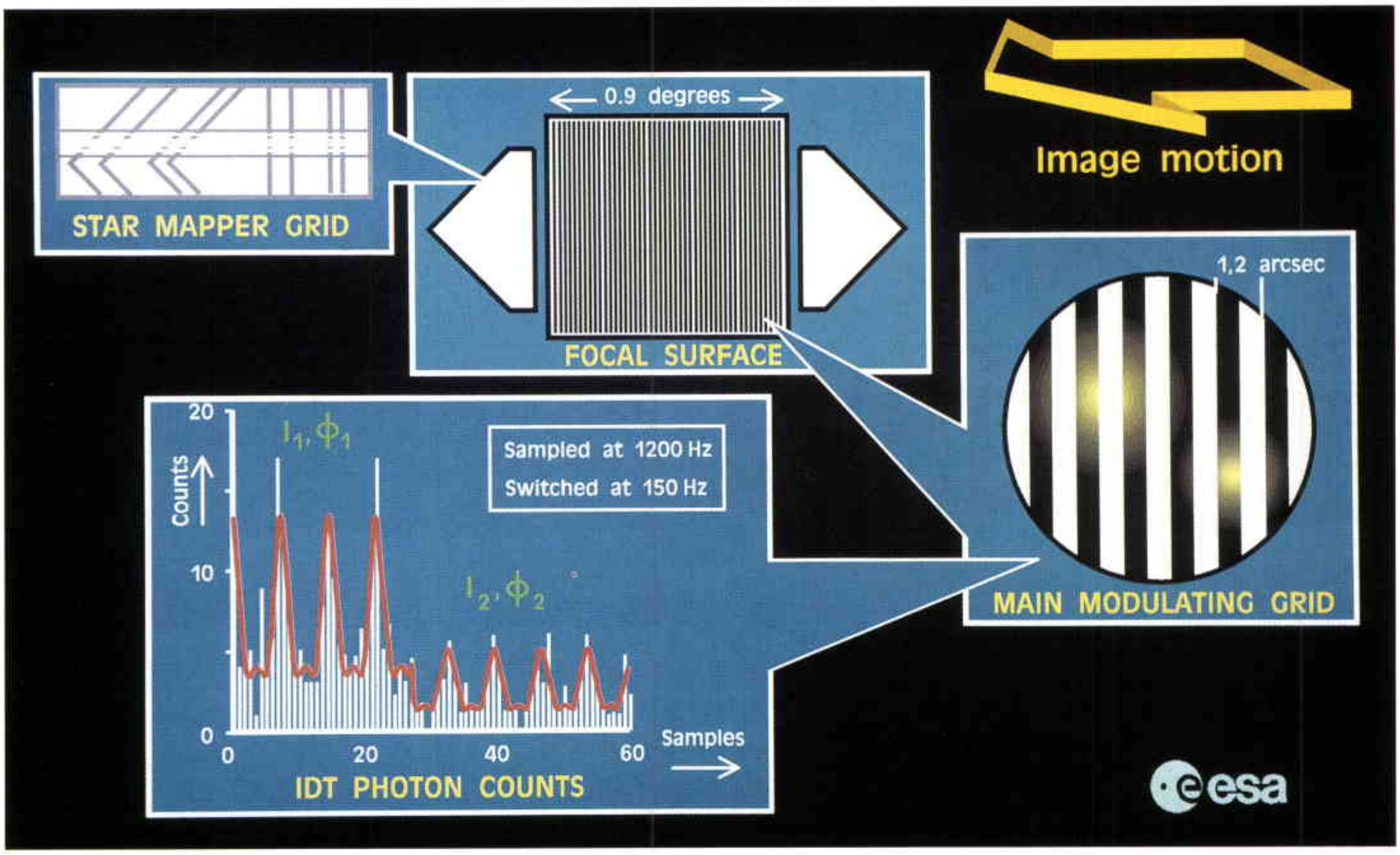

Figure 2. The Hipparcos relative-phase measurement principle

every 2 h) about its spin axis, which itself moves slowly around the sky. Stars enter and leave the fields of view as the satellite spins, and in this way a dense measurement network of relative star positions is built up (Fig. 2) over the entire mission duration. As the direction of the satellite's spin axis moves across the sky, relative measurements are made at different orientations and at different times, from which the star positions and their motions can eventually be deduced (Fig.3).

The overall flow of data through the reduction algorithms is shown in Figure 4. Within the data reductions, measurements taken over an interval of about 10 h, corresponding to the orbital period of the satellite in its revised elliptical orbit, are combined together. The first part of the three-step method consists of estimating the relative one-dimensional positions of all the stars contained in the strip of sky scanned during the 10 h interval (roughly a circle of 1° width), each with respect to the others. Essential inputs to this task are the modulation signals for each star, analysed to yield an intensity and a phase of modulation (the relative phases themselves provide an estimate of the relative positions of the stars in the scanning direction), and estimates of the satellite's attitude throughout its scanning motion (derived from the star mapper and, in the case of one of the analysis teams, using the on-board gyro signals; Fig. 5).

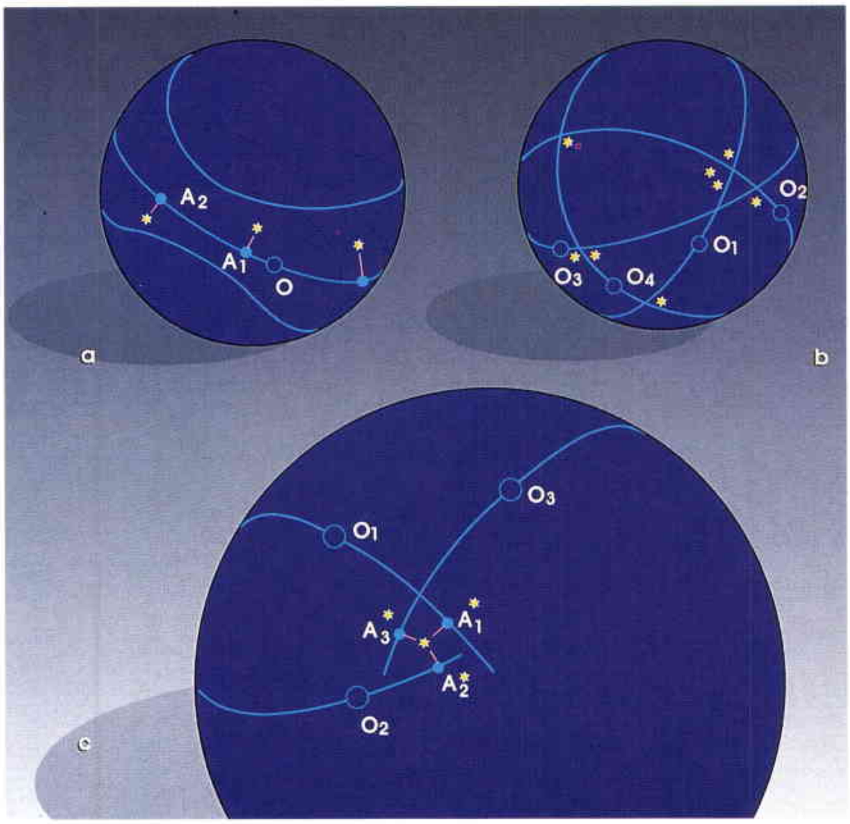

Figure 3. The elements of the three-step method adopted for data reduction. In (a), star-position measurements made on successive scans (which approximate to true great circles) are projected onto a well-defined reference circle; in (b), the origins (O) of the different circles are solved for in the 'sphere solution' process; in (c), the astrometric parameters of each star (A) are solved for by considering their positions on different circles built up throughout the mission

Typically, about 2000 stars are contained within such a strip of the sky. Strong closure conditions exist in the system of equations that describe these 'great circles' on the sky, and this fact allows for a solution to be made of the transformation that describes how the sky actually 'maps' onto the focal surface of the instrument. Monitoring this transformation versus time gives an indication of how well the equations can be solved, how accurate the star positions determined are, and how the instrument itself changes with time. The resulting description of the instrument can be formulated to a remarkably high level of accuracy: for example, the angle between the two viewing directions is determined to about 0.2 milliarcsec every 10 h, and it is seen to change by only 1 milliarcsec or so per month. This behavioural quality is even better than the original payload specifications, and such detailed information has allowed a good model to be constructed which describes how these instrumental parameters are related to changes that are taking place on-board the satellite. Other parameters in the transformation between the coordinate system on the sky, and the coordinate system on the telescope's grid, are determined at the same time as the basic angle (Fig. 6).

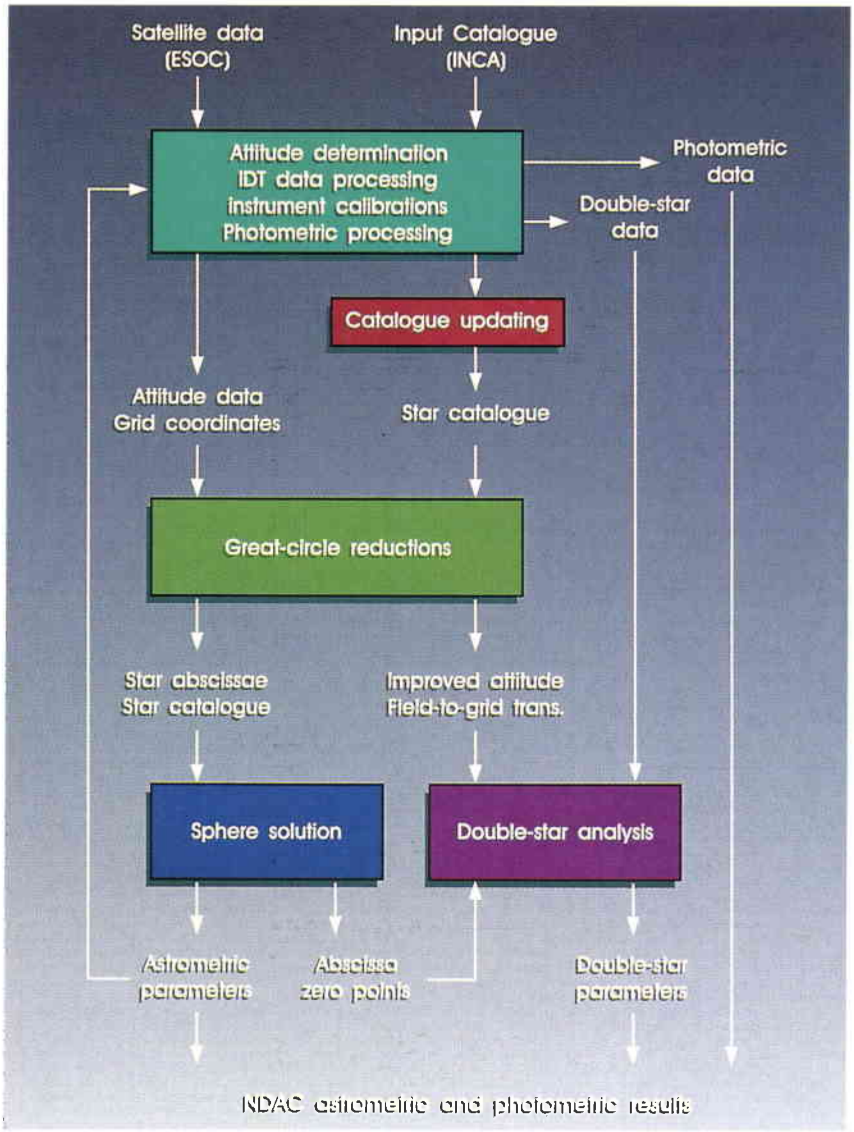

Figure 4. The flow of data through the data-analysis tasks (showing the procedures followed by the NDAC Consortium)

Combining circles into spheres

Every 10 h orbit therefore yields a set of 2000 one-dimensional star positions covering one great circle on the sky. In the data-analysis process, these results are calculated from the raw satellite data, then put aside until enough circles are available to carry out step 2 of the three-step procedure. This involves the interconnection, and interlocking, of a large number of these circles, obtained over a period of a few months or more. This process is referred to as the 'sphere solution' step in the Hipparcos terminology.

Since all the stars in the great-circle step are connected only relatively to each other, it follows that the one-dimensional positions derived have, in practice, an unknown origin, or zero-point. In connecting together large numbers of these circles, it is evident that these origins can no longer be viewed as arbitrary – only one value for the origin of each circle will give the most consistent results for all of the circles taken together. The sphere solution is essentially the process of solving for the origins of the circles and, in the process, converting the relative positions on the circles into 'absolute' (but still one-dimensional) positions. Figure 7 shows some results from the very first such solutions carried out by the data-reduction teams.

The final element of the three-step method then consists of collecting together the absolute one-dimensional positions for each star observed at the level of each great circle, and examining how these various pieces of information can be assembled to yield not only the star's two-dimensional position on the sky (corresponding to latitude and longitude on the celestial sphere), but also its spatial motion and its distance. The very large number of observations (typically 100 over a 2–3 year mission) and the small number of 'astrometric parameters' (just five per star) that are being solved for, means that there is generally sufficient information available to indicate whether these parameters have been well estimated, giving an overall indication of the measurement error for each parameter, or to indicate whether the achieved fit is symptomatic of something more complex going on: for example, the star being a component of a double or multiple system.

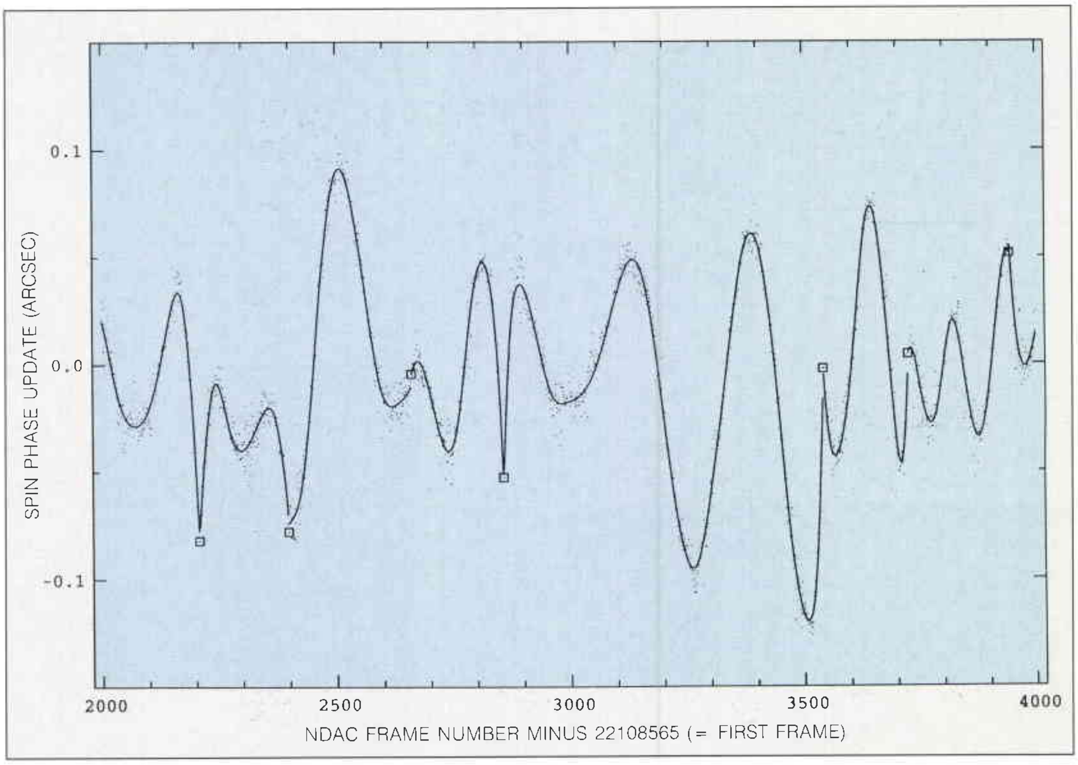

Figure 5. Reconstruction of the satellite's attitude during the great-circle analysis step. The attitude is estimated during each unit of observation time (2.133 s), shown in the figure as a dot. A subsequent processing stage relies on the steady satellite motion between attitude-correction gas-jet firings (squares) to derive a smoothed attitude (solid line) which, in turn, yields improved relative star positions. The results are taken from the NDAC Consortium's analysis (Courtesy of C. Petersen)

The whole of the three-step procedure therefore actually results in an improvement in the star positions within the observing programme. However, the results, especially in the early stages of the mission data processing, still include a dependence on the original poorly known star positions available from ground-based observations. This is because the determination of the satellite attitude, which itself relies on the ground-based positions for its estimation, actually enters into the determination of the positions at the level of the great-circle processing. As a result, the entire solution has to be 'iterated' or repeated, perhaps several times, using the newly-derived positions as inputs to the attitude-estimation process. This procedure results in the derivation of new and improved positions from the sphere-solution process.

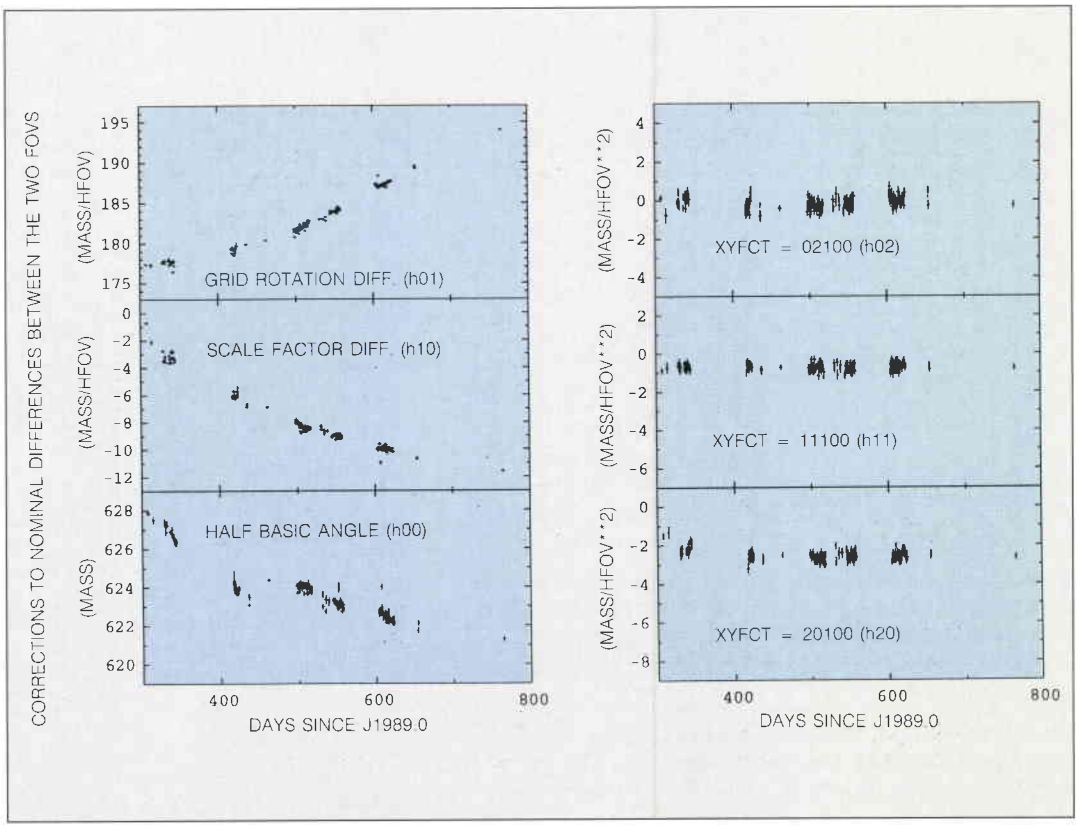

Figure 6. Changes in instrument parameters with time, showing how the transformation between the sky coordinates and the instrument coordinate system changes due to small structural or optical changes within the payload (the symbols refer to specific terms in the transformation of coordinates). These steady changes are solved for in the data-processing tasks, and allow the one-dimensional star coordinates along a great circle to be accurately determined. The results are taken from the NDAC Consortium's analysis (Courtesy of C. Petersen)

Interestingly, it has only been certain aspects of the attitude-reconstruction task that have required significant revision due to the revised elliptical orbit (due to the higher perturbing torques that act on the satellite at the lower altitudes). The incomplete ground-station coverage (particularly for the parts of the orbit around perigee) and the frequent and longer Earth occultations affect the total amount of useful scientific data retrievable, but not in general its quality. The longer and more frequent eclipses affect the satellite's power system, but not the quality of the data. The frequent passage of the satellite through the Van Allen belts has resulted in a slightly faster drop-off in the light throughput of the payload's optical elements, and the Cerenkov emission generated in these elements also results in an increased detector background signal for data collected near perigee. Apart from the complications that these phenomena introduce into the administration of the data reductions, the overall effect of the revised orbit is principally to reduce the fraction of scientifically useful data that can be collected from the 90% mission target to about 60%, or about 15 h of high-quality data per day.

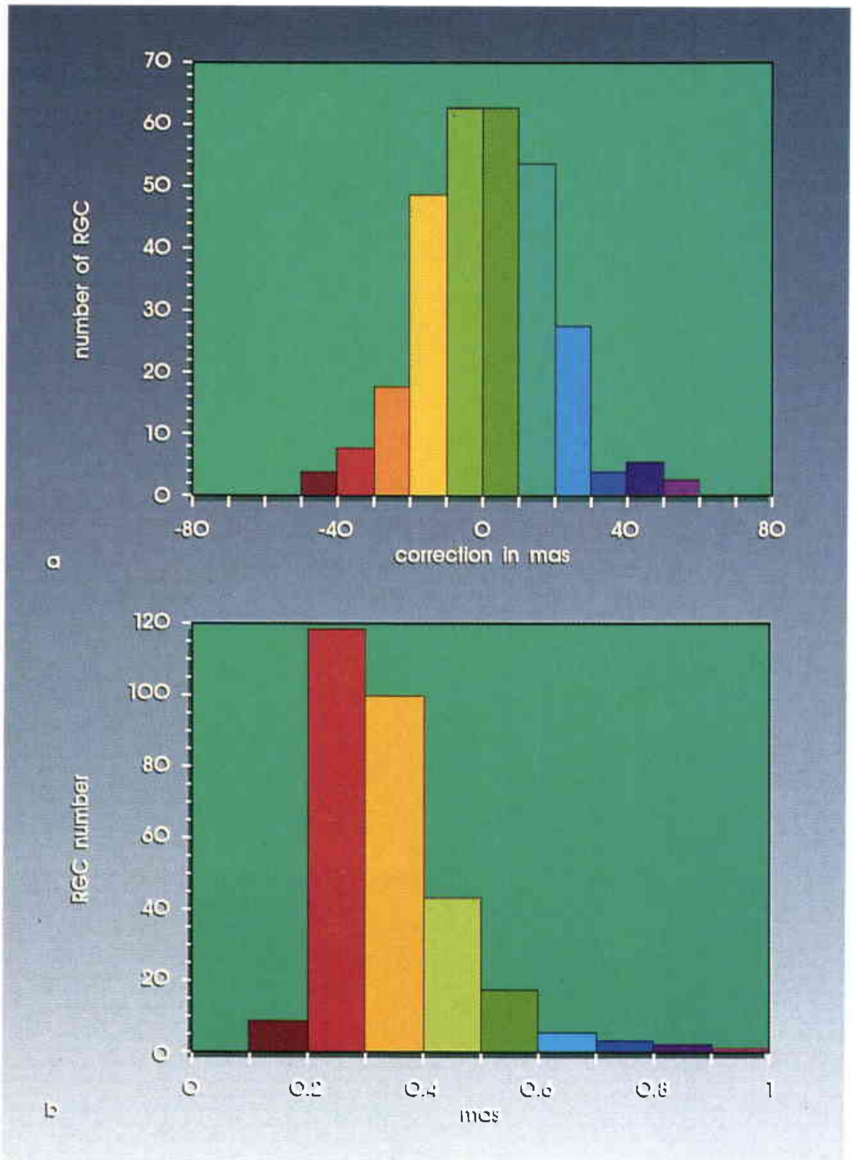

Figure 7. Results from one of the first 'sphere solutions' of the Hipparcos data, carried out with only a limited number of great circles. The upper figure shows the distribution of offsets that must be applied to each circle to bring it into line with the collection of circles as a whole (the number of reference great circles, or RGCs, versus the correction in milliarcsec, or mas). It can be seen that these adjustments are of the order of 30 milliarcsec or so. The lower figure shows both the precision on the determination of these offsets, and that they can be interlocked to about 0.2–0.3 milliarcsec. The data are taken from the FAST Consortium's analysis, and show results obtained using the first six months of satellite data (Courtesy of M. Froeschlé)

Other 'off-line' tasks

The above description is an outline of how the main data-processing tasks are organised within each Consortium. In addition, the groups are involved in various activities (Fig. 4) which are classified as 'off-line' tasks, i.e. activities that are not strictly part of the main processing chain. These include numerous calibration activities (e.g. calibration of the instrumental parameters referred to above, of the satellite's gyroscopes and thrusters, of the photometric responses of the main and star-mapper detectors, etc.). Two very important 'off-line' activities are the photometric processing, and the analysis of the signals to detect double and multiple star systems.

The photometric processing is essentially a byproduct of the treatment of the main detector modulated signal; in determining the phases of the signal, the intensity of the modulation can be estimated as well. By relating the intensity of the modulation to the known intensities (or magnitudes) of some of the programme stars, and calibrating these relationships according to the position of the star within the field of view at the time of observation, very accurate measurements of the star's intensity can be derived on each occasion that it crosses the telescope's field of view. The advantage of the Hipparcos photometry (which is carried out using a very broad optical bandwidth) over ground-based photometry is that the measurements are carried out in the absence of the perturbing atmosphere, and using a single instrument to cover the entire sky – something that it is impossible to achieve from the ground. It is anticipated that the measurement of star magnitudes with Hipparcos will result in the discovery of large numbers of previously unknown variable stars, an expectation that the early results are already confirming most dramatically.

Double or multiple star systems (systems in which two or more stars are in a physically bound orbit around their common centre of mass) occur very frequently in our Galaxy, and have considerable astrophysical importance. They are, nevertheless, most difficult objects to observe systematically from the ground. Because of the wide variety of separations and magnitude differences that the components of such systems may possess, it is difficult, if not impossible, to design a system that can detect and measure all ranges of such possibilities. Hipparcos is no exception in that it has been possible to optimise certain features of the detection system with the observation and discovery of double and multiple stars in mind, but the system is only optimised over a certain range of separations and magnitudes. At the limits of these distributions, results will not always be unambiguous. Adding the fact that the components of such double systems may well have perceptible (orbital) motion, and the components themselves may even be variable, the automatic task of detecting such systems within the Hipparcos data chain becomes a very challenging problem.

Within both data-analysis teams, special activities are undertaken to search for the signature of double-star systems within the data stream for the main detector. By comparing the results with systems already known from the ground, the expected performances of the double-star detection and measurement algorithms have already been substantially verified. The parameters of known double systems are fully consistent with the ground-based knowledge, and there are already indications that many thousands of new systems will be discovered by the Hipparcos satellite.

The Tycho Catalogue

The main data-processing chain makes use of data coming from the satellite's star mappers as a first estimate of its attitude, or pointing direction, in space at any instant. Bright stars crossing the star-mapper slits can be compared with their positions known from the ground, and the satellite's attitude can then be estimated, on-board and in real-time, with an accuracy of about 1 arcsec. This is sufficient to point the sensitive area of the main detector to the images of the programme stars as they cross the main grid, and as a first estimate of the satellite's attitude for the purposes of the main mission data processing.

However, not only these 'known' bright stars are crossing the star-mapper slits. In practice, every star down to a certain limiting magnitude can be detected, and the information necessary to reconstruct its position is sent to the ground. The star-mapper optical path within the satellite is split into two separate channels, each with its own detector and optical filters, so that the star-mapper data chain actually allows the derivation of positions and intensities (or magnitudes) in two separate colours for each star, at each instant that the star crosses the fields of view. The photometric signal is recovered by comparing the modulation intensity of each star with the known intensity of certain 'standard stars'. The position of each star is estimated by relating its transit times across the grid to the transits of stars whose positions are already, or will be, known from the main mission processing, in combination with an estimate of the satellite's attitude.

It is the very power of the Tycho experiment in detecting all stars down to its sensitivity limit that also severely complicates the data-processing routines needed to extract the information for any given star in the presence of the signals from the many nearby stars crossing the star-mapper slits. The solution adopted involves the use of a catalogue of ground-based star positions, based on the Guide Star Catalog of the Space Telescope Science Institute, as a list of stars from which the signals are to be searched for. Even so, the 'confusion' resulting from nearby stars, from stars in the other field of view, and from the two sets of slit systems present in the star mapper, make the Tycho data processing a lengthy and complex task. Again, several 'iterations' will be needed to pinpoint which particular signal is related to which particular star. The expected benefits are, nevertheless,

Past and Present Task Leaders within the Data-Analysis Consortia

FAST Consortium
J. Kovalevsky (Team Leader), P.L. Bernacca, D.T. van Daalen, F. Donati, J.-L. Falin, M. Froeschlé, I. Galligani, A. Guerry, D. Iorio-Fili, H. van der Marel, F. Mignard, B. Morando, F.P. Murgolo, J.L. Pieplu, R.A. Preston, S. Röser, H. Schrijver, H.G. Walter.

NDAC Consortium
L. Lindegren (Team Leader), A.M. Cruise, D.W. Evans, E. Høg, F. van Leeuwen, N. Lund, C.A. Murray, M.J. Penston, C. Petersen, N. Ramamani, M.A.J. Snijders, S. Söderhjelm.

TDAC Consortium
E. Høg (Team Leader), G. Bässgen, U. Bastian, P.L. Bernacca, D. Egret, M. Grewing, J.L. Halbwachs, J. Kovalevsky.

ESA Project Scientist
M.A.C. Perryman

The above names represent the involvement of some 60 scientific personnel in the preparations for and execution of the data analysis.

dramatic. The number of stars that can be detected increases very strongly with the threshhold of observability that can be reached in the detection process, and present indications are that as many as one million stars could be detectable in the Tycho Catalogue. For many of these, positions (while not as good as those for the main Hipparcos mission catalogue) will be a factor of ten or so better than can be measured from the ground, and magnitudes will be determined in each of two colours. The dense reference frame system that Tycho will provide will be of immense value in many fields of astronomical positional research.

The data-analysis consortia organisation

As previously noted, two separate groups process the main Hipparcos mission data, and these are known as the NDAC and FAST Consortia. The former includes institutes within Denmark, Sweden and the United Kingdom. FAST includes institutes from France, Germany, Italy and The Netherlands, with some participation in off-line tasks from scientists in the USA. The TDAC Consortium is responsible for the Tycho data processing, and includes institutes from Denmark, France and Germany responsible for the bulk data processing, while other individuals and institutes from the NDAC and FAST teams (from Italy, Sweden, The Netherlands, Switzerland and the UK) also contribute to essential aspects of the Tycho processing.

The two main data-processing consortia, NDAC and FAST, have adopted different organisational procedures for the data analysis: in the case of NDAC, data from the satellite are received at an institute in the UK, where the first stage of the data processing takes place; then, the results are forwarded to an institute in Denmark and then to Sweden for subsequent stages of the data treatment. In the case of the FAST Consortium, all data-processing tasks, with the exception of some off-line activities, are centralised within the CNES computing centre in Toulouse. The numerous institutes involved in the preparations and implementation of the data-processing tasks throughout the ESA Member States reflect the very different capabilities and interests of the relevant groups, which include astronomers, mathematicians, opticians, geodesists and computer experts.

More significant than their organisational structure is the fact that the two consortia have adopted different analysis methods, albeit within the three-step procedural method described above. The groups work in different coordinate systems, using different numerical methods, calibration philosophies, and in many cases different procedures (e.g. for the attitude-determination stage). The overall effect is to have two independent analyses of the Hipparcos data set. Perhaps of equal importance is the fact that the software coding, the inclusion of assumptions, and the interface between the various data-reduction procedures, is treated totally independently within the two groups.

Regular meetings are of course held to review progress by the two groups, and the results from each are presented and discussed. In addition, very detailed activities have been established to compare the intermediate results of the three-step method, for example, at the level of the determination of the signal-modulation parameters, for the attitude determination, for the great-circle results, and for the photometry. These comparisons are used to identify software or other accidental errors, and to encourage a critical discussion of the data-processing results. The existence of two analysis teams has demonstrated that, far from one group being redundant, their dual presence encourages a spirit of positive competition, and has proved to be a powerful tool in uncovering errors that could have lain hidden possibly for ever, or at least until a very late stage in the data processing when re-analysis of the entire mission dataset may well have proved impossible or unrealistic in view of the resources (computer and manpower) required for re-processing.

At the present time, the various software elements of all three of the data-analysis teams have been validated, both on simulated data before launch, as well as on extensive stretches of real satellite data (selected as representative data segments from the first year of mission data). Good confidence has been achieved in the quality of their results, obtained by processing these 'provisional data sets' through to the 'sphere solution' stage, and examining and intercomparing their results. Consequently, all teams are now well underway with the 'mass data' processing, which started in mid-1991. Already, the results from this processing are proving most encouraging, and can be considered to validate fully the observational, operational and data-reduction procedures that have been established during the mission's preparation and implementation. Some of the corresponding scientific results that have emerged to date are presented in an accompanying article.

Early Scientific Results from Hipparcos and Future Expectations

The Hipparcos Science Team

The first results of the lengthy Hipparcos Star Catalogue construction process are now becoming available. The star positions and distance estimates emerging from the data analyses give a dramatic indication of the outstanding scientific results that ESA's Hipparcos mission can be expected to provide.

Introduction

The Hipparcos satellite, in orbit since August 1989, has acquired scientific data for a little more than two years. It is unusual among the scientific satellites of ESA due the nature of its observational programme, designed to determine the positions, distances and spatial motions of 120 000 pre-selected stars. With the observational programme fixed throughout the duration of the (nominally) two and a half year mission, the satellite scans the sky in a complex manner, frequently returning to observe the same parts of the sky, but with different scanning directions. The system of highly accurate relative star-to-star measurements that is acquired in the process is of massive proportions. Some 500 000 million bits of data have been acquired so far, representing many hundreds of thousands of relative star positions determined at different times. The data analysis and reconstruction process that takes place on the ground consists of assembling all of the information that is collected into a single self-consistent and highly accurate catalogue of astrometric parameters (positions, motions and distances) of each of the programme stars.

The scientific aims

An inescapable consequence of the way in which the Hipparcos observations are acquired and reduced is that the first star positions from the mission would only become available many months after launch. Two conditions had to be met: first, enough data had to be acquired to provide a sufficient network of sky measurements from which the positions of even a subset of the stars could be derived. Secondly, the complete data-processing chain of the two main Hipparcos data-analysis teams, the NDAC and FAST Consortia, had to be fully operational and validated using substantial amounts of real data.

The manner in which the data reductions are carried out has been described in the previous article: briefly, sets of 'great circles' of data, covering time intervals of about 10 h, are firstly constructed. Large numbers of these resulting 'great circles' are then interconnected by means of the 'sphere solution' algorithms. Only when many months of data have been acquired is it possible to determine two-dimensional positions on the sky for a significant fraction of the programme stars – the interconnection of the great circles is simply not rigid enough to allow this to be done (due to the way in which the satellite scans the sky) for data intervals of only a few weeks. Roughly a year of data is needed before the star distances can also be disentangled from the vast collection of relative star separations, and some 18 months of data is needed before the star motions through space can be discerned (Fig. 1). Thereafter, as the network of interconnected measurements continues to grow, the expected accuracies on each of the parameters slowly improves with time (Fig. 2).

Scientifically, these slow improvements are the key to the success of the Hipparcos mission. From observations made from the ground, positional measurements are limited to about 0.2 arcsec. The star motions in the plane of the sky (or 'proper motions') can be determined precisely from the ground by extending the programme of positional measurements over many tens of years,

Members of the Hipparcos Science Team

P.L. Bernacca, M. Crézé, F. Donati, M. Grenon, M. Grewing, E. Høg, J. Kovalevsky, F. van Leeuwen, L. Lindegren, H. van der Marel, F. Mignard, C.A. Murray, M.A.C. Perryman (Chairman), R.S. Le Poole, H. Schrijver, C. Turon although the accuracy of these motions can be limited by the regional, systematic errors that exist in ground-based positional star catalogues. The determination of stellar distances, through the parallax displacement of a star as the Earth moves in its orbit around the Sun, is a difficult task to carry out from the ground. This is because of the very small displacements that have to be measured, and because ground-based measurements only easily reveal a 'relative' parallax with respect to stars nearby in the sky, rather than an absolute parallax, which is a true indication of the star's distance.

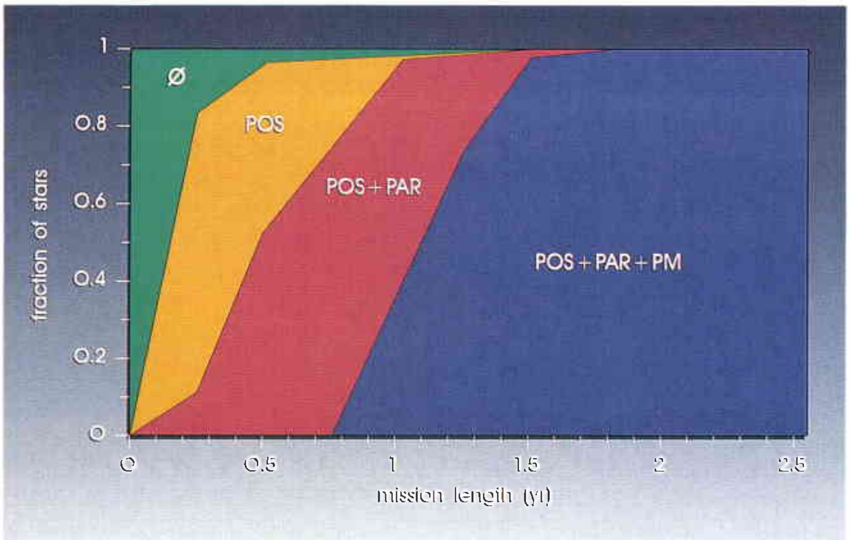

Figure 1. As the mission progresses, the data acquired allow the determination of more of the astrometric parameters for a larger and larger fraction of the 120 000 programme stars. The curves indicate the stars for which positions (POS), parallaxes (PAR) and proper motions (PM) can be determined as the mission duration grows. As of February 1992, just over two years into the mission (as has been the case for the past few months), all five astrometric parameters of all programme stars can now be estimated. (Figs. 1 and 2 have been derived from simulations carried out within the NDAC Consortium; Courtesy of L. Lindegren)

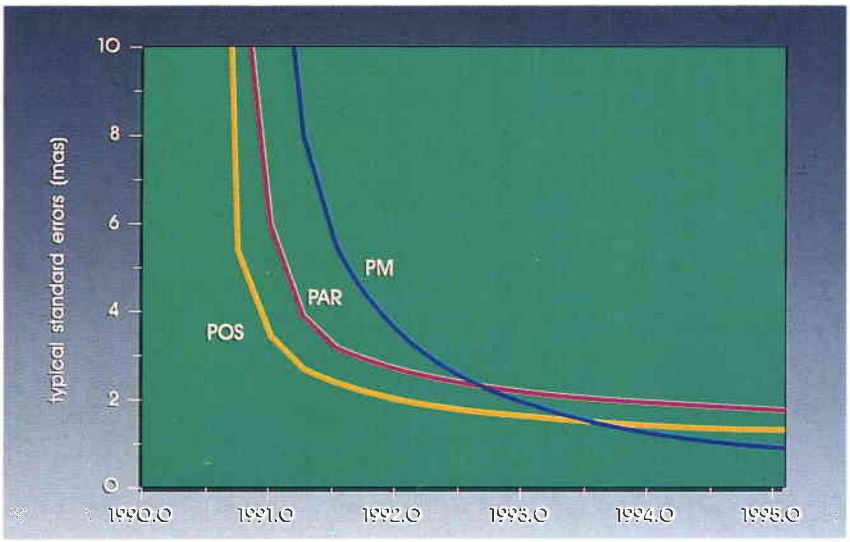

Figure 2. With increasing measurement time, the average accuracy that can be achieved for each of the astrometric parameters also improves. Satellite consumables suggest that operations extending until early 1994 may be possible

At a distance of just over 1 parsec, the nearest star to our Solar System has a parallax of somewhat less than 1 arcsec. Only about 40 stars lie sufficiently close to the Sun to have a parallax larger than 0.2 arcsec. As the ability to measure stellar parallaxes improves, so the distance estimate (and those of related physical parameters) of the star improves. Our three-dimensional view of the distribution of stars in our Galaxy effectively comes progressively into better and better 'focus', and the volume of space that can be explored is a function of the third power of the distance. By means of its accurate positional measurements, Hipparcos will 'iron out' the warps and wrinkles that are known to exist in the system of star positions that are built up from the ground. It will measure stellar motions through space that are not only very precise and homogeneous for a very large number of stars, but are also free from the level of systematic errors present in existing proper-motion compilations. Moreover, it will measure distances, for thousands of stars, to an unprecedented accuracy, again free from systematic effects at the level of one thousandth of a second of arc.

The data treated

As described in the previous article, the validation of the data-reduction software has been carried out on a subset of the main mission data acquired so far – some three months of data in total, extending over nearly one year of satellite operations. These data (constituting a 'validation set') have been studied extensively by both data-reduction teams and, in the case of the NDAC Consortium, have been processed through to the sphere-solution level. More recently, 'mass data processing' for the nominal mission data has been commenced by both groups, and in the case of the FAST Consortium six months of data, starting from the end of November 1989, have been processed as far as the sphere-solution level. Thus, preliminary positional catalogues, albeit using different data sets, have been generated by both consortia. The following paragraphs are devoted to a presentation of these preliminary results. Meanwhile, more data are being included into the analyses by both scientific teams.

Results of data treatment by the FAST Consortium

The results shown here refer to 300 'great circles' constructed from the data obtained between the end of November 1989 and

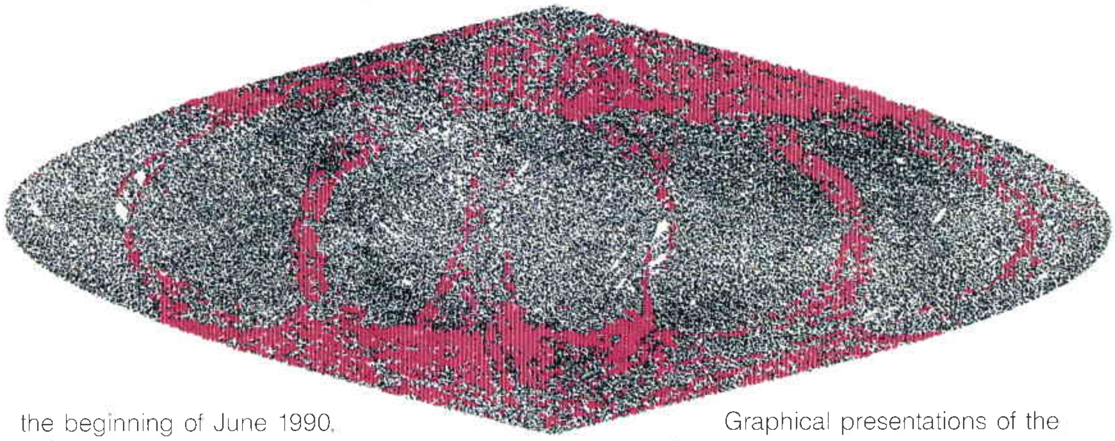

Figure 3. The distribution of star observations over the celestial sphere (in ecliptic coordinates) over the first six months of the mission (black points), and the distribution of stars over the sphere for which positions have been determined by the sphere solution of this data set (red points). (Figs. 3–5 have been derived by the FAST Consortium, on the basis of software supplied within the international collaboration; courtesy of M. Froeschlé)

the beginning of June 1990. This data set includes 486 006 one-dimensional star positions for 116 952 observed stars. Over six months, the scanned sky coverage is very non-uniform, and as a result only a fraction of this data set could be fully interconnected through the 'sphere solution' programmes (Fig. 3). The sparseness of the data connections means that positions could be determined for just 10 759 stars, corresponding to 75 374 one-dimensional star coordinates. (It should be stressed that the data omitted in this solution will nevertheless be usable once larger intervals of data are incorporated).

Graphical presentations of the results of the positional determinations of these 10 759 stars are shown in Figures 4 and 5. Figure 4 shows the corrections that must be applied to the Input Catalogue (i.e. best ground-based) positions in order to achieve consistency at the sphere level. No obvious biases are present, and the distributions reflect our knowledge of the type of errors that were expected to be present in the ground-based observations. Figure 5 shows the corresponding estimated errors for these positional determinations. The stars solved for in the sphere solution process are predominantly rather bright,

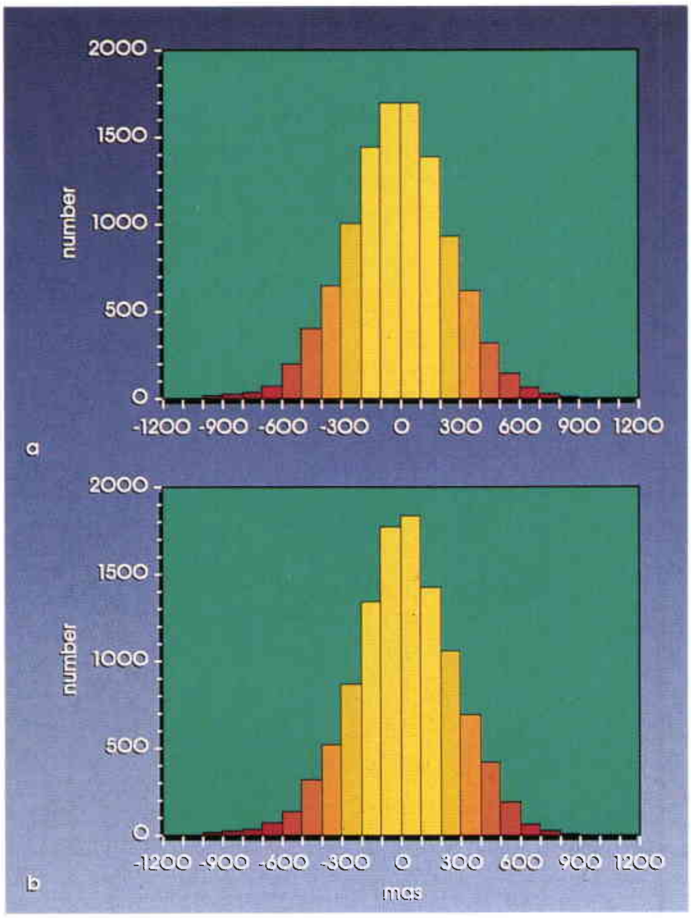

Figure 4. (a) and (b) show the corrections that must be applied to the Input Catalogue (i.e. best ground-based) positions in order to achieve consistency at the sphere level for the first six months of mission data processed by the FAST Consortium, in ecliptic longitude and latitude, respectively

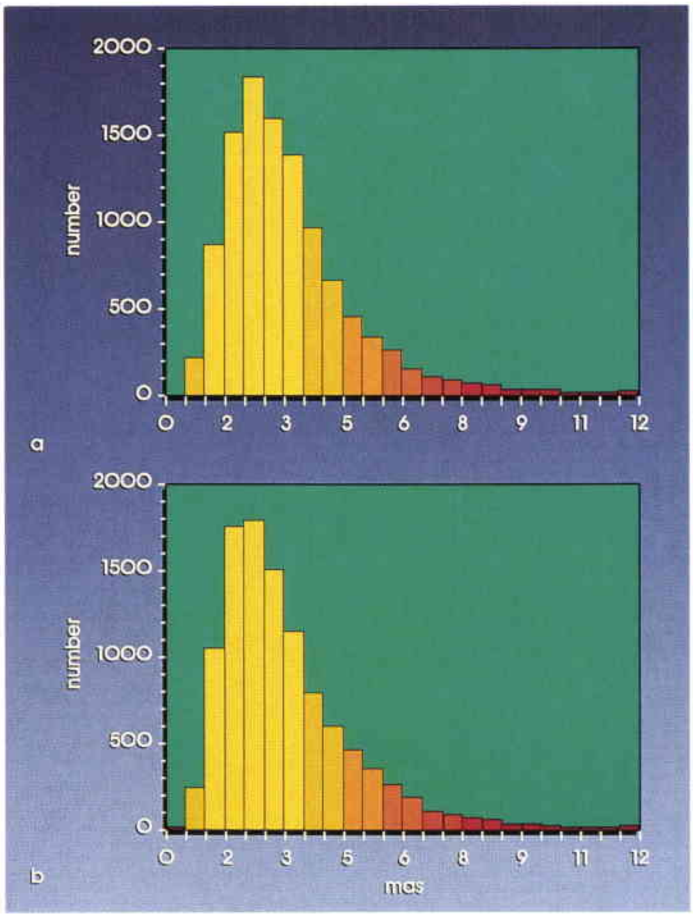

Figure 5. (a) and (b) show the corresponding estimated errors for the positional determinations shown in Figure 4. The tail of larger errors is due to the fact that the corrections to the Input Catalogue proper motions and parallaxes are not determined over the short (six-month) data interval, and these will not be negligible in all cases

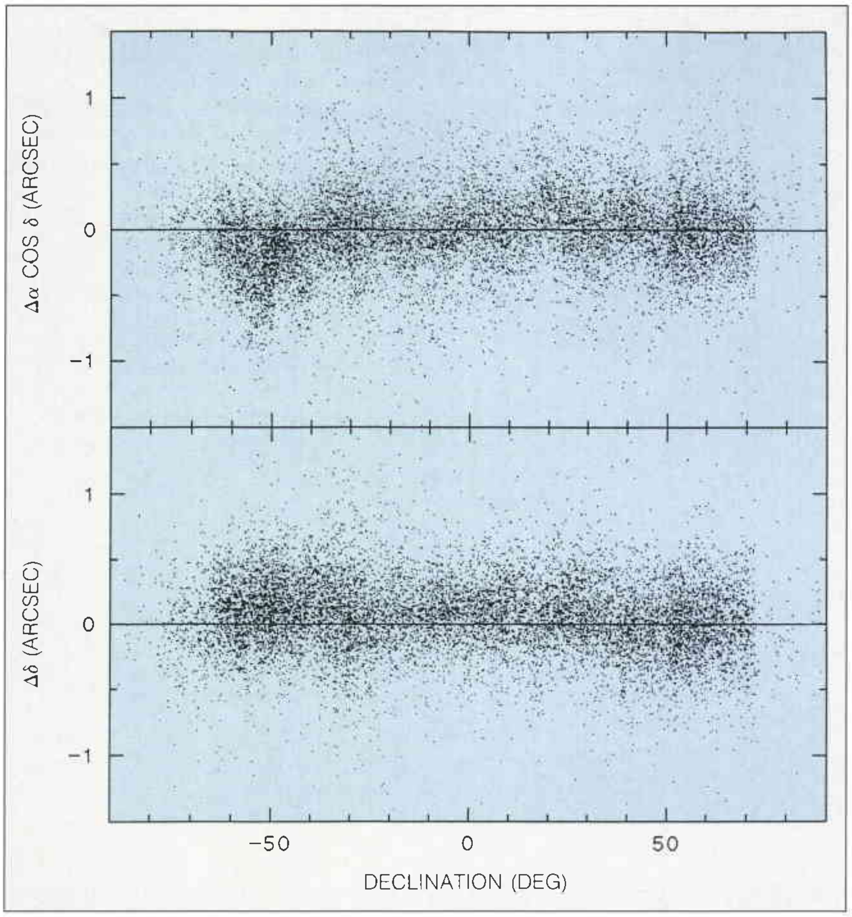

Figure 6. Positional corrections to the starting (Input) catalogue determined from the NDAC sphere solution using the 'validation data set'. Results are shown for the two coordinates (right ascension and declination) versus the declination of the star. (Figs. 6–8 have been derived by the NDAC Consortium, and supplied courtesy of L. Lindegren)

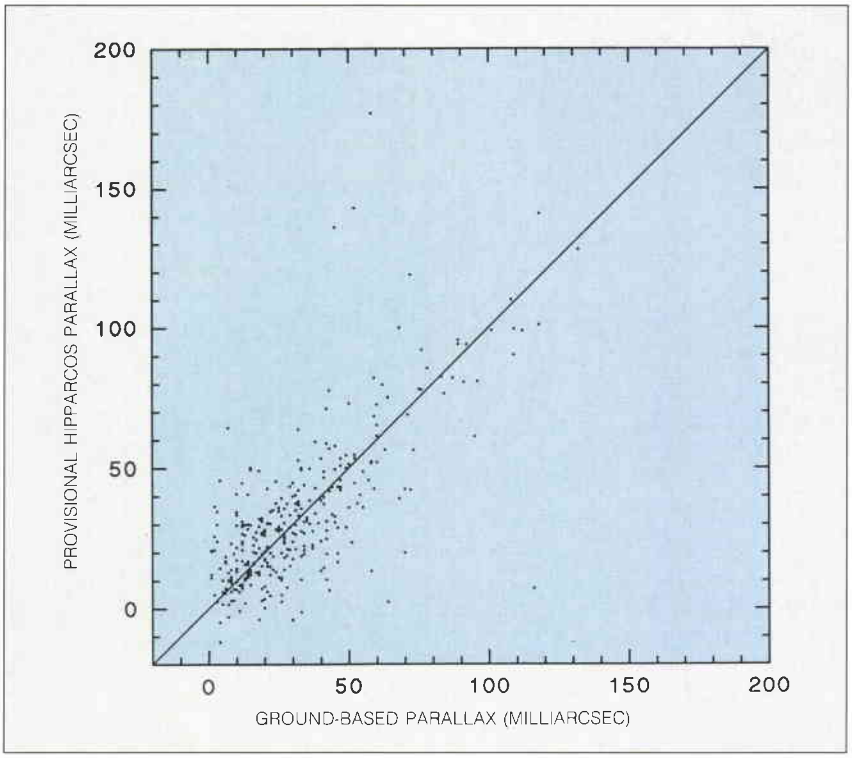

Figure 7. Comparison of the NDAC parallax results, from the 'validation data set', with the (relatively small number of) parallaxes already estimated from ground-based observations

which partly explains why the typical errors on the positions (of about 2–3 milliarcsec) are already very good, even for such a short measurement interval.

Results of Validation Data Set treatment by the NDAC Consortium

The data set treated during the course of the software validation by both Consortia contained about three months of satellite data in total, but spread over a period of nearly one year. For the purposes of the first assessments of the preliminary sphere solution results, this set has the advantage that parallaxes may also be solved for, due to the time interval spanned by the observations. The accuracy achieved will not be high (in the context of the Hipparcos goals) for such a limited data set, but the results will provide an indication of the stability and reliability of the sphere solution process.

Figure 6 shows positional corrections to the starting catalogue determined from the sphere solution. The results are similar to those shown in Figure 4, but this time are shown for the two coordinates (right ascension and declination, analogous to geographical longitude and latitude) as a function of the star's declination. The scatter is centred around zero (as for Fig. 4), with a distribution of about 0.3 arcsec (corresponding to the expected errors on the positions contained in the Input Catalogue), and with clear 'zonal' or regional errors varying with declination on the sky.

Figures 7 and 8 show some results from the determination of the first parallaxes from Hipparcos. Figure 7 compares the NDAC results from the 'validation data set' with parallaxes already estimated from ground-based observations, where the errors on the parallax estimates are typically around 10 milliarcsec. While the general agreement between the two sets of results is quite satisfactory on average, certain individual star measurements are seen to show large discrepancies between the space and ground-based observations.

Figure 8 provides a powerful indication of the validity of the Hipparcos parallaxes and their estimated errors. For some 3000 stars for which the Hipparcos-estimated parallax errors are in the range 0–4 milliarcsec (again, for the small data sample involved), the histogram shows the distribution of the corresponding parallax estimates. As the parallax angle is inversely related to the object's distance, it may seem at first sight surprising that the figure includes negative parallaxes, but this is merely a reflection of the measurement errors. The dotted line shows the distribution of expected parallaxes based on our knowledge of the star distributions within our solar neighbourhood. When this distribution is modified to take account of possible measurement errors (solid line), good agreement between the observations and the model is found for inferred errors which are consistent with the formal error estimates arising from the sphere solution. We can thus say that the observed parallax distribution is not only understandable qualitatively, but it matches in quantitative detail what we know statistically about the Galaxy, and what we believe about the space-based parallax errors. This confidence augurs well for the final detailed Hipparcos results.

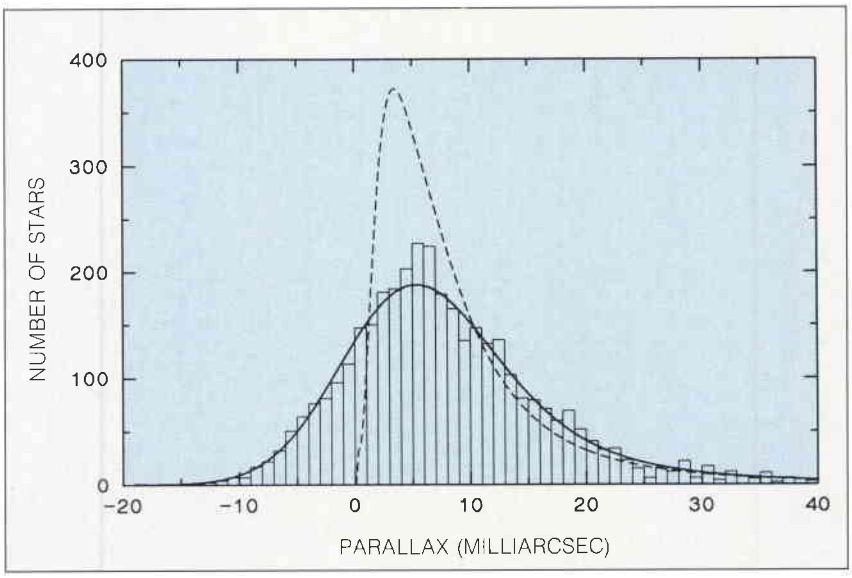

Figure 8. This figure demonstrates the general validity of the Hipparcos parallaxes and their estimated errors. The histogram shows the distribution of the parallax estimates. The dotted line shows the distribution of expected parallaxes based on our knowledge of the star distributions within our solar neighbourhood. When this distribution is modified to take account of possible measurement errors (solid line), good agreement between the observations and the model is found for inferred errors which are consistent with the formal error estimates arising from the sphere solution

Photometry

It is an impressive byproduct of the astrometric mission that star magnitudes or brightnesses can be determined from the modulated stellar signal at the same time as the positional information is extracted. The virtues of the Hipparcos photometric measurements are that stars over the entire sky are measured with the same instrumental set-up, and observations are repeated on each star on numerous occasions throughout the mission's lifetime. Each star is, of course, only observed when it happens to lie on the path of the scanning motion of the satellite; for any individual object, the scanning pattern typically crosses its field at intervals separated by about 20 min (the time separation between the scans of each of the two telescope fields of view), then again 2 h later as the scanning 'great circle' sweeps past it again. Depending on whether the objects lie close to the node or anti-nodes of the circles, the objects may be viewed repeatedly several times in this manner before the scanning motion of the satellite moves on across the sky, returning perhaps a few months later. By very careful calibration of the detector's response using a system of 'standard stars' with magnitudes accurately known from ground-based observations, each such measurement of each star provides an accurate magnitude at a given time. Collecting together the magnitudes relating to every star throughout the course of the mission will result in an enormous collection of light profiles for every star in the observing programme. Similar photometric results will eventually be obtained for the hundreds of thousands of stars in the Tycho Catalogue, this time in each of two distinct colour pass-bands.

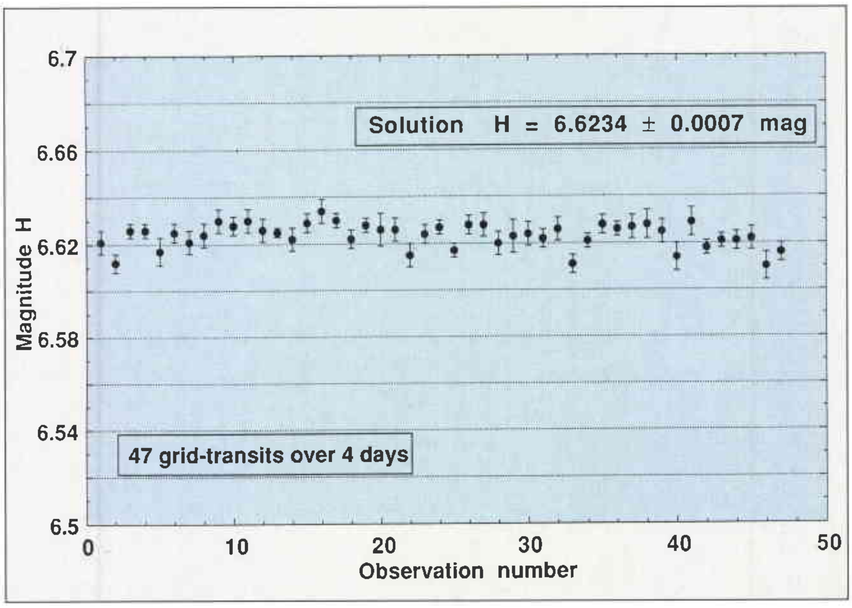

Figure 9. Photometric results for a star that is confirmed to be constant in its energy output (and hence magnitude). The average of all of the observations shown suggests that the magnitude can be estimated with a precision of about 0.06%. (Figs. 9–12 are early results of the photometric signal processing by the FAST Consortium, and are supplied courtesy of F. Mignard)

Figures 9–12 show some early results of the photometric signal processing by the FAST Consortium. They correspond to the observation of objects close to nodes of certain scanning circles, where a relatively large number of measurements have been made on each star over an interval of only a few days. Many stars in the pre-planned observing programme were identified as suitable 'magnitude' standards for carrying

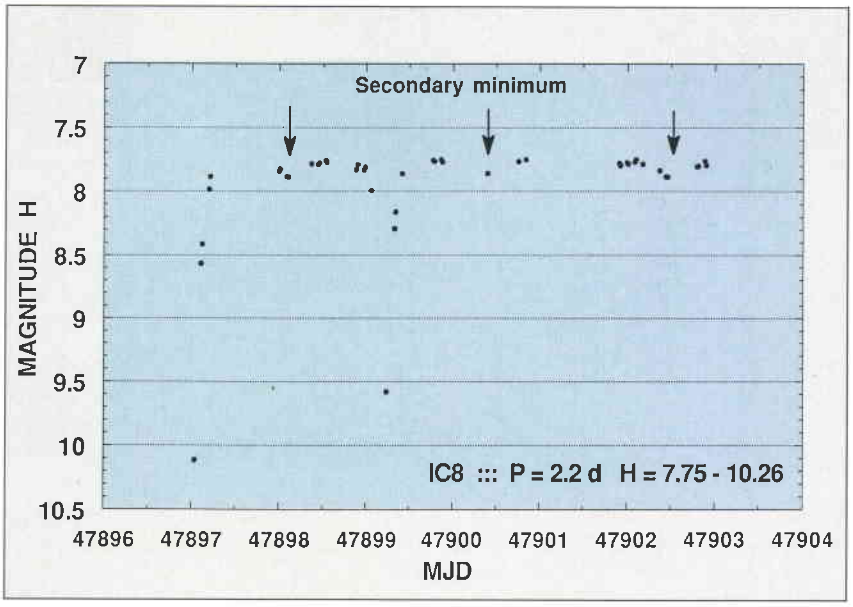

Figure 10. Hipparcos light curve for a previously known eclipsing binary star system. Such systems show minima in their light outputs due to the obscuration of one star by another as the two very close bodies orbit around their common centre of mass. Such systems are important in determining stellar masses

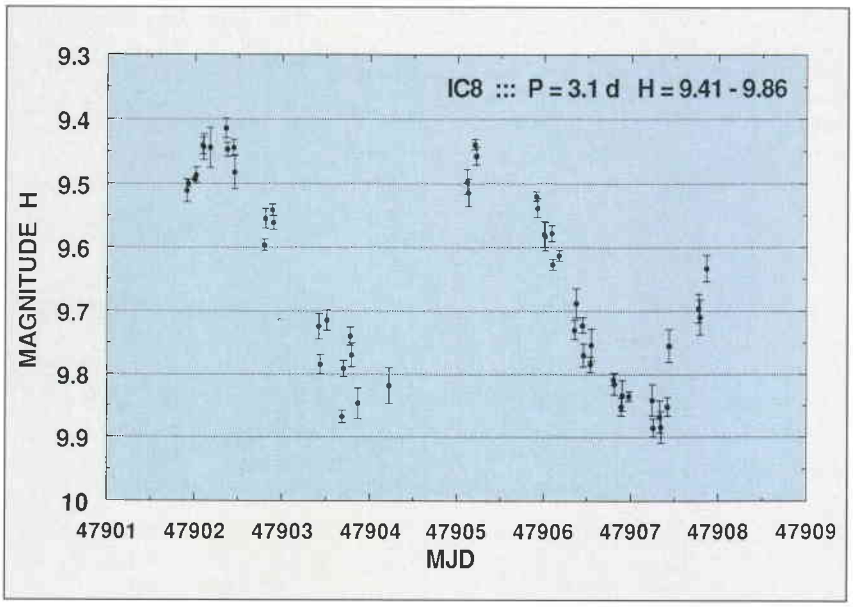

Figure 11. Hipparcos light curve for a previously-known Cepheid variable star. Because of the rather well-behaved relationship between the luminosity of a Cepheid star and its period of variability (caused by pulsations within the star), such stars are important in understanding distance scales within our Galaxy and beyond

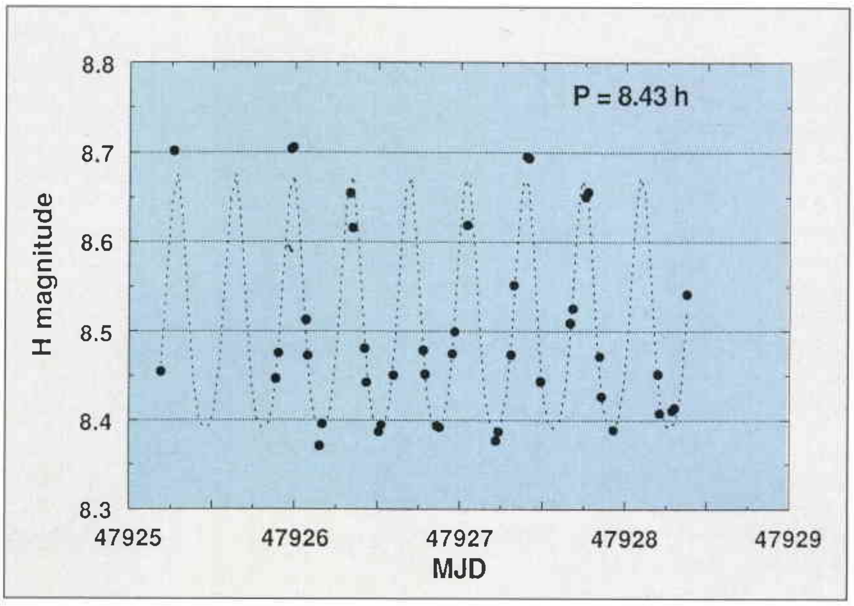

Figure 12. The discovery of a previously unknown variable system. While the observed points (dots) seem to be highly scattered, with an amplitude of about 30%, a fit to a smooth curve (dashed line) gives a strong indication of a variability period of 8.43 h

out the in-flight calibration of the observations. Figure 9 shows the results for a star that is confirmed to be constant in its energy output (and hence magnitude), and the average of all of the observations shown suggests that the magnitude can be estimated with a precision of about 0.06%.

Many stars do not have a constant energy output over time. These variable stars typically occupy interesting locations within the known evolutionary stellar sequences, and the measurement of their distances with Hipparcos will be of great importance. Simultaneous determinations of their light curves, or the discovery of previously unknown, perhaps low-amplitude variability objects, can be expected to greatly enhance the scientific value of the Hipparcos positional measurements. Figures 10 and 11 show derived light curves for a previously-known eclipsing binary star system, and a Cepheid variable star, respectively. Figure 12 shows the discovery of a previously unknown variable system. While the observed points seem to be highly scattered, with an amplitude of about 30%, a fit to a smooth curve gives an unambiguous indication of a variability period of 8.43 h.

Double stars

The treatment of double and multiple star systems (in order to extract information about the relative separations and magnitudes of the stars in the system) is an involved problem and one that is being treated by special teams within each of the data-analysis groups. Final reliable results will only be available during the very last stages of the data processing, when all the measurements of each such system can be pieced together into a sort of map. First indications of the data quality can already be derived from the star-mapper data processing, and Figure 13 shows some results from the NDAC Consortium's processing. The upper figure shows a comparison between the angular orientation of known systems on the sky, compared with some star-mapper estimates of the same quantity. The lower figure compares the difference in separation between the components for the same systems, known to be double before launch. The agreement is excellent, and points the way to the detection of many new double and multiple systems as the mission progresses.

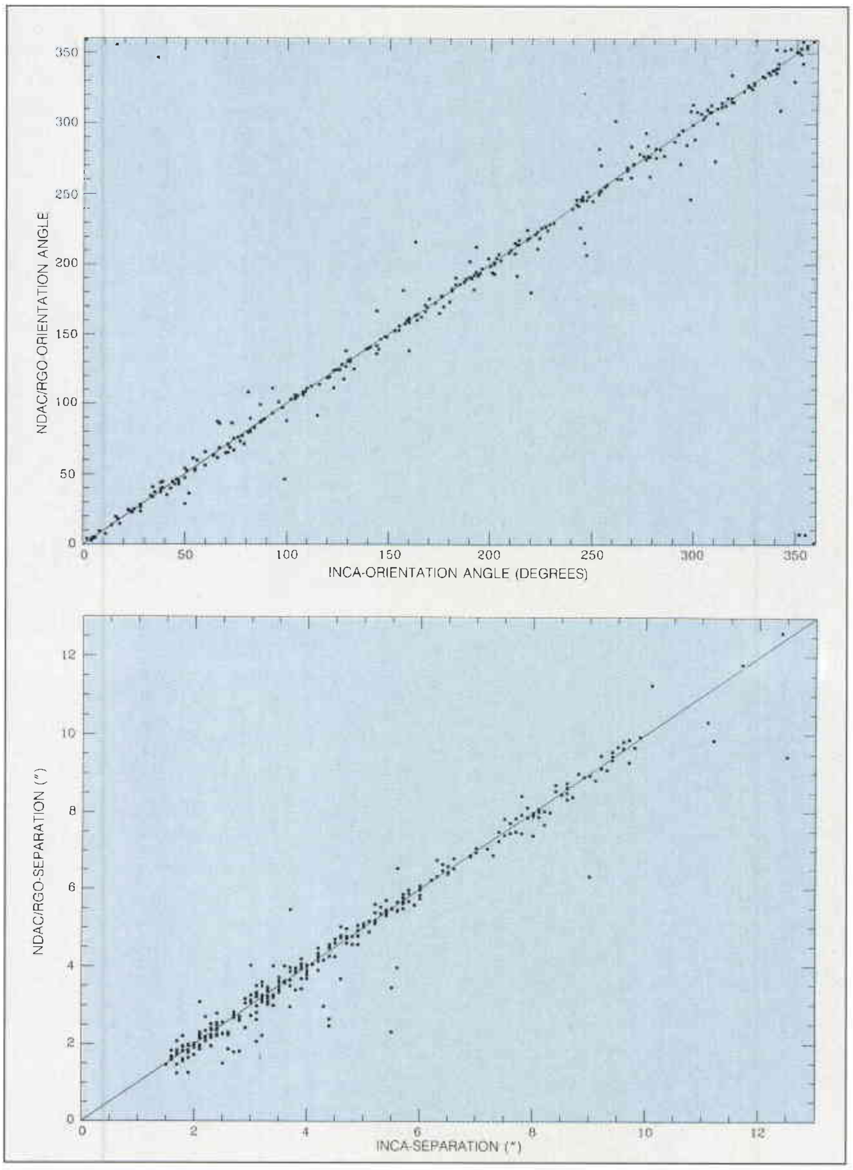

Figure 13. Results from the NDAC Consortium's star-mapper data processing on double-star systems. The upper figure shows a comparison between the angular orientation of known systems on the sky, compared with some star-mapper estimates of the same quantity. The lower figure compares the difference in separation between the components for the same systems, known to be double before launch. (The figures have been derived by the NDAC Consortium, and supplied courtesy of F. van Leeuwen)

Conclusion

The results shown in this article give a highly encouraging picture of the final results that are now expected to come out of the Hipparcos astrometry mission. The present results are preliminary, based on the treatment of relatively short data sets (different data intervals having been treated so far by the two data-reduction groups). The accuracy of the results will improve as more data are included into the solution, and confidence in the results will grow as further checks and comparisons are carried out between the participating groups. With satellite observations continuing until the end of 1992, the original target accuracies of 2 milliarcsec in each of the positions, parallaxes, and annual proper motions should indeed be achievable.

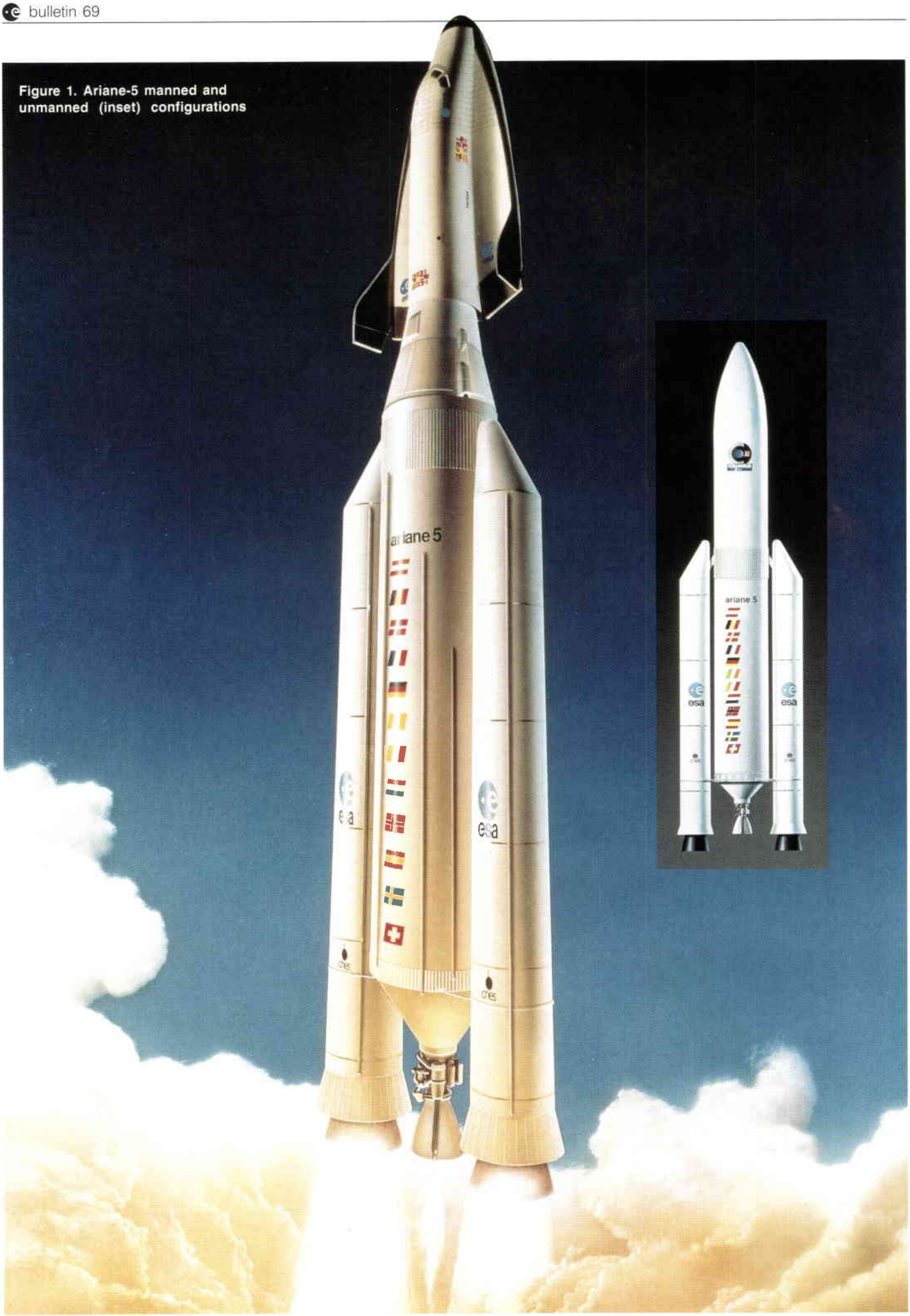

Figure 1. Ariane-5 manned and unmanned (inset) configurations

Solid-Propellant-Stage Development for Ariane-5

J. Gigou
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Development of the Ariane-5 solid-propellant engine started as recently as 1988. Today, its definition is complete, the first tests on the subassemblies have been carried out, and full-scale test-stand firings will be starting over the next few months.

Ariane-5, currently under development by the European space community, is the successor to the Ariane-4 generation of this family of launchers, all of which are designed for:
- optimum performance
- low launch costs
- very high reliability and safety
- operational flexibility.

Today, work on the Ariane-5 Programme is well under way in preparation for the vehicle's first launch in an unmanned, automatic configuration in the mid-1990s, to be followed at a later date by a man-rated configuration carrying the Hermes space plane (Fig. 1). Ariane-5 is being developed under the auspices of ESA, which has delegated the Programme's financial and technical management to CNES, the French National Space Agency.

For the first two minutes of Ariane-5's flight, propulsion will mainly be provided by two large solid boosters (P230s). These solid-rocket stages (Fig. 2), along with the cryogenic main stage, form the complete lower section of the Ariane-5 launcher.

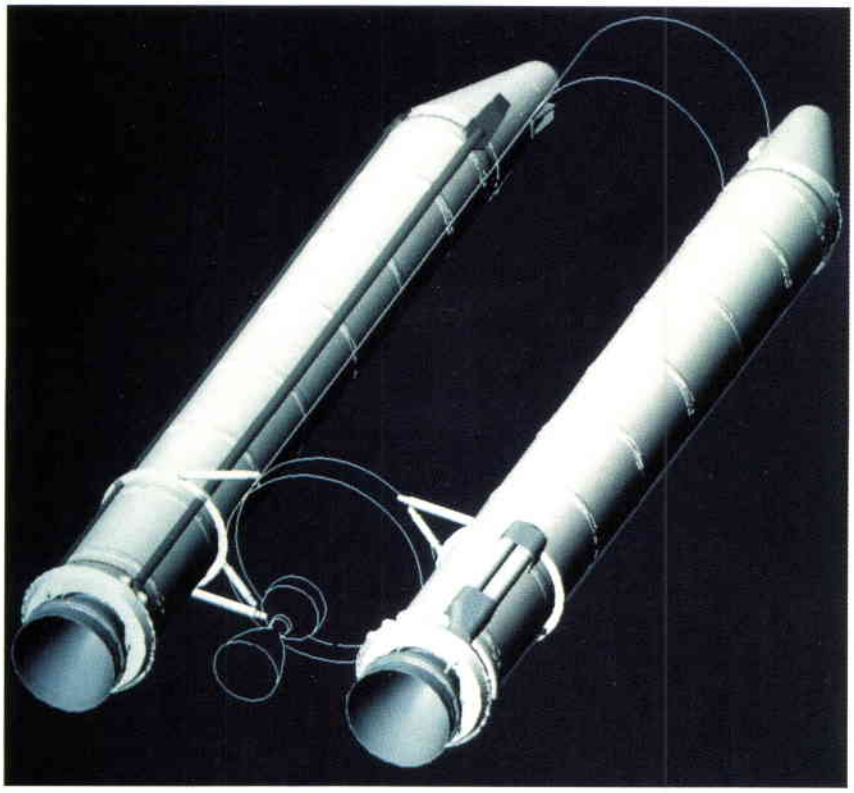

Figure 2. The twin P230 solid boosters

The twin solid boosters are designed by:
- Aerospatiale (F), which is responsible for the solid-booster stage, and whose main subcontractors are Sabca (B), Fokker (NL) and Dassault (F)
- Europropulsion, a joint venture involving SEP (F) and BPD (I), which is responsible for the solid-propellant engine.

In order to develop and manufacture the solid-booster stages, large new industrial plants have been built both in Europe and in French Guiana, and these are already operational.

The main elements of the P230 stage (Fig. 3) are:
- a solid-propellant engine, whose main job is to provide thrust
- an aft skirt, which acts as a support for the launcher in the waiting phase prior to firing
- a forward skirt, which transmits thrust to the cryogenic main stage and includes an aerodynamic forward cone
- a forward attachment device, which transmits the longitudinal and transverse loads between the solid-booster stage and the cryogenic main stage
- an aft attachment device, whose main task is to transmit transverse loads between the solid-booster stage and the cryogenic main stage

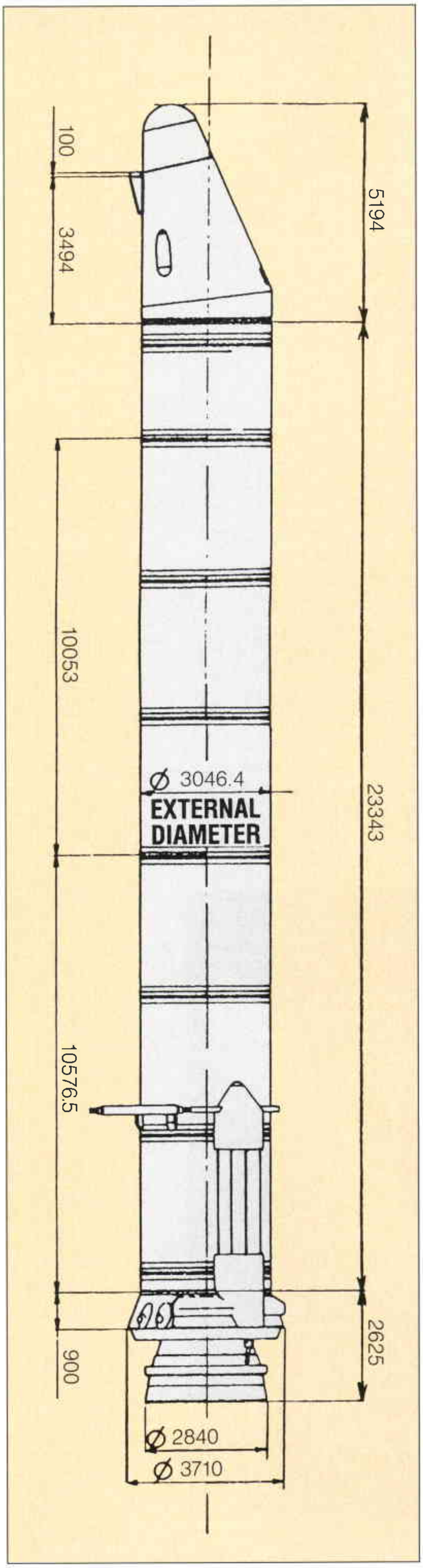

Figure 3. Solid-booster stage

- a nozzle actuation unit, which directs thrust
- a recovery system
- electrical and telemetry subsystems
- a pyrotechnic subsystem
- supports, casings and accessories.

Industrial infrastructure

Development of the state-of-the-art P230 solid-propellant engine, whose dimensions (length 27 m, diameter 3 m), loaded mass (236.5 t), technology (HTPB composite grain in three segments, steerable flexseal-bearing nozzle), and boost capability (maximum thrust in vacuum of more than 600 t) are competitive with the US Space Shuttle and Titan booster engines, has been entrusted to an industrial infrastructure that draws together all the European expertise and experience available in the field of solid propulsion. The development contract has been placed with three co-contractors:

- BPD Difesa e Spazio, the Italian firm that produces, inter alia, the strap-on boosters for Ariane-4
- SEP, which has participated in all the propulsion programmes for France's armed forces
- Europropulsion, which is the prime contractor for the solid-propulsion programme for civil space applications, in which SEP and BPD also take part.

Work started three and a half years ago and in that time the industrial tooling for constructing an engine of this size has been set up, and the design of its main components has been validated. In addition, the first major tests to assess the engine's behaviour are being prepared and will take place in the first half of 1992.

The three level-1 contractors – Europropulsion, BPD Difesa e Spazio and SEP – are assisted by other European firms in various areas of activity, e.g. by MAN Technologie and Fiat for structures, and by SNPE for propellants. Moreover, separate industrial organisations have been set up, like Regulus, a BPD and SNPE subsidiary responsible for running the propellant plant in French Guiana, and Eupera, another subsidiary of SNPE and BPD, which produces ammonium perchlorate.

Tasks have been allocated as follows (Fig. 4):

- BPD Difesa e Spazio is responsible for developing the thermal protection, propellant charge, and the igniter. Its main subcontractors are SNPE, SEP and Regulus.

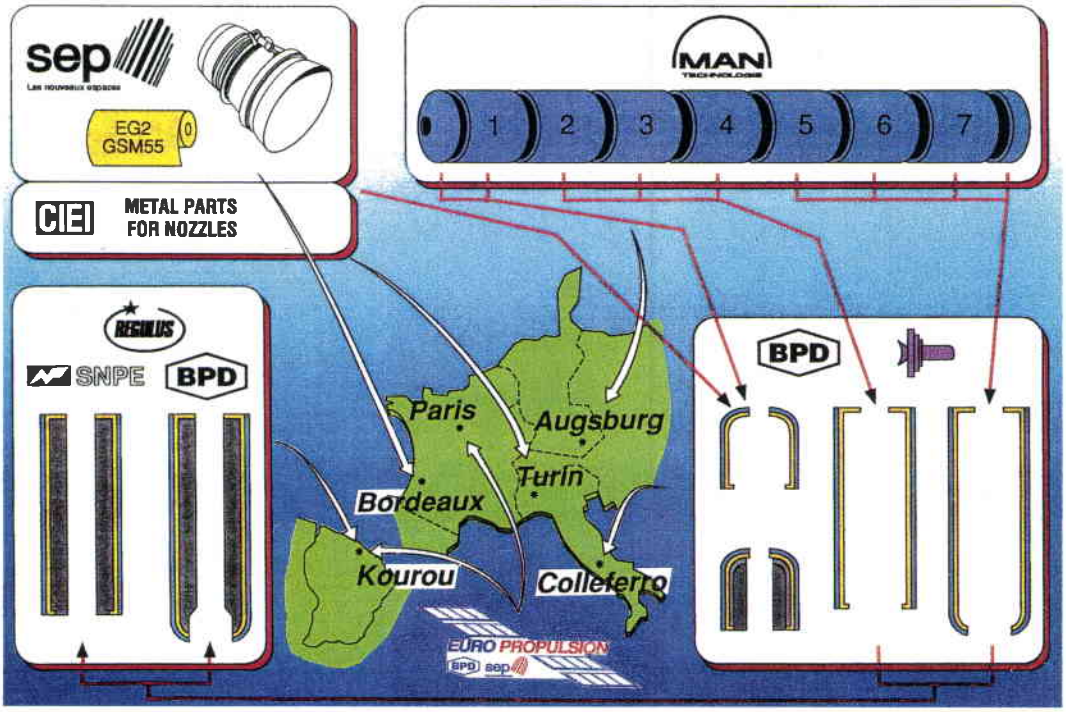

Figure 4. Industrial work allocation for the solid-propellant engine

- SEP is responsible for development of the metal casing and the nozzle; its subcontractors are Fiat and MAN Technologie.
- Europropulsion, as agent for SEP and BPD, plays a prime-contractor role, with responsibility for assembly tasks, testing and transport.

Production cycle for charged segments

The production cycle starts at the Augsburg (D) factory of MAN Technologie, where seven cylindrical sections and two domes for the booster casing are manufactured. MAN Technologie procures the blanks for both types of part from two steel manufacturers: Saarstahl in Germany, and Aubert & Duval in France.

Once the parts have been manufactured and pressure-tested, MAN Technologie assembles them to form the three segments, which are then sent to BPD in Colleferro (I). At the same time, the aft attachment device ring is produced for MAN by Andritz (A) and sent directly to the engine integration site in French Guiana.

In a special plant, BPD fits the three segments with thermal protection made from a rubber material produced by SEP.

The forward segment is then loaded with propellant (22.5 t) at the Italian grain plant on the same Colleferro site. The insulated central and aft segments are shipped to Regulus in French Guiana, where they are cast in the propellant plant located just a few kilometres from the launch pad. This arrangement avoids the need for long-distance transport, which could impair the quality of charges exceeding 100 t.

Eventually, the main raw materials for the propellant (ammonium perchlorate, hydroxyl-terminated polybutadiene binder – HTPB, and aluminium) will be produced in Europe.

Production cycle for the igniter

The igniter is manufactured by BPD at its Colleferro plant and the metal casing is supplied by Fiat.

Production cycle for the nozzle

The nozzle is produced at a dedicated SEP plant, at Le Haillan, near Bordeaux (F), which also makes the phenolic liners. Here, SEP casts and tests the flexseal bearing, assembles the nozzle, and carries out all testing.

The carbon–carbon blanks come from other SEP/Le Haillan workshops and the metal parts (shims, steel immersion cone and lightweight alloy housings for the nozzle and divergent) are produced by Fiat, in Turin.

Engine integration and testing

At the Guiana Space Centre (CSG), the nozzle, charged segments, igniter and aft attachment device ring are brought to the Booster Integration Building (BIP) on the No. 3 Launch Site (ELA-3). It is in this building that Europropulsion assembles the engine and prepares it for the test-stand development firings.

On the same site, Aerospatiale integrates the engine with the additional equipment (skirts, actuation unit, pyrotechnic separation and distancing system) needed to complete the launcher's booster stage.

The booster test-stand (BEP) is 1500 m from the Booster Integration Building, and is linked to it by a railway track along which the booster will be rolled on the platform trolley planned for ELA-3. CNES is responsible for operating the test-stand.

Engine definition

The engine has been designed in the light of various technology choices and tasks to be performed. The latter fall into three main categories:
(i) thrust capability
(ii) launcher flight control
(iii) interfaces.

The choice of which technology to use was influenced by both European and American experience, and by the conscious decision to give reliability, availability, maintainability and safety considerations priority over performance.

The main technologies used are highlighted in Figure 5, while Figures 6–8 show the architecture of the assembled engine, the charged segments, and the nozzle.

Thrust capability

The engine and its propellant charge have been designed to meet the requirement to deliver full thrust while respecting a thrust profile (Fig. 9) and a burn time corresponding to general load thresholds for the launcher. The most critical moment is $t=35$ s, when the flight-control system is most in demand, for entering the transonic phase.

The charge shape was defined following an iterative series of computer calculations. The 236.5 t charge, together with the mass characteristics of the inert components, determines the engine's performance levels (Fig. 10).

Launcher flight control

Throughout the engine burn time, the launcher's flight is controlled almost exclusively by deflecting the engine's nozzles. This requirement is determined by the aerodynamics of the launcher and its payload (satellites in the fairing, or Hermes), and by thrust imbalance between the two boosters. The latter is all-important during the thrust tail-off phase, whereas the former is a dimensioning factor between 0 s and 70 s and for Hermes launches because of aerodynamic constraints in that configuration.

As far as the engine is concerned, the necessary specifications are for a maximum deflection angle throughout flight of 6.6°, based on deflection law profiles defined in terms of deflection integrals and frequency/amplitude diagrams.

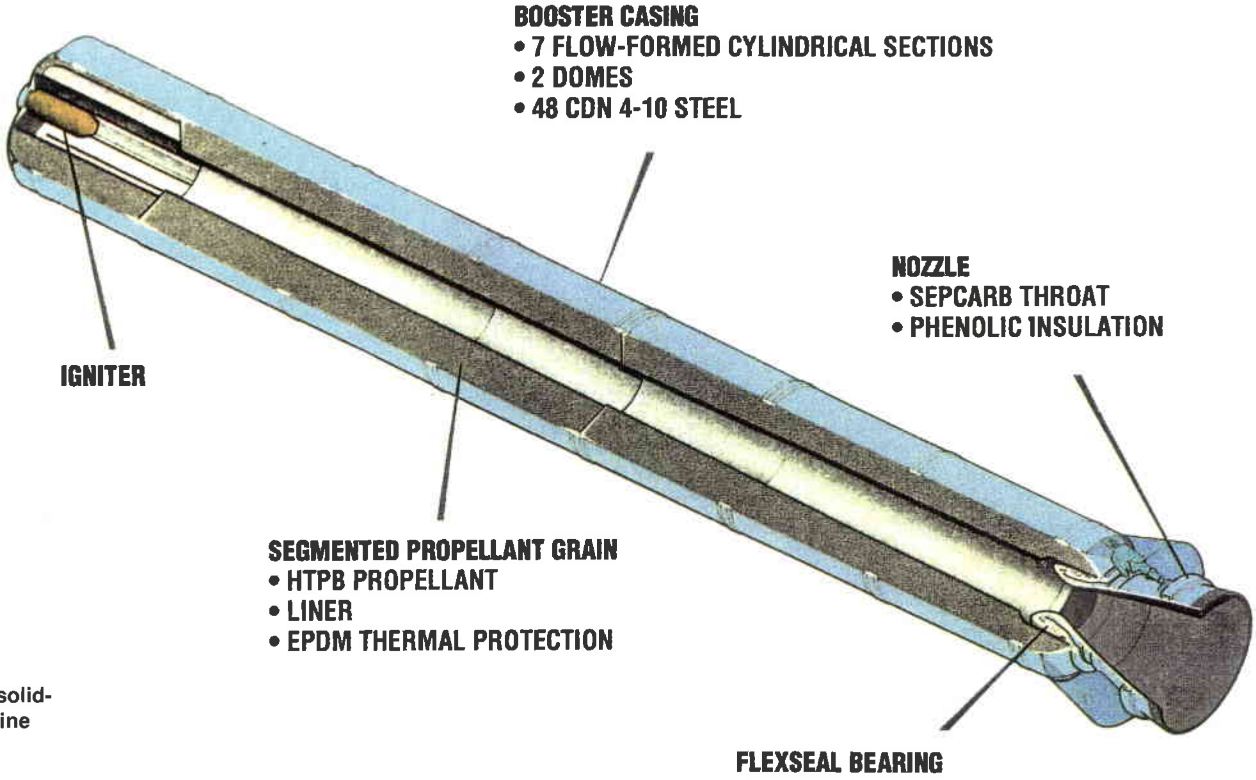

Figure 5. The solid-propellant engine technology

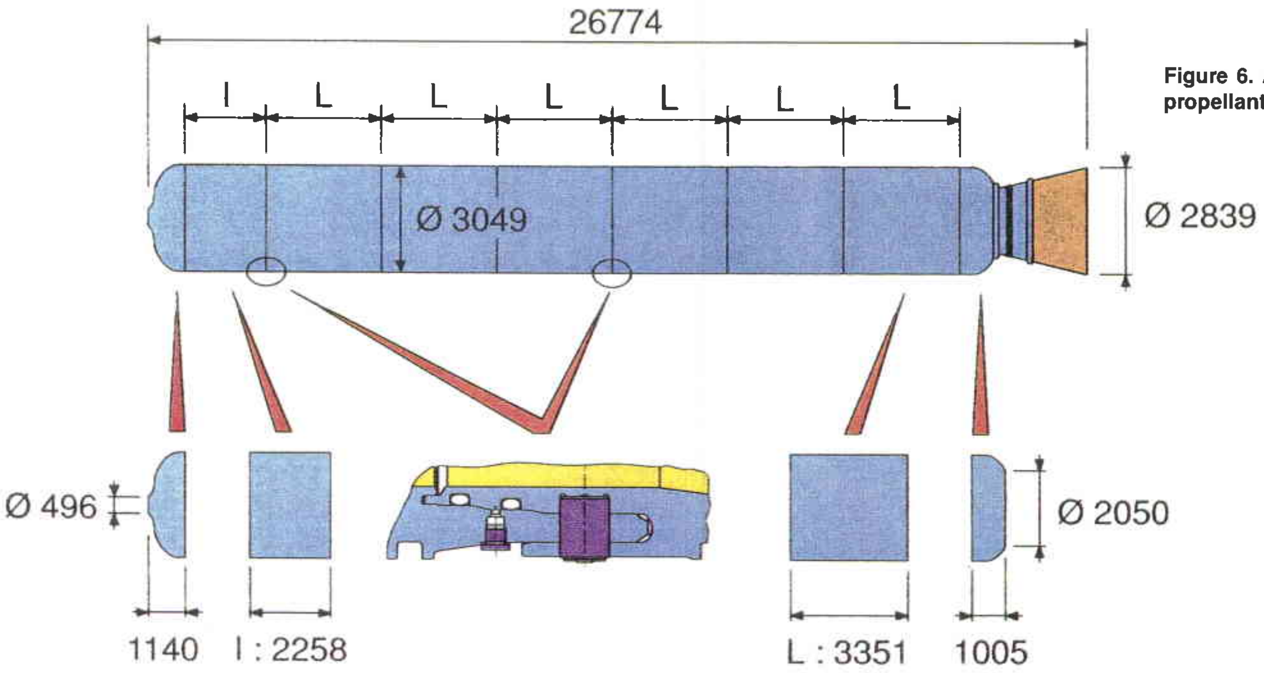

Figure 6. Assembled solid-propellant engine

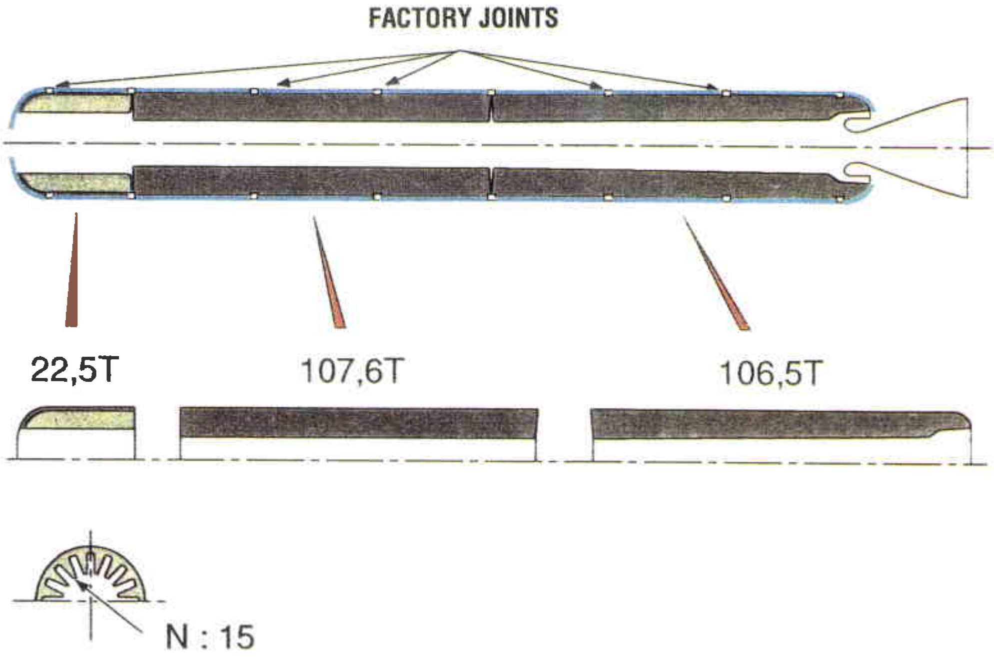

Figure 7. Solid-propellant engine grain

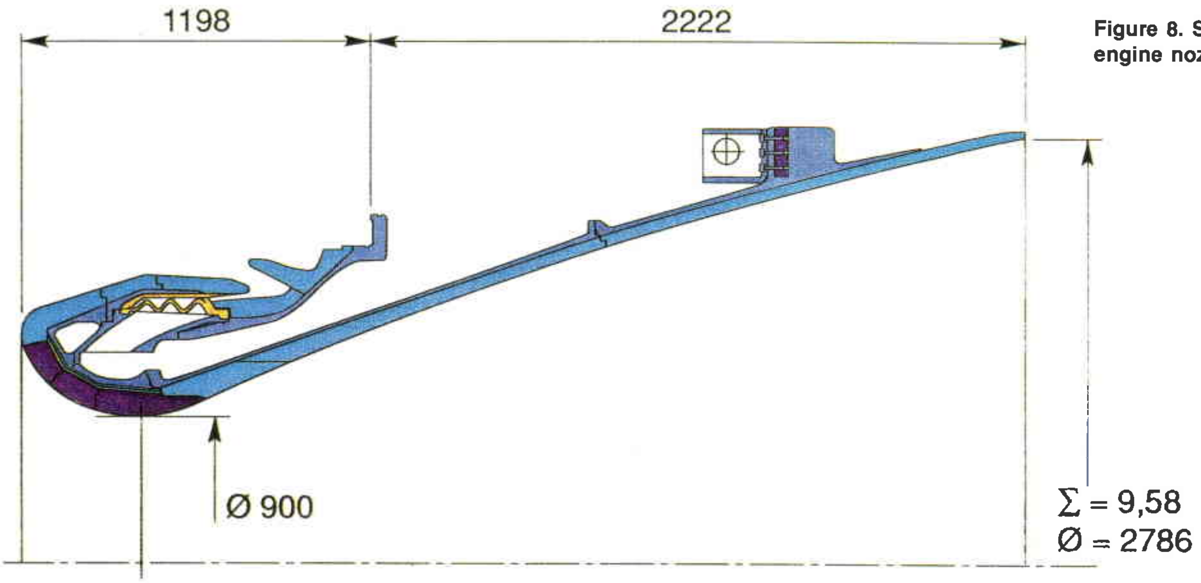

Figure 8. Solid-propellant engine nozzle

Figure 9. Solid-propellant engine thrust profile

TOTAL MASS	(T)	264,9
PROPELLANT MASS	(T)	236,5
INERT MASS BOOSTER CASING THERMAL PROTECTION NOZZLE IGNITER TOTAL	(T)	 19,5 4,7 6,1 0,3 30,6
MAXIMUM PRESSURE	(BAR)	59,7
BURNTIME	(s)	129,5
IN VACUO SPECIFIC IMPULSE	(s)	271,2
THRUST ON GROUND AT T0	(kN)	5400

Figure 10. Solid-propellant engine performance figures

Interfaces

The three main engine interfaces are to be found at:

- the forward and aft skirts, where the junction frames are connected by positioning pins similar in design to those of the field joints
- the aft attachment device ring mounted on the rear segment; this ring has three ball-and-socket joints to which the rods attach
- the nozzle, with steering fittings for the servo-actuator attachments.

In addition, the aft attachment device ring will be equipped to hold the nozzle actuation unit's pressurised bottles in place. The booster casing will have attachments for the safety destruct system.

Status of engine subassembly development

The subassemblies have been developed in parallel with engine definition work. To start with, the work consisted of: (a) producing feasibility parts that preceded the first nominal manufactured parts, in order to set up the critical procedures involved; and (b) running elementary tests on full-sized engine parts with a view to determining how they performed.

Casing

This is made of 48 CDN-4-10 steel with an elastic resistance of 1300 MPa, a fracture resistance of 1500 MPa, and a fracture-toughness specification of a minimum of 78 MPa $m^{1/2}$.

The two main problems that arose at the start of the development work related to perfecting most of the manufacturing procedures deemed critical because of the dimensions of the parts (flow-forming, thermal treatment, and precise joint machining), and designing joints equipped with pins, particularly for the field joint.

One of the main concerns was to get the industrial set-up organised, with the result that the first flow-forming tests were able to start as from October 1988. The technology qualification programme, based on nine cylindrical sections and four domes, brought to light several difficulties, notably as regards thermal treatment, which involves salt-bath quenching. These problems are on the point of being solved with the production of the first items of equipment for the H0 hydraulic test.

Another concern, exacerbated by the 'Challenger' Shuttle disaster, was the design of the field joint and, in particular, making it absolutely leak-tight using O-ring-type seals. In order to overcome this obstacle as quickly as possible, representative parts with a nominal diameter were produced for the purpose of studying how the joint behaved. Two pressure tests have been conducted so far, under both nominal and downgraded stress conditions (seal cut, pin omitted, etc.). The results show that in all cases the seal clearance is less than 0.2 mm, and modelling of the phenomenon matches actual experience.

Nozzle

Prior to the first test-stand firing, materials used for the nozzle were characterised and some of its structural functions were checked. As far as the materials are concerned, the novel features lie in the lining of the throat of such a large-dimension nozzle with a carbon-carbon material, and in polymerisation of the phenolic liners in an autoclave (the best procedure in production-cost terms).

Nominal-dimension parts have been produced for characterisation in a laboratory. In addition, several firings of a booster charged with 6 to 15 t of grain have made it possible to study ablative and insulating behaviour under sufficiently representative conditions (thermal stress, duration, composition of combustion gases).

Notable events in terms of structural aspects include:
- development work on moulding of the flexseal bearing: four test bearings have been moulded as well as three units for the first nozzles
- hydraulic testing of the immersion cone: the purpose of this test was to verify structural dimensioning and characterise the joint between the aft dome and the field joint, the latter being potentially the most critical joint in terms of leak-tightness
- rigidity testing of a nozzle extension: the first phase of this test used bare housings, while in the second phase the housings were fitted with their phenolic liners.

Internal thermal protection
As with the other materials, development of this system has entailed two types of problem:
- The setting up of manufacturing procedures suitable for producing protection systems with masses of several tonnes, given that conventional systems used on current engines weigh only about a hundred kilogrammes.

  The solution adopted was to produce two mockup sections – an aft segment MVP1 and a forward segment MVP2. They will be charged with inert grain so that validation of the procedures can continue up to the casting and curing stage.

- The characterising of materials as closely as possible to match the stresses to which they will be subject in a large engine. In addition to scale, there is also the problem of using existing materials to produce thermal protection for the segments.

  The solution adopted was to produce a 15 t segmented engine, which was fired on the test-stand in December 1989, i.e. the SSM1 test.

In addition, the SSM1 test made it possible to qualify a technique for measuring ablation using sensors buried in the thermal protection. After the first firing of the solid-propellant engine, this technique will be used to optimise the thermal-protection thicknesses.

Grain charge
The propellant for the solid-propellant engine, an HTPB composite containing 68% ammonium perchlorate and 18% aluminium, has been designed to achieve the requisite performance levels as regards:
- specific impulse
- burn speed
- mechanical property, and therefore reliability
- target costs.

It has been tested in the SSM1 engine.

Work is under way at the two grain plants, in Italy and French Guiana to perfect, with the industrial facilities that will be used for production, the two most critical procedures: mixing, in particular in the 1800 gallon mixers that will be able to provide 12 t of grain per batch, and liner pulverising to ensure that the thermal protection adheres properly to the grain charge.

In addition, it has been possible to validate the casting/curing operations and to conduct non-destructive testing with the two inert segments MVP1 and MVP2.

Once all of this work had been completed, authorisation was given to charge the first unit, B1.

Internal ballistics for segmented engines
With the Ariane-5 solid-propellant engine, Europe will be producing a segmented engine for the first time. Two activities have been carried out to validate and calibrate the internal ballistics models:
- a segmented engine has been fired on a scale compatible with available manufacturing and test facilities (the SSM1 engine configuration is shown in Figure 11)
- a test programme is being run and codes are being developed to establish combustion stability margins as regards a low-frequency pressure oscillation that may be caused by the field joints (first mode at 25 Hz).

This programme, which includes mockup tests, is being carried out by BPD in collaboration with the Chemical System Division of the United Technology Centre (UTC-CSD) in the USA, the Von Karman Institute in Belgium, and ONERA in France.

Igniter
Development work is in progress on the igniter. Before the first full-scale test-stand firing, two igniters will have been fired. So far, the fracture tests on the main charge casing

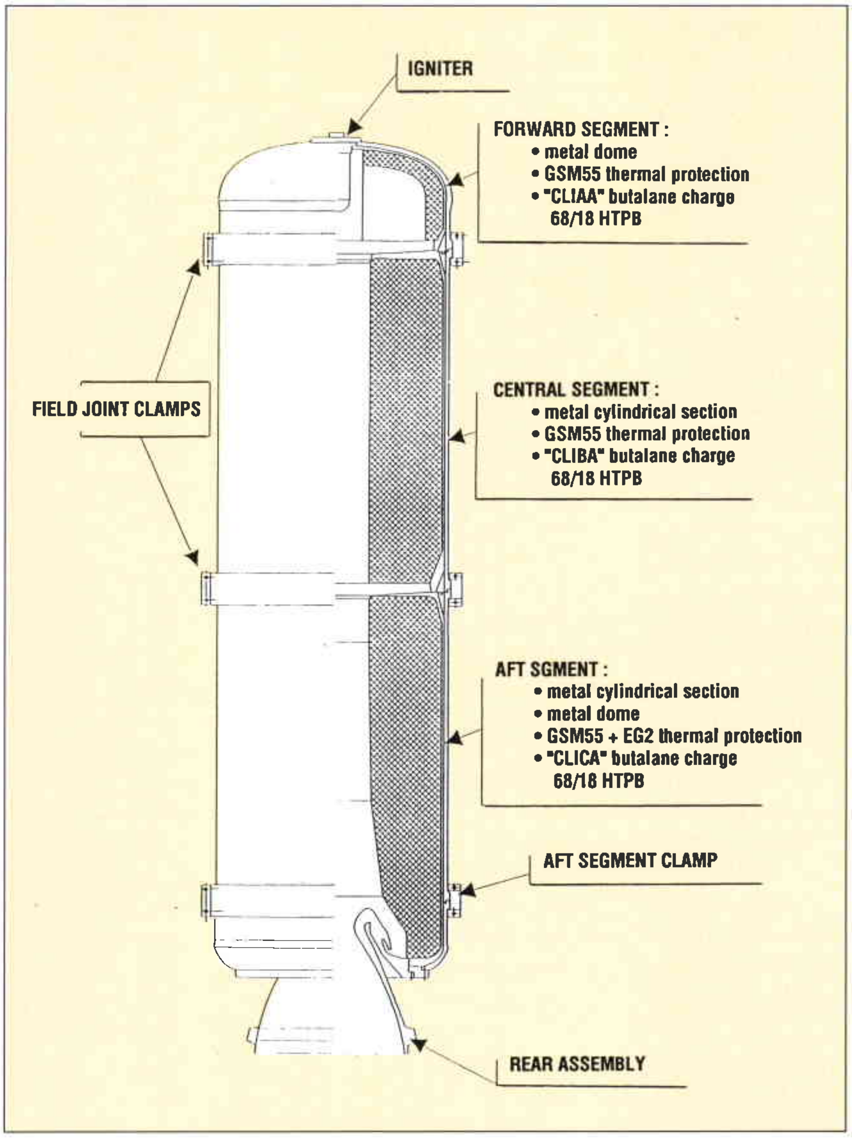

Figure 11. SSM1 engine configuration

have been carried out, as have pyrotechnic igniter tests using an igniter initiator.

Major engine-development tests

These comprise subassembly qualification testing, engine test-stand firings, and reliability testing of joints.

Hydraulic tests on casing

The major development test phase has started with the first of two hydraulic qualification tests on the casing. This first test involved only the forward and aft segments and the adjacent structures (igniter plate, immersion cone, and aft attachment device ring). Using this minimum configuration, all the casing components have been subjected to a high level of stress to reach the safety margins in the current definition.

The test took place in June 1991 and the successful burst test on the casing at 89.7 bar represents a safety factor of J = 1.4 vis-a-vis maximum operating pressure (Fig. 12).

A second, similar test will take place next year. However, in view of the machining tolerances for large-diameter work pieces, the risk of a loss of leak-tightness cannot be excluded out of hand. It has therefore been decided to run a series of tests on nominal parts to characterise how the joints behave. Testing will consist of rapid pressurisation using a gas generator, applied to joints containing internal thermal protection that can affect the efficiency of the O-ring seals. These tests will also aim to test resistance to defects and redundancy effectiveness.

The test configuration (Fig. 13) has two cylindrical sections and two domes fitted with five joints (one at igniter level, three field types, and one at the immersion-cone level).

Reliability testing of joints

The criticality of the leak-tightness of the solid-propellant engine joints results from the clearances in the O-ring seals under the effect of distortions caused by pressurisation. These clearances have been minimised by a design change which introduces lips that block them.

Pressurisation is achieved in 300 ms by a generator containing 45 kg of propellant, and pressure is maintained for 120 s until a release valve opens.

Figure 12. Hydraulic casing testing in progress

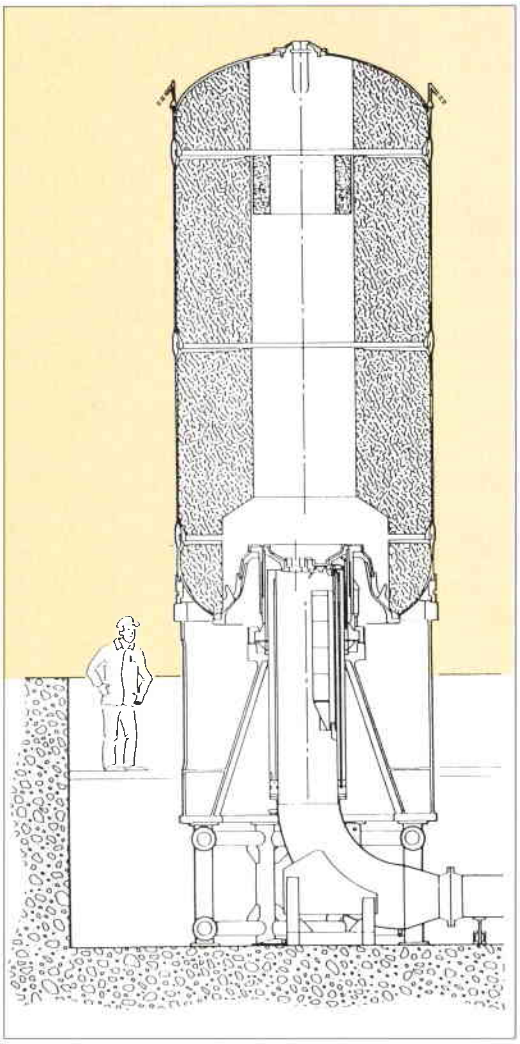

Figure 13. Joint pressure testing configuration

These tests will be conducted at SEP's Istres facility from early 1992 onwards.

Test-stand firings

One of the fundamental choices made in the solid-propellant engine programme has been to design a test-stand on which the nozzle can be fired downwards. This also allows the engine to be tested with its nominal attachment fittings (Fig. 14); in addition, the engine itself can be prepared with the same facilities used for flights.

The test-stand has therefore been sited near the ELA-3 Booster Integration Building. Ten firings are planned, two of which will take place in a heavy-walled case (so-called 'B firings'):

- the first (B1) will take place without waiting for the completion of casing development
- the second (B2) will include an additional 20 t segment to increase burn time by about 15%, for the purpose of qualifying the nozzle.

Four development firings (M1 to M4) will make it possible to:

- evaluate the engine's overall behaviour
- measure its thrust levels and adjust the charge definition to meet specifications
- progressively test deflection capability

Figure 14. Solid-propellant engine test-stand firing set-up

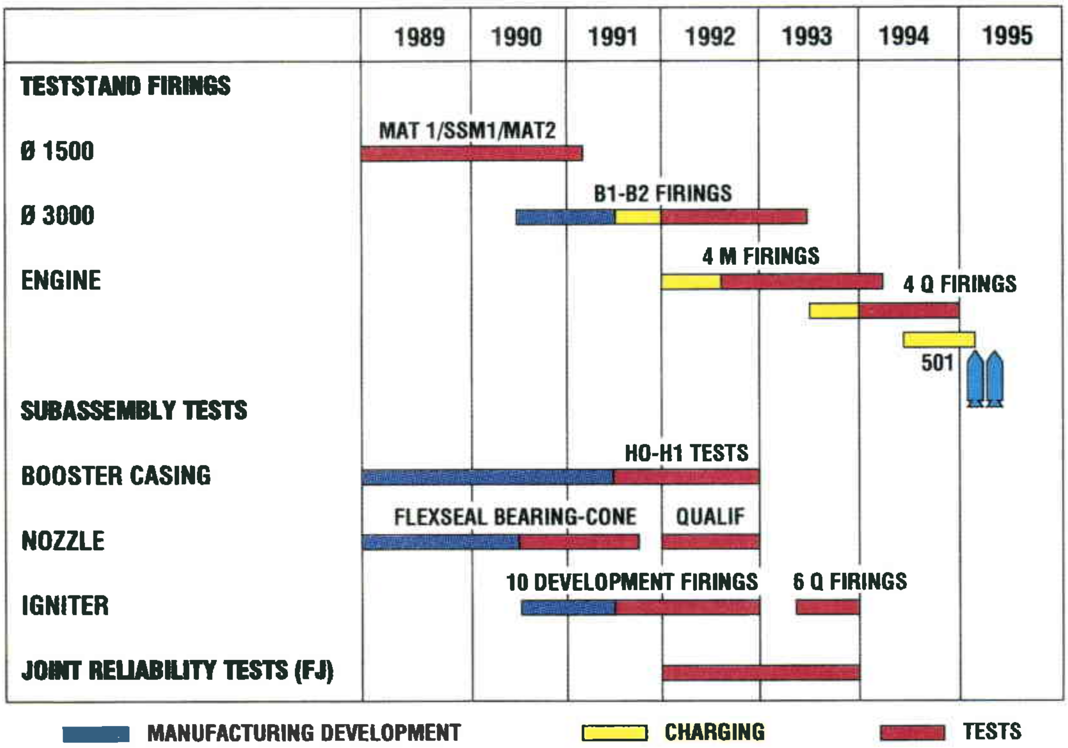

Figure 15. Solid-propellant engine development — Major tests

- demonstrate the joints' resistance to assembly defects, these having previously been tested during the reliability testing of joints
- verify compatibility with the stage hardware (skirts, power unit, servo-actuators, aft attachment device).

The four firings will be followed by four qualification firings; for the last two, the entire solid-propellant stage will be used.

The test-stand firings follow a rigorous logic, which has several objectives:

- characterisation of engine operation: the engine's environment (adjacent structures) and instrumentation (600 parameters) are meticulously defined so that the results obtained can be used to adjust performance models for the various items of equipment;
- adjustment of the specifications: a special analysis is planned for some tests in order to obtain data that will make it possible to dimension the definition as closely as possible to the specified safety coefficients.

  The best example of this is optimisation of the thermal-protection thicknesses, which will take place after the B1 test and will be applied to the M3 unit about 20 months later. However, because of the duration of the manufacturing cycles, only one iteration is possible for each item of equipment.
- hardened tests or testing for resistance to defects: this will involve the B2 long-duration firing, in which the nozzle will be overstressed, and the M2 firing with built-in defects in the joints.

The qualification programme for the solid-propellant engine is geared to the first Ariane-5 flight, which is planned for the first half of 1995 (Fig. 15).

Conclusion

Development of the solid-propellant engine is certainly one of the major challenges of the Ariane-5 Programme. The industrial structure that has been established to meet it pools the best European expertise available in this field. Care has also been taken to provide the technical, and financial, input required to ensure that industrial production tooling was available from the outset of the development programme, to avoid problems arising during the subsequent industrialisation phase. In addition, a very specific product-assurance policy common to the firms involved in the engine's development has been defined and implemented to ensure that the final product is second to none in terms of quality, performance, reliability, availability, maintainability and, last but certainly not least, safety.

Acknowledgements

I would like to thank CNES, Aerospatiale and Europropulsion for their helpful cooperation during the preparation of this article.

Re-entry Vehicle Thermal-Protection Developments in Europe

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Every vehicle entering a planetary atmosphere from space is exposed to a complex high-temperature environment. In this extremely hostile environment, the structural integrity of the vehicle's outer skin has to be maintained and the temperature limits for the internal elements and payload must be respected. To meet these demanding requirements for future re-entry vehicles, efficient thermal-protection systems are already under development in Europe.

Introduction

When a vehicle enters a planetary atmosphere from space, aerobraking is used to dissipate the majority of its kinetic energy, in order to slow it sufficiently for a safe final landing or perhaps for a docking manoeuvre. This dissipation of kinetic energy causes high atmospheric gas temperatures and thus leads to considerable aerodynamic heat fluxes on the spacecraft's surfaces.

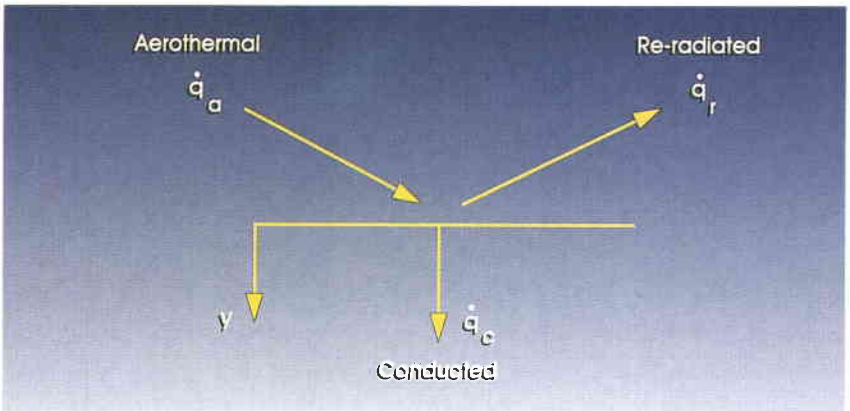

Figure 1. Surface heat balance between aerodynamic heat (q_a), re-radiated heat (q_r) and heat penetration (q_c)

These heat fluxes depend on many parameters, including entry velocity, entry angle, ballistic coefficient, vehicle bluntness, enthalpy characteristics of the atmospheric gases, atmospheric density and temperature, etc. Typical maximum heat fluxes range from 200 kW/m^2 to nearly 10 MW/m^2 for ballistic capsules, and from 300 kW/m^2 to 800 kW/m^2 for winged re-entry gliders. To protect the structural integrity of the vehicle's outer skin and maintain the appropriate internal temperatures (for crew, electronic equipment, etc.) under such hazardous conditions, extremely efficient heat-rejection and heat-flow control is required.

Structural integrity is threatened during atmosperic entry by thermo-mechanical stresses, by mechanical loadings at high material temperatures, and by potential material changes. The thermo-mechanical stresses are due to differential thermal expansion in the materials. Dynamic pressures, aerodynamic shear forces and acoustics contribute to the mechanical loads. Material changes are caused by high-temperature chemical reactions between atmospheric constituents and surface materials, and by phase changes or chemical decomposition within the materials themselves.

Basic design options

The re-entry vehicle's surface temperatures are determined by the balance between incident aerodynamic heating, heat re-radiated from the surfaces to the environment, and heat soaked into the vehicle. Accordingly, they can be reduced by reducing the aerodynamic heating, increasing re-radiation, and increasing heat soak.

Injection of mass into the boundary layer and use of smooth and low-catalytic surfaces are two engineering means of reducing aerodynamic heating for a given vehicle shape. Higher surface emittances increase the re-radiation of heat.

Radiative heat transfer from hotter to cooler surfaces within the vehicle is one possibility for increasing the heat soak. Application of this principle to, for example, the nose cap of a re-entry glider, leads to temperature reductions in the order of 200°C for the hottest spots. Other means of increasing the heat soak include giving the spacecraft's skin a high thermal inertia or promoting heat exchange between the skin and internal thermal 'sinks', e.g. by exploiting high-temperature heat pipes between skin and sink.

On the other hand, however, heat penetration to temperature-limited areas of the vehicle has to be minimised. Means of achieving this objective include low-conductance thermal insulations and the absorption of heat near the skin via endothermic chemical reactions and phase changes.

These considerations lead to basic architectures of the type shown in Figure 2 for the primary load-carrying structures of re-entry vehicles. Generally speaking, the thermal performances of internal insulations are superior to those of external ones because of the less stringent mechanical load environment. Thus, the hot-structure architecture basically results in a lower thermal-insulation mass. The main design problems of the hot-structure architecture are presented by differential thermal expansions and by the connections to other structural elements. Material and manufacturing capabilities constitute a further challenge.

Today's materials

The latest materials and manufacturing technologies are the basic building blocks to be exploited in providing thermal protection. We will concentrate first on thermo-structural materials suited for primary structures operating at temperatures above 350°C, and then on external insulations capable of withstanding direct exposure to the entry environment.

Ceramic Matrix Composites (CMCs)

Carbon/carbon thermo-structural materials are applicable for service temperatures far above 2000°C in a non-oxidising environment. However, above 400°C, resistance to thermal oxidation becomes poor and must be improved by using surface coatings. A two-layer coating composed of silica and silicon-carbide is the popular choice for skin temperatures up to 1700°C. Multi-layer coatings with other material combinations suitable for higher temperature applications are under investigation.

There are two common manufacturing routes for producing carbon/carbon (C/C) structures. In the first, the carbon-fibre preform is infiltrated at high temperature with a carbon vapour (CVI) until a dense structure is achieved. In the second, the carbon-fibre preform is impregnated with pitch or a similar substance, which is subsequently fired under high pressure. Both processes are rather complex in practice, which results in long manufacturing cycles and high costs.

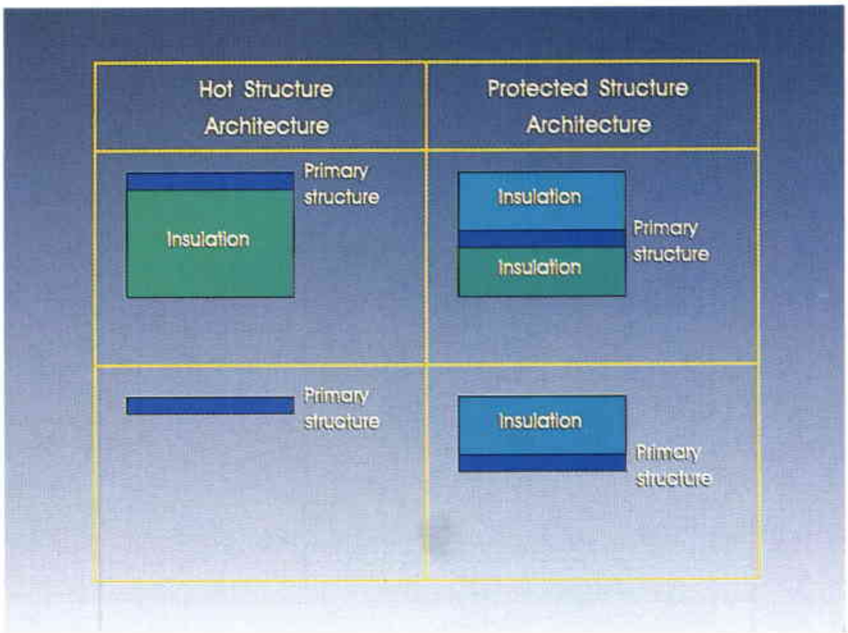

Figure 2. Basic passive thermal-control architectures

Inherently better oxidation resistance is achieved if the carbon matrix is replaced by silicon carbide, to produce carbon/silicon-carbide (C/SiC) thermo-structures. High-quality C/SiC materials can be used up to some 1700°C. Below 1500°C, their mechanical-performance/weight ratios are superior to those of C/C. This material is

Figure 3. Skinex^{R} carbon/silicon-carbide (C/SiC) large thermal space-plane structure (Courtesy of SEP)

Figure 4. Ablation test in an arc-jet test facility (Courtesy of Dornier)

therefore being investigated for use in thermally and mechanically highly loaded structures for lower surface temperatures than C/C. The CVI manufacturing route has so far proved to provide the highest quality of C/SiC materials.

Metallic alloys

Super alloys using cobalt and nickel as a basis can be used up to about 1000°C. These materials are well-characterised in terms of physical properties and manufacturing capabilities, but their rather high densities imply a need for sophisticated constructions in order to achieve low mass.

Beryllium offers a high specific stiffness and high specific heat. Inherent brittleness, joining problems and toxity somewhat restrict its application. Used primarily for specialised parts/equipment, its maximum service temperature is in the order of 650°C.

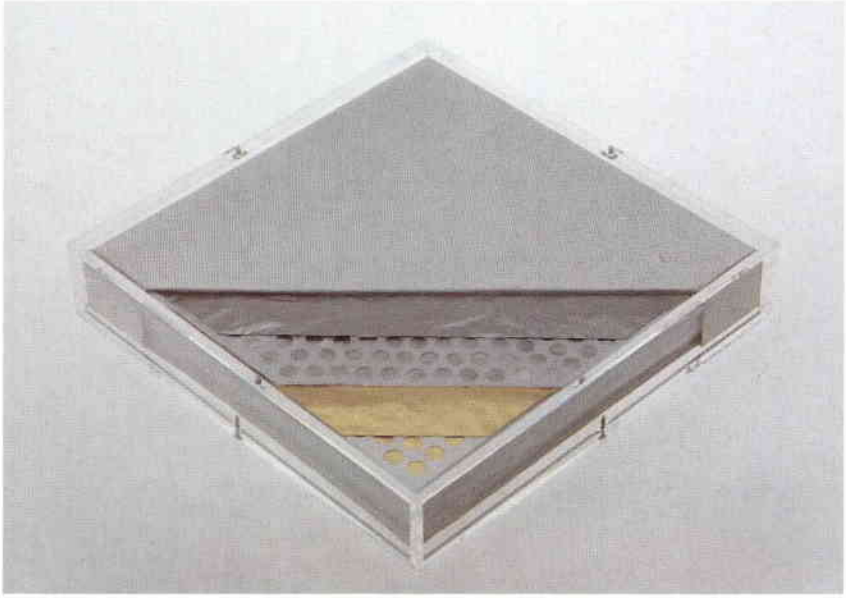

Figure 5. Lightweight high-temperature multi-layer insulation with noble-metal-coated ceramic screens (Courtesy of MAN)

In the medium temperature range, highly efficient structures can be made from titanium alloys. Super-plastic forming and diffusion bonding are well-established manufacturing processes here. Long-term application in an oxidising atmosphere at elevated temperatures requires improvement of oxidation resistance, e.g. by applying diffusion barrier coatings.

External ablators

Carbon-phenolic ablators can be used for even the highest heat loads. Their mechanical integrity is good in an external flow environment, but their density is rather high for an insulation.

Phenolic-resin-impregnated silica felt retains sufficient short-term mechanical integrity in an external flow environment up to some 1500°C, although resin decomposition starts above 400°C. The manufacture of such medium-density (ca. 300 kg/m^3) materials (AQ60) is already mastered in Europe.

Other medium-density ablators include silicone elastomers, such as silicone reinforced by ceramic microspheres (e.g. 'Prosial'). Prosial is sprayable, thereby facilitating assembly procedures, though its limited mechanical integrity under shear forces at high heat loads can sometimes be a drawback.

External insulations

Rigid ceramic tiles are produced by sintering together alumina-silica fibres. Depending on the alumina content of the fibres, the maximum service temperature can be raised from 1200°C to 1700°C, but specific thermal insulation performance then decreases. Tiles made from high-purity silica fibres provide excellent thermal insulation up to some 1250°C.

Flexible silica-fibre blankets provide the lightest external insulation for temperatures up to 800°C at mechanically less loaded locations.

Internal insulations

Ceramic-fibre mats made from alumina-silica fibres can be used for lightweight internal insulation. Their applicable service temperature increases with the alumina content of the fibres.

Owing to the dominant radiative heat-transfer mode at elevated temperatures, a high-temperature multi-layer insulation is thermally the most appropriate. The insulation consists of several layers of highly reflective foils, separated by ceramic-fibre spacers. Major advances have been achieved by the development of noble-metal-coated ceramic screens, which can be used up to 1450°C.

Thermal-protection challenges of future ESA missions

Science

Cassini/Huygens

This is a cooperative international mission, the primary objectives of which are to put a spacecraft (provided by NASA) into orbit about Saturn and to deliver a probe (provided by ESA) into the atmosphere of Saturn's moon Titan.

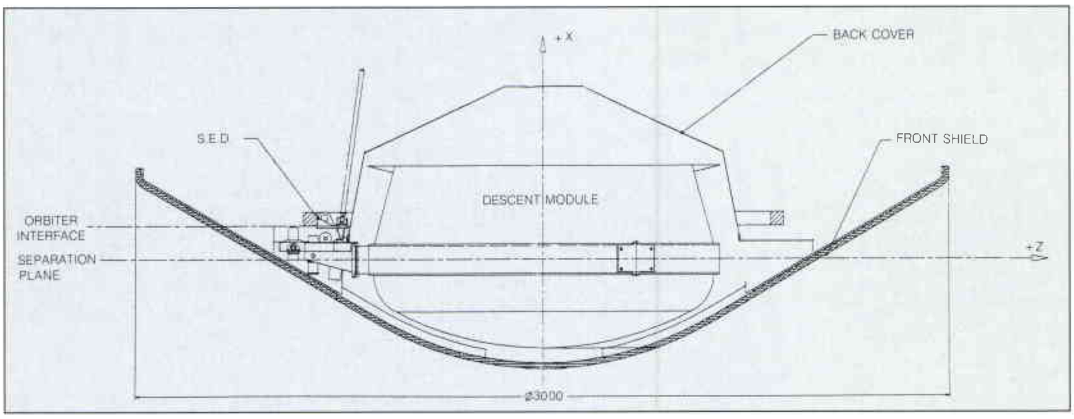

Figure 6. Huygens Probe aeroshell (Phase-B design)

Titan's cold atmosphere is denser than that of the Earth and is composed of nitrogen, methane, and traces of higher hydrocarbons. A deeper understanding of both the organic chemistry and the dynamics of this complex atmosphere will be prime scientific objectives during the Probe's descent.

A few minutes of high heat fluxes will occur during the Probe's ballistic entry into Titan's atmosphere. Clearly, given the scientific objectives, no contamination of the descent measurements by hydrocarbons and nitriles deposited on the Probe's surface during the entry or earlier phases is acceptable. This risk is to be minimised by employing an aeroshell/descent-module configuration, the aeroshell being used only for entry purposes.

A trade-off was initially made between a hot-structure architecture, using a C/C thermo-structure with ceramic-fibre insulation inside the compartment housing the descent module, and a protected-structure architecture. Primarily for schedule reasons, a protected aluminium aeroshell was chosen, due to its lower technical risk and higher state of development. The evaluation of arc-jet tests representative for the predicted high heat loads resulted in the selection of AQ60 as the thermal-protection baseline.

Potential aeroshell mass savings are promised by a more agressive design in which the aluminium primary structure is replaced by one made from materials with higher maximum service temperatures, such as titanium alloys.

At the end of the entry phase, the rear cover of the aeroshell will be jettisoned and a parachute deployed to separate the descent module from the aeroshell.

Rosetta

Rosetta is one of the so-called 'Cornerstone' missions of ESA's Long-Term Scientific Programme:Horizon 2000. Its major scientific objective is the acquisition and return to Earth of samples of cometary material.

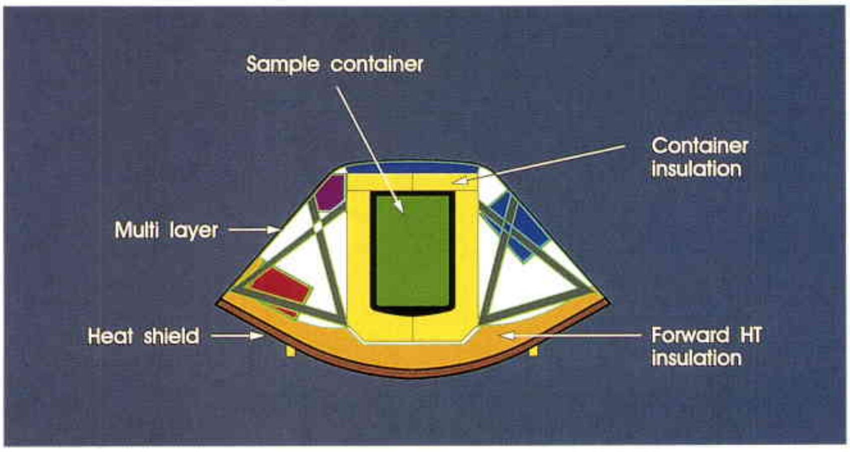

Figure 7. Rosetta Earth Re-entry Capsule (ERC) principal thermal-design features

The spacecraft being considered for this mission has three main modules, known as the Carrier, the Lander and the Earth Re-entry Capsule (ERC). The Carrier transports the Lander and the ERC close to the comet, and the ERC (the only module which returns) back to the vicinity of the Earth.

The cometary samples are to be stored in a container inside the ERC and should be kept at temperatures below 130 K. Because of its high re-entry speed of more than 16 km/s, the ERC will be exposed to the highest heat fluxes encountered by any space probe so far studied by ESA. Preservation of sample temperatures during and after re-entry is therefore a very challenging thermal-control task.

The heat fluxes encountered during re-entry will exceed the service temperature limits of thermo-structures and external (non-ablating) insulations. Among the ablators, only carbon-phenolic has sufficient mechanical resistance for the front shield's thermal protection. The SEPCORE front-shield design therefore combines the advantages of carbon-phenolic ablator, C/SiC thermo-structure, and high-temperature multi-layer insulation. A mass saving of about 70 kg (43%) compared to a conventional carbon-phenolic-protected aluminium shell is expected.

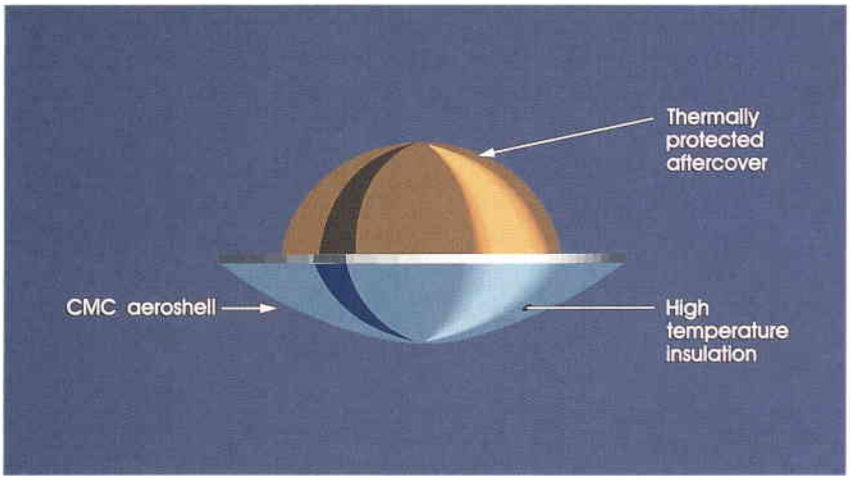

Figure 8. Aeroshell configuration for the deployment of semi-hard landers on Mars

The sample container is thermally decoupled from the ERC shell by means of low-conductance structural links and exterior conventional multi-layer insulation. The sample container itself is baselined as a dewar-like cylindrical vessel with low-conductance struts between its walls.

During the return cruise phase, the capsule door and the container lid will remain open, thereby exposing the container radiator to deep space and allowing low sample temperatures. Low initial sample temperatures are important because the samples warm up during the Earth-entry and recovery period. Calculations have indicated that every degree reduction in temperature achieved during the cruise extends the admissible recovery time by about 1 h.

Marsnet

Over the last 25 years, a significant number of spacecraft fly-bys, supplemented by imaging and surveillance of Mars from orbiting vehicles and landers, have provided valuable scientific information about the planet. The results obtained from these missions have highlighted many similarities between Mars and Earth, but at the same time have also provided evidence of major differences, thereby stimulating further scientific research and the need for further Mars exploration.

ESA's feasibility studies have shown that the most promising option for Agency participation in the future exploration of Mars is provided by the deployment of a Martian surface network for conducting extended geophysical, chemical and meteorological measurements. Beyond its immediate benefit to the scientific community, such an option seems to have very high potential as part of a precursor mission.

The Mars network stations are to be protected within an aeroshell during atmospheric entry. The aeroshell provides the aerodynamic shape required for hypersonic deceleration of the entry speed and thermal protection of the network stations against aerodynamic heating.

The rather mild heat fluxes to be expected during entry allow a variety of thermal-protection solutions, including two different hot-structure architectures and one protected-structure architecture:

(a) coated C/C or C/SiC aeroshell with internal high-temperature porous insulation

(b) aluminium aeroshell protected by a lightweight ablator (several materials possible)

(c) coated C/C or C/SiC hypersonic decelerator and a lander-housing aeroshell compartment made from beryllium with internal medium-temperature insulation.

In extending the past applications, the European Marsnet studies also investigated deployment at higher topographical altitudes. Due to the thinness of the Martian atmosphere, this would require even greater mass savings and/or the survival of high impact speeds. Some mass-saving potential for concepts (a) and (c) is provided by improvement of the insulation's thermal efficiency. Higher service temperatures for the aeroshell's primary structure are beneficial for concept (b). Replacement of aluminium by CFRP, e.g. C/PI or C/PEEK, promises the greatest benefits.

Microgravity

Ariane Recoverable Orbital Carrier (AROC)

Up to now, European experiments destined for space and return to Earth have remained dependent upon US Space Shuttle flights or Soviet recoverable payload capsules. A recoverable payload capsule tailored to the Ariane launcher would provide European independence in this area.

The proposed AROC capsule can be lifted into low Earth orbit as complementary cargo on commercial satellite missions, with the capsule's final orbit being provided by its own propulsion system. Once the microgravity experiments have been completed in orbit, the capsule returns to Earth.

The geometry of the capsule is based on that of the Apollo capsule, scaled down by a factor of 0.9 to achieve compatibility with the Ariane-4 fairing yet still provide sufficient payload volume. The Ariane capsule's structural elements are manufactured from an aluminium alloy, to provide a low-cost and low-risk approach. An ablative shield provides external thermal protection to the primary structural elements.

Parts of the capsule's structure and equipment are reusable for up to five missions.

Space transportation

Hermes

The Hermes reusable space plane is currently the most challenging European aerospace project in terms of thermal-protection development. Hermes will be put into low Earth orbit by the Ariane-5 launcher, and this provides the envelope for the space plane's mass and wing size.

Hence, Hermes' thermal-protection system will need to make extensive use of a hot-structure architecture. The nose cap and leading edges of the airframe, which are exposed to the most severe heat-flux environment, will be made from C/C thermo-structures, rather like those of the Shuttle Orbiter. However, the need for mass saving calls for, and fortunately technological progress allows, considerable reductions to be made in skin thicknesses. The thermally and mechanically highly loaded winglets, rudders, elevons and the body flaps are made from C/SiC thermo-structure.

Verification of the integrity of these CMC components by combined thermal and mechanical testing is itself a technologically demanding task, beyond the initial design, material and manufacturing challenges.

The fuselage and wings are made from an aluminium alloy. Thermal protection is achieved by using Flexible External Insulation (FEI) for surface temperatures below 650°C and Rigid External Insulation (REI) for higher temperatures. The main REI components are the C/SiC shingles accommodating the aerodynamic loads and the IMI internal high-temperature multi-layer insulation providing the required thermal performance.

Figure 9. Model of the Ariane capsule (Courtesy of MAN)

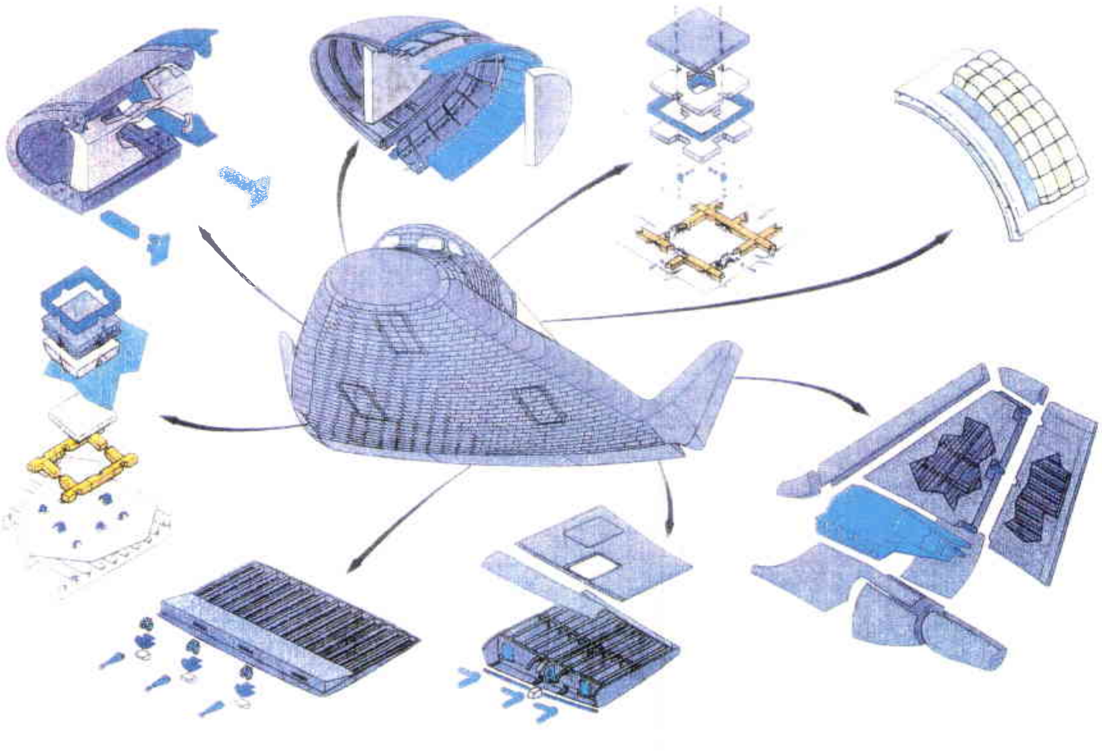

Figure 10. Exploded view of Hermes' thermal protection (Courtesy of Dassault Aviation)

Figure 11. Full-scale carbon/carbon nose cap and leading-edge section (Courtesy of Aerospatiale)

The Hermes thermal-protection development effort is applying many advanced design principles, manufacturing and verification methods, thereby expanding the technical knowhow in Europe. Each component has to have guaranteed survival of thirty re-uses in a very demanding environment, in combination with meeting stringent low mass and high safety requirements.

Reusable winged launchers

Current developments in expendable launchers like Ariane-5 are enabling a further improvement in the efficiency/cost ratio for space transportation. However, if the demand for delivering payloads to low Earth orbit is to continue to grow, a further significant reduction in launch costs will be mandatory. Such cost reductions are promised by fully or partially reusable space-transportation systems.

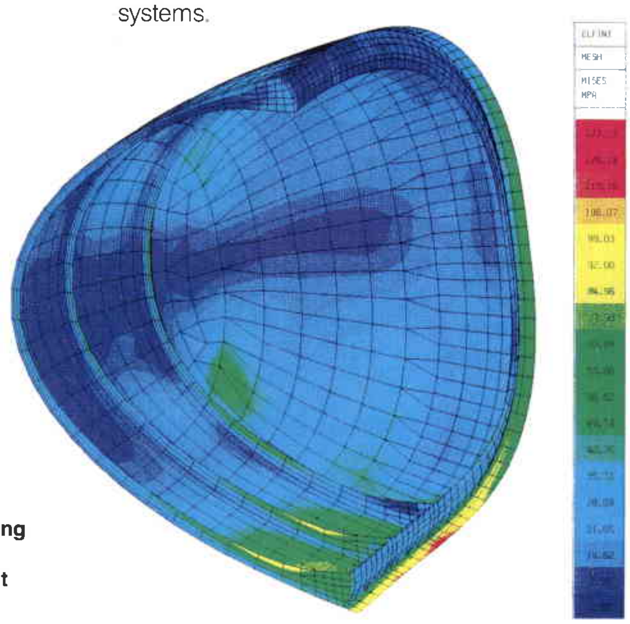

Figure 12. Predicted thermo-mechanical stresses for Hermes' nosecap, derived using the ELFINI program (Courtesy of Dassault Aviation)

Several reusable-launcher concepts are presently under consideration in Europe, including single-stage-to-orbit space planes and two-stage-to-orbit vehicles, as well as air-breathing and rocket-propulsion modes.

The predicted heating rates at stagnation points/lines and on the control surfaces of reusable launchers are well below the equivalent Hermes values. C/C or C/SiC thermo-structures developed for Hermes will therefore still be usable if the higher dynamic pressures at high temperatures can be met and oxidation resistance can be further improved. Up to 500 reuses are being considered for some launcher types.

The windward surface dynamic pressures on winged launchers during ascent and re-entry operations are more or less comparable to those for pure re-entry gliders like the Shuttle and Hermes, while the heating rates on large surface areas are predicted to be below the Hermes values. Large surface areas and moderate heating rates make metallic thermal protection competitive with ceramic thermal protection, though the latter gives higher temperature margins and improved thermo-shock resistance.

Particular thermo-structural problems occur when very high heat loads (possibly above 1 MW/m^2) combine with high dynamic pressures on the inlet surfaces of air-breathing propulsion systems.

The way ahead

Design tools

The design of large structures in combined thermal and mechanical load environments taxes the capabilities of standard structural and thermal analysers like NASTRAN, SINDA, etc., because each of these tools has been optimised for its main application. There is almost no coherence between analysers optimised for thermal and structural purposes because thermal nodes and structural finite-element meshes are generally not compliant.

The overall mathematical model of the Shuttle's thermal protection consisted of 118 three-dimensional local models, each with about 200 nodes. The trend towards increasing temperatures for mechanically highly loaded structures, and the mass criticality of future projects, means that the size of thermal models will increase still further and that better coherence between thermal and structural-analysis models is required.

In addition to the need for improved thermo-structural design tools, sophisticated methods are required for optimising specially tailored constructions and materials; e.g. tools for predicting the thermal response of an ablator or the heat-transfer-mode dependencies in fibrous insulations and CMC materials. Prediction of CMC mass losses in an oxidising environment is another problem area.

Many of these methods are presently under development or refinement, either sponsored directly by the Agency or in the context of Hermes development.

Emerging materials

The main challenges as far as CMC materials are concerned are: further improvement of oxidation resistance, improved quality control, and reduction of manufacturing-cycle durations.

The future trend in thermal-protection mass reduction is towards hot thermo-structures, or at least protected structures with higher primary-structure service temperatures. Several new materials are emerging at the laboratory stage and might be applicable in practice after the year 2000. In addition to mass savings for the thermal protection itself, these emerging materials promise improved specific strength when replacing conventional metallic alloys.

Aluminium matrix composites might replace conventional titanium alloys for medium-temperature applications. Compatibility between fibre and aluminium matrix has to be further improved. The feasibility of all of the industrial processes required to form complex-shaped parts without degrading their performances has also to be demonstrated.

Application of titanium aluminides is a potential substitute for conventional super alloys, though their brittleness at room temperature has to be overcome and the feasibility of several industrial production aspects has to be further demonstrated.

Insulation performance is expected to increase in a more evolutionary way, through the modification of existing products. This applies to all insulations in use between high and cryogenic temperatures. Further mass reductions and increased durability are the main avenues of development.

Verification aspects

Aside from the standard thermal and structural test approaches for materials, parts and components, new aspects arise when addressing the verification of lightweight thermal-protection systems:

- The need for non-destructive inspection and reliable failure-prediction methods for CMCs and MMCs.
- The increasing need for combined thermal and mechanical loading tests for thermo-structures and primary structures at elevated service temperatures.
- The need for relying on analytical methods, supported by coupon tests, for ablators, due to the decomposition of the ablative materials in the real entry environment.
- The task of gathering European hypersonic flight-test results to validate and further refine the prediction tools used in thermal-protection development. ●

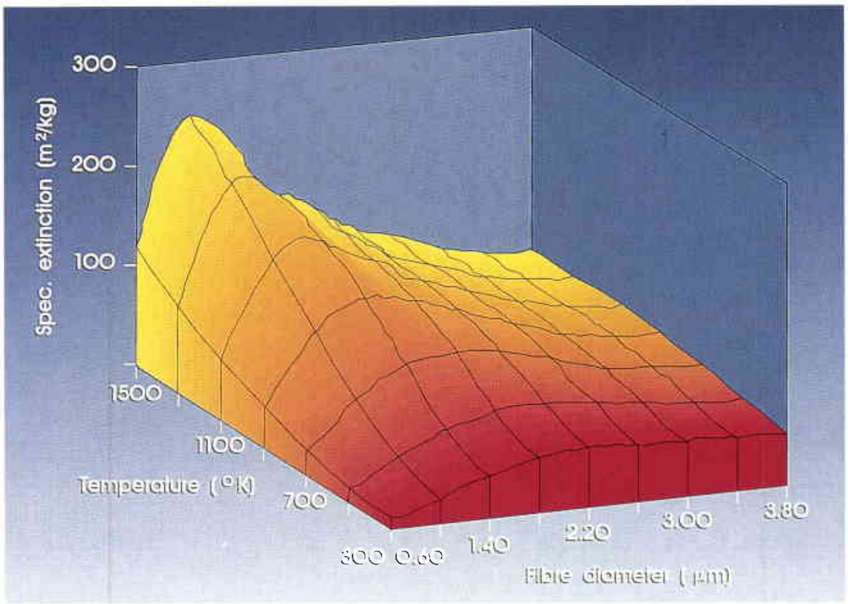

Figure 13. Specific infrared extinction coefficient of fibrous insulation

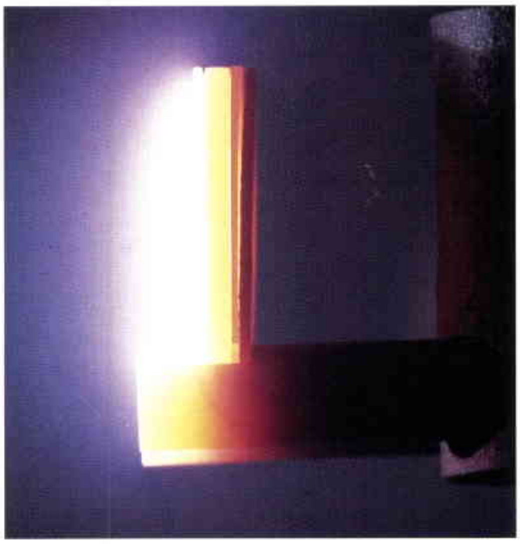

Figure 14. Carbon/silicon-carbide (C/SiC) material erosion test at 1800°C in the IRS arc-jet test facility (Courtesy of DLR)

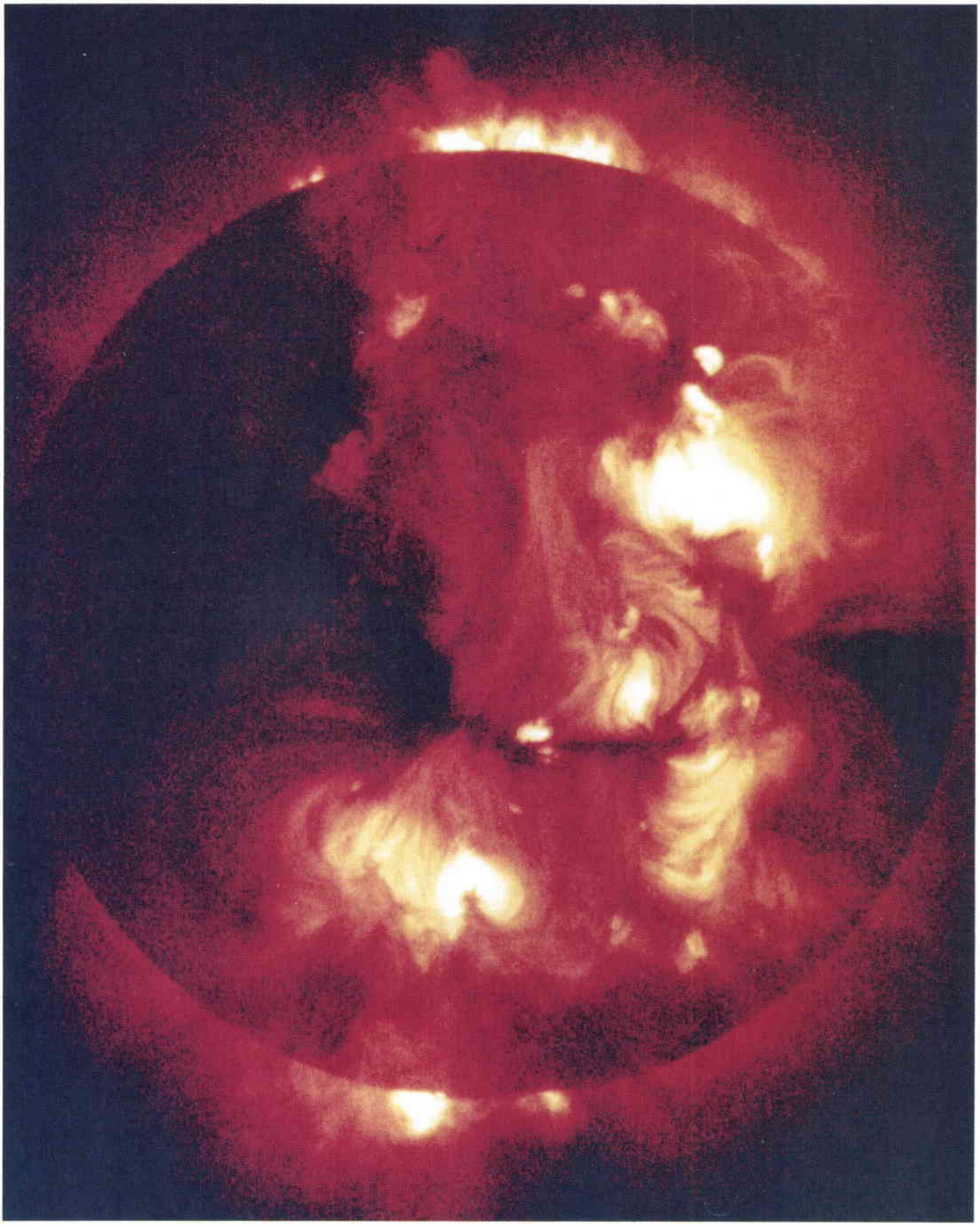

Figure 1. Picture of the Sun taken in vacuum-ultraviolet radiation by the Soft X-ray Telescope on-board the Yohkoh spacecraft (Courtesy of the Institute of Space and Astronautical Science, Tokyo)

Radiometric Calibration of Solar Space Telescopes — The Development of a Vacuum-Ultraviolet Transfer Source Standard

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The development of a source standard for the vacuum-ultraviolet spectral region will facilitate the laboratory calibration and radiometric intercomparison of the coronal telescopes to be flown on ESA's Solar and Heliospheric Observatory (Soho) spacecraft. Perhaps surprisingly, the Sun's output in this spectral region is not well known, because variations in the output itself, and those due to the instrument-sensitivity and radiometric-calibration uncertainties of earlier space telescopes, could not be satisfactorily resolved. Radiometric intercomparison of Soho's instruments on the ground, strict attention to cleanliness, and in-orbit intercomparisons are providing the means for vastly improved solar radiometry, which is of interest not only to astrophysicists but also to aeronomists.

Introduction

The Sun's emission in the vacuum-ultraviolet region of the spectrum varies greatly, both over the solar surface and with time. The radiation in question emerges from the highly inhomogeneous outer layers of the solar atmosphere (Fig. 1). The structure of these layers is governed by the magnetic field, which effectively contains the hot, ionised matter at various densities and temperatures in ubiquitous magnetic loops.

The solar output in the vacuum ultraviolet waxes and wanes with the 11-year sunspot cycle, i.e. with the level of magnetic activity on the Sun. This is because the number of active regions (seen as bright areas in Fig. 1) also varies with the sunspot cycle. Similarly, coronal holes, which are open-field regions whose rather low density makes them appear as extended dark areas in Figure 1, tend to cover a diminishing area as the sunspot cycle reaches its peak.

The emergence and disappearance of solar active regions, the solar rotation with a period of four weeks and the 11-year sunspot cycle result in the vacuum-ultraviolet solar irradiance, i.e. the solar radiation received at the Earth, having a complex behaviour.

Surprisingly, neither the actual spectral irradiance, particularly in the extreme vacuum-ultraviolet (see accompanying box), nor its variation is well known. The necessary series of measurements spanning one or two decades are not available: regular rocket flights of the type carried out in the late sixties and early seventies have been discontinued, and satellite observatories covering this wavelength range have not had sufficiently long lifetimes.

Also, from experience with the Orbiting Solar Observatories (OSO) and the Apollo Telescope Mount (ATM) on Skylab, we know that the sensitivity of vacuum-ultraviolet solar satellite instruments can change significantly during their time in orbit. On the missions mentioned, this resulted in a sometimes gentle and sometimes dramatic reduction in the efficiency of solar EUV telescopes and spectrometers in space – in some cases with partial recovery. Thus, not only the solar irradiance, but also the instrument sensitivity showed variations!

The reason for such variable instrument performance in orbit is thought to be residual contamination: chemical compounds present in small amounts on optical surfaces are broken up by photo-chemical reactions when exposed to the strong vacuum-ultraviolet solar irradiation above the Earth's atmosphere, and thus the reflectivity of these surfaces is affected.

For the Agency's Soho spacecraft (Fig.2) on which the next generation of vacuum-

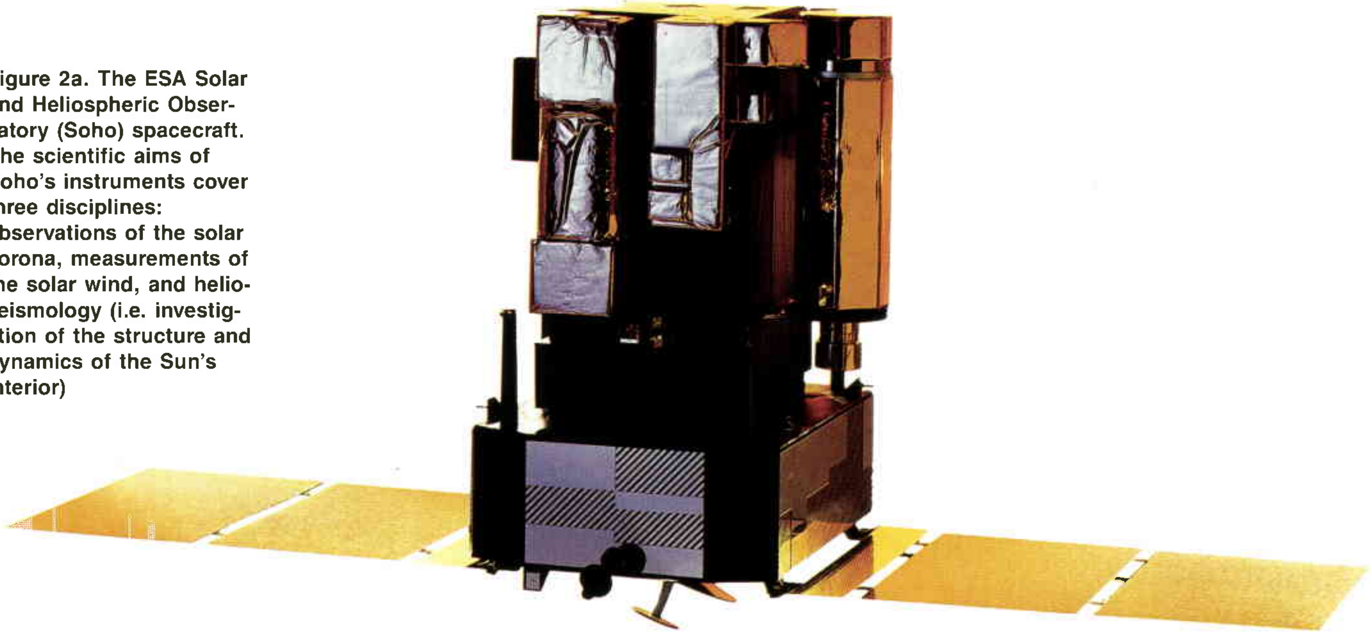

Figure 2a. The ESA Solar and Heliospheric Observatory (Soho) spacecraft. The scientific aims of Soho's instruments cover three disciplines: observations of the solar corona, measurements of the solar wind, and helioseismology (i.e. investigation of the structure and dynamics of the Sun's interior)

THE VACUUM ULTRAVIOLET (VUV)

The vacuum-ultraviolet (VUV) spectral region ranges from soft X-rays with wavelengths around 0.2 nm, to radiation with wavelengths of about 200 nm. The designation 'vacuum' stems from the fact that air is not transparent to such radiation. Consequently, it is necessary to evacuate the laboratory apparatus used for this part of the spectrum. Moreover, solar and stellar radiations at such wavelengths are absorbed by the Earth's atmosphere and can therefore only be measured from space.

Additional, partly overlapping subdivisions of the vacuum-ultraviolet spectral region are sometimes used as well:

Wavelength range	*Abbreviation*	*Name*
0.2–200 nm	*VUV*	*Vacuum Ultraviolet*
0.2–130 nm	*XUV*	*Soft X-ray and Extreme Ultraviolet*
30–130 nm	*EUV*	*Extreme Ultraviolet*
120–200 nm	*FUV*	*Far Ultraviolet*

It is perhaps worthwhile mentioning that the solar spectrum, which consists mainly of emission lines in the XUV, changes into continuum emission, with numerous absorption lines, beginning around 155 nm – the so-called 'Fraunhofer spectrum', which extends through the visible part of the spectrum into the infrared.

Also, the solar spectrum was long believed to remain the only example of an EUV spectrum of celestial objects (with small red-shift). It was thought that photo-ionisation of neutral interstellar hydrogen in interstellar space would effectively block radiation between wavelengths of about 30 and 91.2 nm (the latter being the so-called 'Lyman limit'). However, it was found more recently that the interstellar medium is somewhat transparent in certain viewing directions and, accordingly, an Extreme Ultraviolet Explorer (EUVE) has been prepared for launch. EUV spectra of objects at cosmological distances have been observed; the red-shift of such objects makes the spectrum emitted at EUV wavelengths in their rest frames appear at considerably longer ultraviolet wavelengths, which can be 'seen' by, for example, the International Ultraviolet Explorer (IUE) satellite and the Hubble Space Telescope (HST).

RADIOMETRY, SOLAR IRRADIANCE AND ALL THAT....

Radiometry is concerned with the physical measurement of what is referred to loosely as 'intensity'.

'Solar irradiance' (W m^{-2}) is the flux of solar radiant power passing through a given area (and divided by that area) placed at the distance of one astronomical unit (AU), i.e. at the mean distance of the Earth from the Sun. This quantity, which refers to the solar radiation over the entire electromagnetic spectrum, is also known as the 'Solar Constant' (current value 1367 W m^{-2}, but the quotes indicate that this quantity cannot really be considered a constant).

'Solar radiance' (W m^{-2} sr^{-1}) is the flux of radiant power emerging from a given area on the Sun into a given solid angle (whose unit is the 'steradian'), divided by that area and the given solid angle.

Spectral 'solar irradiance' and 'radiance' (W m^{-2} nm^{-1} and W m^{-2} sr^{-1} nm^{-1}) refer to the above quantities, if measured within a given wavelength interval (whose unit here is the nanometer, i.e. 10^{-9} m), and divided by that interval.

A brief word also on the usage of the terms 'radiometry' and 'photometry': the latter refers to the measurement of radiative quantities that are related to the spectral sensitivity of the human eye, and works with the 'candela' unit, and derived units like the lumen, lux, etc. 'Astronomical photometry' works with spectral sensitivities that are determined by well-defined filters, and uses magnitudes as units, while 'radiometry', in contrast, is not bound to a specific spectral region.

ultraviolet solar satellite instruments will be flown, special precautions are being taken. These will avoid, or at least minimise, the recurrence of such difficulties: the cleanliness of both the spacecraft and its instruments as regards chemical as well as particulate contamination, will be carefully controlled and monitored on the ground, and the monitoring will possibly be continued in orbit. Other in-orbit procedures, such as the use of telescope covers that permit extensive outgassing before vacuum-ultraviolet radiation is allowed to strike the optical surfaces, are also being implemented.

Obviously, in a situation where everything may be shifting in orbit, it is important to have a solid starting point: in particular, the radiometric laboratory calibrations of Soho's main vacuum-ultraviolet instruments must be based on the same standard, so that they are mutually comparable.

For this purpose, a portable vacuum-ultraviolet source standard is being developed. A direct intercomparison of the radiometric sensitivities of several instruments can thus be made, and one can expect their initial sensitivity in orbit to be based on the same absolute scale also. Given the partially overlapping wavelength ranges of these instruments, intercomparisons can be continued in orbit – by using stellar sources (transiting through Soho's field of view) or the Sun itself as a (temporary, but uncalibrated) transfer standard.

We will now outline the various methods of radiometric calibration, and look especially at the problems encountered in the vacuum-ultraviolet spectral region. We will also weigh the advantages and disadvantages of instrument calibration using either the primary electron-storage-ring standard, or the portable hollow-cathode-based source standard.

Laboratory calibration methods

To fulfil its primary objectives, the spatially and spectroscopically resolved investigation of the Sun and its corona in the vacuum-ultraviolet (VUV), Soho will carry a variety of VUV telescope-spectrometer instruments on board.

In the radiometric calibration of these systems, the spectral response of the instrument is determined as the detector response to the incoming spectral photon flux. There are two different ways in which such a radiometric calibration can be performed, one based on the use of a detector standard and the other on the use of a source standard.

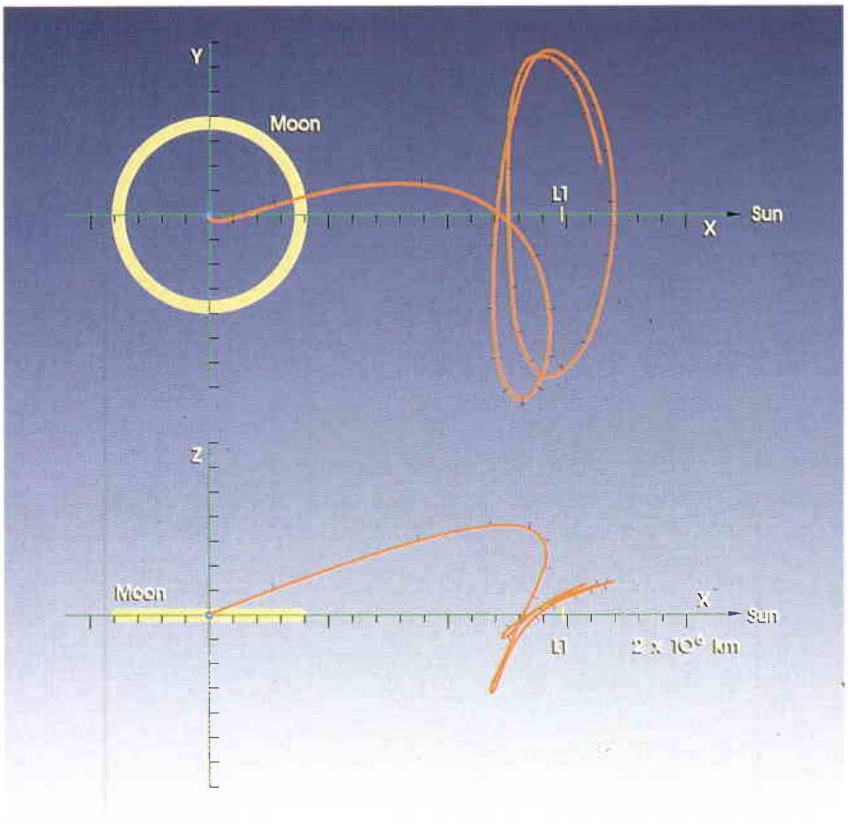

Figure 2b. The halo orbit around the Lagrangian Point (L1), 1.5 Gm from Earth. The transfer orbit from the Earth to L1 is also shown

In the first case, the instrument must be illuminated with a monochromatic source and the detector standard used to determine the monochromatic flux before the radiation enters the telescope. The ratio of the instrument detector response and the flux entering the telescope system then represents the spectral sensitivity of the complete instrument. As this sensitivity changes with wavelength, the procedure must be repeated at different wavelengths to establish the wavelength-dependent spectral sensitivity function of the instrument. The advantage of this method is that no source standard is required. The main disadvantage is that a monochromatic source of sufficient intensity and spectral purity is required. Moreover, a detector standard is needed, and in many cases the overall measurement must be made in several steps, where the transmittances of, for example, the telescope and the spectrometer systems may have to be measured separately.

The other method is based on a source standard of which the spectral emission is known. The instrument is illuminated with this source and the spectral response of the detector measured. From the known spectral flux accepted by the instrument, and from the measured spectral response of the detector, the instrument's spectral sensitivity

PRIMARY STANDARDS

The so-called 'primary standards' are the foundations of metrological work. All quantitative measurements must be traceable to primary standards. A standard is termed a 'primary standard' if it constitutes an internationally defined unit. Generally, primary standards represent the highest metrological level of the realisation of a unit.

In the field of radiometry, the classical primary standard for the realisation of radiometric units is the black-body radiator, which radiates according to Planck's law.

Unfortunately, the temperature of such black bodies is limited to about 3000 K for technical reasons. This means that they cannot be used for vacuum-ultraviolet radiometry, as they emit no useful radiation below 200 nm (Fig. 3).

Today, with the development of the electron storage ring, a new type of primary standard has become available. In such a ring, electrons travel with speeds very close to the speed of light, in a closed orbit, deflected in so-called 'bending magnets'. While travelling through the magnetic fields of the bending magnets, the electrons are accelerated by the Lorentz force, perpendicular to their direction of flight.

As a result, the electrons radiate electromagnetic radiation into a narrow cone in the direction of their flight. This radiation is called 'synchrotron radiation', as it was first observed in a synchrotron.

The radiation emission from an electron storage ring extends from the far-infrared to the X-ray region (Fig. 3) and can be calculated from three parameters: 'electron energy', 'magnetic field' in the bending magnet, and the 'current' represented by the electrons in the ring. Knowing these measurable parameters for a storage ring means that it can serve as a primary standard.

An example of a storage-ring facility is shown in Figure 4.

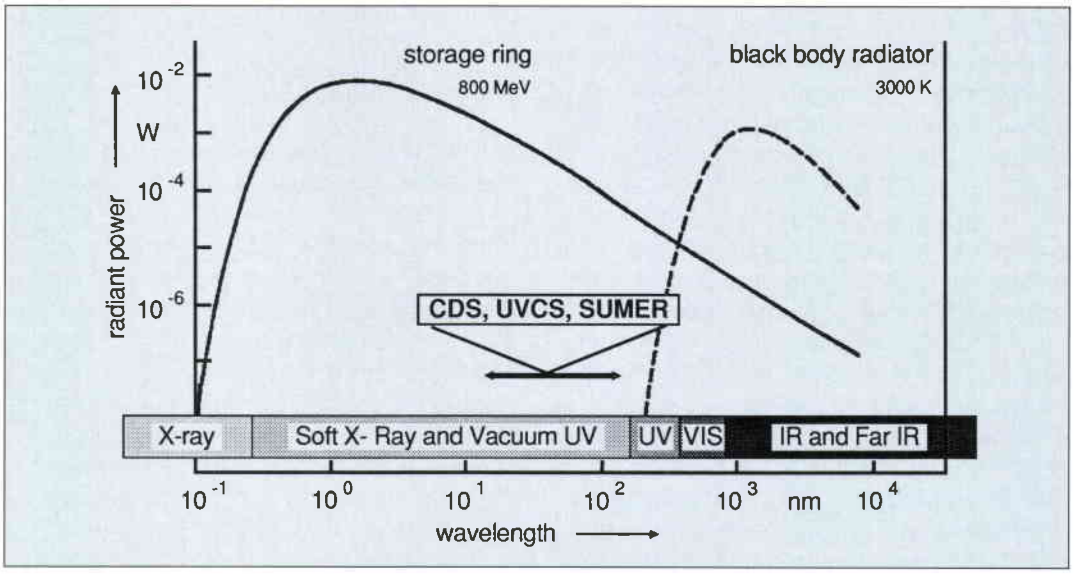

Figure 3. Comparison of a black-body radiator at a temperature of 3000 K and the synchrotron radiation spectrum of the electron storage ring BESSY. The radiation emission is displayed as a function of wavelength into a bandwidth of 1% of the wavelength. The parameters are:

Black body:
- **Temperature 3000 K**
- **Circular emitting aperture with diameter of 10 mm**
- **Flux through a 40 mm x40 mm aperture at a distance of 1 m from the emitting aperture**

BESSY:
- **Electron energy 800 MeV**
- **Magnetic inductance 1.5 tesla**
- **Stored electron current 100 mA**
- **Flux through a 40 mmx40 mm aperture at a distance of 7.5 m from the emitting electron beam located in the electron orbit plane**

can be determined. This is the classical approach for an instrument calibration. The requirement is the availability of a suitable source standard. In the past, such sources have not been available for the calibration of instruments working in the vacuum-ultraviolet.

Over the last decade, the situation has changed as electron storage rings have become accessible as radiation sources covering the wavelength range from the infrared to the X-ray region. The storage ring is indeed a primary radiometric standard (see accompanying box for explanation).

In principle, however, a primary standard is not required for the instrument calibration. Any radiation source of sufficient stability and reproducibility that has been calibrated against a primary standard can also be used as a transfer source standard. Unfortunately, until recently, extreme-ultraviolet transfer source standards have not been available either.

With the development of stable hollow-cathode sources, however, this situation has now changed, so that it has become worthwhile to compare the pros and cons of making a radiometric calibration for a solar EUV telescope by using either a storage-ring primary standard directly, or a hollow-cathode transfer source standard.

Calibration using an electron-storage-ring primary standard

Advantages

Using an electron storage ring as a primary standard provides the possibility of achieving the most accurate calibration. The uncertainty in the calibration is based on that in the spectral emittance of the storage ring and on the uncertainty in the calibration procedure. For storage rings optimised for radiometry, uncertainties significantly below 1% are achievable. The uncertainty in the calibration procedure will generally be much larger and depend on the instrument's design and the wavelength range.

Electron storage rings are ultra-high-vacuum machines. The radiation is produced by relativistic electrons inside the bending magnet. No gases or other contaminants are emitted by the radiation source. This is beneficial for the cleanliness of flight models that have to be calibrated.

Unfortunately, there is also a series of disadvantages connected with the use of a storage ring.

Disadvantages

As electron storage rings are large expensive machines, the calibration must be performed at the storage-ring site, requiring the transport of the flight model to, and its operation at, the storage ring.

Calibrating the instrument at a storage ring requires strict and early commitment to the timing for the calibration period, and leaves no possiblity to recalibrate if instrument components have to be exchanged later on.

Modern electron storage rings are designed to serve a large variety of users, many of them requiring soft or even hard X-ray photon fluxes. Storage rings are therefore designed for maximum radiation emission in the soft X-ray region around typically 1–2 nm, or at even shorter wavelengths. Most of the synchrotron radiation therefore lies at wavelengths below the working range of EUV solar telescopes (Fig. 3). This radiation can significantly increase the background of scattered radiation. Worse still, the shorter wavelength radiation is often partially reflected by the telescope and causes high-order radiation when dispersed by the spectrometer grating. These higher orders overlap with the first-order radiation*, producing a detector signal which is the combined response to first and higher orders.

If the instrument does not sufficiently reject the higher orders due to its design, the calibration cannot be performed, or an additional high-order suppressor has to be installed in front of the instrument. If such a device (with, for example, two or more optical reflections at an appropriate angle) is installed, its transmittance must be determined experimentally as a function of wavelength, and this causes additional uncertainties.

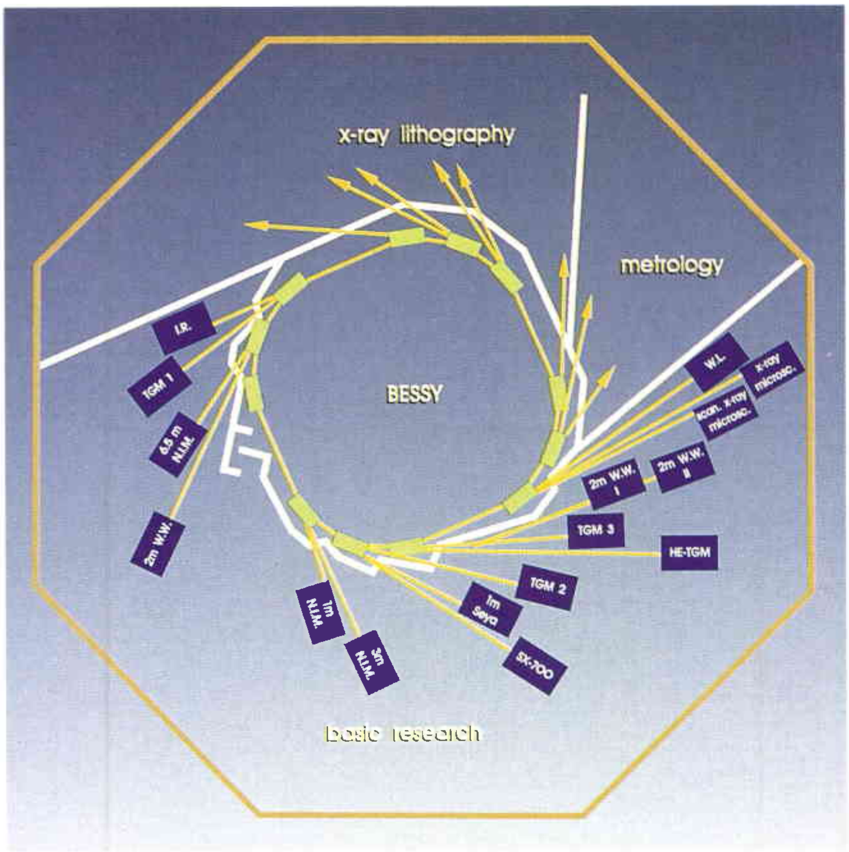

Figure 4. The electron storage ring BESSY
(a) View of the building containing the storage ring and the experiment hall.
(b) Layout of the storage ring and the three laboratories, for basic research, X-ray lithography, and metrology. The latter is the laboratory of PTB.

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* In the vacuum ultraviolet, reflecting diffration gratings are normally used to disperse radiation into its different wavelengths – as prisms are used to separate the various colours in the visible. A grating diffracts the spectrum into several orders: zero order (reflection without dispersion), first, second and higher orders. At the angle into which a given wavelength is diffracted into first order, one will also find higher-order radiations, namely second-order of one half, and third-order of one third of that wavelength etc., at this same angle.

Synchrotron radiation is completely polarised. In the plane of the electron orbit the polarisation is linear, with the electric-field vector oscillating in the orbit plane. Outside that plane, the radiation is elliptically polarised with an angular dependence. As the spectral response of the instrument will, in general, depend on the polarisation of the radiation, measurements have to be performed with the instrument plane parallel and perpendicular to the electron orbit plane.

Calibration using a hollow cathode as a transfer source standard

Advantages

The calibration can be performed at the laboratory where the flight instrument is assembled. Hence all the ground-support equipment that is available at the home laboratory can be used, including the data-handling and processing systems. No transports to and from a different laboratory have to be carried out.

The calibration can be repeated whenever deemed necessary.

For the calibration itself, an unpolarised line-emitting source with a spectral distribution similar to that of the Sun can be used. This eliminates or significantly reduces the problems with high-order radiation, stray light and polarisation effects.

Disadvantages

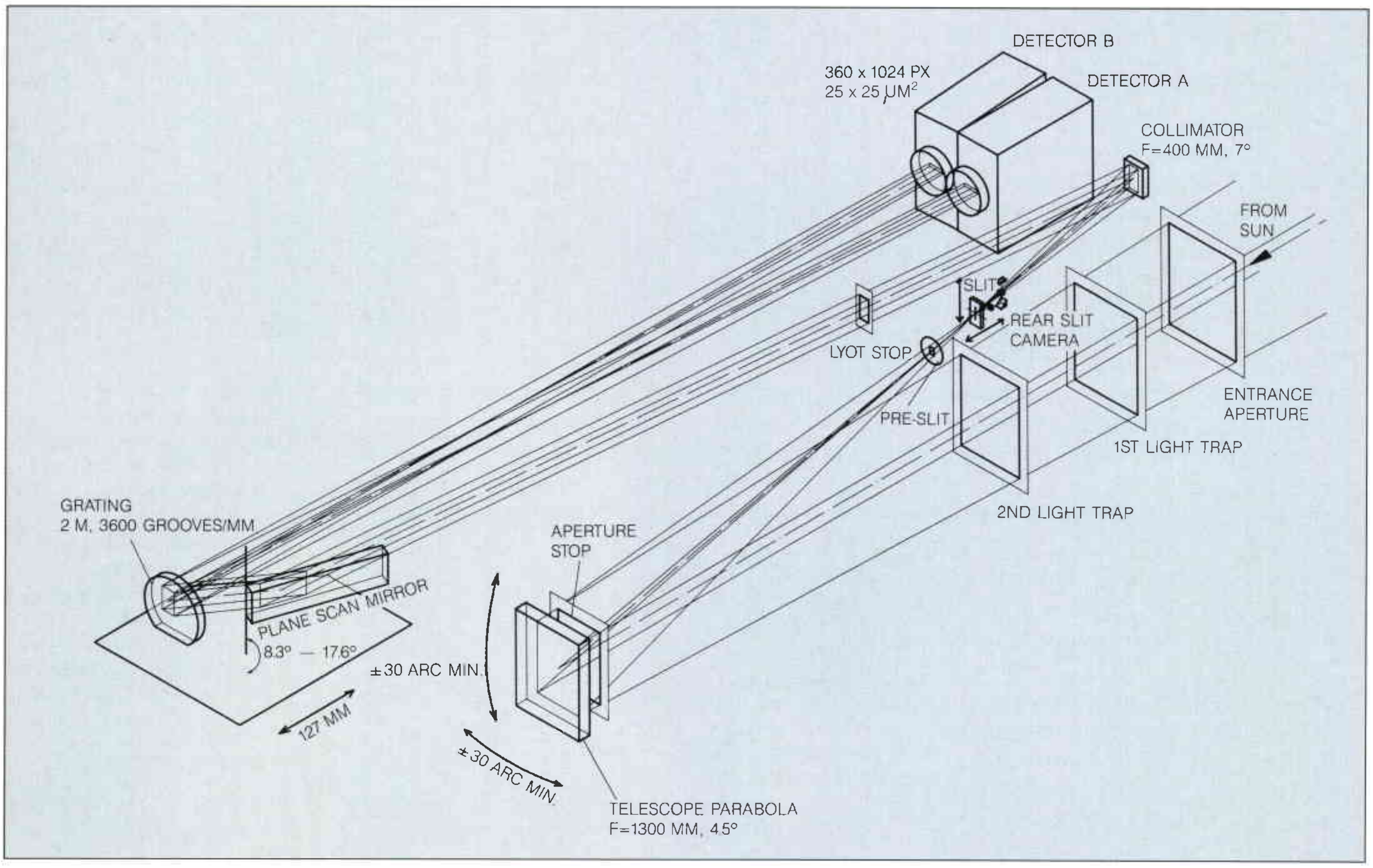
A lower limit for the achievable uncertainty is imposed by the reproducibility of the radiation emission of the source. In addition, the uncertainty in the calibration of the transfer standard using the electron storage ring as a primary standard has to be added. This uncertainty can be minimised if suitable calibration beam lines at a radiometric storage ring are used. The total uncertainty will be strongly dependent on the type of transfer standard, on the design of the calibration station, and on the wavelength range under investigation. For the case of the high-current hollow-cathode source (described in detail below), uncertainties of the order of 15% have been achieved using a calibration beam line at the radiometric laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the Berlin electron storage ring (BESSY).

All plasma sources, including the hollow-cathode source, emit particles and gases that can contaminate, in particular, the optical surfaces of the instrument under calibration. Adequate precautions have to be taken to prevent such contamination.

The calibration of Soho's instruments

Three telescope-spectrometer systems (so-called 'spectro-heliometers' and coronagraphs with spectral capabilities) to be

Figure 5. Schematic of the SUMER telescope spectrometer



carried by Soho are designed to observe the Sun and its corona in the vacuum-ultraviolet with high spectral, as well as spatial, resolution.

These instruments are:

- SUMER (Solar Ultraviolet Measurements of Emitted Radiation), which will observe the Sun and its corona using a normal-incidence telescope and a normal-incidence spectrometer in the wavelength range from 50 to 160 nm (Fig. 5 and Table 1)
- CDS (Coronal Diagnostics Spectrometer), which uses a grazing-incidence telescope and two spectrometers (one with with a normal-incidence grating, the other with grazing-incidence gratings) to observe the Sun and its corona in the wavelength range from 15 to 80 nm, and
- UVCS (Ultraviolet Coronagraph Spectrometer), which will observe mainly the corona in the wavelength range around 50 to 125 nm.

The aim with these instruments is to determine absolute temperatures, particle densities and velocities, which in many cases will require absolute intensity measurements. An absolute spectral sensitivity calibration is therefore essential for all three instruments. Depending on the instrument, the calibration will be based primarily on calibrated transfer source standards, on the direct use of an electron storage ring, or on calibrated detectors.

Hollow-cathode-based transfer source standards will also be used to achieve intercalibration of all three instruments.

Development and calibration of the transfer source standards

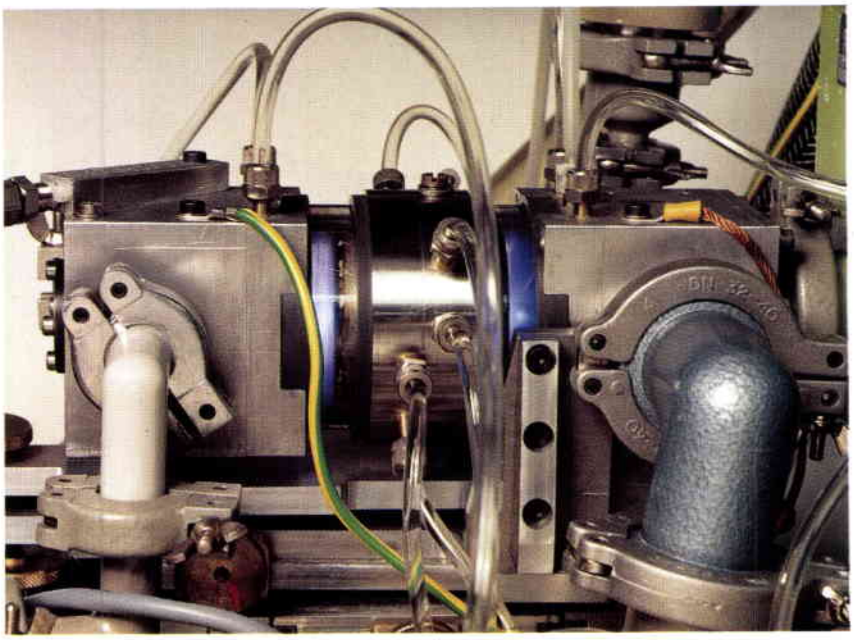
As a compact vacuum-ultraviolet radiation source covering the full spectral range of the above three telescope-spectrometers, a high-current hollow-cathode source has been chosen. Like the Sun, this source emits an unpolarised vacuum-ultraviolet line spectrum*.

To simulate the distance of the Sun, the hollow cathode has to be combined with an adequate optical imaging system, which converts the source's diverging radiation into a nearly parallel beam. This combination of hollow cathode and imaging optics simulates the Sun in the laboratory. If its radiant power is known, it serves to perform the spectral-sensitivity calibration of the solar telescope-spectrometers.

Table 1. SUMER telescope and spectrometer characteristics

Item	Parameter	Value
Telescope	Material	Silicon carbide
	Focal length	1300 mm
	Collecting area	90×130 mm^2
	Equivalent f-ratio	1:11
	Image scale	0.16 arcsec/μm
Slits: 1 arcsec $\hat{=}$ 715 km on the Sun	Lengths	300 arcsec
		120 arcsec
	Widths	4 arcsec
		1 arcsec
		0.3 arcsec
Collimator	Material	Silicon carbide
	Focal length	400 mm
Grating	Material	Silicon carbide
	Groove density	3600 lines/mm
	Spherical radius	3200 mm
	Incident angles	16.7—35.2°
Detectors: Two micro-channel plate detectors in photon-counting mode with two-dimensional multi-anode array	Pixel size	25×25 μm^2
	Array size	360×1024 pixels
	Spatial scale	645 km/pixel
	Instantaneous spectral coverage	20 Å 2nd order
		40 Å 1st order
	Spectral scale	20 mÅ/pixel 2nd order
		40 mÅ/pixel 1st order

Figure 6a. The high-current hollow-cathode source being operated with argon



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* Strictly speaking, the solar vacuum-ultraviolet spectrum is polarised, since it originates mainly from magnetic loops. This would, in principle, require that the polarisation of the radiation to be measured be determined, and that corrections for the polarisation sensitivity of the instrument calibration be applied. However, it is estimated that (within uncertainties) polarisation has no influence on the radiance actually derived.

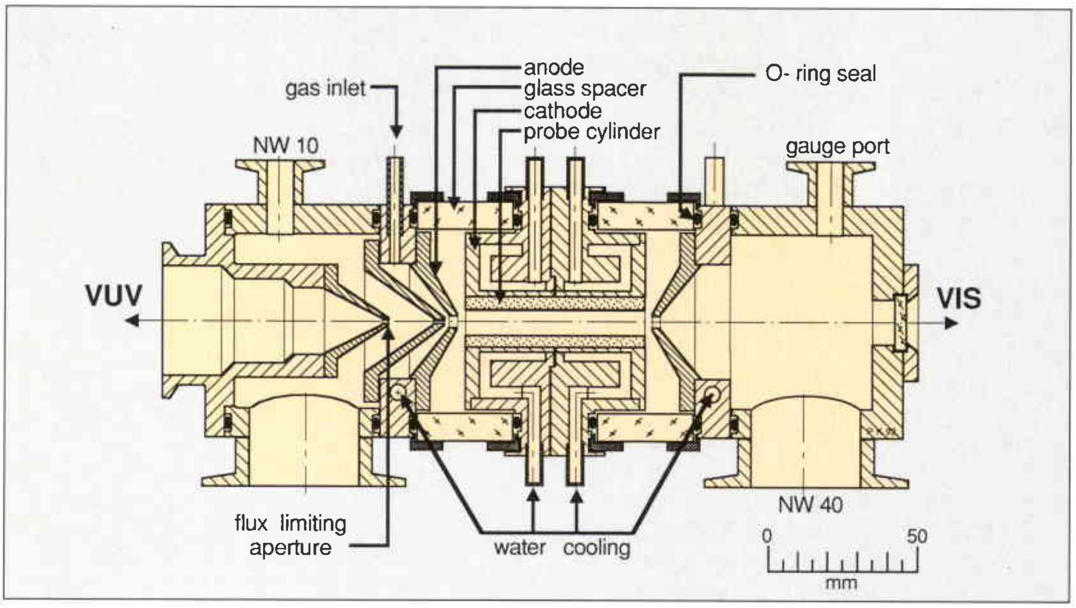

Figure 6b. Longitudinal section of the hollow-cathode source with integrated two-stage differential pumping system

The hollow-cathode source

The hollow-cathode source (Fig. 6a) was jointly developed by the Institut für Plasmaphysik, Universität Hannover, and PTB in Berlin. A longitudinal section of the rotationally-symmetric source is shown in Figure 6b. It consists of two anodes and one cathode, accurately separated and isolated from each other by precisely manufactured glass spacers.

The source is vacuum-sealed by Viton O-rings and pumped by a small turbo-molecular pump. The cathode insert is a hollow aluminium cylinder with a central bore of 8 mm and a length of 60 mm. Central bores of 4 mm in both anodes allow end-on observation of the plasma. Since there are no materials available that are transparent in the vacuum-ultraviolet region below 105 nm, a two-stage differential pumping system is used to allow windowless observation. The flux-limiting aperture of the source is exchangeable and different diameters (0.6, 0.9 and 1.2 mm) are available.

When the hollow cathode is operated, material from the cathode insert is sputtered onto the two anodes. To avoid clogging of the aperture, the gas inlet is located between the anode and the first pumping stage with a bore of 1.5 mm.

The hollow cathode is operated with a current-stabilised power supply. The two anodes are maintained at ground potential, while the cathode is held at a high negative voltage. During the calibration, the hollow cathode is operated with a fixed current and a fixed voltage (e.g. 1 A, 500 V). The voltage drop over the discharge is adjusted by regulating the buffer-gas pressure.

In order to provide a large number of emission lines for the telescope-spectrometer calibration, the hollow cathode can be operated with different rare gases serving as the buffer gas. Pressure inside the cathode is about 1 mbar, depending on the buffer gas used. When operating at a typical working point of 1 A and 500 V, the discharge burns reproducibly for more than 40 h. The emission values of the spectral lines chosen change by ≤ 5% during telescope calibration. Cleaning the anodes and glass spacers of sputtered aluminium and replacing the cathode insert restores the original emission values.

Use of collimators

For the pre-flight calibration of the solar telescope-spectrometers on Soho, the hollow cathode has to be combined with an optical system that simulates a source at infinite distance. Due to the different spectral ranges of the telescopes, different imaging optics are required. For the SUMER and UVCS calibration source (Fig. 7), a spherical mirror coated with gold is sufficient, while for the CDS calibration source (Fig. 8) a Wolter type-II telescope, which works in grazing incidence, must be used to collimate the radiation.

The SUMER calibration source has already been assembled and tested in the PTB radiometric laboratory at the Berlin electron storage-ring (BESSY). The flux-limiting aperture stop of the hollow cathode is placed at the focus of a concave gold mirror with a focal length of 1090 mm. The angle of incidence between the mirror normal and the incoming beam is 3°.

As the diameter of the parallel beam is

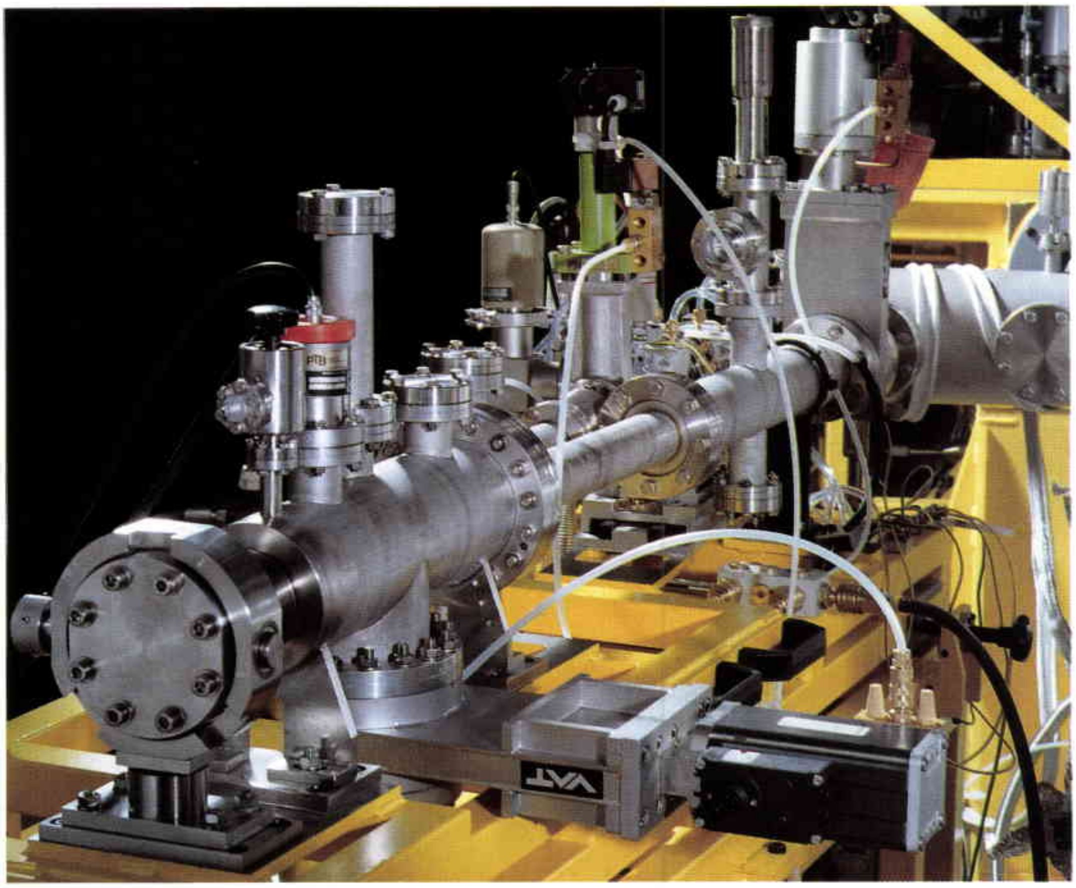

Figure 7a. The transfer source standard for the radiometric calibration of the SUMER telescope

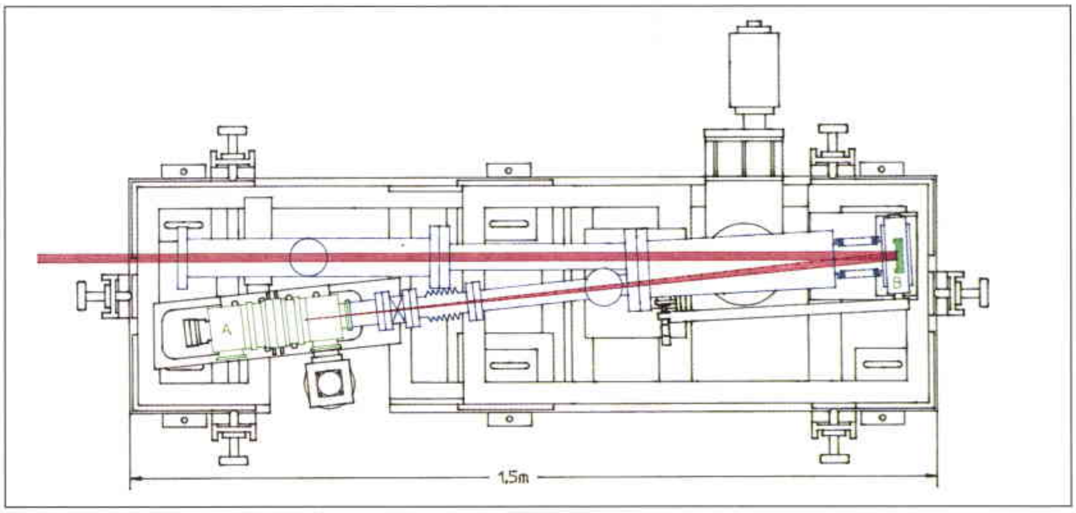

Figure 7b. Schematic of the SUMER calibration source. The diverging radiation from the hollow cathode (A) is collimated by a concave gold mirror (B)

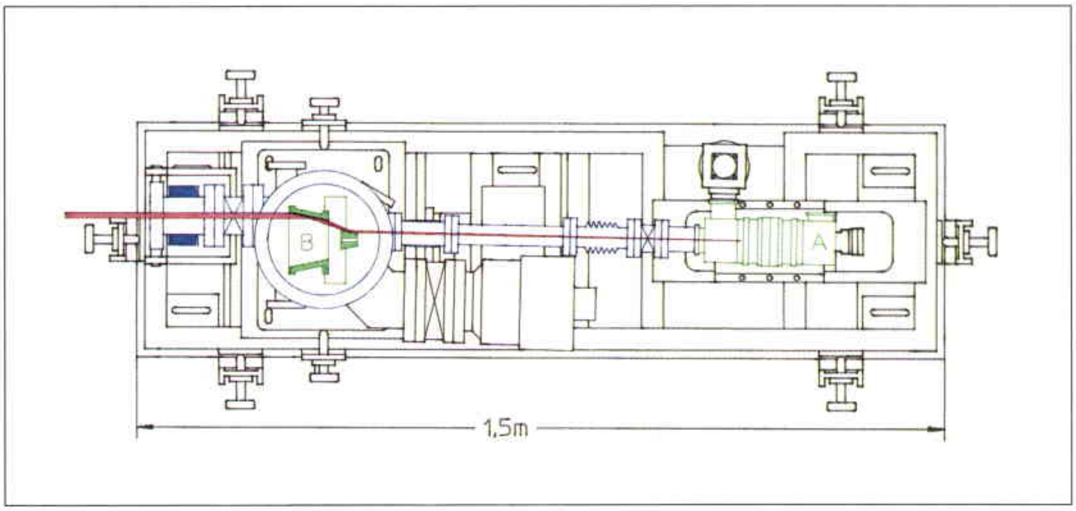

Figure 8. Schematic of the CDS calibration source. The diverging radiation from the hollow cathode (A) is collimated by a Wolter type-II telescope (B)

limited to less than 15 mm, the primary mirror of the SUMER telescope (cf. Fig. 5 and Table 1) cannot be fully iluminated. The concave mirror of the transfer source-standard can therefore be tilted about two perpendicular axes to allow a mapping of the telescope mirror.

The mirror chamber of the SUMER calibration source is made of stainless steel (according to ultra-high-vacuum standards) and is pumped by a turbo-molecular pump. When the hollow cathode is in operation, the pressure inside the chamber rises to about 10^{-5} mbar, depending on the buffer gas used. The pressure in the test tank itself can be further reduced to the desired level by employing additional pump systems.

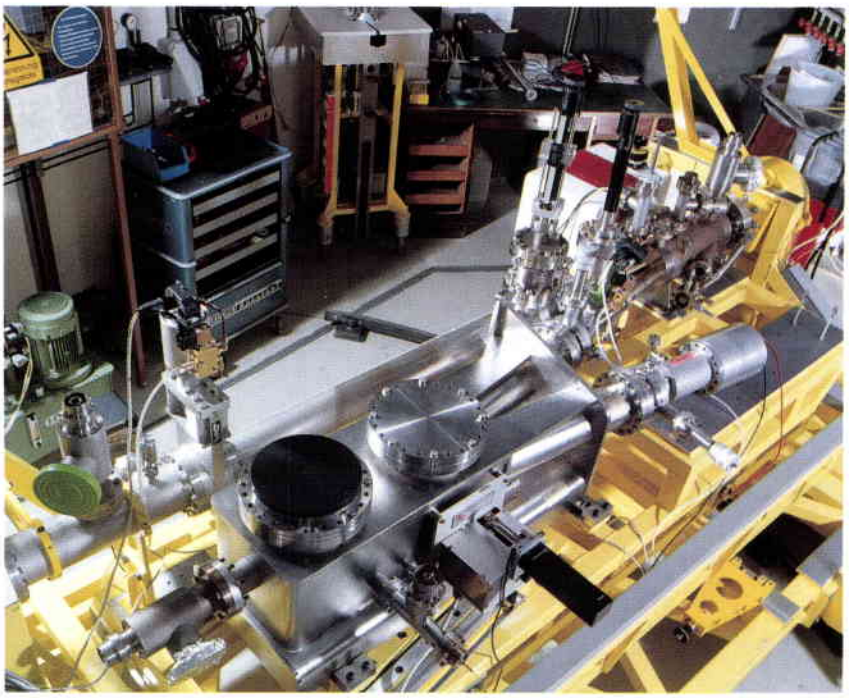

Figure 9a. The instrumentation for the characterisation of transfer source standards from 40 to 400 nm

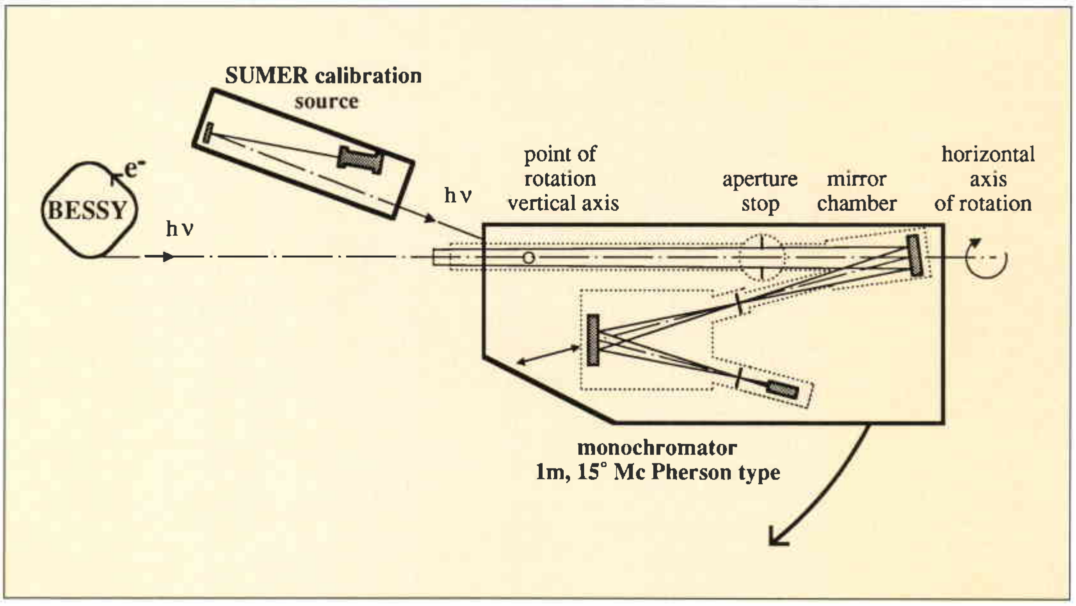

Figure 9b. Schematic of the instrumentation for the characterisation of transfer source standards, the synchroton radiation beam line, and the SUMER calibration source

Calibration of the transfer source standards

PTB is operating a dedicated VUV radiometry laboratory at BESSY, which has been optimised for this purpose and is a proven primary radiometric source standard. Special beam lines have been set up in the laboratory for the radiometric characterisation of transfer source standards in the range from 0.6 to 400 nm.

The calibration principle is based on a comparison of the unknown spectral radiant power of the source under investigation with the calculable spectral radiant power of the storage ring. From the soft X-ray region up to 40 nm, this comparison is done with grazing-incidence optics, while above 40 nm normal-incidence optics are used.

Due to the CDS telescope's 15–80 nm spectral range, the CDS calibration source has to be characterised with grazing-incidence techniques in the short-wavelength region and with normal-incidence techniques for the longer wavelengths. The SUMER and UVCS calibration sources, however, can be completely characterised at a normal-incidence station capable of calibrating vacuum-ultraviolet sources from 40 to 400 nm (Fig. 9).

For the comparison of the transfer standard with the primary standard (BESSY), the whole calibration station can be rotated about a vertical axis, so that a concave mirror is either imaging the tangent point of the storage ring or the transfer standard into the entrance slit of a 1 m monochromator (McPherson type 15°).

Synchroton radiation is highly polarised, whereas the hollow cathode emits unpolarised light. The polarisation properties of the complete optical instrument must therefore be determined by rotating it about a horizontal axis and detecting the synchroton radiation with the optical plane parallel and perpendicular to the orbital plane of the electrons.

As the storage ring emits a continuous spectrum, the calibration of a transfer source standard requires that the influence of higher-order radiation be evaluated and subtracted.

From measurements with the SUMER calibration source, more than 30 emission lines have been selected in the 50–160 nm spectral range which are suitable for the calibration of the SUMER telescope (Table 2). The photon fluxes of these lines are typically in the range of 10^7 to 10^9 photons s^{-1} per line. Illuminating the SUMER telescope with the calibration source will therefore produce count rates that can be expected to match well with the count rates produced by the Sun when the telescope is in orbit.

At present, the absolute emission characteristics of the SUMER calibration source are being investigated. The first test calibrations of the engineering model of the SUMER telescope-spectrometer are scheduled for mid-1992. The CDS calibration source is presently being assembled at PTB, ready for operation in spring 1992. The first test calibrations with the CDS telescope-spectrometer are planned to follow later in the year.

Table 2. Selected emission lines of the hollow-cathode source for the radiometric pre-flight calibration of the SUMER telescope.

The right-hand column indicates the spectrum to which a given line belongs (e.g. He I – spectrum of neutral helium; Ar II – singly-ionised argon; Kr III – doubly ionised krypton)

1	53.70 nm	He I
2	54.29/54.32 nm	Ar II
3	54.75 nm	Ar II
4	58.43 nm	He I
5	60.29 nm	Ar II
6	66.19 nm	Ar II
7	67.09/67.19 nm	Ar II
8	71.81 nm	Ar II
9	72.20 nm	Kr III
10	72.34 nm	Ar II
11	72.55 nm	Ar II
12	73.09 nm	Ar II
13	73.59 nm	Ne I
14	74.03 nm	Ar II
15	74.37 nm	Ne I
16	76.92 nm	Ar III
17	88.41/88.63 nm	Kr II
18	89.10 nm	Kr II
19	91.74 nm	Kr II
20	91.98 nm	Ar II
21	93.21 nm	Ar II
22	96.50 nm	Kr II
23	104.82 nm	Ar I
24	106.67 nm	Ar I
25	110.04 nm	Xe II
26	115.85 nm	Xe II
27	116.49 nm	Kr I
28	118.31 nm	Xe II
29	123.58 nm	Kr I
30	124.48 nm	Xe II
31	146.96 nm	Xe I
32	153.98 nm	Al II

Conclusion

The new portable vacuum-ultraviolet radiometric source standard that has been described will considerably enhance the radiometric calibration of Soho's spectroscopic telescopes, as well as permitting a comparison of the laboratory calibrations of these telescopes.

The source standard has a spectral-irradiance distribution similar to the solar EUV spectrum and produces count rates in the instrument detectors that are comparable to those that will be measured in orbit. The standard source can be mounted on any vacuum tank being used for general testing of the instrument in question. A special calibration tank, as is usually needed for detector-standard-based calibrations, is therefore not required. Use of the primary source standard, the electron storage ring, with its inherent scheduling constraints, is also avoided.

By ensuring a common scale for the laboratory calibration (via the intercomparison just mentioned), a major step has been made towards reliable solar-radiance and irradiance measurements with ESA's Soho spacecraft, particularly since comparisons between the three main spectroscopic telescopes will also be possible in orbit. Knowledge of these highly variable solar parameters is of interest not only to astrophysicists, but also to aeronomists, because this radiation dominates the physics and chemistry of the terrestrial mesosphere.

L'Espace: une solution aux problèmes d'énergie de la Terre?

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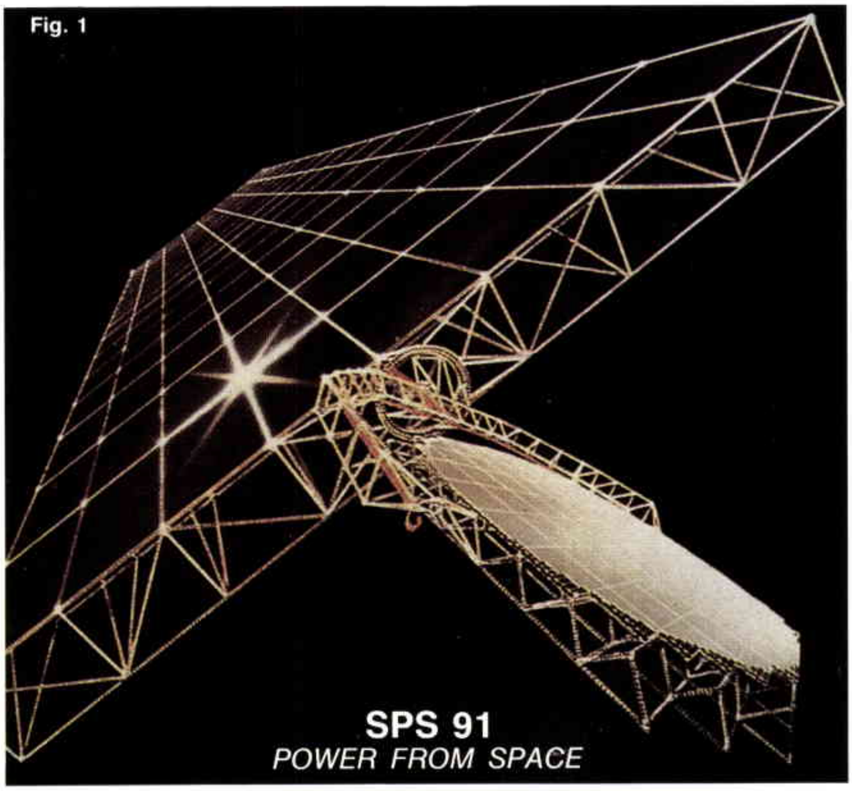
Au début des années 80, le Dr. Gläser avait émis l'idée de collecter hors de l'atmosphère l'énergie inépuisable que représente le rayonnement solaire, et de la transmettre au sol. Après quelques années d'études menées par la NASA et le 'Department of Energy', le projet (Fig. 1) fut mis en sommeil. Le Symposium SPS '91, 'Power from Space', organisé cette année en France (Gif-sur-Yvette) a permis de faire le point sur le sujet et a montré que de nouvelles solutions pourraient être apportées par l'Espace.

La situation actuelle

Plus de 4 milliards d'habitants de la Terre consomment annuellement plus de 10 terrawatts* d'énergie, dont plus de 30% sous forme d'électricité. Les sources d'énergie sont représentées à 90% par des combustibles fossiles (fuel, gaz, charbon), et le reste (10%) essentiellement par l'énergie hydroélectrique et nucléaire. Une analyse plus fine de ces chiffres montre que:

- 1/5 des habitants (pays industrialisés) consomment grosso modo les 3/5 de l'énergie totale. La Figure 2 illustre d'une manière éloquente l'évolution de la consommation d'énergie par habitant en fonction du PNB
- plus un pays s'industrialise, plus sa consommation en énergie électrique augmente; (la consommation totale des Etats-Unis a augmenté de moins de 7% entre 1972 et 1988 alors que la consommation en électricité a augmenté, elle, de 55%)
- en matière de production d'électricité, la quote-part du nucléaire est très variable: elle représente 11% en Europe de l'Ouest alors qu'en France elle atteint (record absolu) 75%.

Fig. 1



Quand on tente de faire des prévisions il faut prendre en compte:

- une stagnation ou même une diminution de la consommation des pays qui sont industrialisés depuis longtemps (grâce

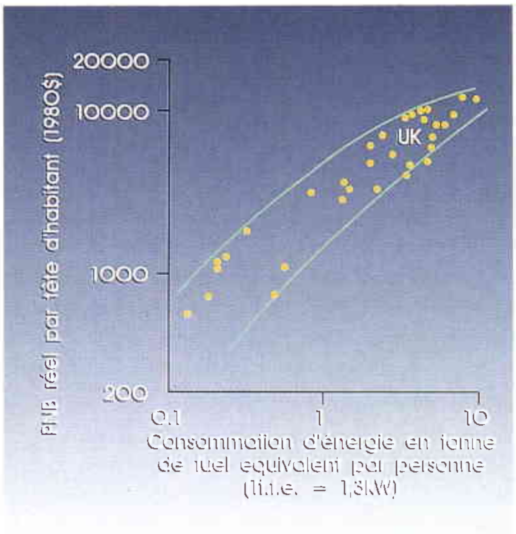


Figure 2. Consommation d'énergie en tonne de fuel equivalent par personne (1 t.f.e.= 1,3 kW)

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* 1 terrawatt = 10^{12} watt

à une meilleure gestion de l'énergie, de meilleurs rendements, etc.)
- une augmentation de la consommation par habitant des pays nouvellement industrialisés
- une augmentation du nombre total d'habitants devant plafonner selon l'ONU, à 10 milliards vers 2100 (Fig. 3).

En prenant en compte ces différentes tendances, les experts pensent qu'au cours du siècle prochain la demande en énergie s'établira autour de 20 à 30 terrawatts.

Les sources

Regardons maintenant la situation en matière de source d'approvisionnement d'énergie.

Les ressources 'fossiles'
La situation est préoccupante selon les experts car il y a non seulement épuisement des gisements à terme, mais encore un impact sur l'environnement, en particulier en contribuant au réchauffement global de la planète par production de dioxyde de carbone.

L'énergie hydroélectrique
Sa contribution aura bientôt atteint ses limites. En effet, les sites encore disponibles pour l'implantation de barrages sont rares. De plus, l'attitude du public limitera probablement, au nom de la protection de l'environnement, l'implantation de nouvelles centrales hydroélectiques dans des sites sensibles.

L'énergie nucléaire
Basée sur le processus de fission, ce mode de production d'électricité ne jouit pas en général d'un grand soutien de la part de l'opinion publique: certains pays (Etats-Unis par exemple) ont même été conduits à en stopper le développement. Des événements récents, en particulier à Tchernobyl, ont renforcé la méfiance du public vis-à-vis de ce mode de production, considéré comme dangereux. Les experts estiment que cette attitude limitera l'implantation des centrales nucléaires dans les pays où le potentiel scientifique et technique ne permet pas de garantir une sécurité acceptable au niveau de leur fonctionnement et de leur entretien.

Il faut également, à propos de l'énergie nucléaire, mentionner le problème de l'élimination des déchets nucléaires qui n'a pas trouvé de solution satisfaisante.

Les autres sources
L'énergie solaire terrestre reste une source marginale. Malgré l'augmentation du rendement des cellules photovoltaïques et la simplicité de fonctionnement des installations, les experts ne prévoient pas un très grand développement de cette filière.

Les autres formes d'énergie (marée, vent, géothermie) représentent une fraction tout à fait négligeable de la fourniture totale.

Une nouvelle source d'énergie: la fusion nucléaire?

Une nouvelle source d'énergie apparaît à certains experts comme prometteuse. Il s'agit de la fusion nucléaire: c'est ce processus qui est la source d'énergie du soleil. Sa manifestation la plus spectaculaire est l'utilisation qu'en ont faite les militaires avec la bombe thermonucléaire à hydrogène.

Les essais d'utilisation du processus de fusion nucléaire consiste à contrôler une réaction entre des atomes de deuterium et d'autres atomes, par exemple de tritium. Cette réaction produit un isotope de l'hélium en libérant une grande quantité d'énergie (Fig. 4) sous forme de neutrons et/ou de particules chargées. La production d'électricité serait donc obtenue soit à partir de la chaleur dégagée (comme dans le processus de fission) soit directement à partir des particules chargées. Cette forme d'énergie nucléaire est 'propre'. Certes les neutrons résultant de certaines réactions de fusion induisent de la radioactivité. Mais les niveaux en jeu sont très inférieurs à ceux résultant de la fission. Naturellement en phase opérationnelle certaines précautions seront nécessaires tant au niveau du fonctionnement des centrales que de leur entretien. Il faudra également éliminer des déchets radioactifs (encore une fois à des niveaux bien inférieurs à ceux résultant de la fission).

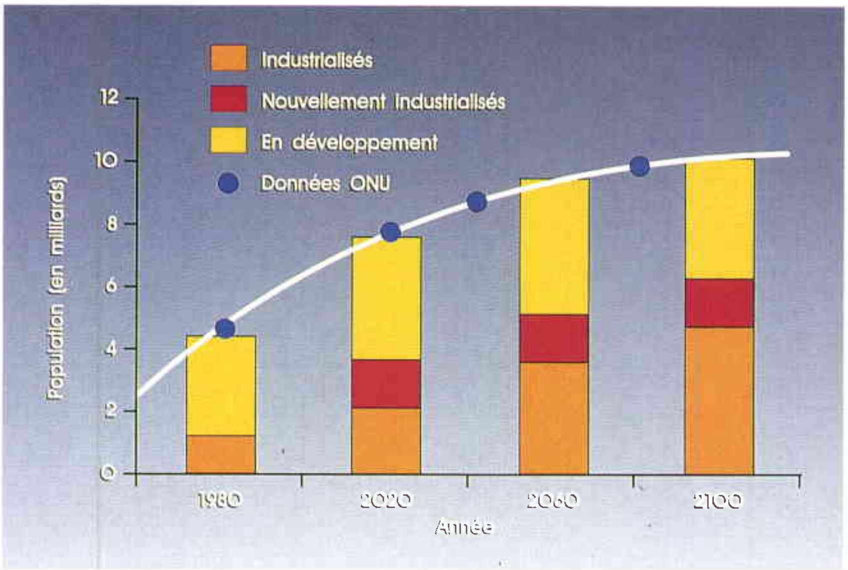

Figure 3. Projection de l'accroissement démographique mondial (à partir des données de l'ONU avec l'hypothèse que 33% des pays en développement deviennent des pays développés tous les 40 ans)

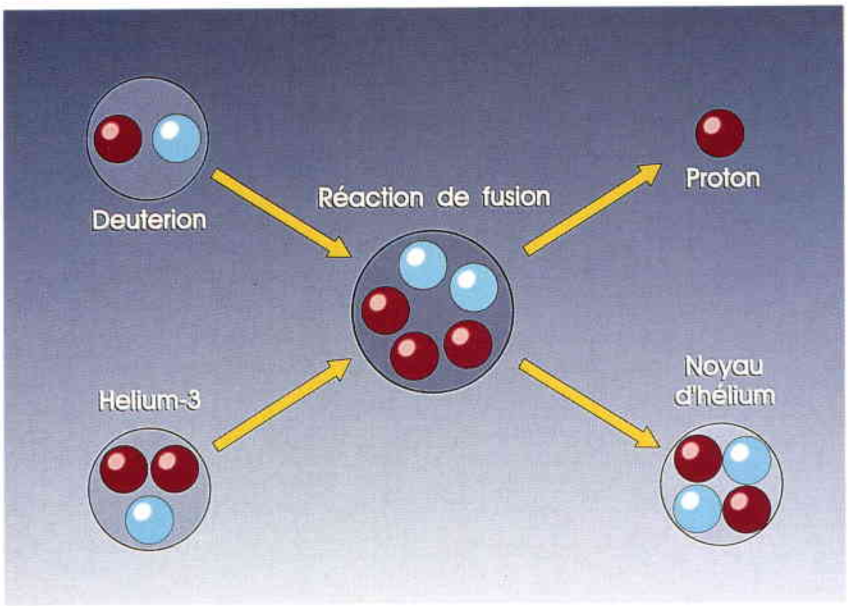

Figure 4. Processus de fusion nucléaire

Les difficultés techniques associées à la maîtrise de la fusion sont énormes: la physique des plasmas en jeu est extrêmement complexe et les technologies à développer et à mettre en oeuvre sont à la limite du réalisable. Ceci explique pourquoi, alors que depuis plus de 30 ans de nombreux centres en Europe, aux Etats-Unis, en URSS, au Japon, travaillent sur la fusion, et que plus de 20 milliards de dollars aient été investis dans les recherches, la perspective d'utilisation du processus de fusion contrôlée comme source d'approvisionnement en électricité n'a cessé de s'éloigner.

Cependant les progrès des dernières années ont été très rapides en particulier en Europe. La dernière expérience conduite par les Européens au Royaume-Uni dans le cadre du programme JET (Joint European Torus) en novembre 1991 a permis de franchir une nouvelle étape en produisant 2 gigawatt de puissance grâce à la fusion deuterium/tritium pendant une durée de 2 secondes. La rapidité des progrès ces dernières années conduit les experts à penser qu'au début du siècle prochain la fusion pourrait être une des sources d'approvisionnement en énergie électrique.

Essentiellement, les centres de recherche travaillent sur trois couples:

deuterium + deuterium
deuterium + tritium
deuterium + hélium 3.

Les réactions correspondant aux deux premiers sont techniquement des plus faciles à maîtriser et l'on pense que ce sont celles qui seront initialement mises en oeuvre lorsqu'on entrera en phase d'exploitation. Cependant elles produisent des neutrons rapides, générant des déchets radioactifs.

La troisième filière, deuterium + hélium 3, souffre de deux handicaps. Le premier est qu'elle nécessite la création d'un plasma à très haute température. Le second concerne l'approvisionnement en hélium 3. En effet cet isotope de l'hélium ne se trouve sur Terre qu'à l'état de trace dans le gaz naturel ou comme sous-produit de l'évolution de matières fissiles utilisées dans les armes thermonucléaires. Son avantage essentiel est qu'elle génère peu de neutrons (et de plus faible énergie) que la réaction deuterium/tritium, mais des particules chargées et des radiations synchrotrons. Celles-ci pourraient être utilisées directement, c'est-à-dire sans avoir recours à la conversion thermique (la transformation chaleur-électricité en utilisant des turbines et des alternateurs). Dans ce cas on pourrait espérer un rendement pouvant atteindre 80%.

Compte tenu des très grandes difficultés à vaincre, les efforts ont donc surtout porté sur le couple deuterium/tritium, comme au JET. Cependant les craintes croissantes pour l'environnement assurent un regain de faveur pour la fusion deuterium/hélium 3, sachant qu'à terme, si la commercialisation de cette fusion se révélait possible, une solution devrait être trouvée pour l'approvisionnement en hélium 3.

Les solutions 'spatiales' pour la production d'énergie

La première solution étudiée au début des années 80 (conséquence du choc pétrolier) proposée par Gläser est bien connue: collecter l'énergie solaire en dehors de l'atmosphère au moyen de cellules photovoltaiques et la transmettre au sol par l'intermédiaire de faisceaux micro-ondes (2,45 gigahertz) et la capter par des antennes au sol. L'avantage par rapport à l'utilisation terrestre des cellules photovoltaiques est double: l'absence de nuit (en choisissant la bonne orbite) et le flux solaire plus important en dehors de l'atmosphère. Le projet est gigantesque.
La configuration de référence étudiée conjointement par la NASA et le 'Department of Energy' donne une surface de cellules solaires de 50 kilomètres carrés, le satellite lui-même ayant une masse de 50 000 tonnes. De telles masses nécessitent naturellement le développement d'un lanceur lourd, délivrant 425 tonnes en orbite basse. 400 astronautes sont nécessaires pour les opérations d'assemblage qui durent 7 mois. Au sol, des antennes de 75 kilomètres carrés

recueillent l'énergie et sont raccordés au réseau de distribution d'électricité. Une telle station délivre une puissance de 5 gigawatts (à peu près la capacité de 5 centrales nucléaires).

Citons pour mémoire la deuxième solution, une variante de la première; toujours en orbite géostationnaire, elle utilise la Lune comme source de matériaux. Cette proposition s'appuie sur deux arguments:

(i) L'énergie nécessaire pour mettre depuis la Lune une charge utile en orbite géostationnaire terrestre représente le vingtième de celle nécessaire depuis la Terre.

(ii) L'analyse faite sur les échantillons ramenés par les équipages des missions Apollo montre que l'on trouve des métaux en abondance (fer, aluminium, magnésium, titane) ainsi que du silicum et de l'oxygène. Tous ces éléments pourraient servir à la construction depuis la Lune des éléments de base de la centrale solaire.
Une telle option, en supposant qu'une infrastructure lunaire soit mise en place pour d'autres raisons (programme SEI, Space Exploration Initiative) est bien entendu extrêmement complexe à mettre en oeuvre.

La troisième option est à nouveau une variante de la première: la station est installée sur la Lune, l'énergie étant toujours transmise par faisceau micro-ondes jusqu'à la Terre (Fig. 5). Plusieurs systèmes permettent de compenser l'alternance de nuit et de jour sur la Lune. Des miroirs en orbite terrestre relaieraient l'énergie sur la face 'cachée' (vue de la Lune) de la Terre. Cette option comme la précédente prend naturellement avantage d'une infrastructure lunaire telle que proposée par le programme SEI.

La dernière solution est liée au processus de fusion deuterium/hélium 3. En effet, si l'hélium 3 n'existe qu'à l'état de trace sur la Terre, l'analyse des échantillons lunaires a montré qu'il existe en quantités importantes sur la Lune — environ 36 grammes par tonne — déposé par les vents solaires.

La fourniture d'hélium 3

D'après le rapport NASA 'Lunar Energy Enterprise Case Study Task Force' de juillet 1989, si la totalité de la fourniture en électricité des Etats-Unis était assurée par la fusion nucléaire, il suffirait de 25 tonnes par an d'hélium 3 pour alimenter les centrales correspondantes (1 tonne d'hélium 3 peut théoriquement fournir 10 000 megawatts/an d'électricité).

Or, le sol lunaire, d'après l'analyse des échantillons rapportés par la misison Apollo et par la sonde soviétique automatique

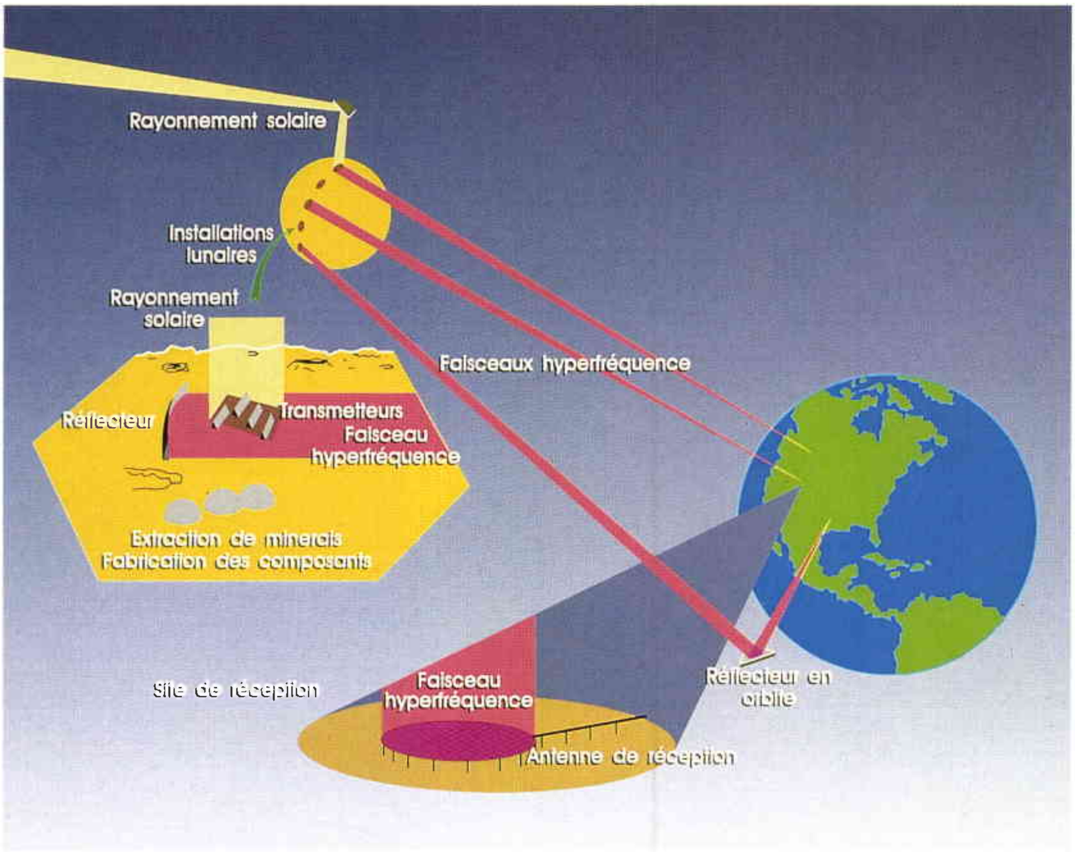

Figure 5. Conception d'une centrale d'énergie installée sur la Lune

LUNA, doit contenir environ 1 million de tonnes à sa surface (à moins de trois mètres). Son extraction est envisageable en chauffant à 600°C la couche superficielle 'raclée' par une machine (Fig. 6). Aprés séparation des autres gaz, l'hélium liquifié serait transporté automatiquement jusqu'à la Terre.

Cette opération nécessiterait naturellement des moyens gigantesques. Cependant à ce stade, deux remarques peuvent être faites:

- Tout d'abord les quantités à transporter se chiffrent à quelques tonnes par an, autrement dit, la charge utile correspondante est à la dimension des systèmes de transport que l'on peut raisonnablement envisager au début du siècle prochain. Le trafic correspondant se situerait au niveau de quelques vols par an.
- Ensuite la valeur du produit transporté est considérable. Une tonne d'hélium 3, estimée par équivalence au pétrole, à 20 dollars le barril, 'vaut' 1 milliard de dollars. C'est donc un produit véritablement spatial: la part imputable au coût du transport représenterait une faible fraction du coût total du produit.

De tels chiffres conduisent les auteurs du rapport à penser que l'extraction et le transfert de l'hélium 3 serait une activité rentable.

Perspectives

Des progrès considérables ont été faits particulièrement en Europe, sur la fusion contrôlée. Le problème très préoccupant que représente la fourniture d'énergie aux hommes du 21ème siècle pourrait trouver en la fusion une solution. Dans cette hypothèse, le couple deuterium/hélium 3 bien que plus difficile à mettre en oeuvre que d'autres couples devrait conduire à des réacteurs fiables, propres, sûr et d'un bon rendement. l'espace pourrait apporter une solution à l'approvisionnement en combustible de cette filière.

Naturellement une telle entreprise ne pourrait être conduite sans la participation d'opérateurs humains. Le projet américain d'établir une base sur la Lune tel qu'il est proposé par le programme de Space Exploration Initiative pourrait fournir l'infrastructure de base pour la mise en oeuvre d'une telle solution. Les calendriers des deux opérations, programme de fusion

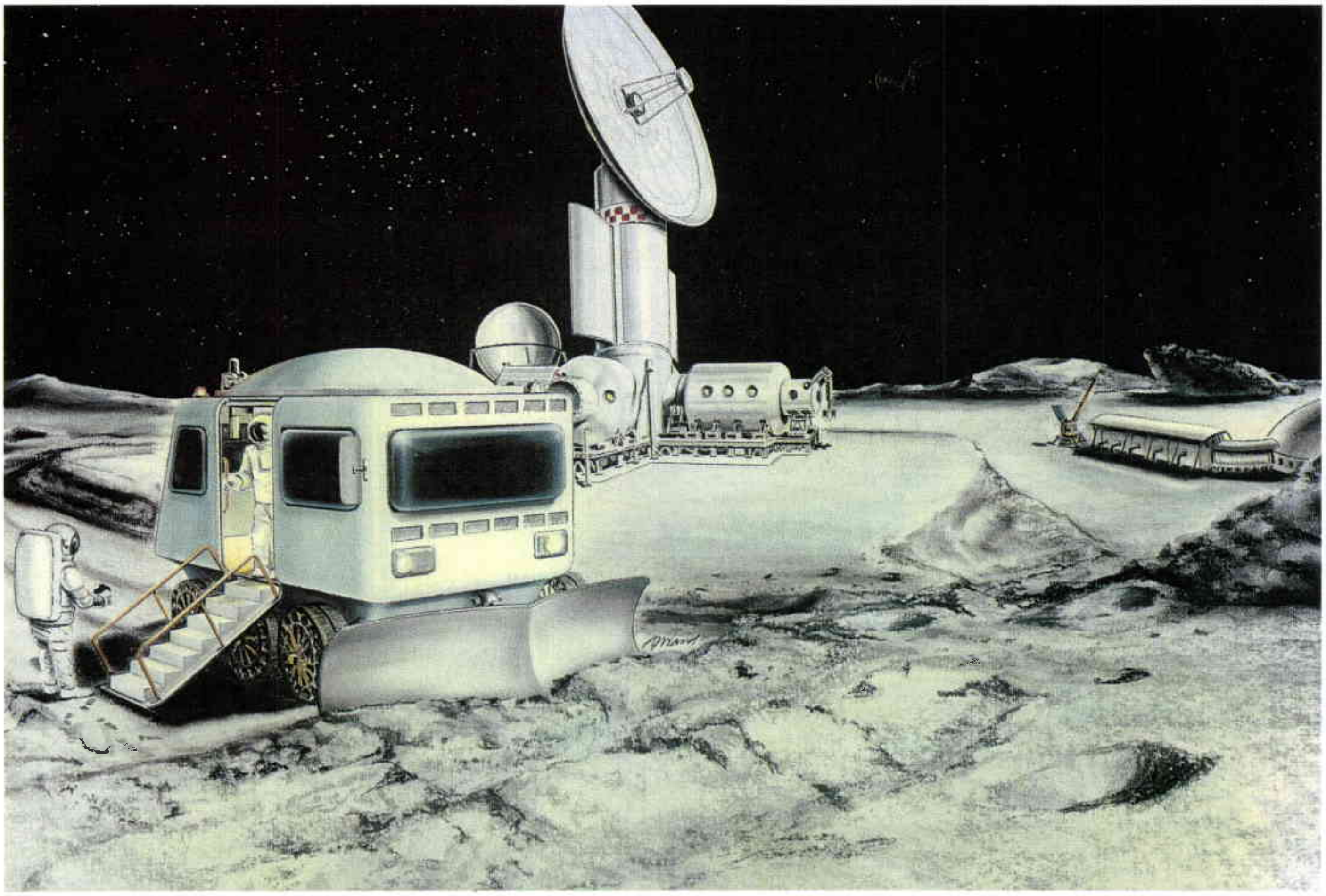

Figure 6. Concept d'une machine 'extractrice' de sol lunaire

nucléaire et établissement d'une station lunaire, sont cohérents. Les communications faites au Symposium 'Satellite Power Systems' par la NASA montrent que 50 kg d'hélium 3 pourraient être ramenés de la Lune chaque année pour alimenter les premiers réacteurs pilotes en hélium 3 dès 2010 et qu'à partir de 2020, 1 tonne par an permettrait le fonctionnement de réacteurs d'une puissance de 10 GW. Des tranches de 10 GW chaque année seraient ajoutées nécessitant l'extraction d'une tonne supplémentaire par an.

Conclusion

Le scénario développé à partir de la fusion nucléaire et de la filière hélium 3 illustre les perspectives considérables que l'espace habité peut ouvrir. Dans ce contexte on imagine sans peine la situation de dépendance de ceux qui n'auraient par la maîtrise de cette capacité. Certes les perspectives commerciales de la fusion sont encore lointaines, et pour la filière hélium 3, même si celle-ci présente d'incontestables avantages sur le plan de la sécurité et de la protection de l'environnement, des difficultés considérables restent à maîtriser. De plus, si cette filière se révélait rentable commercialement, la faisabilité et la rentabilité d'une extraction lunaire devrait être établie. Cependant la taille de l'enjeu est considérable. L'Europe possède de réels atouts dans le domaine terrestre, celui de la recherche de pointe en matière de fusion, elle possèdera grâce à ses programmes habités les moyens de participer à la composante spatiale si celle-ci devait se révéler un élément essentiel de l'approvisionnement en énergie.

Références

NASA Report 'Lunar Energy Enterprise', Case Study Task Force, July 1989, NASA Technical Memorandum 101 652

'Lunar Helium 3 and Fusion Power', NASA Conference Publication 10010, 1990

'Lunar Resources Utilisation and the Space Exploration Initiative', Statement by G. Kulcinski to the House Subcommittee on Space, 10 July 1991

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The World Space Congress

The World Space Congress will be the "premier scientific and engineering symposium" of the ISY.

Next year will be International Space Year (ISY), the first year-long global celebration of the space era. Worldwide celebrations will not only commemorate the beginning of the space age 35 years ago, but also the 500th anniversary of Columbus' voyage to the New World. It is hoped that the spirit of discovery and exploration necessary for both of these ventures can be rekindled to lead us into the future—with space activities at the vanguard. The World Space Congress will be the preeminent ISY gathering of those who make space travel a reality—the scientists and engineers. It brings together an unparalleled concentration of the most prominent individuals in this area.

What is the World Space Congress?

The World Space Congress is a nine-day meeting of the world's leading space scientists and engineers. It will be the United States flagship event for ISY. Vice President Quayle has called it the "premier scientific and engineering symposium" of this worldwide celebration of space activities. It will combine two of the world's most prestigious international space meetings, the science-oriented 29th Plenary Meeting of the Committee on Space Research (COSPAR) and the engineering-oriented 43rd Congress of the International Astronautical Federation (IAF), both organizations are based in Paris.

When and where will it be held?

Program

It will be held from August 28 to September 5, 1992, in Washington, DC. The meetings will be held in three locations: the Washington Convention Center, the Ramada Renaissance Techworld, and the Grand Hyatt Hotel. There will also be a host of special social functions and industry-related tours.

Exhibits

The World Space Congress will be held in conjunction with an international exhibition featuring industry and government exhibits from all space-faring nations. This exposition will be held in the Washington Convention Center from August 31 to September 4, 1992.

Who is sponsoring this event?

The World Space Congress is a collaborative endeavor that will be held under the auspices of the United States National Academy of Sciences (NAS) and the National Aeronautics and Space Administration (NASA). It is being hosted and organized by AIAA, and the general chairperson is Gerald A. Johnson, president, McDonnell Douglas Corporation. The World Space Congress has the endorsement of the United Nations, which views it as strong encouragement for international cooperation in both space science and its applications for the betterment of humanity.

Does it have a theme?

"Discovery, Exploration, and Cooperation" will be both the theme and focus of not only this event but also of ISY. It will bring together leading international space scientists, engineers, administrators, and policymakers to share ideas, exchange results, develop strategy, and plan for a new space age.

How many people will attend?

It is anticipated that thousands of space professionals from over 50 developed and developing countries will attend this ISY event.

Will papers be presented?

Yes. Over 3000 invited and contributed papers will be presented by notable space professionals in 30 concurrent sessions each day. In addition to the technical program there will be a series of Distinguished Lectures and Panels by the world's leading authorities in space science, exploration, and engineering.

Will the papers be technical?

The core of the World Space Congress will be the presentation of technical papers that relate to all science and engineering aspects of space technology and exploration. However, this program will be supplemented by sessions that feature the world's leading space experts, government officials, policymakers, and academicians who will discuss policy and strategy issues. The annual colloquium on the Law of Outer Space, organized by the International Institute of Space Law, will also run concurrently with the World Space Congress.

How can I get more information?

More information about the World Space Congress can be obtained from the American Institute of Aeronautics and Astronautics (AIAA) by sending your inquiry to "World Space Congress," AIAA, The Aerospace Center, 370 L'Enfant Promenade, SW, Washington, DC 20024-2518 or by calling 202/646-7569. ✦

ESA's Software Engineering Standard — The Foundation for Reliable Software

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The updated version of ESA's software engineering standard (called PSS-05) was issued in February 1991. It defines the steps necessary to produce quality software that meets the user's requirements within the established timeframe and budget. The standard applies to all software developed by ESA or its contractors for ground, space, information systems, and operations. It provides a common working culture for the entire European space software community.

Introduction

ESA's software engineering standard is a guide to the software development process; it emphasises the areas in the process that really influence software development. The single, 120-page document defines the production of software in an integrated fashion, and describes the management functions that support that process. The objective is the efficient production of software to the right quality. The software engineer is guided by 'rules' that are structured by project phase and management activity. The standard injects as much discipline as possible into appropriate areas, and provides guidance for the more creative aspects. It provides management with a clearer view of progress during the development, and a greater probability of producing software that meets the requirements.

Software has become important, pervasive and expensive for almost every aspect of satellite development and operations. Handling software development in a disciplined manner is essential. ESA contracts out much of its software, and the standard tells contractors exactly what is expected, without intruding too far into their own methods. The standard provides a coherent culture and vocabulary within a project and across project boundaries. Many European companies are already very familiar with the standard, and this helps them work easily with ESA.

After more than a decade of steady evolution, the new issue is up-to-date technically, and is well accepted and applied by ESA's own software engineers. The document is essential reading for every software engineer, for every ESA manager controlling a software project, and for every contractor developing software for ESA.

Why is software so important to ESA?

Good software helps ESA stay competitive, and ESA must take an active role toward software development. Software has always been something to be left to the experts, but in the space of two decades, it has quietly become highly influential at every stage of a satellite's life. ESA has to make sure that software is developed properly and efficiently. Although managers may not need to understand the detail involved in software development, they must make sure that, in projects under their control, software is developed efficiently, and that progress is always visible. This is where the software engineering standard comes in.

Software has a large impact on the satellite's performance, cost, and schedule. Analysis software now affects the satellite design as much as any materials technology. Software is also a major influence on-board the satellite; it has provided many new capabilities. During the satellite's development, information systems communicate project management information and documentation, speeding up the development process. When the spacecraft sends back its results, that information is relayed to the user community of scientists through the control of software programs.

How was the standard generated?

Although software has always played an important role within ESA, it became even more important (and more expensive) by the late 1970s. In those early days, there were great difficulties in developing software — the software often did not work, it was difficult to determine the status of the development project, and engineers even had difficulty communicating technically across different projects.

The software engineering standard was first developed in 1978 in response to those problems, and after some pilot trials, it was released in 1980. It was then updated in 1984 and 1987. The application of the standard was mandatory, but few resources were available for enforcing it. With each new version, the standard improved, engineers understood it better, and use of PSS-05 steadily spread, first within ESA, then to ESA contractors.

In 1989, the standard was reviewed by ESA software engineers and contractors and about 200 improvements were proposed. The quality of those suggestions showed the intensity with which the standard was being used — more than 80% of the recommendations resulted in changes to the standard.

While the overall structure of the document remains the same, the new issue accommodates different approaches to the software lifecycle. The managerial aspects have also been streamlined and, in particular, the area of verification has been enhanced following many suggestions made during the review. The position of software development within a systems development project has also been better defined, and the guidelines for how to capture and manage user requirements are much stronger. In addition, a few small gaps in the previous standard have been corrected, and this led to changes in some of the names of documents that are prepared as part of the software development process.

Contents of the software standard

The standard is divided into three main parts. Part I describes the characteristics of the product to be developed, and the phases into which the development is divided.

Part II describes the management procedures for a software development project. The main areas are project management, configuration management, verification and validation, and quality assurance.

Part III contains appendices such as a glossary of software engineering terms, and standard tables-of-contents for the different software documents. In addition, all of the standard's mandatory rules have been extracted and gathered into a checklist for each phase and for each management activity. This list can be used for technical audits of projects or company software development processes.

Phases of software development

The software lifecycle is divided into phases. The boundaries of each phase have been carefully chosen to allow progress to be measured. Figure 1 shows the phases in the basic ESA software lifecycle.

For each phase, PSS-05 defines inputs and outputs. Acceptance of each output or deliverable forms a milestone, and the deliverables of one phase must be approved before the activities of the subsequent phase can begin. To measure the progress and quality of the whole system, the project manager can monitor the progress of the deliverables against the plan, from either a technical or a project management point-of-view. At the end of each phase, there is a complete system review or test. The documentation produced in the early phases defines and controls the activities in the later phases.

Definition of user requirements

In the first phase, the user requirements definition phase, the 'problem' that must be overcome is defined clearly, without consideration for the software that could be used. This activity usually involves interviewing users, reviewing existing documentation, and evaluating similar systems in order to document the process that must be supported by the software.

The end result should be a clear, non-technical statement of the problem, understandable by both the users and the developers. This is one of the hardest phases to complete; it requires good communication skills and persistence in order to find out what the users really need.

Definition of software requirements
In the next phase, the software requirements must be defined. Software requirements identify what the system must do, its performance, and the constraints that apply to it. They are requirements that apply to the solution rather than those imposed by the user.

When the functions required are being described, they must be actions, expressed using verbs. However, while this phase defines what the system must do, it does not specify how it must be done. Software requirements should be concise and clear, but detailed enough to allow users to understand what they will receive and to form a basis for design and testing.

The functional requirements of software are more stable than the design, i.e. a design change often does not affect the functionality of the system. Performance requirements are attached to the functions, to state necessary throughputs or response times. Constraints in the software requirements phase come from 'professionals', imposing factors such as the required reliability, maintainability or portability.

The creative part of this phase involves building a simple, clear functional model that is understandable by all, clearly meets the user requirements, is good enough to test the working system against, and is also good enough as a basis for design.

Architectural design
The design process then starts. The design is done in two stages: first the architecture is defined, and then the detailed design is undertaken. The architectural design defines the main components of the software. The interfaces between these components are also identified, at a high level. Different alternative designs can be examined, and a best system chosen, because the system design is still flexible enough for such easy manipulation. Decisions about commonality can now be made; for example, a programming language or a data base management system should be chosen by this stage. Sensible compromises in this phase can often save large amounts of money.

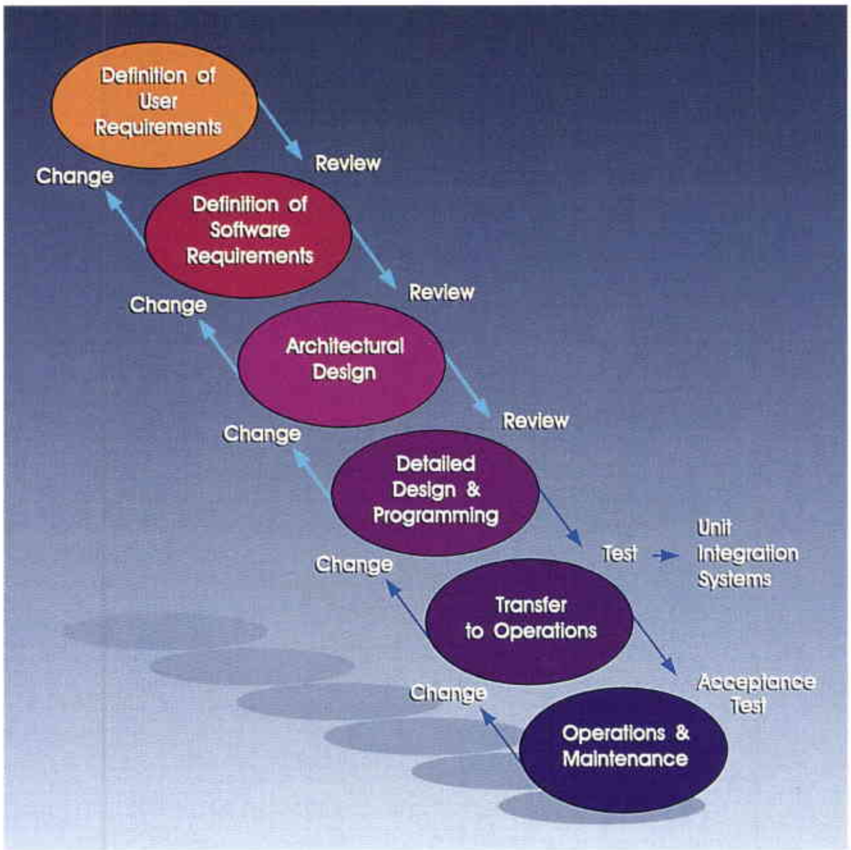


Figure 1. Basic phases of the software lifecycle

When the architectural design is completed, it should be possible to assess software costs within about 10%. With good interfaces, the architecture can be divided into parallel work packages, linking the technical work into project management.

Detailed design and programming
The detailed design and coding of the software is then undertaken. The architectural components are defined in greater detail, and each unit of the software is designed so that it can be programmed fairly independently. Controlling this programming process requires structure and discipline.

Before the code is written, the work should be subject to peer-group inspections to detect faults. The programming modules and the interface development should be well documented and labelled, as well as readable and consistent. Manuals and help screens can be completed. User manuals should be prepared by specialist writers, who can write from the user's perspective, not from knowledge of the programming details.

Transfer to operations
As the units are produced and tested, they are integrated into a working system. The transfer phase takes the working system into the operational environment, still under the control of the developers. Software is installed and tested on the equipment that it will actually operate on, and the staff or the users are trained to use it.

Operation and maintenance of the software
Provisional operation of the software can start. Once the software has operated satisfactorily for a given period, the users give their provisional acceptance of the software. All errors or 'bugs' are identified and corrected. As the final check on the working software, the software must meet all the original user requirements defined in the first phase of the lifecycle. Control of the system then passes completely into the hands of the operations organisation; the development team's tasks have been completed.

Software management activities

Part II of the standard defines the management tasks to be performed during the course of the software development.

As part of each of the four main management activities (described below), a short plan is generated for the next phase of the lifecycle. If the project deviates from the plan, as it invariably tends to do, the manager must detect the change as early as possible, and bring the project back onto schedule or, if that is not possible, revise the plan.

Project management
Managing software projects is never easy. Planning and preparation are all-important. The basic management task is planning in detail for the next phase, and in general for the rest of the project. The competence of staff is by far the most significant factor in developing good software. However, adequate resources and tools, solid requirements, well-defined roles, proper delegation, a good working environment, trust and cooperation are also required for success.

The project management functions include:

- handling of resources and external elements
- contract management
- change management
- systems optimisation
- management of the review process.

Configuration management
The configuration is the structure through which development is controlled. In general, the configuration is based upon the deliverables: each deliverable, called a configuration item, forms the basis for programming, maintenance and testing. Configuration management involves controlling the labelling, storage and issuing of baselines, so that all development staff are working with the same version of the system. This avoids 'double maintenance' and wasted work.

Software products for configuration management should be used on all but the smallest development projects. PSS-05 does not specify which tools to use, but it imposes requirements on the configuration management process.

Verification and validation
Requirements must be stated in a verifiable form because they are the basis for verification as well as for design. Verification involves reviewing, inspecting, tracing, and auditing as well as testing all the products of the software lifecycle. Verification demands the construction of a second, test system, which is used to check the product against the requirements. Verification is always a compromise; costs and time must be balanced against reliability and quality, as well as knowing when to stop.

Planning for verification forces software to be modular, testable, and maintainable. The three golden rules of verification are 'do it early', 'do it at as low a level as possible' and 'use your cleverest people'. Verification detects errors at earlier stages in the development, where they cost less to correct. Quality cannot be tested into software. Errors are more efficiently removed by source code inspections than by testing, but it is better to avoid them in the first place.

Verification work starts during the user requirements phase, when the users specify the type of test that would satisfy them that their requirements have been met. These specifications can improve the engineer's understanding of the requirements themselves. Testing is 'bottom-up' (Fig. 2); it starts when a module has been completed and continues as the system is assembled. Modules are tested against their specification as stated in the detailed design document, integrated modules are tested against the architectural design, and the completed system is tested against the software requirements. Two final tests, the preliminary

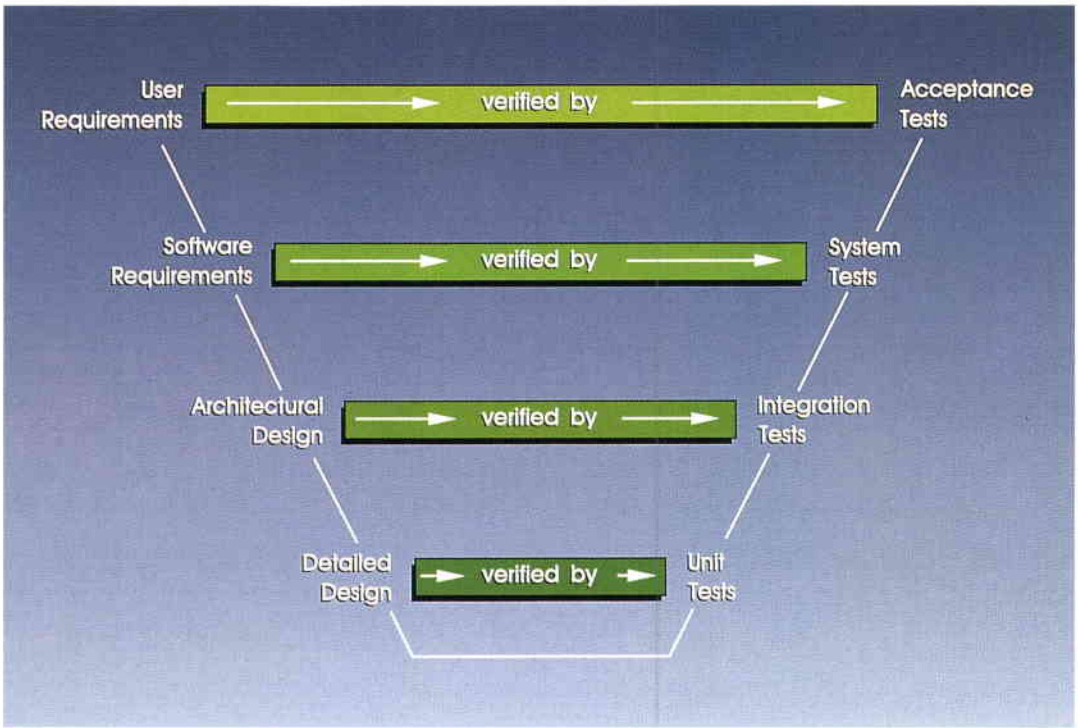


Figure 2. Verification sequence

and the final acceptance tests, are then performed against the user requirements. Based on a successful preliminary test, the operation of the software starts, and based on a successful final acceptance test, the system is handed over to operations staff, ending the development team's involvement in the project.

Quality assurance

Quality assurance is the most misunderstood role in software development. Good engineering practices, not good managers, produce quality software. The project manager must assure the quality of the system, while specialised quality assurance staff may handle the policy and planning for quality assurance as well as the reviews and audits. Quality is 'conformance to requirements', but total quality management is 'efficient conformance to the right requirements'. This means that the proper requirements must be generated and then it must be ensured that the product conforms to them. The status of the requirements must be kept up-to-date throughout the project to allow the users to determine the progress being made. Quality assurance provides confidence that the requirements will be met, even during the course of the project.

Modelling different lifecycles

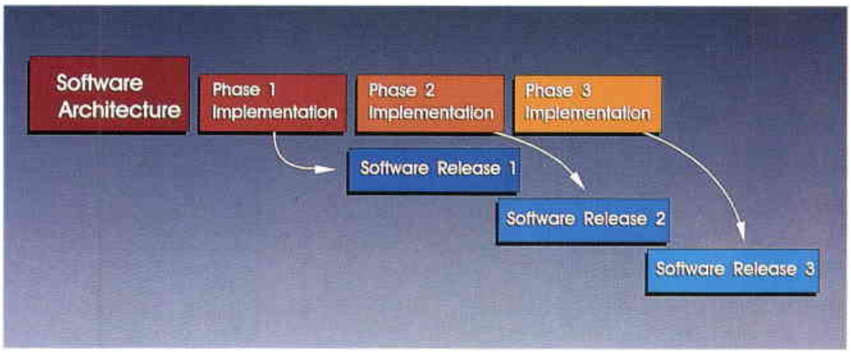
The ESA standard defines the basic tasks to be performed in a software lifecycle but, because of the range of problems faced by ESA, the tasks may have to be combined in a different manner. Other approaches are necessary, for example, when the software must be implemented in several stages, or the requirements cannot be determined without a prototype being built. The new issue of the standard encourages a modular approach, so that the basic phases can be re-assembled to form incremental or evolutionary lifecycles. A few different lifecycles are described below.

Incremental delivery and evolutionary development approaches

The incremental delivery approach follows the basic lifecycle process, in which the phases are executed sequentially (Fig. 1), up to the early design phase. The architecture is then implemented in stages (Fig. 3). A simple working system is first produced, and subsequent systems are then developed.

Incremental development is usually better than the basic lifecycle approach, especially on large or ill-defined projects. The simple working systems produced provide early feedback and payback, and reduce the long gap between the definition of the requirements and the implementation of the system.

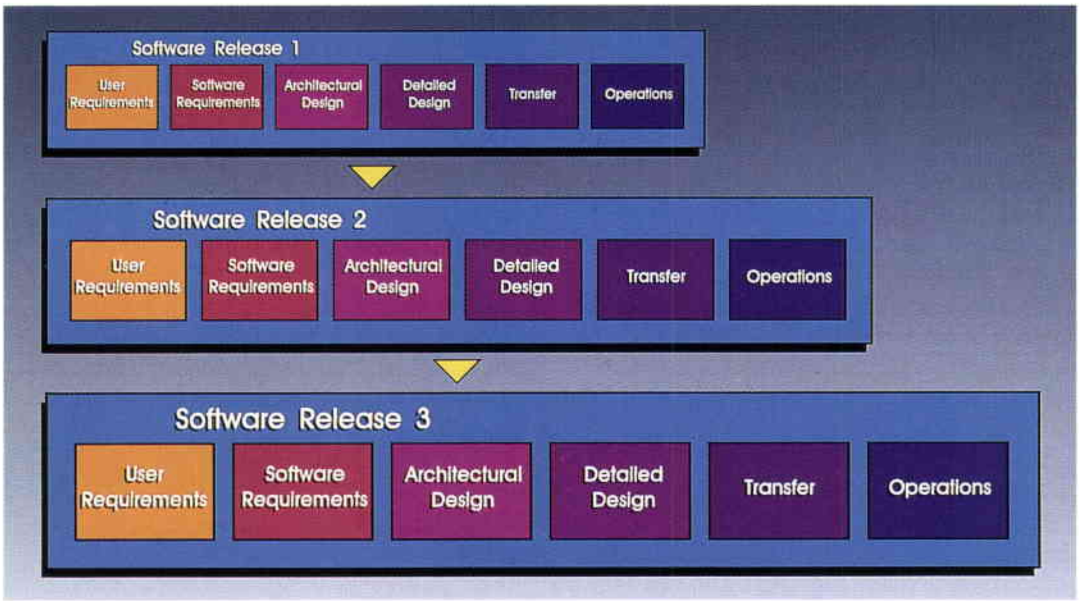
Figure 3. Incremental delivery approach



Another approach, evolutionary development, is the repeated application of the basic lifecycle, with new requirements being collected each time the system is revised and the whole lifecycle re-run (Fig. 4). This approach is suited to projects where the underlying requirements are weakly understood, the technology to be used is not yet mature enough, and the software has yet to evolve to cope. The problem with such an approach is that the software may have to be re-written for each subsequent implementation.

From the technical point of view, both of these approaches are almost always better than using the basic lifecycle, but they involve more organisation, are difficult contractually, impose constraints upon the architecture, and demand modular design and interfaces. For a partial system to be useful, the parts implemented first have to be carefully chosen. A flexible structure is generally an advantage, but not in all cases.

Figure 4. Evolutionary development approach



Buying commercial software
Buying commercial software is a different approach to software development. If this approach is used, PSS-05 is still applicable, but some phases and tasks can be eliminated. When existing commercial software meets most user requirements, it should be purchased rather than developed.

Customers tend to buy the first product offered by salesmen only to find better products later. Instead, commercial software should be chosen competitively, against a set of requirements. Essentially, the customer runs a multi-stage competition against the user requirements, first as a paper exercise, then with acceptance trials and critical cost-benefit negotiations, followed by final acceptance of the best product. The process can be slow, but it is worth the effort because of the importance of the software.

Prototyping
In PSS-05, prototyping is not considered to be a lifecycle, but it is a technique used within the lifecycle. Prototyping might be used to generate a requirements document or an algorithm, but not for the final production of the software. However, it can be used for several purposes: defining requirements or ensuring a feature is really practical. The project manager should always consider the following: What is the objective of the prototype? Is it worth the cost? Will the result of prototyping be ready for the main development?

If prototyping is intended to derive requirements, the software produced must be just well enough developed to show to the users to get their comments. Requirements, not software, are the net product, and they must be ready before finishing the requirements phase.

Similarly, to evaluate an architectural element of the design, the implementation has to be just realistic enough to allow the engineer to make a sensible decision.

Key concepts of the standard
Firstly, PSS-05 is a 'minimum' standard. It defines the minimum that is needed regardless of the type of software being developed. It is presented in a concise, readable framework, and does not try to dictate a rigorous step-by-step approach to

software production. The range of tasks faced by software engineers is far too large for a dogmatic approach to succeed. Instead, PSS-05 defines the discipline needed to handle the repetitive aspects of software development, but encourages creativity outside those boundaries. In general, the standard does not impose solutions upon the software development methods and standards of ESA contractors. The solution must meet the user and software requirements while conforming to ESA's standard. Despite this minimum approach, following the 430 mandatory practices requires a disciplined approach. The standard has to be interpreted sensibly — it would be unfair for ESA to insist that a contractor comply fully with every rule, just as it would be unfair for a contractor to deliver a product that reflects a minimum interpretation of the rules.

Secondly, PSS-05 is an 'integrated' standard. All activities necessary to produce good quality software are defined relative to the state of the project. Management tasks are defined functionally, not by job title, so that different contractual arrangements are feasible. For example, verification, configuration management and quality assurance tasks are integrated with the development of the software products.

Thirdly, PSS-05 emphasises the formative aspects of the software development process, such as project management, planning, and requirements control. These activities are at least as important for software development as technical issues such as programming, computer languages or configuration control. Although the technical aspects have to be performed correctly, the quality of management and requirements handling have a direct impact on the cost and schedule of a software project and on the performance of the products.

Fourthly, the underlying concepts of PSS-05 transcend software. The standard is not about tools, box-drawing techniques or data headers, but about doing the job properly. The principles of planning, monitoring progress, determining requirements, defining an abstract solution, then steadily moving into design detail can be readily understood by all project members.

Lastly, PSS-05 is 'modular'; the building blocks of the lifecycle can be re-assembled by the software engineer to suit different problems.

Promoting the new issue

Having a good standard is one thing, but making sure that it is applied requires some effort.

All ESA staff members who are involved in developing software have a copy of the standard. Any space contractor working on software can obtain a copy. More than half of ESA's 2000 contractors have copies, and many use it for developing their own company software. To inform managers about the importance of the standard to their own work, a short booklet addressing the twenty questions most commonly asked about the standard, is also available from ESA.

The future

Lower level guidelines are being prepared to provide more detailed guidance to the software engineer (Fig. 5).

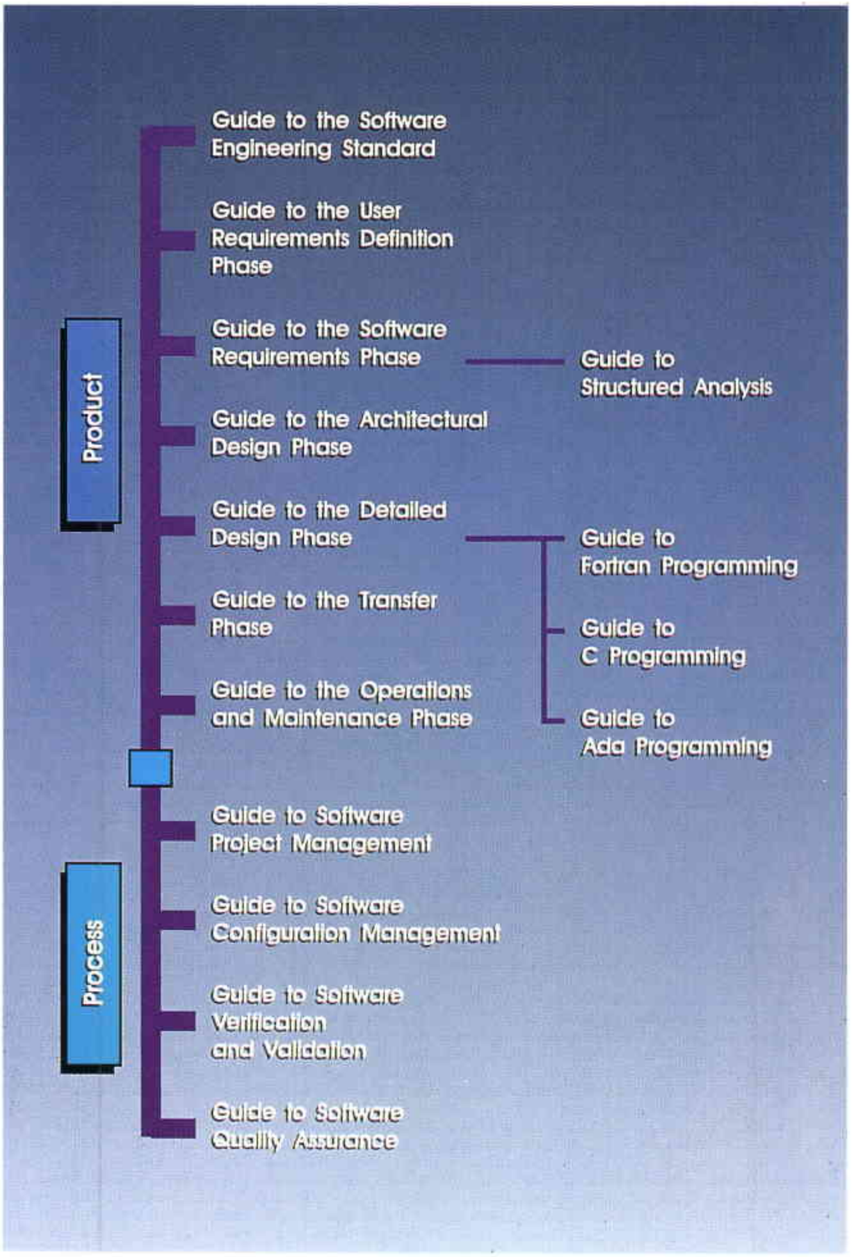


Figure 5. Guides to the ESA software engineering standard

They describe the phases and the management activities in more detail as well as specialised areas such as programming in Ada. They are only guidelines and not mandatory practices.

Conclusion

ESA's software engineering standards provide a common working culture for the entire European space community. The new issue of the software is up-to-date, and has been very well received by ESA staff and contractors. The overall approach emphasises practicality. Promotion and training are now needed to drive home the message.

PSS-05 is one of the few ESA mandatory standards. It distills 20 years of experience in developing software to support space missions. Applying the standard is essential to the production of software with the reliability, maintainability, and quality required for the technologically advanced missions of current ESA programmes. However, the standard cannot provide all that is needed to produce such software — software development requires intelligence, hard work, creative judgement, a good team atmosphere, and a stable working environment. Developing software is a human and creative activity, and good software engineers are always needed to produce good software. A good standard is the starting point for applying intelligence and creativity.

ESA Software Engineering Standards (PSS-05-0)
Issue 2 (50 Dutch guilders).

Software — The ESA Way:
Twenty Questions and Twenty Answers on ESA Software Engineering Standards (ESA-INT 3) (no charge).

Available from: ESA Publications Division, ESTEC,
Postbox 299, 2200 AG Noordwijk, The Netherlands.

University of
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Department of
Aeronautics and
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Short Courses in Spacecraft Engineering for 1992

The Department of Aeronautics and Astronautics has been a major centre for the training of industrial engineers since 1974, and continues its programme with the following courses for 1992.

SPACECRAFT TECHNOLOGY

29 March - 11 April 1992
6 - 19 September 1992

This is a two week residential course aimed at providing training for staff of graduate or equivalent status who have recently begun a career in the spacecraft industry.

SPACECRAFT SYSTEMS

12 - 17 July 1992
13 - 18 December 1992

This course gives a broad view of the spacecraft, and an insight into the working of its systems and how they interact with each other. This is the equivalent of the course we hold at Estec for ESA personnel.

For further information please contact:

Continuing Education Secretary
Department of Aeronautics and Astronautics
University of Southampton
Southampton SO9 5NH, UK

Tel: 0703 593383 (overseas 44 703 593383) **Fax:** 0703 593058 (overseas 44703 593058)

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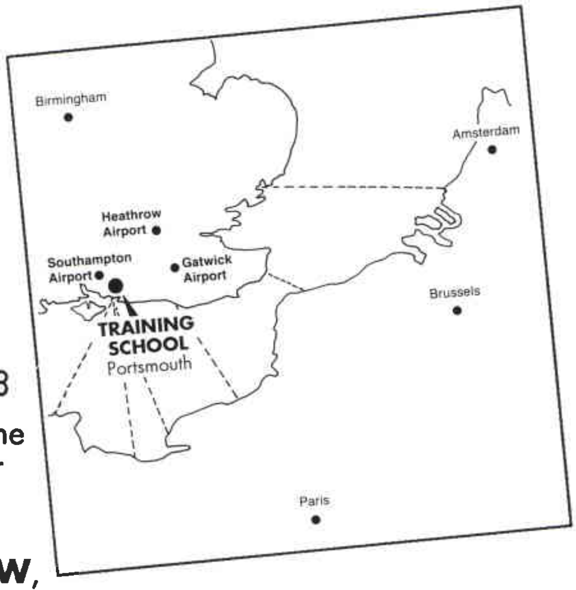
Based in the Department of Trade & Industry approved Southern Regional Electronics Centre, the Training School is easily accessible by plane, (Gatwick, Heathrow or Southampton), motorway, rail or car ferry.



ESA certificated courses regularly offered include:

EO1 Hand soldering to ESA specification PSS-01-708
EO2 Inspector training to ESA specification PSS-01-708
EO3 The preparation and solder termination of semi-rigid cable assemblies to ESA specification PSS-01-718
EO4 Rework and Repair to ESA specification PSS-01-728
EO5 Surface mount technology to ESA specification PSS-01-738

Other services available include advice, consultancy and the design and implementation of unique training packages for individual client companies, either centre-based or on-site.

Further details and current update from **BARRIE CUCKOW**,
Centre Manager, Regional Electronics Centre, Highbury College of Technology, Cosham, Portsmouth, Hampshire PO6 2SA,
ENGLAND

Phone **0705 383131 extension 212** •• Fax **0705 325551**

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Focus Earth

ERS-1 SAR Image of Cabo Frio, Rio de Janiero State, Brazil

This image of the northeastern part of the State of Rio de Janeiro, Brazil, was taken with ERS-1's Synthetic Aperture Radar (SAR) on 9 September 1991.

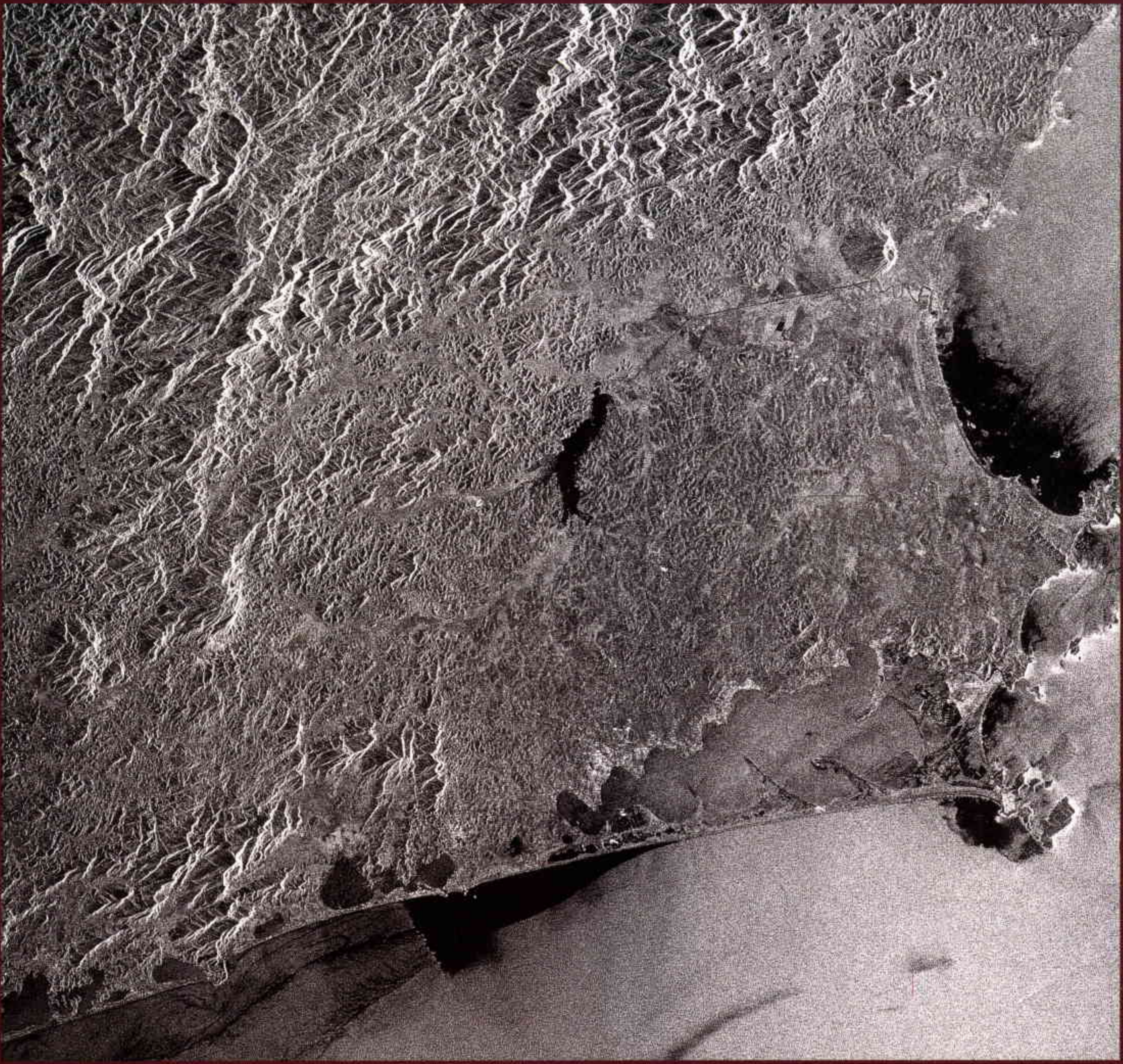
The lake, 'Lagoa de Juturnaiba', in the centre of the image is a water reservoir that was constructed in the 1970s. The water channel and the river (Rio Sao Joao) flowing east can be clearly identified. Just before the channel reaches the sea, near the town of Barra de Sao Joao, there is an interesting alkaline intrusion known as 'Morro de Sao Joao' (Sao Joao Mountain), which is covered with forest.

The mountainous area in the upper part of the image is mostly covered with natural sub-tropical forest, and is called 'Mata Atlantica'. The very large lagoon in the lower part of the image, close to the coast, is called 'Lagoa de Araruama'. It is surrounded in the north by small towns, and there are salt flats which are typical of the area along the ripple-like shoreline in the south, as well as to the west and east (darker areas). At the eastern end of the lagoon lies the city of Cabo Frio.

The two dark areas on the sea surface in the lower part of the image are oil spills. The exact cause of the large triangular-shaped dark area along the coastline and the variable ocean surface patterns further to the southwest is not known, but they are not the result of an oil spillage.

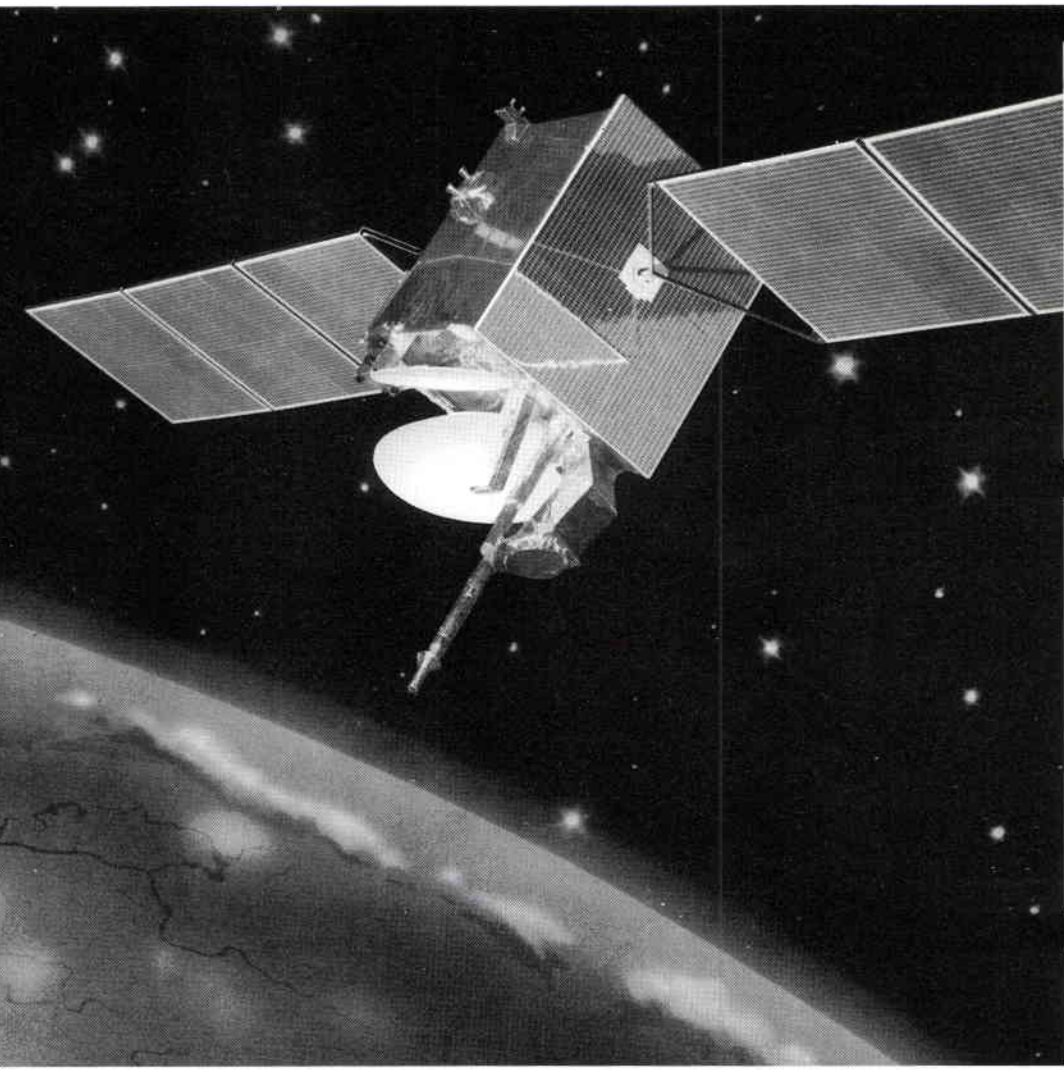
Image Characteristics:

- Data acquired at Cuiaba, Brazil, on 9 September 1991 at 12:53 UTC
- Data processing by INPE, Brazil
- Spatial resolution 25 m
- Coordinates of image centre: Latitude 22°42S — Longitude 42°21 W

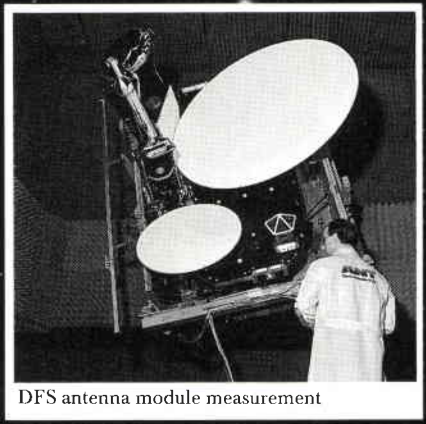


Satellite Technology from ANT:

DFS Kopernikus – The German Telecommunications Satellite



Satellite integration hall at ANT



DFS antenna module measurement

ANT 8927 E Schr.

DFS Kopernikus, the first German telecommunications satellite, has gone into orbit. The satellite programme was designed and manufactured by the ANT/MBB consortium. The system consists of two spacecraft and a ground spare. ANT supplies the entire telecommunications payload.

Kopernikus is equipped with eleven transponders which can be simultaneously operated for the transmission of speech, text, data and TV programmes in the 11/14, 12/14 and 20/30 GHz frequency ranges. Six further transponders are mounted onto the satellite for redundancy operation.

Furthermore, ANT supplied the receiver systems for 32 small DFS earth stations and was the main contractor for the 11/14 GHz DFS earth station in Berlin as well as for the conversion to DFS operation of an earth station in Usingen.

ANT Nachrichtentechnik GmbH
Gerberstrasse 33, 7150 Backnang
Telephone + 49 (0) 71 91/130
Telefax + 49 (0) 71 91/13 32 12

ANT
Bosch Telecom

In Brief

Experimental Campaign Seeks Candidates

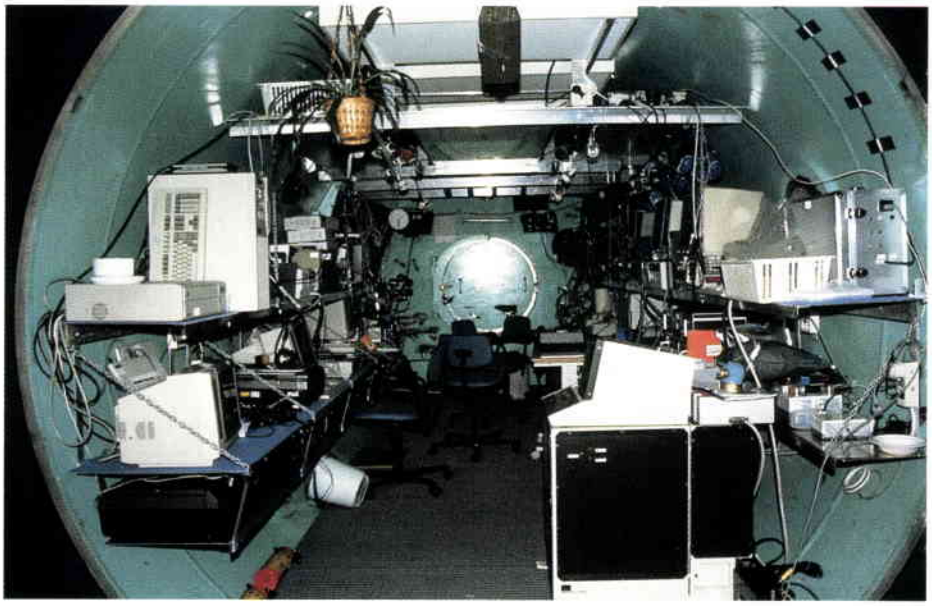
ESA's Directorate of Space Stations and Microgravity will undertake a simulation of a manned space mission in September and October 1992. In this simulation, called EXEMSI '92, an international crew of three will be confined in an isolation facility for 28 days, to study various aspects of living and working in space.

To investigate the human-related aspects involved in long-duration, manned spaceflight, the crew will undertake a series of scientific, technological and other space-related experiments. The crew members may also be able to carry out their own experiments and research.

ESA is seeking candidates who are interested in participating in the campaign either as a Crew Interface Coordinator or as a Crewmember. Applicants should meet the following requirements:

- Male or female.
- A national of an ESA member state or of an ESA associated state.
- Preferably between the ages of 27 and 37 (although no mandatory age limits will be applied).
- In the height range of 153 to 190 cm.
- Speak and read English.
- Possess a university education (or equivalent) in Natural Sciences, Engineering or Medicine. Post-graduate professional experience is considered an asset.
- Have a satisfactory medical history, a sound state of health, with a normal weight and a normal psychiatric disposition.
- Prepared to provide a full family and personal history, and permit the collection of further information if deemed necessary by the examining medical body.

Isolation facility where crew will live and work.



All information provided will be treated as confidential. The deadline for application is 2 March 1992. For further information, contact:

Prof. F. Rossitto
European Astronauts Centre
Linder Hoehe, Postfach 906096
D-5000 Koeln 90 (Porz), Germany

Tel: 49-2203-600120
Fax: 49-2203-600166

Launch of 48th Ariane

The 48th Ariane vehicle was successfully launched on 16 December from the Kourou Space Centre in French Guiana.

The Ariane 44 L rocket placed two Eurostar satellites, Inmarsat-2 F3 and Telecom 2A, in orbit. To date, four Eurostar satellites have been launched. The next two, Inmarsat-2 F4 and Telecom 2B, are planned to be launched in the spring of 1992.

The Inmarsat-2 F3 was placed in geostationary orbit over the Pacific Ocean and began operations for the International Maritime Satellite Organization (Inmarsat) on 19 January 1992. It greatly increases the capacity for commercial mobile communications in the Pacific region including the western United States, eastern Asia, Australia, New Zealand, and most of the Pacific Ocean. Each Inmarsat-2 can carry the equivalent of up to 250 simultaneous voice circuits. The total capacity previously available in the Pacific Ocean region amounted to 50 simultaneous voice circuits. Inmarsat-2 F3 takes over the tasks of Inmarsat's previous Pacific Ocean region satellites, Intelsat MCS-D and Marisat F1, which will become spare satellites for that region.

The French government's Telecom 2A satellite will be used for telephone and television traffic in France, and between the French mainland and French overseas departments. It was placed in geostationary orbit over the equator over Africa.

ESA Hands Over Meteosat-5 to Eumetsat

Following a successful launch and subsequent thorough in-orbit checkout and testing, ESA recently handed over the Meteosat-5 satellite to the European Organisation for the Exploitation of Meteorological Satellites (Eumetsat).

ESA is undertaking the procurement, launch and operation of the Meteosat-4, -5, and -6 satellites on behalf of Eumetsat. Meteosat-4 was launched in March 1989. Meteosat-5 was launched two years later, in March 1991. Meteosat-6 is now being built and will be ready for launch towards the end of 1993.

These three satellites, developed as part of the Meteosat Operational Programme, will provide images from space for meteorological applications, until at least the end of 1993.

Formal transfer of ownership of the satellite on 14 January 1992, at ESA headquarters in Paris. Seated: J. Morgan, Director of Eumetsat (left), and J-M. Luton, Director General of ESA (right). Standing: W. Thiebaut, Legal Affairs, ESA (left), and K-E. Reuter, Head of Cabinet, ESA (right).

Meteosat-2 'Buried' After Long Life

On 2 December 1991, ESA's Operations Centre (ESOC) in Darmstadt (Germany) began re-orbiting the meteorological satellite Meteosat-2 by increasing the satellite's altitude by approximately 330 km. The satellite had been positioned in geostationary orbit, i.e. 35 800 km above the Equator, since 1989. It was finally switched off on 6 December.

The geostationary orbit is being used by an ever-increasing number of telecommunications and meteorological satellites, which means that there is a growing risk of collision between controlled and uncontrolled spacecraft. Unlike in low-Earth orbit, there is no removal mechanism such as air-drag, whereby orbits ultimately decay after a satellite has ended its useful life. Currently, the only practical solution is to move the satellite into a higher orbit where it will continue to circle the Earth without danger to other, operational spacecraft. ESA, which has adopted this approach as part of its policy on the clearing of space debris, has undertaken similar action in the past, by re-orbiting the scientific satellite Geos-2 in 1984, and the telecommunications Orbital Test Satellite (OTS) in January 1991.

Since its launch in June 1981, Meteosat-2 has taken approximately 284 000 images of the Earth. It was used as a back-up satellite since August 1988, when Meteosat-3 came into service. After more than 10 years in space, Meteosat-2 was still in good order but the hydrazine fuel supply required to control its orbit had almost been consumed.

Establishment of the European Astronauts Corps

ESA is in the process of establishing a European Astronauts Corps to support the requirements of the Columbus precursor flights and the Hermes Development Programme and its subsonic test flights.

To assist in the selection of the future astronauts, each of ESA's 13 Member States and Canada were requested to propose three to five candidates for the Corps. The Member States received approximately 6000 applications for the positions. From those applicants, the Member States proposed a total of 60 candidates to ESA.

After seven months of extensive interviews and medical and psychological tests, 25 candidates have been selected to continue in the selection process. A second round of interviews will be conducted in February. Based on the results, ESA's Director General will name the successful candidates, and first members of the Corps, by mid-March.

Three of the successful candidates will be recruited as soon as possible after the selection has been made. They will undertake a short period of basic training at the European Astronauts Centre (EAC) in Cologne, Germany. By September, two of those laboratory specialist type of candidates will be detached to NASA's Johnson Space Center in Houston where they will join an international cadre of astronauts and will be trained as mission specialists. The third candidate recruited will remain at EAC as a back-up.

Up to seven more European candidate astronauts can be selected through that 1992 selection process. Depending upon the decision made regarding the ESA programmes at the next Council Meeting at Ministerial Level, the remaining candidates can be recruited between 1992 and 1994.

IML-1 Mission Successful

The first International Microgravity Laboratory (IML-1) mission was successfully completed on 30 January, after eight days in orbit aboard the Space Shuttle Discovery (STS-42). The objective of the IML-1 mission was to investigate the complex effects of weightlessness in orbit, particularly through experiments in the areas of life sciences, materials sciences and fluid physics. More than 200 scientists from 13 countries and six international research organisations collaborated on the mission.

The IML-1 experiments were housed in Spacelab, a reusable research laboratory which is carried in the payload bay of the Space Shuttle Orbiter. Spacelab was developed by ESA and has now flown in space six times. This pressurised laboratory allows astronauts to work efficiently in a shirt-sleeve environment.

ESA also provided the IML-1 mission with two major pieces of experiment hardware:

— Biorack
A multipurpose facility designed to investigate the effects of microgravity on cells, plants, tissues and other biological samples. It contains three incubators that provide a temperature-controlled environment; a glovebox or enclosed environment which protects samples from contamination; and a cooler/freezer unit. That equipment allows crew members to grow, handle, and preserve hundreds of biological samples, often at various stages of development, for further study on Earth.

— Critical Point Facility
A temperature-controlled facility that supports the investigation of fluids at their critical point, where liquid and vapour phases coexist.

The facility's electronic system runs each experiment automatically, according to the scenario predefined by the principal investigator. Crew members maintain the facility and report on samples at their critical points. Video images and thermal data are transmitted directly to the investigators for analysis.

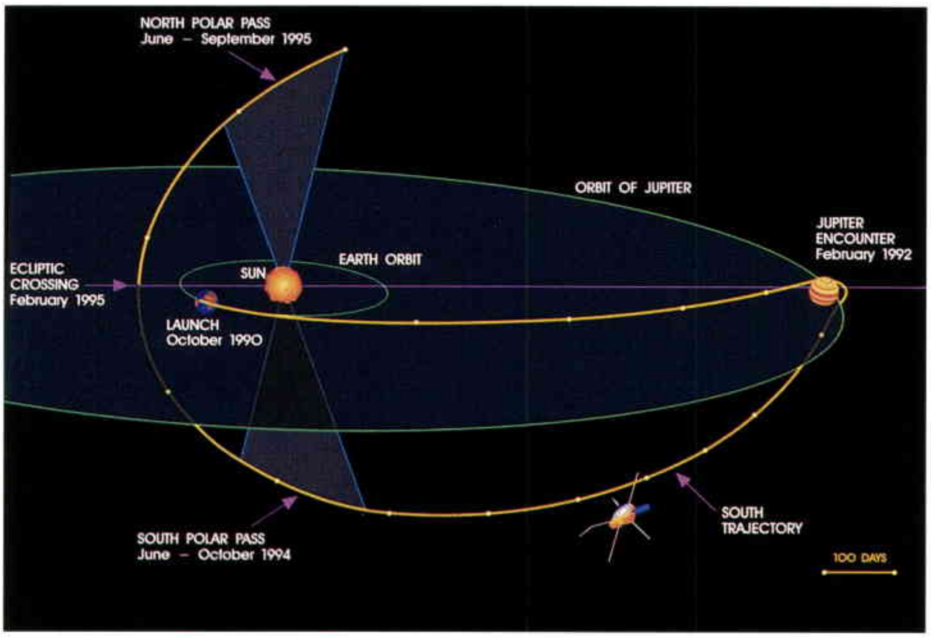
Forty-two experiments were flown aboard IML-1; 21 of them used the ESA facilities.

The ESA astronaut, Ulf Merbold, was one of two payload specialists on board. He previously flew on the first Spacelab mission (STS-9 in 1983).

The second IML flight, IML-2, is planned for the first quarter of 1994. Along with providing other experiments, ESA will re-fly the Biorack and the Critical Point Facility.

Ulysses Swings by Jupiter

The Ulysses spacecraft made its closest approach to the planet Jupiter on Saturday, 8 February, at 12:02 GMT, precisely on schedule. Gripped by Jupiter's immense gravitational field, the ESA deep space probe was deflected into its final orbit. That orbit will eventually take Ulysses over the poles of the Sun, making it the first spacecraft to do so. As Ulysses emerged from the intense radiation belts which fill the inner regions of the Jovian magnetosphere close to the planet, all systems on board the spacecraft were functioning nominally and the precision of the fly-by manoeuvre was excellent.



Ulysses's trajectory, viewed from 15° above the ecliptic plane

Starting on 31 January, the antennas of NASA's Deep Space Network provided 24-hour per day real-time coverage, and the onboard Data Storage Units were switched off. Throughout the fly-by, the one-way trip time for the radio signals carrying commands to the spacecraft or returning data to the ground was 37 minutes, a consequence of the large distance between the Earth and Ulysses (667 million km).

Almost a week before closest approach, on 2 February at 17:33 GMT, Ulysses crossed the Jovian bow shock at a distance of 113 Jupiter radii, and shortly thereafter made its entry into the magnetosphere. During the next few days, many of the scientific instruments were commanded into configurations more suited to the magnetospheric environment, with its intense magnetic fields and radiation belts. As has been the case since launch, the nine onboard experiments have provided a wealth of new information, even though in most cases they were not designed specifically to make measurements at Jupiter. Many of these results will be available in late February.

Hermes Mock-Up Undergoes Logistics Verification

A mock-up of the Hermes spaceplane was recently brought to ESA's environmental testing facilities at ESTEC to be used in a simulation of the movement and handling sequences that are foreseen when the real Hermes spaceplane undergoes full testing in the late 1990s.

During this logistics verification, the mock-up was subjected to several exercises, including handling upon its arrival and departure from ESTEC, placement in both the horizontal and vertical configurations, and transfer between the different testing facilities. The mock-up was placed in front of one of ESTEC's test facilities, the Large Space Simulator (LSS), to determine the manoeuvres that will be required to place it in the LSS during the actual Hermes testing. The LSS, which replicates the conditions of the space environment, will be used for a simulation of the heating that will occur during Hermes's orbital operations and its re-entry into Earth's atmosphere. The mock-up was also placed in another ESTEC test facility, the Large European Acoustic Facility (LEAF). The LEAF simulates the stress of the acoustic noise which occurs during the launch phase of a mission.

Hermes mock-up in ESTEC's Large European Acoustic Facility (LEAF) during fit-check and handling manoeuvres.

Telemedicine in Manned Space Missions

Crew health care is one of the main concerns in manned space missions. To improve its knowledge and experience in this field, ESA is undertaking a series of studies to investigate the benefits of using telemedicine in the prevention and diagnosis of illness in astronauts during missions as well as in their curative care. These studies are being carried out within the framework of the European Manned Space Infrastructure (EMSI) activities, under the management initiative of ESA's Long-Term Programme Office (LTPO).

Telemedicine is a way of providing medical support to people at a remote site, where physicians are not available. On Earth, it concerns mainly the medical support to isolated communities such as workers on ships and oil rigs, and at Antarctic bases. In space, it should contribute to the development of suitable health care protocols for manned missions. To date, ESA has initiated four studies in telemedicine.

Telemedicine for EMSI (TELEMSI) experiment

Two organisations that perform telemedicine, the Centre de Consultation Medical Maritime (CCMM) in Toulouse (F) and the Instituto Social de la Marina (ISM) in Madrid (E), began the first study in 1990. They responded to a total of 3323 emergency phone calls from seafarers over a two-year period. All the medical cases were collected and analysed in order to obtain statistics on pathology, distribution of traumas and illnesses, their severity and treatments, and the number of medical evacuations.

In spite of several differences between applying telemedicine to ocean and space scenarios, this study provided data that confirmed that, even with limited training and means of telecommunication, valuable remote health care can be provided to a 'remote population'. Recommendations were made concerning the improvement of operational procedures in order to develop a more efficient interface between remote crews and the 'ground-based' doctor during the telemedecine sessions.

TELEMSI confirmed the potential interest of this field of research and called for further investigation with a more space-oriented approach.

Telemedicine for ISEMSI (TELISEMSI) experiment

The TELISEMSI study was carried out in conjunction with the isolation campaign (called ISEMSI) performed at the Norwegian Underwater Technology Centre (NUTEC) in September and October 1990 (see ESA Bulletin No. 67, page 51-58). During that isolation study, a crew of six EMSInauts was isolated for 28 days in a hyperbaric chamber pressurized at approximately 1.5 bar. In the TELISEMSI study, four telemedecine consultations, in which illnesses were simulated, were performed using audio, video and data communication links. The experiment assessed the telemedicine procedures between external doctors and the crew, the training protocols for the EMSInauts acting as telemedicine assistants, and the hardware for telecommunications, diagnosis and practice.

Telemedicine at a real remote location (TELEREMSI) experiment

The TELEREMSI study started in December 1991 and was contracted to RGIT Survival Centre in Aberdeen, Scotland. Over a twelve-month period, telemedicine will be practised at a real remote site (most likely an oil rig or an Antarctic base), with communication devices and conditions that are more similar to those found in space. The goal is to collect data on how telemedicine can be used to handle real illnesses or diseases occurring at a remote site, to make diagnoses and prescribe therapy for simulated cases, and to perform periodic medical check-ups on remote crews.

Since the telemedicine protocol is still being prepared, the campaign has not yet started. Many operational 'lessons learnt' and recommendations are expected from TELEREMSI.

Telemedicine for EXEMSI (TELEXEMSI) experiment

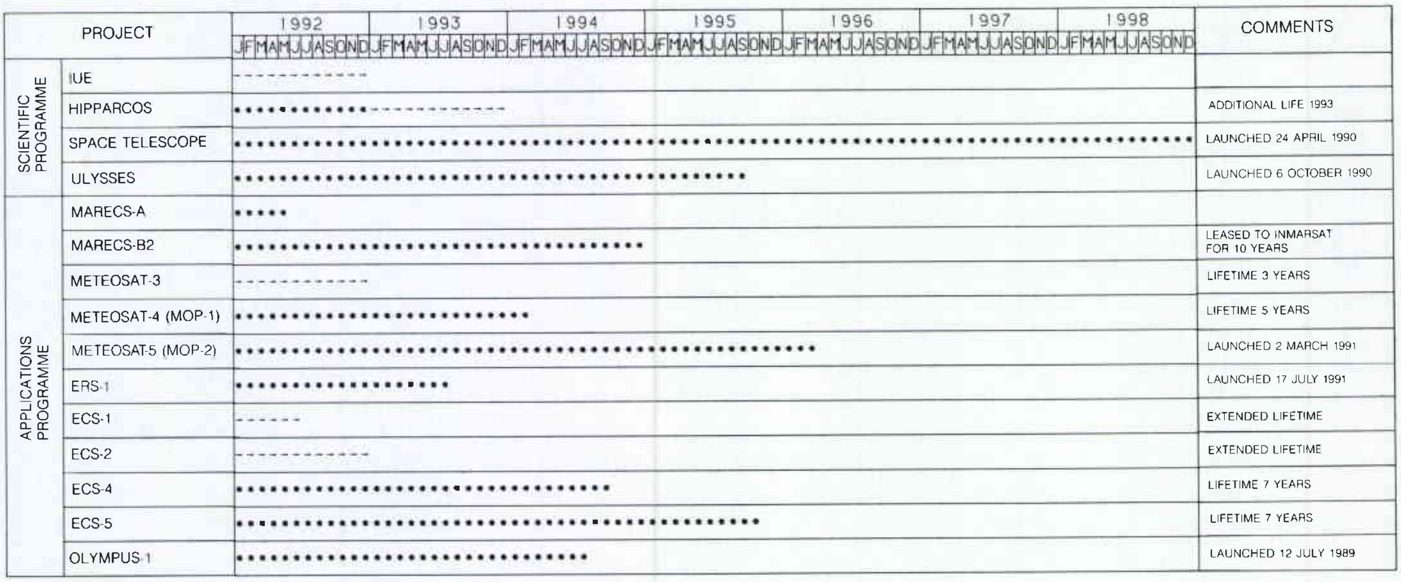
As a follow-on activity to previous simulation/isolation campaigns, ESA is planning a new experiment, called EXEMSI, for September and October 1992. This isolation campaign will take place at DLR, Cologne, with a mixed crew of four EMSInauts (three men and one woman) isolated for 60 days. The goal of TELEXEMSI is to perform a telemedicine experiment with a multimedia tool which has already worked successfully in a previous teletraining experiment (developed by Cat Benelux). The operation of the audio/video link between 'the ground' and 'on-board' via a normal phone channel will be of particular interest. User-friendly software, operated on a normal personal computer with the medical information on a laser disk, is to be used as a medical database or expert system. In addition, the doctor on the ground may use an overlay facility to draw directly on the video screen to provide the crew with useful information, for example, to demonstrate how to precisely place an electrode on the body of a sick crewmember.

These telemedicine experiments are intended to confirm the feasibility and interest of adapting many aspects of remote health care already used in the maritime environment to a space scenario. They will lead to a better definition of medical procedures, training communication needs and hardware to support the design requirements of the health care facility needed for manned space missions. These studies are still preliminary, and a lot of work remains to be done in order to determine the best location for the physician, i.e. on the ground or on board, and how to provide the best medical support to remote crews.

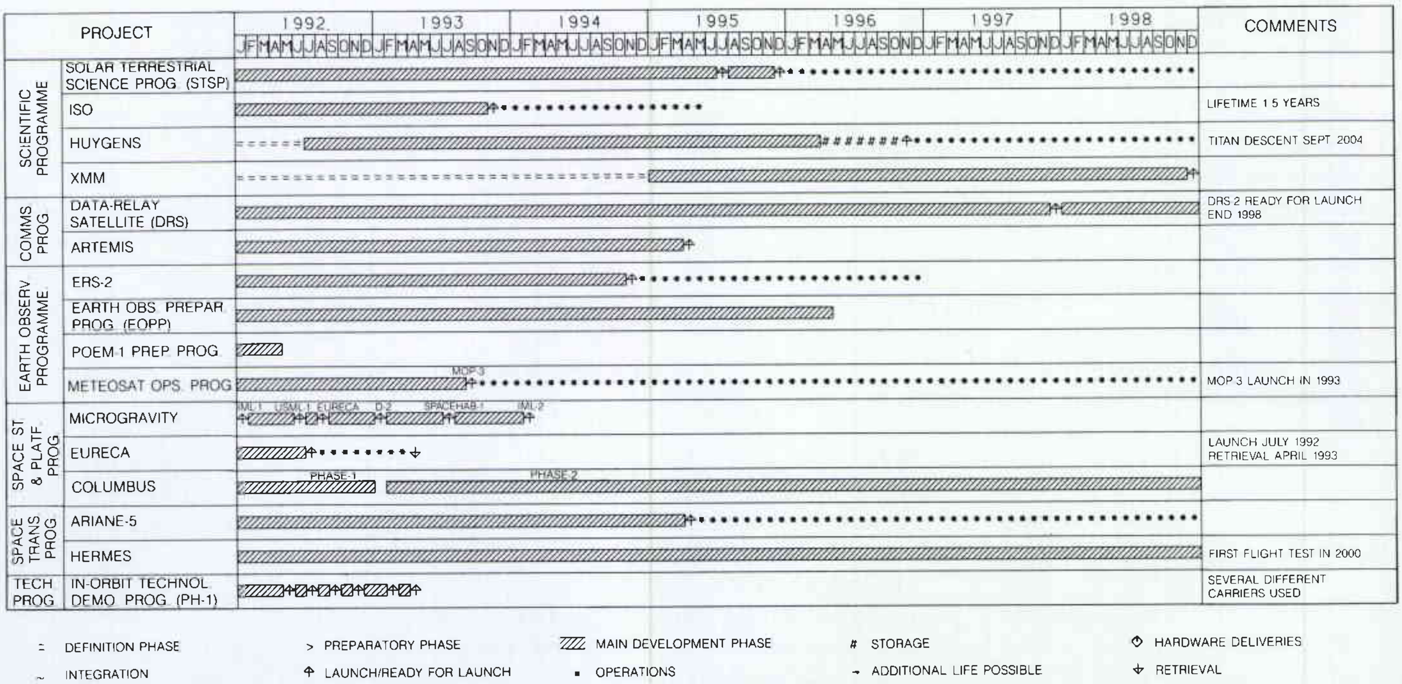
C. Soulez-Larivière, ESTEC

Programmes under Development and Operations / Programmes en cours de réalisation et d'exploitation

In Orbit / En orbite



Under Development / En cours de réalisation



Olympus

Le satellite Olympus a bien fonctionné au cours de la phase de transition qui a suivi l'opération de sauvetage spectaculaire relatée dans le Bulletin précédent. Les essais de fonctionnement des charges utiles qui ont été entrepris après le sauvetage du satellite en orbite et sa remise à poste à 19° ouest se sont achevés en septembre. Les résultats ont montré que la plupart des équipements embarqués avaient survécu aux très basses températures enregistrées au cours de la panne, et que les paramètres de fonctionnement de chacune des charges utiles étaient pratiquement inchangés par rapport à leurs valeurs avant l'anomalie.

Les charges utiles ont fonctionné en continu pendant la phase de transition et ont été beaucoup utilisées par les expérimentateurs. Dans la pratique, les inconvénients subis par les utilisateurs du fait de l'absence d'alimentation électrique et du manque de précision de pointage pendant l'utilisation, de nuit, du mode de référence gyro pour le contrôle du satellite, sont restés minimes.

Un vaste programme d'utilisation des quatre charges utiles Olympus en 1992 devrait commencer à la fin de la phase de transition. Des expériences très diverses sont prévues, notamment la démonstration du système de télévision haute définition (TVHD) pendant les Jeux Olympiques d'hiver et d'été.

Les travaux techniques se sont poursuivis en ce qui concerne les activités de la phase de transition. Le nouveau mode de contrôle par gyro et roues à réaction a été intégralement mis au point et expérimenté au sol avant d'être utilisé à bord du satellite. Les activités de revue et d'essai de toutes les nouvelles procédures opératoires sont en voie d'achèvement. La commission d'enquête procèdera à une revue officielle d'aptitude à l'exploitation au début de 1992, avant la fin de la phase de transition.

Soho

La principale phase de développement du satellite (phase C/D), mise en route en mai 1991 sous la conduite de Matra, progresse rapidement. Le problème majeur, qui n'a pas encore été résolu, est de maintenir l'intégrité technique et scientifique de la mission malgré un certain nombre de difficultés techniques et industrielles, tout en respectant les contraintes de coût et de calendrier du projet. Ces difficultés tiennent d'une part au degré de technicité élevé de Soho, et d'autre part à la complexité des interfaces requises par la structure industrielle et la réalisation de ce programme en coopération.

Les activités de modélisation mathématique du système (principalement pour les aspects mécaniques et thermiques) ont souffert du retard enregistré dans la réalisation de certains modèles d'expériences, mais les étapes clés ont été maintenues. Les principaux bilans du système ont été soigneusement étudiés et des marges suffisantes ont été prévues selon les besoins.

Certains problèmes ayant trait aux interfaces, en particulier les interfaces mécaniques avec le lanceur, doivent encore être examinés.

Coopération entre l'ESA et la NASA

La coopération entre l'ESA et la NASA se déroule sans problème particulier. Bien que les paramètres d'interfaces aient, pour la plupart, fait l'objet d'un accord avec les responsables du lanceur, il reste quelques problèmes à résoudre.

Les spécifications de l'enregistreur sur bande (Odetics, USA), de l'amplificateur haute puissance (Cubic, USA) et du suiveur solaire de pointage fin (Adcole, USA) ont été passées en revue et les documents correspondants permettant d'officialiser les accords ont été définitivement arrêtés. La NASA procèdera aux premières livraisons en janvier 1992.

Les travaux relatifs aux opérations en vol et à la mise en oeuvre du secteur sol se poursuivent normalement.

Charge utile

Les travaux de développement de la charge utile de Soho ont bien avancé. Les études techniques ont beaucoup progressé pour l'ensemble des expériences, et des essais de vibration des modèles structurels ont déjà été réalisés pour un grand nombre d'entre elles. La livraison des modèles structurels devrait avoir lieu, conformément aux prévisions, entre février et juin 1992.

L'ESA et la NASA ont examiné en commun l'état d'avancement de la charge utile pour mettre en évidence tout risque technique qui pourrait retarder sa livraison à l'ESA. Les onze instruments ont tous été passés en revue (à l'exception de celui qui est fourni par la NASA). Un bilan des résultats de ces revues sera remis au directeur du programme scientifique de l'ESA.

La septième réunion du groupe de travail scientifique s'est tenue en novembre à l'ESTEC (Noordwijk, Pays-Bas).

Cluster

L'industrie a pratiquement terminé la conception détaillée des différents sous-systèmes; ces différentes activités se termineront par les revues de conception des sous-systèmes prévues pour le premier trimestre 1992.

Le modèle mécanique du véhicule spatial est en voie d'achèvement et la date prévue pour le début du programme d'essais est maintenue à début mars 1992. Ce programme visera un double objectif: confirmer la conception mécanique du véhicule spatial et démontrer qu'il peut résister aux charges de qualification d'Ariane-5.

L'intégration du modèle d'identification est prévue pour la mi-1992; elle devrait être suivie par un programme détaillé d'essais électriques qui doit s'achever fin 1992.

Le programme de développement de la charge utile scientifique de Cluster se poursuit de manière satisfaisante, les unités du modèle d'identification devant être livrées à la mi-1992 pour répondre aux impératifs du programme au niveau système.

L'état d'avancement des travaux sur le système de données scientifiques de Cluster est prometteur en ce sens que tous les participants se sont récemment mis d'accord sur les normes et les outils logiciels à utiliser pour la phase de mise en oeuvre du système qui doit commencer à la mi-1992.

Olympus

The satellite has been operating well in a transitional phase following the spectacular recovery operation reported in the last issue of the Bulletin. Payload testing after the satellite's recovery in-orbit and relocation to its correct orbital position of 19°W, was completed during September. The results indicated that most of the on-board equipment had survived the very low temperatures experienced during the anomaly, and that the performance characteristics of each of the payloads were little different from their pre-anomaly values.

The payloads have been operating continuously during the transitional phase and have been used extensively by the Experimenters. In practice, inconvenience to the users due to lack of power or lack of pointing accuracy when the gyro reference mode has been used during the night for control purposes has been minimal.

An extensive utilisation programme for Olympus' four payloads in 1992 is expected to start at the end of the transitional phase. The wide range of experiments planned include demonstrations of HDTV during the Winter and Summer Olympic Games.

Technical work has continued on the transitional-phase tasks. The new gyro and reaction-wheel control mode was fully developed and tested on the ground before being used on the satellite. Review and testing of all of the new operating procedures is nearing completion. A formal 'operational readiness' review will be held by the Enquiry Board before the transitional phase is completed early in 1992.

Soho

The satellite's main development phase (Phase-C/D), which began in May 1991, with Matra as the Prime Conractor, is advancing rapidly. The main problem has been and continues to be one of maintaining the mission's technical/scientific integrity despite several technical and industrial problems, whilst still respecting project cost and schedule constraints. These problems are due partly to the sophistication of the Soho technical requirements, and partly to the complex interfaces necessary to comply with the industrial structure and the cooperative nature of the Programme.

The system mathematical modelling activities (mainly thermal and mechanical) have been adversely affected by the late availability of some experiment models, but the key milestones have nevertheless been maintained. The major system budgets have been carefully scrutinised and sufficient margins have been created where necessary.

Some interface problems, particularly those related to the mechanical interfaces with the launcher, still require attention.

ESA/NASA cooperation
Cooperation between ESA and NASA is proceeding without major problem. Although most interface parameters have been agreed with the launcher authorities, some problems still remain.

The specifications for the tape recorder (Odetics, USA), the high-power amplifier (Cubic, USA) and the fine-pointing Sun sensor (Adcole, USA) have been reviewed and the relevant documents for the formalisation of the agreements have been finalised. The first set of deliveries by NASA will take place in January 1992.

Work on the flight operations and the implementation of the ground segment continues to progress satisfactorily.

Payload
The Soho payload is well ahead in its planned development. All experiments are in an advanced stage of engineering and many experiments have already undergone structural-model vibration testing. Delivery of the structural models is expected to take place on schedule, in the February – June 1992 time frame.

The status of the payload has been reviewed jointly by ESA and NASA to establish fully any associated development risks that could jeopardise its timely delivery to ESA. All eleven instruments were reviewed (with the exception of one provided by NASA). A report summarising the outcome of the reviews will be presented to ESA's Director of Scientific Programmes.

The Seventh Science Working Group Meeting took place at ESTEC in Noordwijk (NL) in November.

Cluster

Detailed design of the individual subsystems is nearing completion in industry, and these activities will culminate in subsystem design revues scheduled for the first quarter of 1992.

The structural-model spacecraft is nearing completion and the planned start of the test programme in early March 1992 is being maintained.
The test programme will serve a dual purpose, both confirming the structural design of the spacecraft and demonstrating that it can withstand the Ariane-5 qualification loads.

The engineering model is due for integration in mid-1992, followed by a detailed electrical test programme scheduled for completion by the end of 1992.

The development programme for Cluster's scientific payload is proceeding satisfactorily, with engineering-model units scheduled for delivery in mid-1992, to meet the requirements of the system-level programme.

Progress on the Cluster Science Data System has been promising in that all participants have recently agreed on the software standards and tools to be used for the system's implementation phase, which is due to commence in mid-1992.

ISO

Scientific instruments
The flight models of the four scientific instruments are undergoing final testing and calibration and are expected to be delivered by March. The flight-spare models for three scientific instruments are being assembled, and ISOCAM is investigating the possibility of modifying its qualification-model focal-plane unit to serve as a flight spare.

Satellite development model
This model has been mechanically tested to qualification levels at the Prime

ISO

Instruments scientifiques
Les modèles de vol des quatre instruments scientifiques en sont à l'essai final et à l'étalonnage et devraient être livrés d'ici mars. Les modèles de vol de rechange sont en cours d'assemblage pour trois instruments scientifiques tandis que l'équipe ISOCAM étudie la possibilité de modifier le plan focal du modèle de qualification comme rechange de vol.

Modèle de développement du satellite
Ce modèle a subi des essais de qualification mécaniques chez le contractant principal. Ces essais acoustiques et en vibration ont montré que le modèle de vol ne nécessitait que quelques modifications de conception locales.

Modèle de vol du module de charge utile
La plupart des composants du module de charge utile ont été fabriqués et sont en cours d'assemblage. La conception des vannes d'hélium liquide du modèle de vol a été modifiée en raison de leurs anomalies de fonctionnement, et les deux premières vannes de fabrication nouvelle ont donné des résultats prometteurs. Deux équipes se relaieront pour accélérer les essais de qualification.

Il est apparu que la lumière diffuse provenant de parties relativement chaudes du module de charge utile pouvait pénétrer en trop grande quantité dans les instruments scientifiques. Des études sont en cours pour déterminer les modifications de conception et les méthodes de vérification qu'il faudra mettre en oeuvre.

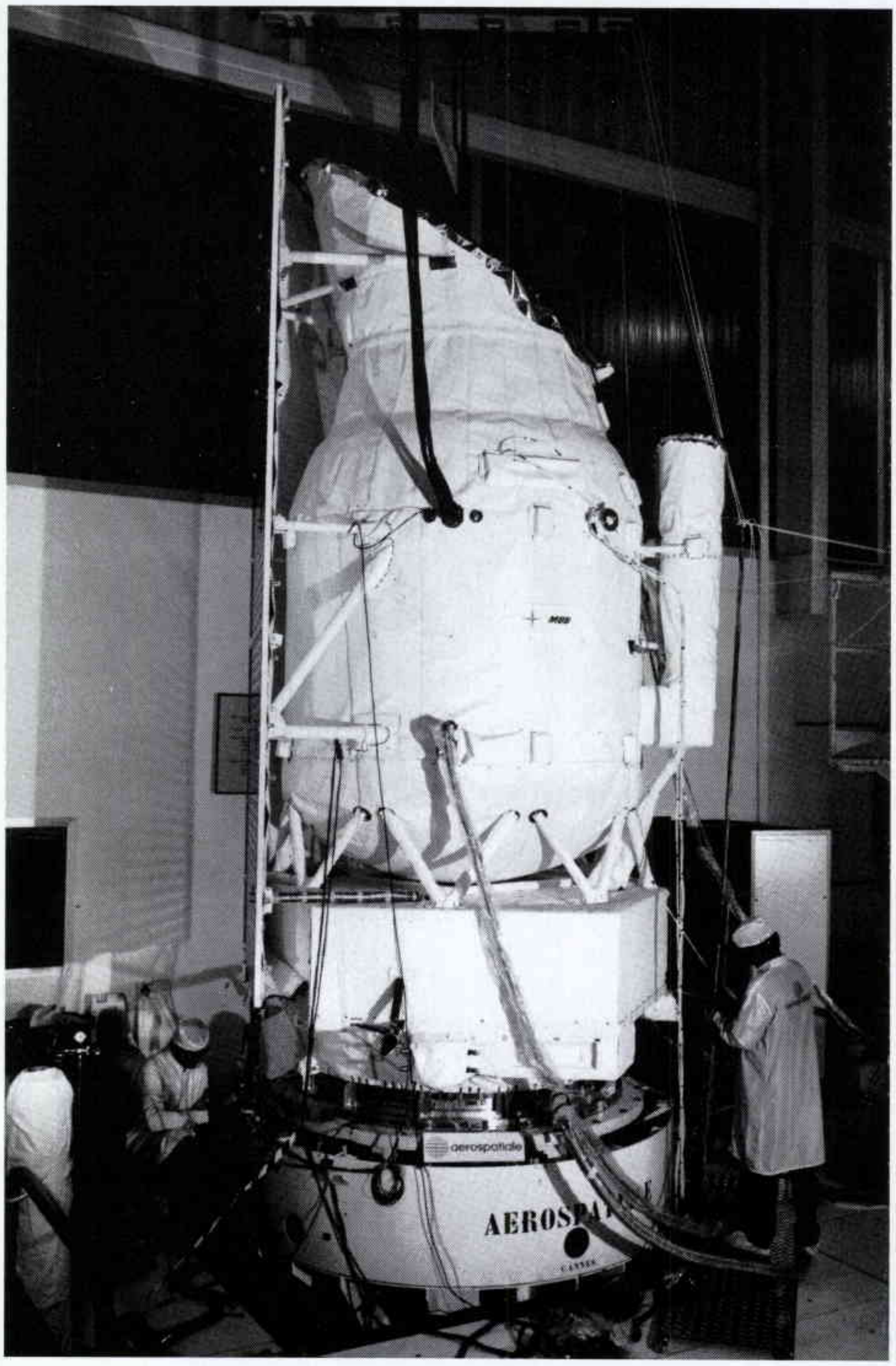
L'assemblage du télescope du modèle de vol commencera en janvier, la livraison de l'instrument étant prévue en mai.

Modèle de vol du module de servitude
En novembre, le contractant principal a pris livraison de la structure du module de servitude, avec le câblage électrique, le sous-système d'alimentation électrique et le répéteur RF. L'intégration de ce module a été mise en route.

L'essai du sous-système de commande d'orientation se déroule de manière satisfaisante. Les modifications nécessaires ont été apportées à la conception de l'unité de commande de l'électronique gyro, et l'on remédie actuellement à l'excès de sensibilité thermique qui affectait le support de l'optique du suiveur stellaire.

Secteur sol
L'ESOC prépare actuellement l'intégration et les essais finaux de l'ensemble du secteur sol. La constitution de l'équipe opérationnelle scientifique a considérablement avancé.

Calendrier du projet
Un retard de plusieurs mois a été enregistré à la suite de certains problèmes techniques liés, en particulier, aux vannes d'hélium liquide. Selon l'information communiquée au Comité du programme scientifique (SPC) de l'Agence, les travaux se déroulent dans la perspective d'un lancement en novembre 1993.



Modèle de développement d'ISO aux essais en vibration à l'Aerospatiale à Cannes (F)

ISO development model at Aerospatiale, Cannes (F), during vibration testing

Contractor's facilities. Those acoustic and vibration tests have revealed the need for just a few local design changes to the flight model.

Payload-module flight model
Most payload-module components have been manufactured and are being assembled. The design of the malfunctioning flight-model liquid-helium valves has been modified and the first two new valves have shown promising results. Two teams working in double shift will be used to accelerate qualification testing.

It has been found that excessive stray light from relatively warm parts of the payload module could enter the scientific instruments. Investigations are under way to identify the necessary design changes and verification methods.

Assembly of the flight-model telescope will start in January and it is expected to be delivered in May.

Service-module flight model
The Prime Contractor took delivery of the service-module structure, with the electrical harness, power subsystem, and radio-frequency transponder, in November. Integration of the service module has now started.

The testing of the attitude-control subsystem is progressing satisfactorily. All design corrections to the gyro electronics drive unit have been implemented. The excessive temperature sensitivity of the star-tracker optics mounting is being corrected.

Ground segment
ESOC is preparing for final integration and testing of the overall ground segment. The build-up of the science operations team has progressed considerably.

Project schedule
A number of technical problems, particularly with the liquid-helium valves, have caused several months' delay. The Agency's Science Programme Committee (SPC) has been informed that the project is now working towards a launch date of November 1993.

Huygens

The cuts in NASA's budgets for 1992 have directly affected the Cassini/Huygens mission, as had been feared. Realignments of schedules within NASA and JPL have resulted in a scenario that now provides for a launch of the Cassini Saturn Orbiter and Huygens Titan Probe no earlier than November 1996. ESA has now introduced this launch date into its baseline plans for Huygens.

A Preliminary Design Review (PDR) was held during October to establish both the the Probe's design status and readiness to proceed with preparations for its development and manufacture. During the Review, the revised launch date was introduced and a new overall schedule developed in broad terms. Phase-B2 of the project was extended and Phase-C/D slowed down. This revised plan permits certain design aspects to be reworked, particularly those impacted by yet another change in baseline mission, as well as aligning the Probe's development to the schedule for the JPL Orbiter and NASA-funded experiments, with which there are numerous interfaces and, of course, hardware deliveries. The schedules are being reworked in detail and the technical issues are being rigorously examined in preparation for PDR closure at a meeting scheduled for mid-February 1992.

XMM

Negotiations have been held with Industry on the programme of work leading to the production of the mirror development model, which will validate the very demanding X-ray imaging optics of the high-throughput X-ray mission (XMM). A milestone has been achieved in that the aluminium blank to be used to manufacture the mandrel, on which the largest mirror shell will be replicated, has been delivered to Zeiss. The largest mirror shell will have a diameter of 700 mm, a length of 600 mm, and a focal length of 7.5 m.

Instrument development continues as planned, with optical breadboard units due to be delivered in early 1993 for X-ray testing with the mirror development model.

ERS

ERS-1

ERS-1, launched on 17 July 1991, is nearing completion of its in-orbit commissioning phase. Its performance has proved to be excellent, meeting or exceeds specification in nearly all respects. The associated ground-control and data-processing and dissemination system has reached a high degree of operability.

The technical performance of the satellite is excellent, with the platform performance well within specification, and with all core payload elements in optimal health. Availability of the instruments (AMI, RA, ATSR-M) and the Instrument Data-Handling and Transmission (IDHT) system has proved to be virtually 100%.

The commissioning phase has permitted fine tuning of the instruments and corresponding full/partial release of data to users. SAR image fast-delivery products have been routinely available since October 1991, following calibration using the dedicated SAR ground transponders. Some problems with the calibration of the Scatterometer ground transponders meant that tuning for the wind products was somewhat delayed. However, the extensive ground-truth exercise in the North Sea (the Haltenbanken Campaign) has clearly demonstrated the accuracy of these products, which will be available shortly in fully verified form.

The Wave products are now well-characterised and are being released to users. The Radar Altimeter fast-delivery product-processing algorithm has been going through several tuning iterations and full product release is expected shortly.

The mission planning and control system has now been run up to full operational status, with the PEPs (Preferred Exploitation Plans) being routinely generated by the CUS (Central User Service) at ESRIN (I) as inputs to the MPS (Mission Planning System) at ESOC (D).

Given the excellent performance of the satellite, the mission operations being performed currently provide:

- global ATSR, RA and AMI Wind/Wave data

Huygens

La réduction des crédits attribués à la NASA pour 1992 a, comme on le craignait, directement affecté la mission Huygens/Cassini. Selon le nouveau scénario qui a été établi à l'issue de la révision des calendriers de la NASA et du JPL, le lancement de la plate-forme Cassini, qui gravitera autour de Saturne, et de Huygens, la sonde de Titan, n'aura pas lieu avant novembre 1996. L'ESA a maintenant inscrit cette nouvelle date de lancement dans ses plans de référence pour ce qui concerne Huygens.

Une revue de conception préliminaire (PDR) s'est tenue en octobre afin de faire le point sur la conception de la sonde et de déterminer si la situation permettait d'entreprendre les travaux préparatoires en vue de son développement et de sa fabrication. La nouvelle date de lancement a été adoptée à cette occasion et le calendrier d'ensemble a été révisé dans ses grandes lignes. La phase B2 du projet a été prolongée et la phase C/D ralentie. Ce remaniement permet de réexaminer certains aspects de la conception, en particulier ceux qui sont affectés par une autre modification de la mission de référence, et d'harmoniser le calendrier de réalisation de la sonde avec celui de la plate-forme du JPL et des expériences financées par la NASA, avec lesquelles il existe de nombreuses interfaces. Les calendriers font actuellement l'objet d'une révision minutieuse et les problèmes techniques sont étudiés avec soin en vue de l'achèvement de la PDR lors d'une réunion prévue à la mi-février 1992.

XMM

Des négociations ont eu lieu avec l'industrie au sujet du programme de travaux à mettre en oeuvre pour produire un modèle de développement de miroir destiné à valider l'optique rayons-X très ambitieuse de la mission XMM. Une étape a été franchie avec la fourniture, à Zeiss, de l'ébauche cylindrique en aluminium qui doit servir à fabriquer le mandrin sur lequel le miroir le plus grand doit être reproduit. Ce miroir aura un diamètre de 700 mm, une longueur de 600 mm et une distance focale de 7,5 m.

Les travaux de développement de l'instrument se poursuivent conformément aux prévisions, les montages table optiques devant être livrés au début de 1993 pour réaliser des essais aux rayons-X avec le modèle de développement du miroir.

ERS

ERS-1

ERS-1, qui a été lancé le 17 juillet 1991, est sur le point d'achever sa phase de recette en orbite. Ses caractéristiques de fonctionnement se sont avérées excellentes puisque les spécifications ont été atteintes, voire dépassées dans pratiquement tous les domaines. Le système de contrôle au sol et de traitement et de diffusion des données qui lui est associé a atteint un haut niveau de capacité opérationnelle.

Le fonctionnement du satellite sur le plan technique est excellent, les caractéristiques de la plate-forme étant tout à fait conformes aux spécifications et tous les éléments de la charge utile principale étant en parfait état. Il a été établi que la disponibilité des instruments (AMI, RA, ATSR-M) et du système de gestion et de transmission des données d'instruments (IDHT) était pratiquement de 100 %.

La phase de recette a permis de régler avec précision les instruments et de diffuser en totalité ou en partie les données correspondantes aux utilisateurs. Les produits d'images à livraison rapide du SAR sont disponibles de manière régulière depuis octobre 1991 après l'étalonnage qui a été réalisé à l'aide des répéteurs au sol spécifiques du SAR. En raison de certaines difficultés liées à l'étalonnage des répéteurs au sol du diffusiomètre, le réglage nécessaire à l'élaboration des produits en mode vent a été quelque peu retardé. Toutefois, l'importante série de mesures de vérité terrain conduite en mer du Nord (campagne Haltenbanken) a démontré de façon indiscutable la précision de ces produits, qui seront bientôt disponibles sous une forme totalement validée.

Les produits en mode vagues sont maintenant correctement caractérisés et sont diffusés auprès des utilisateurs. L'algorithme de traitement des produits à livraison rapide de l'altimètre radar a subi plusieurs itérations pour parfaire son ajustement et ces produits devraient bientôt pouvoir être diffusés intégralement.

Le système de planification et de contrôle des missions est maintenant totalement opérationnel, les plans d'exploitation préférentiels (PEP) étant élaborés régulièrement par le Service central des utilisateurs (CUS) à l'ESRIN (I) pour être intégrés au système de planification des missions (MPS) à l'ESOC (D).

Grâce aux excellentes caractéristiques de fonctionnement du satellite, les opérations en cours d'exécution dans le cadre de la mission fournissent actuellement:
- *des données ATSR, RA et AMI en modes vent/vagues à léchelle du globe*
- *des données SAR à l'échelle régionale sur une durée maximale de 12 mn par orbite.*

Les activités préparatoires se sont poursuivies sur les installations nationales de traitement et d'archivage (PAF), qui sont sur le point d'être totalement opérationnelles.

Les instruments ATSR-IR et ATSR-M fonctionnent normalement, les expérimentateurs faisant état d'importants progrès dans la vérification et l'étalonnage des données.

L'expérience PRARE a malheureusement souffert d'une défaillance au début de son fonctionnement en orbite. Une Commission de revue des défaillances a estimé qu'une remise en état était impossible dans le cadre de la mission ERS-1, mais les causes du problème ont été identifiées et des mesures correctives ont été prises pour ERS-2.

La prochaine phase d'exploitation en orbite d'ERS-1 est la phase d'étude des glaces, qui doit durer 3 mois. A l'issue de celle-ci, l'orbite du satellite sera modifiée pour que la récurrence du cycle passe de 3 à 35 jours.

ERS-2

Le projet ERS-2 a continué de progresser comme prévu, l'état d'avancement de la plupart des éléments étant conforme au calendrier. Bien que l'on rencontre toujours certains problèmes avec les composants à haute fiabilité, le calendrier d'ensemble du programme a été maintenu.

- regional SAR data, extending to 12 min maximum per orbit.

Preparation of the national Processing and Archiving Facilities (PAFs) has continued and is approaching full operational readiness.

The ATSR-IR and ATSR-M instruments are functioning nominally, with the experimenters reporting major progress in data verification/calibration.

The PRARE experiment has unfortunately suffered an early in-orbit failure. A Failure Review Board has concluded that its recovery for the ERS-1 mission is not possible, but the causes of problem have been identified and corrective actions instituted for ERS-2.

The next phase in ERS-1's in-orbit operation is the 'ice-phase', which is planned to last for three months. Thereafter, the spacecraft's orbit will be changed from a 3-day to a 35-day repeat cycle.

ERS-2

The ERS-2 project has continued to progress as planned with most elements on schedule. Despite the continuing occurrence of hi-rel parts problems, the overall programme schedule has been maintained.

Industrial contract negotiations have been concluded and preliminary agreement has been reached with Arianespace for the provision of launch services.

EOPP

Aristoteles

The Aristoteles system study, led by Alenia Spazio (I), is progressing according to schedule. The System Requirements Review will take place in January/February 1992. Pre-development of the Gradio accelerometer at ONERA and of the calibration mechanism at TNO/TPD has also progressed. Differential accelerometer tests at ONERA have demonstrated sub-nano-g performance, even under laboratory conditions (i.e. in the presence of gravity).

An ESA/NASA Aristoteles Workshop in Capri (I) in September was attended by more than 150 participants, including Chinese delegates. Strong support for the proposed mission is reflected in the Workshop's Final Resolution. The final decision on undertaking the Aristoteles mission will be taken at the next ESA Council Meeting at Ministerial Level, in late 1992, and the necessary preparatory steps are now under way.

Meteosat Second Generation

The Phase-A study of the enhanced imager has proceeded satisfactorily under an industrial team led by Matra (F). Proposals for the space-segment Phase-A study have been received and are being evaluated, as are the proposals for a scientific package in response to the Call for Ideas.

Eumetsat's Council has asked ESA to develop the Meteosat Second Generation prototype within an Agency programme.

POEM

With POEM-1 Preparatory Programme activities in process, EOPP activities have started to focus on possible instruments and missions to follow POEM-1.

Campaigns

Work has continued on the analysis of campaigns conducted in the previous two years, e.g. MAESTRO 1989, ELAC 1990, and MAC Europe 1991. Meanwhile, preparations for the SAREX 1992 campaign have progressed satisfactorily and, in parallel, a draft plan of activities for the next five years is in preparation.

POEM-1 Preparatory Programme

After a series of negotiations with the Prime Contractor (Dornier) and its subcontractors, the Phase-B contract was kicked-off on 2 August. Dornier has begun preparing detailed instrument support specifications and gathering the inputs from instrument subcontractors necessary to generate the corresponding interface control documents (ICDS). Interface meetings for the Eumetsat Operational Package have taken place, with NASA and NOAA participation. Regular ESA/Eumetsat meetings have been organised to ensure efficient coordination.

Overall technical budgets have been reviewed and updated in close cooperation with the Polar Platform project. The payload-accommodation options are under study.

The enabling resolution for the POEM-1 Programme (Phases-C/D/E) was adopted at the ESA Council Meeting at Ministerial Level in Munich in November.

Meteosat

Meteosat-2 was removed from geostationary orbit on 2 December 1991. Launched in June 1981, it served as the operational spacecraft until replaced by Meteosat-3 in 1988, at which time the on-board fuel had been nearly depleted, leaving only enough to lift the spacecraft into an approximately 330 km higher orbit. This manoeuvre has both liberated a 'slot' on the geostationary arc for another spacecraft and eliminated any risk of collision with other spacecraft.

The third flight unit of the Meteosat Operational Programme, MOP-2, was officially commissioned in October and the Board found the spacecraft ready for operation and for ownership to be transferred to Eumetsat, which funds the Operational Programme. At present, this spacecraft, now officially designated Meteosat-5, is serving as the in-orbit standby for Meteosat-4, while Meteosat-3, stationed at 50°W, is providing the Atlantic data coverage.

The small image instability noted on MOP-2 has been identified as most likely originating in the cold part of the radiometer optics. Corrective action to prevent such an instability on MOP-3 is being implemented.

The ESA Council has agreed to a request from Eumetsat for one more spacecraft of the Meteosat type, and the requisite negotiations with industry are in progress.

Eureca

Having assured itself that the Eureca flight unit is in good condition, the ESA Flight-Unit Acceptance Board agreed to its shipment to the launch site at Kennedy Space Center (KSC).

Les négociations contractuelles avec les industriels ont été menées à bien et un accord préliminaire a été conclu avec Arianespace pour la fourniture de services de lancement.

EOPP

Aristoteles

L'étude système du satellite Aristoteles, conduite par Alenia Spazio (I), se déroule conformément au calendrier. La revue des impératifs système aura lieu en janvier/février 1992. Les travaux de prédéveloppement de l'accéléromètre Gradio à l'ONERA et du mécanisme d'étalonnage chez TNO/TPD ont également avancé. Les essais d'accéléromètres différentiels menés par l'ONERA ont fait apparaître un fonctionnement 'sub-nano-g', même en conditions de laboratoire (c'est-à-dire en pesanteur).

L'atelier ESA/NASA sur Aristoteles organisé à Capri (I) en septembre 1991 a réuni plus de 150 participants, dont un certain nombre de délégués chinois. Comme en témoigne la résolution finale adoptée à cette occasion, la proposition de mission Aristoteles reçoit un accueil très favorable. La décision finale d'entreprendre cette mission sera prise lors de la prochaine session du Conseil au niveau ministériel, fin 1992, et les travaux préparatoires dictés par cette échéance ont déjà été lancés.

Météosat deuxième génération

L'étude de phase-A de l'imageur de pointe s'est déroulée sans problèmes sous la conduite d'une équipe industrielle menée par Matra (F). Les propositions portant sur l'étude de phase A du secteur spatial sont maintenant en cours d'évaluation, de même que les propositions relatives à un lot de travaux scientifiques qui ont été envoyées en réponse à l'appel aux idées.

Le Conseil d'Eumetsat a demandé à l'Agence de mettre au point le prototype du satellite Météosat deuxième génération dans le cadre d'un programme de l'Agence.

POEM

Parallèlement aux activités du programme préparatoire de POEM-1, des études ont été lancées par EOPP sur les instruments et des missions qui pourraient succéder à POEM-1.

Campagnes

Les travaux se poursuivent en ce qui concerne l'analyse des campagnes menées ces deux dernières années, à savoir MAESTRO 1989, ELAC 1990, et MAC Europe 1991. Entre temps, les préparatifs de la campagne SAREX 1992 ont suivi leur cours; parallèlement, un projet de plan d' activités est en voie d'élaboration pour les cinq années à venir.

Programme préparatoire de POEM-1

A l'issue des négociations menées avec le contractant principal (Dornier) et ses sous-traitants, le contrat de phase B a été mis en route le 2 août. Dornier a commencé à préparer les spécifications détaillées de soutien des instruments et à recueillir, auprès de ses sous-traitants chargés des instruments, les informations nécessaires pour établir les documents de contrôle d'interface (ICD) correspondants. Les réunions d'interface relatives au lot opérationnel d'Eumetsat ont eu lieu avec la participation de la NASA et de la NOAA. Des réunions ESA/Eumetsat ont eu lieu à intervalles réguliers pour assurer une coordination efficace.

Les bilans techniques d'ensemble ont été réexaminés et actualisés en collaboration étroite avec le projet de plate-forme polaire. Les scénarios sont à l'étude en ce qui concerne l'aménagement des charges utiles.

La Résolution habilitante relative au programme POEM-1 (phases C/D/E) a été adoptée à la session du Conseil au niveau ministériel qui s'est tenue en novembre à Munich.

Météosat

Météosat-2 a quitté l'orbite géostationnaire le 2 décembre 1991. Lancé en juin 1981, il a joué son rôle de satellite opérationnel jusqu' à son remplacement par Météosat-3 en 1988. Il restait tout juste assez d'ergols pour déplacer le véhicule de 330 km sur une orbite plus élevée. Cette manoeuvre a eu pour effet de libérer un 'créneau' pour un autre véhicule sur la trajectoire géostationnaire, et d'éliminer tout risque de collision avec un autre engin.

La troisième unité de vol du programme Météosat opérationnel, MOP-2, a été officiellement mise en service en octobre. Le Conseil directeur a jugé qu'elle était prête pour un service opérationnel et pour un transfert de propriété à Eumetsat, qui finance le programme opérationnel. A l'heure actuelle, ce satellite, désormais dénommé Météosat-5, sert d'unité de réserve en orbite pour Météosat-4, tandis que Météosat-3, posté à 50° ouest, assure la couverture des données de l'Atlantique.

Il est fort probable que la légère instabilité d'image de MOP-2 provient de la partie froide de l'optique du radiomètre. Des mesures correctives sont en cours de mise en oeuvre pour éviter ce phénomène sur MOP-3.

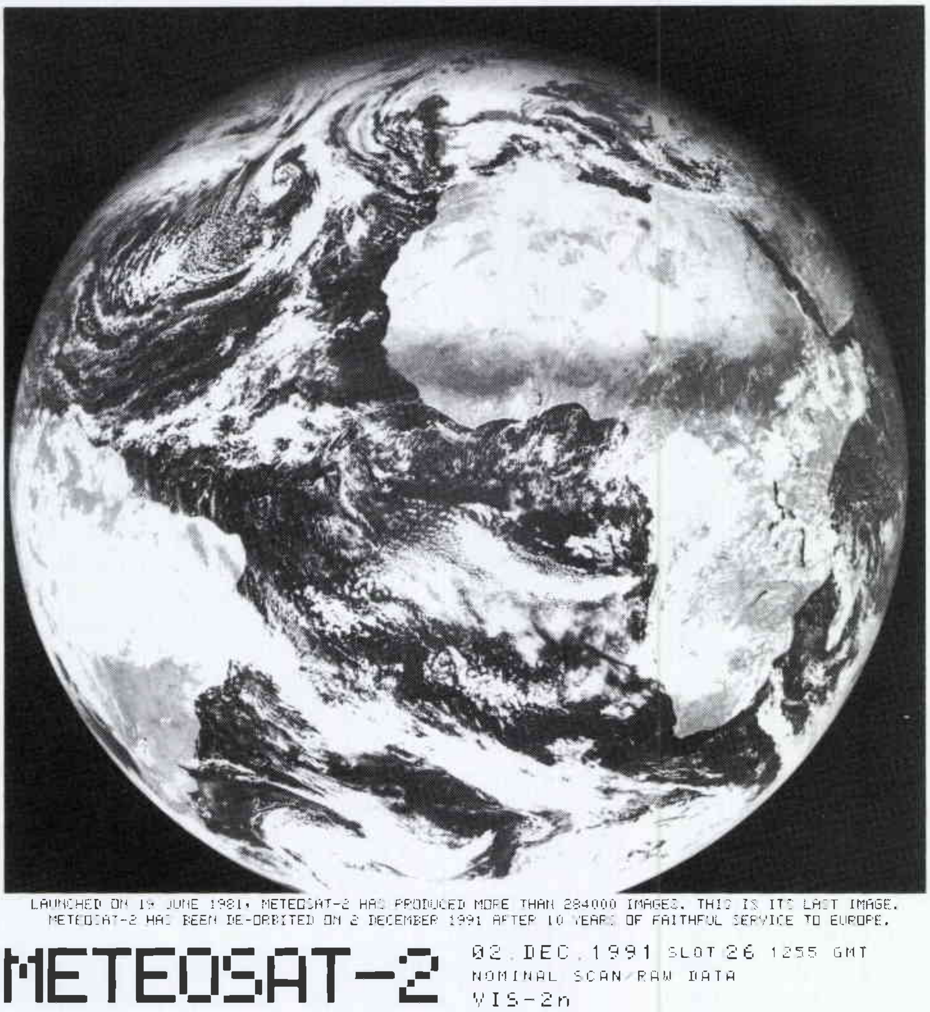
Le Conseil de l'Agence a répondu favorablement à une demande d'Eumetsat portant sur la réalisation d'un satellite supplémentaire de type Météosat. Des négociations sont en cours à ce sujet avec l'industrie.

Eureca

Après s'être assurée que l'unité de vol d'Eureca était en bon état de fonctionnement, la Commission de recette des unités de vol de l'ESA a donné son feu vert à l'expédition d'Eureca sur son site de lancement au Centre spatial Kennedy (KSC).

A son arrivée au KSC le 4 novembre, Eureca a été transporté vers les installations d'Astrotech pour les derniers préparatifs au lancement. Eureca doit être lancé par la Navette spatiale 'Atlantis' (vol STS-46) le 2 juillet 1992 et récupéré par la même Navette (vol STS-57) en avril 1993.

Suite aux décisions prises lors de la session du Conseil de l'ESA au niveau ministériel à Munich les 18 et 19 novembre, deux autres vols d'Eureca sont maintenant programmés pour 1995 et 1997 dans le cadre du programme de vols précurseurs Columbus.



The Earth as seen by Meteosat-2 on 2 December 1991 at 12.55 GMT

La Terre vue par Météosat-2 le 2 décembre 1991 à 12.55 GMT

Upon its arrival at KSC on 4 November, Eureca was transported to the Astrotech facilities for final launch preparations. Eureca is scheduled for launch on Space Shuttle 'Atlantis' (flight STS-46), on 2 July 1992, and for retrieval by the same Shuttle (flight STS-57) in April 1993.

As a result of the ESA Council Meeting at Ministerial Level in Munich on 18/19 November, two more Eureca flights are now planned for 1995 and 1997 as part of the Columbus precursor flight programme.

Space Station 'Freedom'/Columbus

Manned laboratories

The Columbus Programme scenario has been consolidated within the framework of preparing the new ESA Long-Term Plan. This modified scenario, presented by the Director General at the end of August in Darmstadt, is coherent with the Programme objectives established at the Ministerial Meeting in the Hague and is compatible with the overall budget constraints indicated by Member States: it is based on a 1998 launch for the Attached Laboratory and Polar Platform, but the launch of the Free-Flyer is shifted to 2003.

From the system-design point of view, strong emphasis is put during the early years on optimisation of the performance of the 'composite' formed by the Free-Flyer docking in orbit with the Hermes space plane.

At the Council Meeting at Ministerial Level in Munich in November 1991, which confirmed the objectives accepted in The Hague, and the proposed Long-Term Plan 1992–2005 as a strategic framework for the Agency's planning, it was agreed that the Columbus Programme should continue according to this plan during 1992, with a new assessment to be made at the end of the year.

Technical meetings have taken place with NASA during the last months and a Multi-lateral Science Working Group Meeting was held at the end of November, with representatives of the four Partner Agencies present.

On the ground-segment side, the charters for the Users and the System Operations Panels were finalised in September at a multi-lateral meeting involving ESA, NASA and Japanese and Canadian agencies, and were approved by the Multi-lateral Coordination Board in October. The Manned Space Laboratory Control Centre Detailed Definition Final Review and the Attached Laboratory Centre Architectural Design Review were both held in October.

On the utilisation side, a new issue of the 'Columbus Payload Requirement Document' has been published. It includes incremental Reference Missions, progressing from the launch configuration up to the complete outfitting of the Attached Laboratory, and based on the Long-Term Planning of the Microgravity Programme and the new External Viewing Platform concept.

A parabolic-flight campaign, testing in particular crew-support equipment, took place in September. The proposal for a series of Columbus Precursor Flights, to be performed in the 1995–97 time frame with Eureca and Spacelab, as an addition to the Development Programme, has been finalised.

Among the 'Long-Term Programme' activities, the EMSI System Configuration Study Request for Proposals (RFQ) has been issued and the responses received by ESA. The final results of the four-week isolation experiment have been presented at an ISEMSI Symposium.

Polar Platform

The Polar Platform development schedule was revised as part of the Agency's Long-Term-Plan consolidation activities. As a result (and in view of budget limitations), it was decided to postpone its launch from October 1997 until

Déchargement du conteneur d'Eureca au Centre spatial Kennedy

Offloading of the Eureca spacecraft at Kennedy Space Center

Station spatiale Freedom/Columbus

Laboratoires habités

Le scénario du Programme Columbus a été consolidé dans le cadre de la préparation du nouveau plan à long terme de l'ESA. Ce scénario modifié, présenté par le Directeur général fin août à Darmstadt, répond aux objectifs de programme établis lors de la session ministérielle du Conseil à La Haye et est compatible avec les contraintes budgétaires globales indiquées par les Etats membres; il est basé sur le lancement en 1998 du laboratoire raccordé et de la plate-forme polaire, celui au laboratoire autonome étant repoussé à 2003.

Du point de vue de la conception du système, l'accent est mis, pendant les premières années, sur l'optimisation des caractéristiques de fonctionnement du composite formé en orbite après accostage du laboratoire autonome à l'avion spatial Hermès.

Lors de la réunion du Conseil au niveau ministériel à Munich en novembre 1991, qui a confirmé les objectifs acceptés à La Haye ainsi que le plan à long terme 1992–2005 proposé comme cadre stratégique de planification de l'Agence, il a été convenu que le programme Columbus serait poursuivi en 1992 conformément à ce plan et qu'une nouvelle évaluation aurait lieu à la fin de l'année.

Au cours de ces derniers mois, des réunions techniques ont été tenues avec la NASA; fin novembre, des représentants des quatre agences partenaires se sont réunis au sein d'un groupe de travail multilatéral sur les sciences.

Pour ce qui est du secteur sol, un point final a été mis aux chartes du Comité d'exploitation des utilisateurs et du Comité d'exploitation des systèmes lors d'une réunion multilatérale à laquelle participaient l'ESA, la NASA et les agences japonaise et canadienne; ces chartes ont été approuvées par le Comité de coordination multilatéral en octobre. La revue définitive de définition détaillée du Centre de contrôle du laboratoire spatial habité et la revue de la conception architecturale du Centre de contrôle du laboratoire raccordé ont été organisées en octobre.

Pour ce qui est de l'utilisation, on a diffusé une nouvelle version du document sur les impératifs des charges utiles de Columbus. Les différentes missions de référence allant de la configuration de lancement jusqu'à l'équipement complet du laboratoire raccordé y sont exposées; ce document repose sur la planification à long terme du programme de recherche en microgravité et sur le nouveau concept de plate-forme d'observation extérieure.

Une campagne de vols paraboliqes, destinée notamment à vérifier les équipements de soutien de l'équipage a eu lieu en septembre. La proposition d'exécution d'une série de vols précurseurs Columbus en 1995–1997 avec Eureca et Spacelab, en plus du programme de développement, a été arrêtée définitivement.

Parmi les activités du programme à long terme, une demande de proposition relative à une étude de configuration de système EMSI a été diffusée et les réponses ont été reçues par l'ESA. Les résultats définitifs de l'expérience d'isolement de quatre semaines ont été présentés lors du symposium ISEMSI.

Plate-forme polaire

Le calendrier de réalisation de la plate-forme polaire a été révisé dans le cadre des activités de consolidation du plan à long terme de l'Agence. Compte tenu de cette révision et des contraintes budgétaires, il a été décidé de reporter le lancement de la plate-forme d'octobre 1997 à la mi-1998, et l'industrie a entrepris à la fin octobre de revoir ses activités et leur calendrier détaillé.

Les travaux de développement ont progressé, en ce qui concerne notamment les activités découlant de la revue de consolidation de la base de référence. La conception détaillée des moyens sol mécaniques (MGSE) et de la structure de la plate-forme a suivi son cours.

L' approvisionnement des éléments à long délai de livraison du module de servitude a été mis en route; les activités correspondantes en ce qui concerne le module charge utile sont en préparation.

Hermès

Secteur spatial

Les travaux de configuration de l'avion et l'installation des sous-systèmes se poursuivent. La forme aérodynamique de l'avion a été évaluée au cours d' essais subsoniques qui ont confirmé les bonnes qualités de vol.

Pour ce qui est du module de ressources, on étudie la mise en place de moyens de service supplémentaires mid-1998, and a revision of the industrial activities and their detailed planning was initiated in industry at the end of October.

The development activities have continued, including the follow-on actions to the Baseline Consolidation Review. Detailed design of the Mechanical Ground-Support Equipment (MGSE) and the Platform's structure has continued.

Procurement of long-lead-time items for the Service Module has been initiated and the associated activities for the Payload Module are in preparation.

Hermes

Space segment
The configuration of the space plane and the accommodation of subsystems has been further developed. The plane's aerodynamic shape has been evaluated in subsonic tests and good flight qualities have been confirmed.

For the Resource Module, the accommodation of additional servicing capabilities required by the Columbus Free-Flying Laboratory and a change in the structural material to a sandwich technology are under investigation.

Activities at subsystem level have addressed the failure tolerance of the architecture and the identification of mass-driving parameters. The failure tolerance of the spacionic system (both failures in computer hardware and software errors) is particularly demanding, but a promising approach has recently been identified which is now under evaluation.

Another subsystem where major architectural changes are under evaluation is the propulsion subsystem, for which a new, less complex architecture is being considered.

Task forces have been created to improve and control the critical budgets.

A major thermal-protection technology milestone has been achieved with the acceptance of the winglet box and the nose cone (scale: 0.6).

Ground segment
The Hermes Flight Control Centre architecture study has led to definition of the functional architecture and of the subsystems for the control facility.

Progress has also been made on the training facilities, with the evaluation of two candidate training aircraft and analysis of the simulator functions. Support needs for the launch-site facility and the integration facility in Europe are currently under study.

Particular attention has been devoted to achieving coherence between mock-ups, test beds and software.

The status of activities and studies performed to date for definition of the ground segment have been submitted to an independent overall assessment in order to identify priorities for the next years.

Management aspects
The need to comply with annual payment limitations has led to the application of a stretched development scenario for Hermes (so-called 'Darmstadt' or '2002' scenario), which leads to subsonic flight testing in the year 2000, with the first unmanned orbital flight in 2002.

The priorities for 1992 are the consolidation of the financial proposal, critical technologies and system coherence. In addition, the recommendations of the Council Meeting at Ministerial Level in Munich in mid-November concerning cooperation will be investigated.

Ariane-5

The final quarter of 1991 saw numerous major events that give an idea of the scope of the industrial work that has been done.

H155 cryogenic stage
The stage authority's activities culminated in tests on the stage flight-guidance mockup using actual components such as the thrust-frame, actuators and Vulcain engine.

The flight-type structures (forward skirt and thrust-frame) have also been delivered to Les Mureaux (F) and, after the pneumatic, hydraulic and electrical equipment has been integrated, will form elements of the engineering mockup of the launcher.

The most spectacular event involved the tank for this stage, the first example of which passed its proof pressure test. Manufacture of the tank, intended for the H155 dynamic mockup, is consequently continuing at Cryospace with the delicate operation of fitting the thermal protection in place.

Vulcain engine
To date there have been 66 tests of the engine, totalling 4600 s of running and covering the whole flight domain. The third test engine was dismantled for inspection after 17 tests and 2600 s of running.

P230 solid-booster stage
Production of the first forward segment for the booster in Italy went smoothly, and the block of grain appears satisfactory. Two tests on the complete igniter were successful.

Commissioning of the solid-grain plant in French Guiana has taken longer than planned, and the first loading of a real booster segment has had to be postponed. Though this means putting off the first test-stand firing by a few months, it does not cast any doubt on the design of the grain plant.

As with the H155 stage, the stage authority has made a start on flight-guidance activities, using actual parts of the P230 such as the nozzle, actuator amd aft skirt.

qu'exige le laboratoire autonome Columbus ainsi qu'une modification des matériaux de structure au profit de la technologie 'sandwich'.

Au niveau des sous-systèmes, les activités ont porté sur la sensibilité aux défaillances de l'architecture et sur la définition des paramètres déterminants de masse. Les exigences de tolérance aux pannes du système spationique (qu'il s'agisse de pannes du matériel informatique ou d'erreurs de logiciel) sont particulièrement sévères mais on procède actuellement à l'évaluation d'une nouvelle méthode prometteuse.

On évalue également les principales modifications architecturales du sous-système de propulsion pour lequel on envisage une architecture moins complexe.

Des groupes de travail ont été constitués pour améliorer et maîtriser les bilans critiques.

Une étape importante a été franchie dans le domaine de la technologie de la protection thermique avec la recette du caisson de dérive de bout d'aile et du cône d'extrémité (échelle 0,6).

Secteur sol

L'étude de l'architecture du Centre de contrôle en vol d'Hermès a débouché sur la définition de l'architecture fonctionnelle et des sous-systèmes destinés aux moyens de contrôle.

Les travaux relatifs aux moyens d'entraînement ont progressé: les deux avions d'entraînement candidats ont été évalués et on a analysé les fonctions du simulateur. On étudie actuellement le soutien à apporter aux installations du site de lancement et aux moyens d'intégration en Europe.

On a veillé, notamment, à ce que les maquettes, les bancs d'essais et les logiciels soient cohérents.

L'état d'avancement des activités et des études réalisées à ce jour dans le domaine de la définition du secteur sol a été soumis à une évaluation globale indépendante en vue d'établir les priorités pour les années à venir.

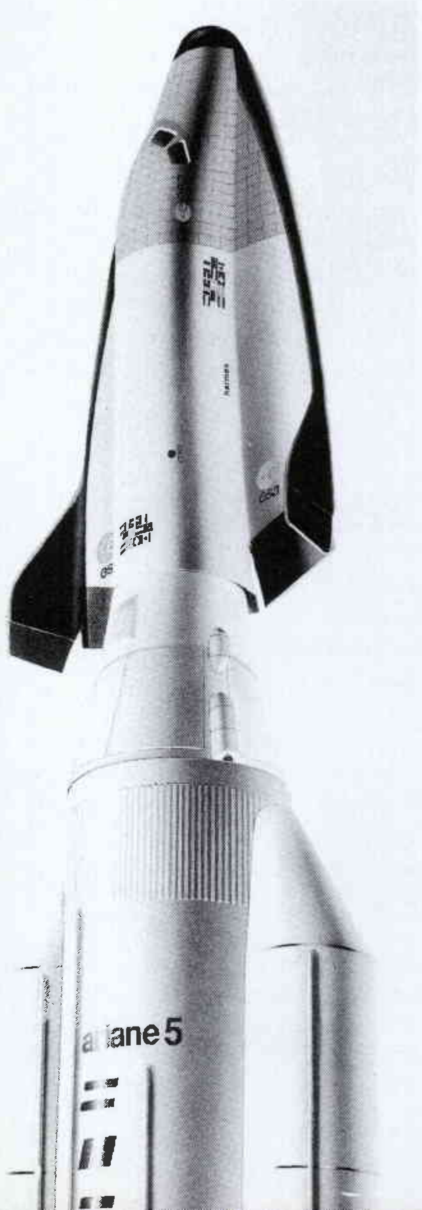
Aspects relatifs à la gestion

La nécessité de se conformer aux limitations annuelles de paiement a conduit à l'application d'un scénario de développement d'Hermès étalé dans le temps dit scénario de Darmstadt ou '2002'. Selon ce scénario, les essais en vol subsonique auraient lieu en 2000 et le premier vol orbital automatique en 2002.

En 1992, priorité sera accordée à la consolidation de la proposition financière, des technologies critiques et de la cohérence du système. En outre, pour ce qui est de la coopération, on étudiera les recommandations formulées par le Conseil lors de la session ministérielle de la mi-novembre 1991 à Munich en matière de coopération.

Ariane-5

Au cours du dernier trimestre de l'année 1991, de nombreux événements majeurs sont intervenus qui démontrent l'importance des travaux industriels réalisés.



Etage cryotechnique H155

Les activités de l'étagiste se sont concrétisées par les essais de la maquette de pilotage de l'étage avec des composants réels tels que: bâti moteur, servo-moteurs et moteur Vulcain.

Par ailleurs les structures de type vol (jupe avant et bâti moteur) ont été livrées aux Mureaux et, après intégration des équipements pneumatiques, hydrauliques et électriques, formeront les éléments de la maquette fonctionnelle du lanceur.

L'événement le plus spectaculaire concerne le réservoir de l'étage dont le premier exemplaire vient de subir avec succès l'épreuve de timbrage. Ce réservoir, destiné a la maquette dynamique de l'étage H155 poursuit donc son cycle de fabrication chez Cryospace, notamment avec l'opération délicate de la pose de la protection thermique.

Moteur Vulcain

A ce jour 66 essais du moteur, cumulant 4600 s de fonctionnement ont été réalisés, permettant d'explorer l'ensemble du domaine de vol. Il faut remarquer que le troisième exemplaire du moteur a été démonté pour expertise après 17 essais et 2600 s de fonctionnement.

Etage à poudre P230

En Italie, la réalisation du premier segment avant du propulseur s'est déroulée sans incident et le bloc de poudre apparaît sain. Il faut signaler également l'exécution satisfaisante de deux essais de l'allumeur complet.

La mise en route de l'usine de poudre en Guyane s'avère plus longue que prévue et le premier chargement d'un segment réel du propulseur a dû être rebuté. Cet incident, qui ne remet pas en question la conception de l'usine, entraîne un report du premier essai au banc de quelques mois.

Par ailleurs, comme pour l'étage H155, l'étagiste a commencé l'activité 'maquette de pilotage' avec des éléments réels du P230 tels que tuyère, servo-moteur, et jupe arrière.

Publications

The documents listed here have been issued since the last publications announcement in the ESA Bulletin. Requests for copies should be made in accordance with the Table and using the Order Form inside the back cover of this issue.

ESA Special Publications

ESA SP-317 // PRICE 90 DFL
PROCEEDINGS OF THE TENTH ESA SYMPOSIUM ON EUROPEAN ROCKET AND BALLOON PROGRAMMES AND RELATED RESEARCH, CANNES, FRANCE 27 – 31 MAY 1991
KALDEICH B (ED.)

ESA SP-326 // PRICE 90 DFL
PROCEEDINGS OF THE THIRD INTERNATIONAL SYMPOSIUM ON SPACECRAFT FLIGHT DYNAMICS, DARMSTADT, GERMANY, 30 SEPT. – 4 OCT. 1991
HUNT J (ED.)

ESA SP-327 // PRICE 50 DFL
LA PROPULSION DES LANCEURS SPATIAUX A L'HORIZON 2010/LAUNCHER PROPULSION TOWARDS THE YEAR 2010, PROCEEDINGS OF INTERNATIONAL CONFERENCE, BORDEAUX, FRANCE, 11 – 12 JUNE 1991
DAVID V (ED.)

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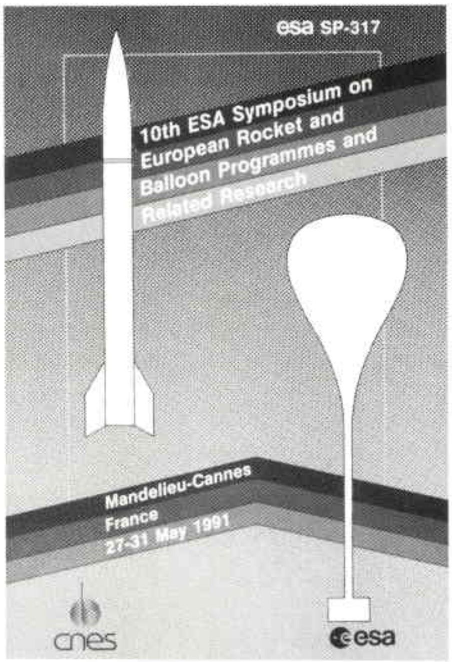

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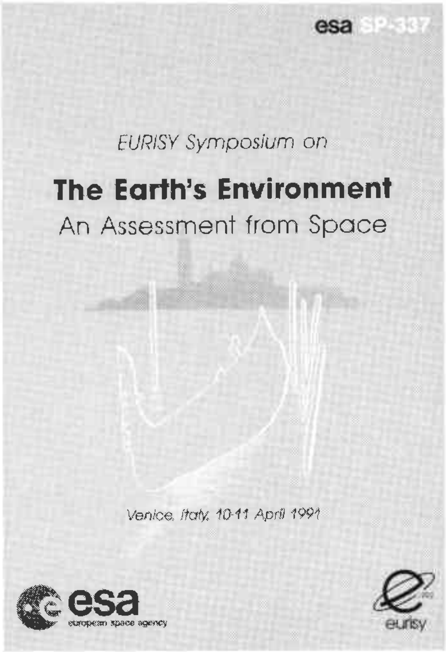

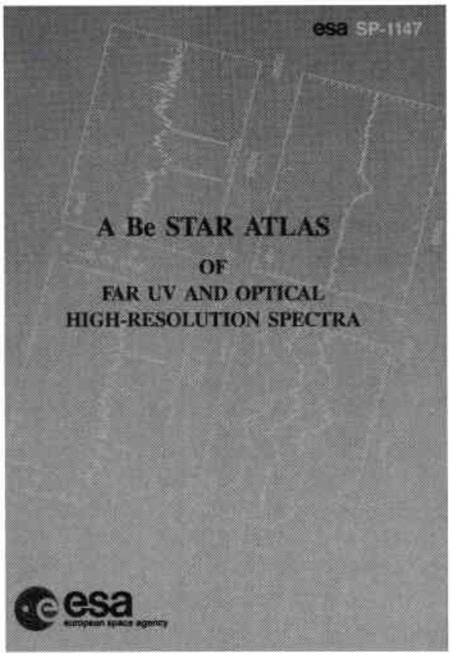

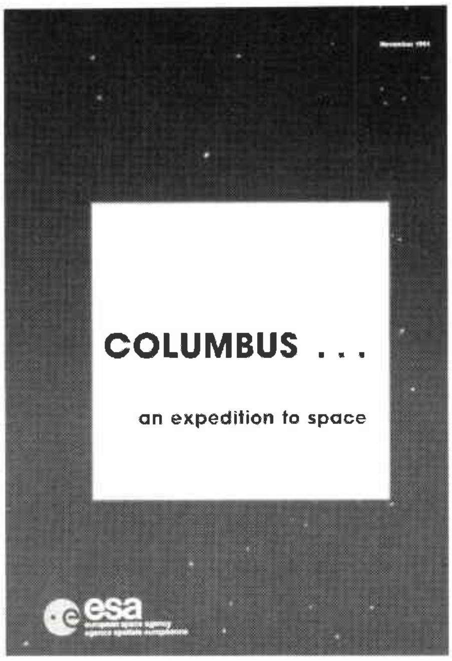

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