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Chapter 24

FROM HF RADIO TO UNIFIED S-BAND: AN HISTORICAL REVIEW OF THE DEVELOPMENT OF COMMUNICATIONS IN THE SPACE AGE[*]

David E. B. Wilkins[†]

In October 1957, *Sputnik 1*, launched by the U.S.S.R., heralded the dawn of the Space Age. At that time, the primary method of long-distance communications was via High Frequency (HF) radio circuits operating at frequencies below 30 Megahertz (MHz). However, no world-wide communications system existed.

In July 1969, when *Apollo 11* made its epic journey to the Moon, the entire mission was controlled by means of a world-wide network of unified S-band tracking stations, which were linked to Mission Control via the NASA communications network. The operating frequencies of the tracking stations were as high as 2300 MHz, while the communications satellites, which provided the long distance circuits between the various sectors of the NASCOM NETWORK, operated at 4 and 6 Gigahertz (GHz) in the radio C-band.

In twelve short years, the "Giant Leap" was not only that famous step of Neil Armstrong onto the lunar surface, but also the frequency explosion into the upper frequencies of the radio spectrum, which is continuing to the present day.

With the arrival in service of the operational communications satellite, the age of HF radio as a primary method of long-distance communications was drawing to a close.

The "Short-wave" radio-communications systems, which had evolved from the early experiments of Marconi and other radio pioneers and which during the 1950s and 1960s attained a high degree of efficiency, were an important part of the command and control systems used in the early years of the Space Age.

This paper will examine the first twelve years of that era, and it will demonstrate the importance of radio communications to the success of manned space flight. The author will draw on his personal experience as a member of the NASA Manned Space Flight Network (MSFN).

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[†] Member of the European Space Operations Center of ESA, in Darmstadt, West Germany.

1957, COMMUNICATIONS SYSTEMS - "THE STATE OF THE ART"

In retrospect, it is difficult to realize that in 1957, the field of long distance, transoceanic communications was still dominated by High-Frequency (HF) Radio.

In 1956, the first trans-Atlantic telephone cable was completed, and for the first time it was possible to communicate between North America and Europe via telephone circuits without having to resort to HF radio circuits [1.c]. This cable provided 48 voice circuits via coaxial cables, and spanned an underwater distance of 2000 miles using 52 repeaters [1.c]. During the next twenty years, the trans-oceanic cable communications systems continued to expand world-wide, but HF radio continued as a primary means of communications until the early 1970s [1.c].

During 1957, the military and commercial communications systems were primarily HF radio systems. The military need to communicate rapidly between the headquarters and far-flung outposts required sophisticated, and powerful means. The deployment of the U.S. Armed Forces over vast stretches of the Pacific (Japan, Okinawa, Formosa, Philippines, Guam, Hawaii) and across continental Europe, dictated the establishment of international communications systems to serve the Administrative and Command communications needs of the military services. Thus, between the end of World War II and 1957, all three U.S. Military services established a world-wide network of long-distance communications facilities, until it seemed that every island in the Pacific was home to an "antenna-farm" of rhombic, dipole, and long-wire antennas.

Papers in the "Proceedings of the IRE" and "IRE Transactions on Communications Systems" placed heavy emphasis on the use of the HF Band. Also papers on developments in new communications systems being developed by the USAF (United States Air Force) and RCA Global Communications System were very common [1.a].

Although all three military services relied on HF radio, the U.S. Army Signal Corps and the USAF systems were probably the most highly developed in this band; the U.S. Navy being particularly involved in developing VLF Communications Systems. The U.S. Army ACAN System (Army Command and Administrative Network) and the USAF AACS System (Airways and Air Communication Service) were typical of advanced HF radio systems in 1957. These systems were primarily designed to transmit teletype traffic via radio circuits at speeds not higher than 50-60 words-per-minute. Voice circuits were limited, and data transmission was only in an experimental stage.

But much research and development was taking place in the fields of ionospheric scatter, tropospheric scatter, microwave radio relay, and voice-channel multiplexing. The U.S. Department of Defense Distant Early Warning (DEW) radar line used tropospheric scatter communications to link the radar sites to the air defense control centers, and this led to the first truly integrated communications system, the White Alice Project. This tropospheric scatter system was installed in Alaska by mid-1958 and formed the back-bone of USAF communications in that region for many years [1.a].

Nomenclature of Frequency Bands (3)

According to the international agreement at the Atlantic City conference, 1947, International Telecommunications Union, the the radio-band designations* were as given in Table 1.

Table 1

Frequency subdivision	Frequency range	Metric subdivision
VLF	up to 30 kcs	Myriametric waves
LF	30–300 kcs	Kilometric waves
MF	300–3000 kcs	Hectametric waves
HF	3000–30,000 kcs	Decametric waves
VHF	30,000 kcs–300 Mcs	Metric waves
UHF	300–3000 Mcs	Decimetric waves
SHF	3000–30,000 Mcs	Centimetric waves
EHF	30,000–300,000 Mcs	Millimetric waves

Frequency Allocations [3]

Although detailed radio frequency allocations were laid out from as low as 10 KHz to 10,500 MHz, no service above that frequency had been allocated. Between 1800 KHz and 29.7 MHz, very precise bands had been allocated to fixed services, mobile services, and amateur service. *The band between 3 MHz and 30 MHz is the HF radio band*, although the so-called short-wave band begins above 1600 KHz, which is the upper-limit of the ground-wave propagation mode and the upper-limit of the AM broadcast band [2].

Radio Propagation (Some Notes)

Propagation of HF Radio Waves via the Ionosphere [2] and [4]. Radio energy radiated at angles above the horizon will travel through space until it reaches the ionized region in the upper atmosphere. There, if conditions are favorable, the path of the wave will be bent earthward. Such a sky-wave may return to Earth at very great distances from the transmitter, and it is the means by which long-distance radio communication is achieved. This is termed ionospheric propagation.

The *Ionosphere* is that part of the atmosphere, at heights above about 50 Kms, in which free ions and electrons exist in sufficient quantities to affect the propagation of radio waves. At frequencies below 30 MHz, regular long-distance transmission is possible by means of ionospheric reflections. At frequencies in the 30-100 MHz region, regular but weak propagation by ionospheric scattering is obtained, as well as strong intermittent propagation by reflection from sporadic ionospheric layers and meteoric ionization.

The ionization in the ionosphere tends to be stratified as a result of differences in the physical properties of the atmosphere at different altitudes and because various kinds of radiation are involved. The levels at which the electron density reaches

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* These definitions are still valid today although new Megacycles have become Megahertz (MHz) and the HF-band would be designated as 3 MHz to 30 MHz vice 300-30,000 Kilo-cycles.

a maximum are termed "layers." Four principal layers affect the propagation of radio waves:

- The **D Region** extends from 50 to 90 Kms in height and is a region of low electron density in collision with neutral gases, mainly causing absorption of radio waves passing through. The cause of ionization is generally taken to be solar photo-ionization of NO by Lyman - α radiation ($\lambda = 1216$ Å). D-region ionization is mainly during daylight hours, although during solar disturbances and, at high latitudes, ionization can be caused by particle radiation.
- The **E-region**, at between 90 to 130/140 Kms, is ionized mostly by solar ultraviolet and X-rays in the day-time, with some night-time ionization caused by cosmic rays and meteorites. A regular E-layer of maximum electron density near 100 Kms is an important reflecting medium for day-time HF propagation.
- The **F-region**, above 140 Kms, is the most important for HF propagation.
- The **F_1 Layer** exists mainly during daylight at heights of 175 to 220 Kms. F_1 depends on daylight solar ionization, but it is also prevalent during ionospheric disturbances. At night, the F_1 layer merges into the F_2 layer at a height of about 300 Kms.
- The **F_2 Layer**, at heights from 200 to 400 Kms, is the principal reflecting layer for long-distance HF communications day and night. Height of the layer and electron density vary geographically, diurnally, seasonally, and with the solar cycle. The absence of the F_1 layer at night, and the reduction in absorption of the E-layer, cause night-time field intensities and noise to be generally higher than during daylight hours.

  Basically the F_2 layer can provide single-hop paths of up to 4000 Kms, while the F_1 layer provides daylight paths of 2000-3000 Kms. The E-layer, on the other hand, provides mainly day-time paths up to 2000 Kms.

While the knowledge of the ionosphere's effect on radio signals, maximum usable frequencies (MUF), predictions of HF propagation, height and density of the ionospheric layers, and the use of great-circle calculations for antenna bearings had been known for many years [2], it is interesting to compare the knowledge of the physical composition of the ionosphere in 1957 with the present knowledge. Terman [2], while describing the ionospheric layers and methods of ionospheric sounding to determine virtual height and critical frequencies, can only postulate on the composition of the D-layer. R. C. Kirby [4], on the other hand, is able to provide a wealth of detail on the chemical and physical composition of each layer and indeed on the lower atmosphere of the Earth. This is because these two references were written twenty years apart and, during the intervening years, numerous scientific satellites orbiting the Earth and hundreds of sounding rockets carrying scientific payloads have measured the composition of our atmosphere. Literally thousands of scientific payloads have now traversed the ionosphere, but in 1957, the ionosphere's precise composition was not clearly defined, and was a subject which would form the basis of much scientific research in the 1960s.

The Arrival of Sputnik 1. On 4 October 1957, *Sputnik 1* was placed into orbit by the U.S.S.R., and its telemetry signals, transmitting on 20 MHz and 40 MHz, were heard around the world. These signals transmitted from an altitude of between 215 and 940 Kms [17], were the first man-made radio signals to traverse the ionosphere from space to Earth.

The event would galvanize the United States space program, then somewhat fragmented, into concerted activity, which, in turn, would place heavy demands on the long-distance communications systems then existing. It is not too far-fetched to say that the arrival of **Sputnik**, more than any other event, precipitated the growth of world-wide communications as we have it today.

NASA AND ITS NETWORKS

Communications engineers were making great strides in improving the availability and reliability of long-distance, world-wide terrestrial systems. But three "extra-terrestrial" events in the late 1950s, although not directly related to the field of communications, were significant contributors to the rapid growth of communications in the 1960s. These were:

- **4 October 1957.** The U.S.S.R. launched *Sputnik 1*, the first artificial Earth satellite. This event generated great interest and action on the part of the American public to support an active role in space research, technology and exploration [14].
- **1 October 1958.** NASA was activated in accordance with the terms of v.s. Public Law 85-568, and non-military space projects were transferred to NASA from ARPA [14].
- **7 October 1958.** Keith Glennan, the NASA administrator, approved the manned satellite project [14]. On 26 November 1958, this project was officially designated "Project Mercury" [14].

These events were all important, and resulted in immensely significant scientific and technological achievements, but as this paper is an examination of communications in the Space Age, and especially communications systems affected by the field of space exploration, it is proposed that we examine communications systems used for space exploration at the time of *Sputnik 1*'s launch, and how these systems evolved to support the first lunar landing in July 1969.

Data Acquisition Networks - The Late 1950s

The principal users and developers of long-distance communications systems in the late 1950s, were the military services. In a similar way, the same was true of the development of data acquisition networks. By this is meant a network of stations designed to acquire telemetry (or other) data from an operational or test source, typically satellites, test aircraft, or launch vehicles, and to record and store this data and to transfer it to a control center [6a].

The USAF North American Air Defense Command (NORAD) used voice telephone circuits to transmit data from the DEW-line radar stations to defense centers in the continental U.S. as early as 1957 by means of the AN/FSQ-7 SAGE System (SAGE = Semi-Automatic Ground Environment). The data, which represented range, height, and azimuth of targets being tracked, was converted to analogue signals to drive air defense controller displays at the regional center.

The USAF at its Atlantic Missile Range, with headquarters at Cape Canaveral, the U.S. Army at White Sands Missile Range, and the U.S. Navy at Pacific Missile Range, Point Mugu, California, all made use of voice-band circuits to transmit test data from the data acquisition stations to the range control centers. A mixture of microwave radio-relay circuits, leased private telephone lines, and submarine cable circuits were put together to provide these services. But the three ranges were basically in the continental United States, and they relied on readily available commercial leased facilities.

NRL and Minitrack. When the U.S. Naval Research Laboratories (NRL) began the design and installation in 1955 of the world-wide minitrack network, required to support the Vanguard Satellite, it soon became apparent that one of the biggest problems would be the reception of tracking data and scientific data at the control center. Tracking data in teletype format would be transmitted to the Vanguard Control Center in Washington, D.C. and then to the Vanguard Computing Center, also in Washington D.C. Orbital parameters would be determined and acquisition data transmitted back to the tracking stations. Scientific data was to be recorded on telemetry tapes at each station and air-mailed to NRL [6].

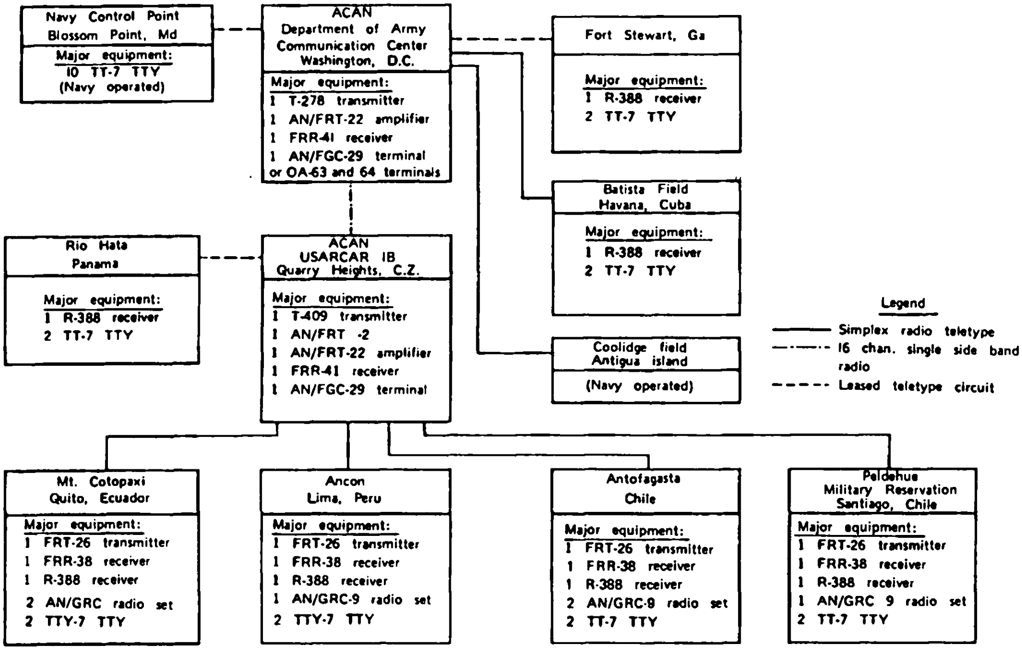

Figure 1 U.S. Army Communications Plan for Prime Minitrack Stations.

Within the continental United States, teletype circuits were readily available between NRL and the minitrack stations at San Diego, Blossom Point (Maryland), and Fort Stewart (Georgia). NRL experienced problems in establishing communications between Washington and the minitrack stations in South America and Australia, mainly because of the lack of existing commercial facilities capable of handling the teletype traffic. The U.S. Army offered assistance in establishing communications to the South American stations, and by 1 October 1957, the installation and check-out of the teletype circuits were completed (see Figure 1). Three days later, *Sputnik 1*, transmitting continuously on 20 MHz and 40 MHz, initiated the Space Age.

NRL engineers rapidly designed a 40 MHz, crossed-dipole antenna, which could be used with suitable converters with the 108 MHz minitrack receiving systems. The 40 MHz crosses were installed initially at Blossom Point, San Diego, and Lima and then, later, at Santiago, and Woomera. Within a few days, good tracking data was being received at Washington D.C.. Thus *Sputnik 1* (and later *Sputnik 2*) became the active test data sources for the validation of the minitrack network.

The teletype circuits to the Woomera, Australia station were connected into the network via USAF and U.S. Navy radio teletype circuits, while the South African station at Johannesburg was served by the TAT-1 submarine cable to London, then via commercial HF radio links to Johannesburg.

Minitrack overseas communications circuits were primarily point-to-point, HF radio links and were almost entirely military systems (see Figure 2). Most of these military teletype circuits were part of the U.S. Army ACAN system using "torn-tape" relay methods (i.e. manual switching). Data rates were limited to 60 words-per-minute (45 Baud), which was adequate for transmission of interferometer tracking data and for administrative traffic between the control center and tracking stations.

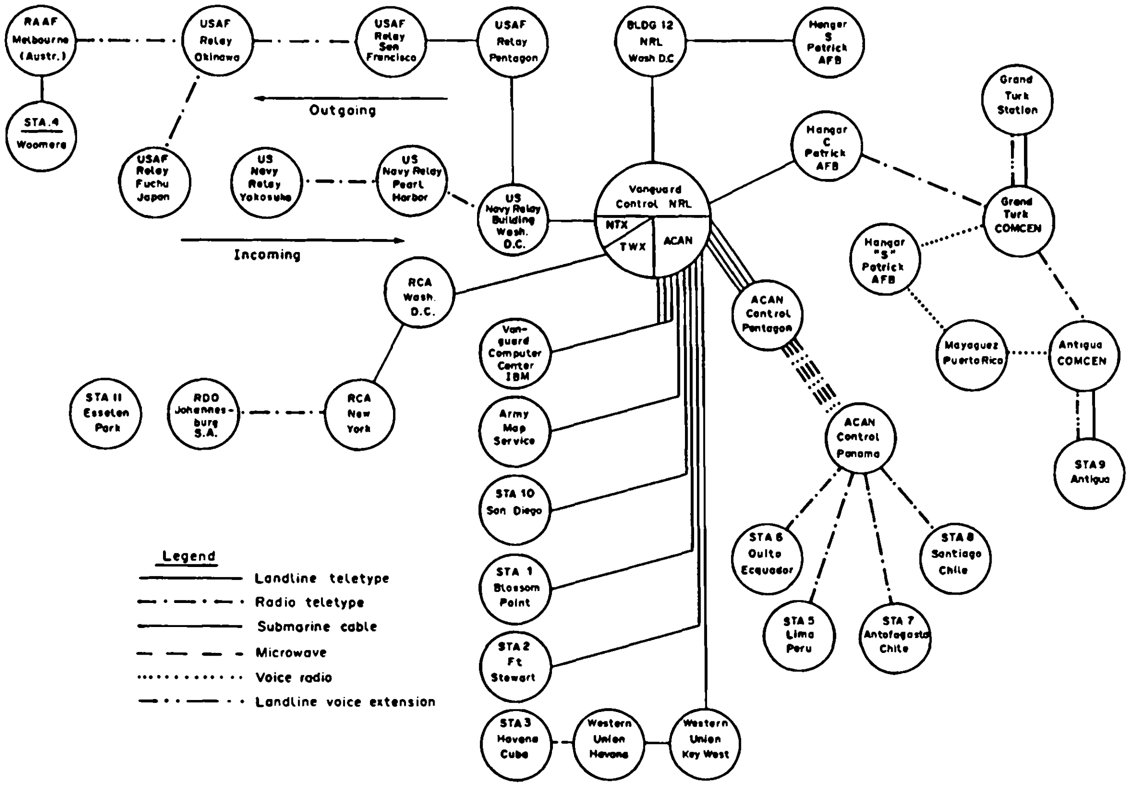

Figure 2 The Minitrack Communications Network (1957/1958).

The communications circuits established for the NRL minitrack operations remained in service for some years, but they were clearly inadequate for use with the new, advanced Explorer and Observatory satellites being designed by NASA and, of course, for manned space activities being planned for Project Mercury.

The NRL Vanguard staff were transferred to NASA on October 1st, 1958, forming the nucleus of the Beltsville (Maryland) Space Center which became, in May 1959, the Goddard Space Flight Center (GSFC) [6, p.27].

The Deep Space Network (DSN). The DSN operated by JPL* for NASA is, in itself, a subject for much study because of the JPL accomplishments in deep space exploration. The DSN consists of a sophisticated tracking network incorporating large antennas (up to 70 meters in diameter), ultra-low-noise amplifiers, precision phase-locked receivers, transmitters, and telemetry error-correction systems [7].

The DSN grew from the microlock tracking and data acquisition system developed by JPL in support of the first U.S. Earth orbiting satellite, *Explorer 1*, in 1958. This system was adequate for communicating at lunar and planetary ranges and was replaced by the TRAC(E) receiving system later in 1958 (tracking and communication, Extraterrestrial). Since then, the DSN has developed into a sophisticated telecommunications network with tracking stations at Goldstone, California, Madrid, Spain, and Canberra, Australia.

The network participated in all the Apollo missions, including, of course, *Apollo 11*. The introduction of a discussion on DSN into this paper is to illustrate two important points:

- The NASA Apollo Unified S-Band system was based largely on JPL-designed equipment, including phase-locked loop receivers, exciters, and pseudo-random noise ranging [8].
- The DSN in its deep space exploration program has contributed significantly to the development of equipment operating in the UHF/SHF region, and it is continuously improving its receiving systems' figure-of-merit.

The first fact will be discussed later. The second fact is pointed out to illustrate the development of ultra-low-noise RF amplifiers based on solid-state microwave maser techniques. Since 1960, JPL has been using this technique, first with UHF ruby masers cryogenically cooled, and now with K-band reflected-wave masers with a band-width of 150 MHz.

Project Mercury - The Mercury Network.

1. The Requirements

The initiation of Project Mercury in October, 1958 [14], led to the issuing, on May 21, 1959, of a NASA Technical Specification to design and build the project Mercury network (NASA Specification S-45: "Specifications for Tracking and Ground Instrumentation Systems for Project Mercury"). This specification was issued to industry as a Request for Proposal on June 22, 1959, and on July 30, 1959, NASA awarded a letter contract to the successful consortium headed by the West-

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* The Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.

ern Electric Company, with Bell Labs, IBM, Bendix and Burns & Roe as subcontractors. The author, many years ago, was provided with a copy of the Technical Proposal (Volume II), submitted by the successful bidders in answer to S-45, and which, eventually, led to the creation of the Mercury network [four of the following diagrams are derived from this document - Ref. 18]. The requirements of S-45 dictated that the operational readiness date of the Mercury network would be 1 June 1960 [6]!

What else was required? First, the use of "off-the-shelf" systems was specified in S-45 as follows:

> The design approach shall emphasize the use of proven reliable systems, which require a minimum of modification or further development. In the planning and design of the system, the safety of the astronaut shall be the major consideration. Conservative design principles shall be used to effect a high degree of reliability.

Second, tracking, telemetry, command voice communications, ground communications, computer, control center, timing, and site specifications were all contained in S-45. But because of the nature of this paper, only the aspects of ground communications will be considered. Basically the ground communications requirements were for real-time, world-wide voice and data circuits. Delays of two to three minutes were acceptable. Duplex teletype circuits operating at 60 w.p.m. and duplex voice circuits with a band-pass of 280-2800 Hz were required. (N.B. 60 w.p.m. circuits were no more effective than the minitrack data rates).

Traffic to be handled consisted of telemetry, command and tracking data, radar acquisition data, voice messages, and routine teletype messages between the sites.

Certain other considerations would enter into the design of the Mercury communications network:

a. The Mission Control Center would be located at Cape Canaveral.

b. The Mercury computers would be located at Goddard Space Flight Center, necessitating a "wide-band," high-speed digital data link between Goddard and the Cape. In mid-1961, this comprised 4 duplex, 4 KHz data circuits, each carrying 1.2 Kbs data streams [6b].

c. Overseas switching centers and relay points would be established to funnel data from overseas stations into a limited number of transoceanic cables (gateway stations); economy and reliability considerations entered into this decision.

For the first time outside the military system, voice, teletype, and digital data circuits would be installed and operated as a single communications network. The sheer size of the system, consisting of a control center, a computing center, and 17 world-wide tracking stations, is still impressive today, in light of the capabilities of that period.

2. The Proposed Solution

In their answer to S-45, Western Electric Co. (WECO) [18] proposed a world-wide network making fullest possible use of leased circuits and facilities. While fully confident of providing reliable "real-time" telemetry and voice circuits from sites on the North American continent, WECO was not so confident of obtaining reliable communications overseas (see Figure 3 for Telemetry Real-Time Data-Transmission System). Their comment under "Radio Communications," summed up the problem:

> High frequency radio in the 3000-30,000 Kcs region of the frequency spectrum constitutes the only feasible means of obtaining long distance point-to-point communications with most of the points outside the continental United States to which communication is required under the Mercury Project. The two notable exceptions to this are the Bell System submarine cable operating to Hawaii and England.

(These cables were MLD-1 and TAT-1 laid in 1958 and 1956 respectively). The WECO report goes on to state:

> "Despite the difficulties of high frequency radio propagation, high frequencies are in continuous use for overseas radio communications . . ."

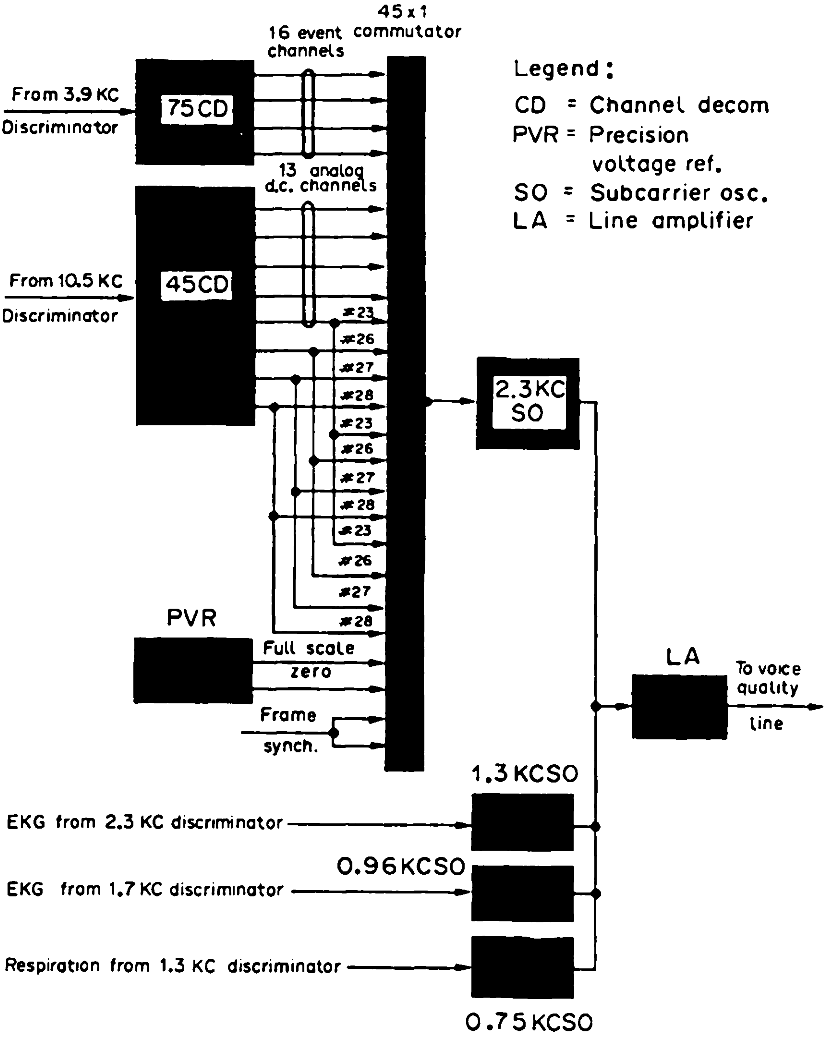


Figure 3 Real Time Telemetry Multiplex Equipment.

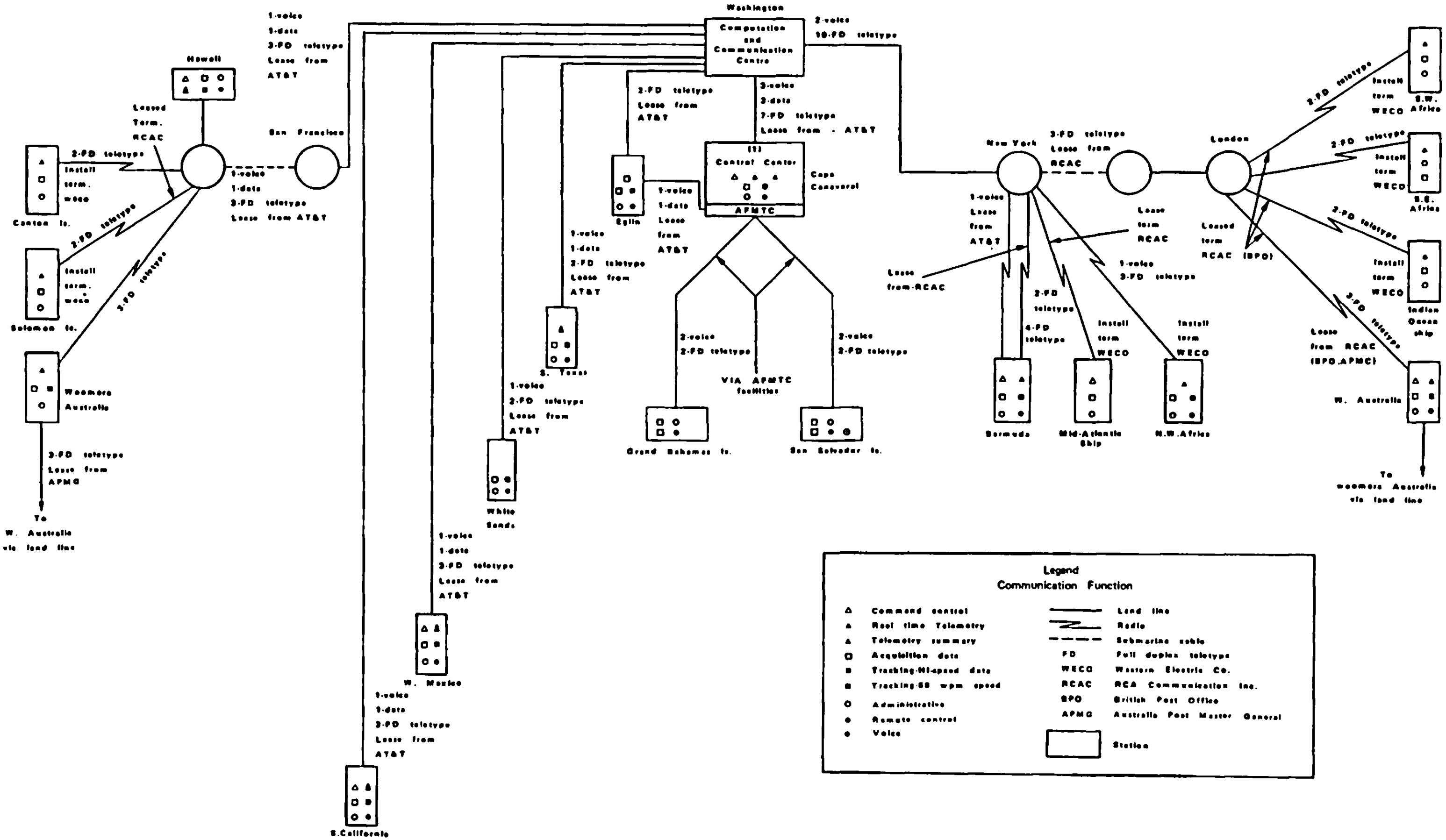


Figure 4 Project Mercury Ground Communication Circuit Requirements.

The proposed communications network, as designed by WECO, is shown in Figure 4 [5]. This was a preliminary design, based on S-45, which itself was being modified by NASA, and consequently many changes were made before final design. In any event, the world-wide tracking and communications network, as it existed in February 1962 [18], is shown in Figure 5. The Mercury network of tracking stations is shown in Figure 6, as of February 1962 [18]. It can be seen that the COMPAC submarine cable from Vancouver to Sydney provided reliable communications between GSFC and the Australian sites. But still Bermuda, the primary (and mandatory for launch) launch and early orbit site was linked to the U.S. only by HF radio circuits. It would not be until early 1963 that the submarine cable between New York and Bermuda became operational and replaced the HF radio circuits [6b].

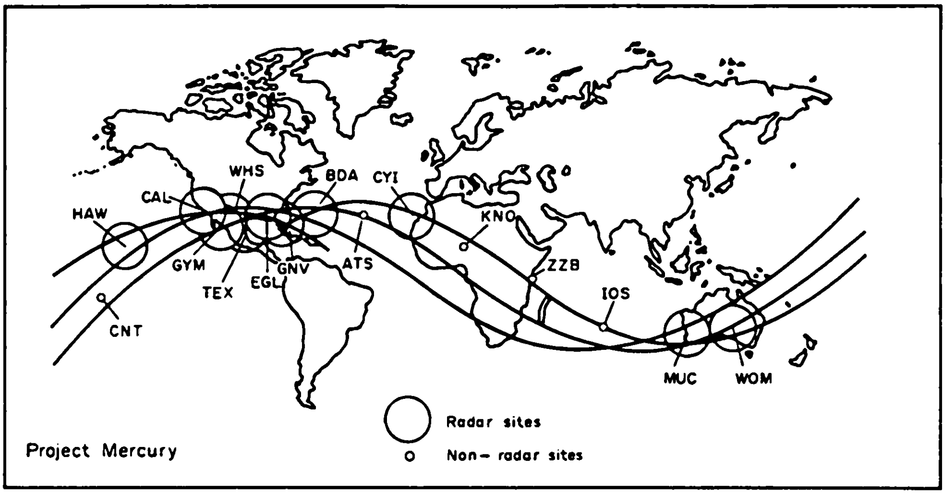


Figure 5 Tracking and Ground Instrumentation System.

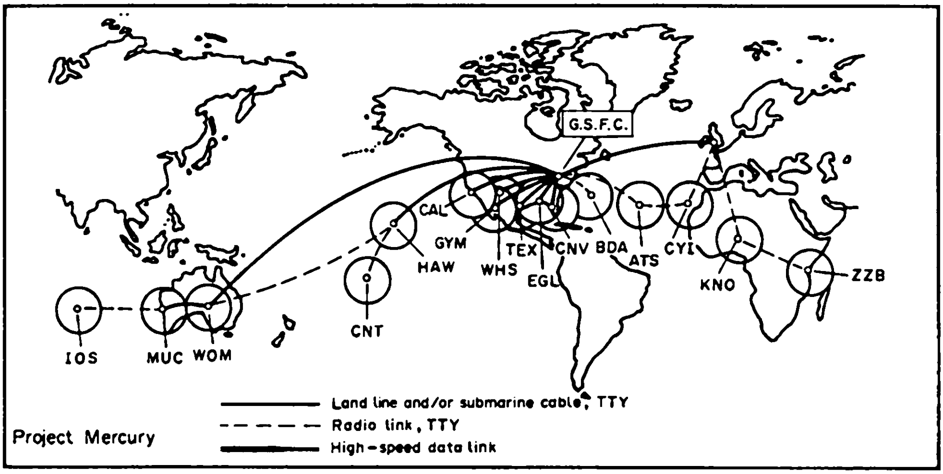


Figure 6 Worldwide Tracking and Communication Network.

The major overseas stations and the two instrumentation ships of the Mercury network relied entirely on HF radio to communicate with the control center at Cape Canaveral and the computing center at GSFC. These stations were Canton Island, Bermuda, Grand Canary Island, Kano (Nigeria), and Zanzibar, plus the ships *Coastal Sentry Quebec* and *Rose Knot Victory*. This situation would not change greatly until 1967, when NASA began using INTELSAT satellite circuits over the Pacific and Atlantic Oceans, although communication tests via SYNCOM 2 and SYNCOM 3 were conducted during the Gemini Program in 1965 and 1966.

WECO [18] proposed an option to use an AT&T tropospheric scatter circuit:

> The AT&T Company will begin operation of a tropospheric scatter radio system late in 1959 between Florida and Naussau.

WECO proposed the use of this circuit extended from the Bahamas by HF radio into Bermuda as a back-up circuit. For various reasons the proposal was not taken up, but it is interesting to note that commercial tropo-scatter circuits were available at that early date.

The Mercury communications network, serving 19 locations, consisted of 102,000 miles of teletype lines, 60,000 miles of telephone lines, and 15,000 miles of high-speed data lines [15].

The limiting factor affecting the Mission Control activities for Project Mercury was the reliability and effectiveness of the ground communications system, necessitating the deployment of flight controllers to overseas sites to provide back-up in case of communications failure. This fact had not been clearly evident in 1959, when NASA Specification S-45 was issued. I quote here directly from Corliss [6, p.86]:

> The network job turned out to bigger than anyone had anticipated. First, somewhat to their surprise, the Langley study group found that there was no such thing as a commercial or military, world-wide communications system.

THE GEMINI PROGRAM - TWO MEN IN SPACE

The Requirements

The Gemini program, which developed from an "improved" Mercury concept in early 1961, led to a massive up-grading of the Mercury network. First of all, the Mercury Control Center was quite inadequate for a dual-vehicle mission (Gemini and Agena), and a new control center designed for Gemini (and later Apollo) Mission Control was built at Clear Lake, near Houston, later to become the Manned Spacecraft Center (now Johnson Space Center) [16/6b].

Secondly, the Manned Space Flight Network (MSFN), as the Mercury network became known, would need major modifications to support the Gemini Project which required multiple-vehicle rendezvous and docking maneuvers and long-duration flights. The network had to have the capability to track two vehicles simultaneously, and to provide dual command data based on orbital elements, orbital plane changes, rendezvous maneuvers, and re-entry control to the vehicles' onboard computers. The amount of information generated and transmitted during a single Gemini flight was over 40 times the amount generated and transmitted to the control center during the most complex of the Mercury flights.

This meant, of course, that the communications network would have to expand both in terms of data rates and in reliability over extended periods of time.

The Communications Challenge

The immediate consequences of long-duration missions (up to 14 days duration) meant that:

- The geographical coverage of the MSFN would have to be increased;
- There was an increase in network reliability requirements;
- Station staff would need to adopt shift operation;
- Spacecraft rendezvous meant doubling many antennas and transmitters to support two spacecraft;
- The presence of two spacecraft, one of which was much larger and more complex than the Mercury capsule, would necessitate expansion of telemetry and ground communication capabilities. The Agena target vehicle required complete new sets of consoles, instruments, operators, etc.; and,
- Two maneuvering spacecraft would require more ground control displays and command capabilities.

In sum, the Gemini network requirements would expand the functions of the MSFN. However, Gemini also represented an opportunity to improve the state of the art in communications, computation, and network automation in preparation for the Apollo program, which was proceeding in parallel with Gemini.

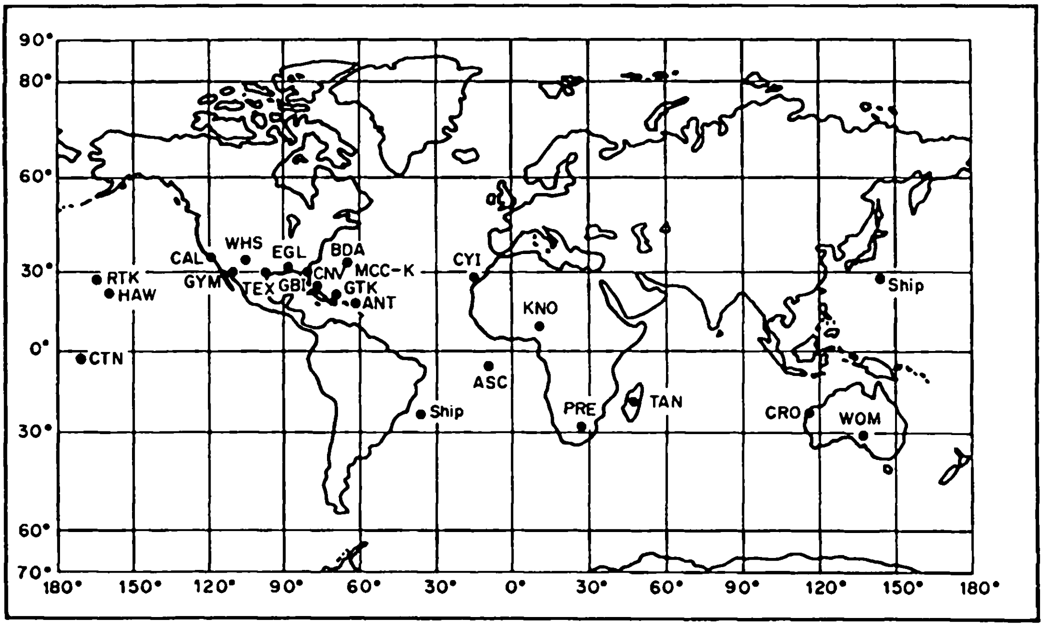


Figure 7 Gemini Network Stations.

One Gemini guideline, that had a significant effect upon the MSFN, was the relaxation of the Mercury requirement for almost continuous orbital coverage, requiring 17 fully instrumented tracking stations. The MSFN could concentrate heavily instrumented facilities at a few "primary" sites and place secondary sites, with more limited capabilities, where they were needed for particular missions.

During Mercury, it had been assumed that some of the communications links between the control center and the stations would occasionally be lost. Such instances were so rare, in fact, that NASA decided to remove flight controllers from many stations and to centralize control at Houston. Flight controllers remained at a few primary Gemini sites, throughout the Gemini Program, at locations where communications reliability was less than required. See Figure 7 for location of Gemini network stations.

Also during the Mercury Project, the telemetry data (PAM/FM) was decommutated and displayed, via analogue meters, to the on-site flight controllers. They, in turn, read the values of key parameters from the meters during the pass of the Mercury capsule over the station, and plotted these values on site. The readings, expressed for each parameter in Percent-Full-Scale (PFS), were also sent post-pass via teletype to the control center. That is, all evaluation and reporting of telemetry parameters was a visual and manual process, except for real-time data from the North American continental stations.

In the latter days of the Mercury Program (during MA-8 and MA-9 specifically), tests were made, using a AN/UYK1 digital computer (8 kilo-bit memory), to perform data reduction and reporting via digital data-links. The tests were very successful, and they led to the use of on-site data processors during Gemini for automatic generation of post-pass and near real-time telemetry summaries and command histories.

The major changes from Mercury to Gemini, which were to have an impact, more than anything else, on the communications system were as follows:

- o Telemetry data would be transmitted via Pulse Code Modulation Formats at bit-rates between 51.2 Kbs and 72 Kbs. (Mercury used an Analogue PAM/FM System rather than the PCM Digital Telemetry);
- o Digital computers (UNIVAC 1218) would be installed at primary sites to buffer the high-bit rate data, select required parameters, and act as a data compression system, enabling telemetry data in reduced format to be transmitted to Houston MCC via 2.4 Kbs data links or, (from most overseas stations) via teletype circuits at 60 or 75 wpm.
- o Digital command systems would be installed at Gemini tracking stations. These devices, equipped with non-volatile memories, could be used for real-time commanding by on-site flight controllers after the memory had been loaded (and validated) from Houston by teletype. This was significant, since in Mercury the capsule could accept only 9 commands, on Gemini the two spacecraft could accept and process over 360 different commands.
- o Bio-medical data would be transmitted (via FM/FM IRIG formats) from the primary sites as well as being displayed to flight surgeons on-site.
- o Air-to-ground spacecraft communications would be remote-controlled from Houston at certain sites.

- The new equipment would be of solid-state design and would be basically digital in function. This was in marked contrast to Mercury, where almost all the electronics equipment at the stations were analogue in nature and used vacuum-tubes.

This last item resulted in a vast expansion in the NASA training requirements, which further resulted in a large program to train the MSFN technical staff in digital techniques. The MSFN Engineering and Training Center, at Wallops Island, Virginia, trained over 800 engineers and technicians in the new systems, and in semi-conductor theory and digital logic between September, 1963, and the end of 1964 [20].

With the move of the Mission Control Center (MCC) to Houston, the communications links between GSFC and Houston became vastly more complex than the so-called "wideband" links between GSFC and Cape Canaveral (Mercury Control). The following circuits were established by early 1964:

1. 40.8 Kbps wide-band data lines for transmission of telemetry data from the MSFN.
2. 2 Kbps high-speed data lines for command, tracking and telemetry data.
3. 100 wpm teletype lines for command, tracking, acquisition, telemetry, and telex message traffic.
4. Video lines for television signals.
5. Audio lines for voice communications between MCC, and MSFN and the spacecraft.

From the above, it can be seen that the Gemini Program required not only sophisticated and complex electronic instrumentation at the tracking stations, but also a vastly more complex communications system than that used for Project Mercury. This challenge was met by NASA and by the staff of the MSFN.

The NASA Communications Network - NASCOM

Creation of NASCOM. This paper has mainly addressed the support given by NASA and the communications industry to the Manned Space Flight Program because, in the early 1960s, this was the driving force in establishing the need for reliable voice and data circuits.

However, as NASA scientific satellites and JPL lunar and planetary probes became more and more sophisticated, a need developed for digital data links to serve the telemetry and command needs of these programs. Thus, with the digital instrumentation of the Gemini Program being implemented, the MSFN, DSN and STADAN tracking networks all had similar communications needs.

This led, in July, 1963, to the establishment of the GSFC Communications Division. NASA Headquarters defined all NASA long-line communications as "NASCOM" and delegated the management of NASCOM to GSFC [6a]. As of mid-1964, as the project Gemini network was being completed, the NASCOM mission was clearly defined, and the GSFC Communications Division was now charged with meeting the new requirements of Gemini and Apollo, as well as the ever more complex, unmanned spacecraft [10].

The Gemini Program was successfully concluded in November, 1966, and the race for the Moon was on. In nine short years from the launch of *Sputnik 1* (4 October 1957), the world's first world-wide consolidated voice/data switching networking had been constructed and had successfully passed two major milestones: the Mercury and Gemini Manned Space Flight Programs.

PROJECT APOLLO

In 1963, as the Mercury Program ended and the Gemini Program went into high gear, the configuration of the Apollo network was being established by NASA [6b]. The following tasks had been identified:

1. The expansion of seven Gemini stations to include the 9-meter dish Unified S-Band (USB) equipment.
2. The construction of four brand-new 9-meter USB stations at Merrit Island (Florida), Ascension, Antigua and Guam.
3. The construction of three new MSFN 26-meter USB stations at Goldstone, Canberra and Madrid.
4. The addition of DSN "wings" to the co-located JPL stations at Goldstone, Canberra and Madrid.
5. Conversion of five ships to provide USB and C-Band radar support.
6. Conversion of eight jet aircraft to provide VHF/UHF and USB support.

The analysis of this massive task has been the subject of many papers, and it is certainly beyond the scope of this paper. Instead, we shall concentrate on two aspects of this overall task: the Unified S-band System; and, the communications network from Mission Control to the lunar surface and back. Also, the greatly increased computer power available at the MSFN stations, at GSFC, and at Houston, will be discussed to illustrate the final and most dramatic changes as the MSFN entered the Apollo era.

The NASA Unified S-Band (USB) System

General Description. In July 1965, Goddard Space Flight Center held a technical conference which, for the first time, presented in detail a review of the future Apollo USB system [8].

It must be remembered that Gemini stations were equipped with VHF telemetry and A/G Voice Systems, UHF Command Systems, C-Band and S-Band Tracking Radar, and VHF Tracking Systems. This led to a proliferation of antennas and frequencies. Although these same systems would, in many cases, be re-used for the early Earth-orbital Apollo missions, it was clear that the existing instrumentation (1965) was not capable of supporting reliable tracking and communications to lunar distances. To expand the range of existing MSFN equipment would have required development of high-powered radar beacons and a major expansion of the VHF and UHF equipment capability. Since JPL was already using a unified system for their lunar and planetary missions, this was a logical choice for the USB system.

The design of the USB system was based on the coherent Doppler system and the pseudo-random range system developed by JPL. The S-Band system utilized the same techniques, but it added voice and data channels.

A single carrier frequency was assigned in each direction for the transmission of all tracking and communications data between the spacecraft and the ground. The voice and up-data were modulated onto sub-carriers and combined with the ranging data. This composite information then phase-modulated the transmitted carrier frequency (see Figure 8).

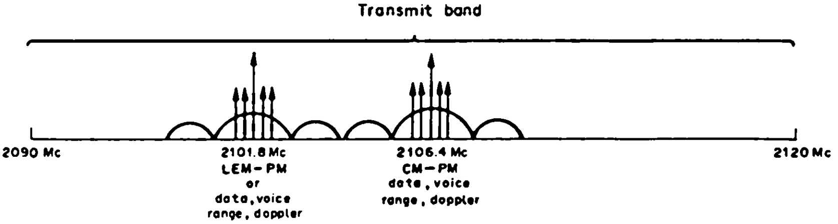


Figure 8 The USB Up-Link Spectrum.

The received and transmitted frequencies were coherently related, permitting measurement of the carrier Doppler frequency by the ground station for determination of spacecraft radial velocity.

In the spacecraft transponder, the sub-carriers were extracted from the RF carrier and demodulated to produce voice and command information. The binary ranging signals, modulated directly onto the carrier, were detected by the wide-band phase detector and translated to a video signal.

Voice and telemetry data transmitted from the spacecraft were first modulated onto sub-carriers, then combined with video-ranging signals, and finally used to phase-modulate the down-link carrier frequency. The transponder transmitter could also be frequency-modulated for transmission of television data or recorded TLM data, in playback mode (see Figure 9).

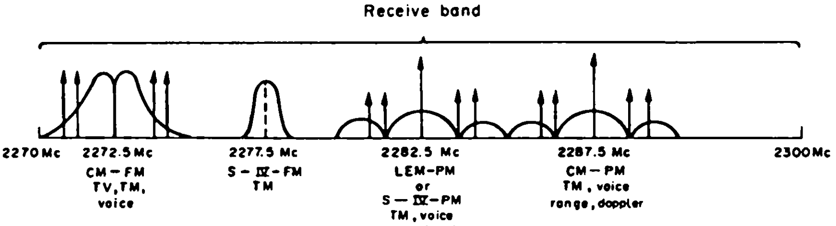


Figure 9 The USB Down-Link Spectrum.

The basic USB system was capable of providing tracking and communications data for two spacecraft simultaneously, providing that they remained within the beamwidth of the single antenna. The primary mode of tracking was via the PM mode of operation, using two sets of frequencies separated by 5 MHz.

The selection of the S-band frequency band was dictated by the ITU radio regulations assignment of 2.1 - 2.5 GHz frequencies for "Space Research." The C-Band is actually much better for Earth/space communications, but it is assigned to communications satellites. If one considers the following figure (see Figure 10) [22], one can immediately see that S-band is a most useful frequency band, when one considers noise, atmospheric absorption phenomena, and frequency allocations.

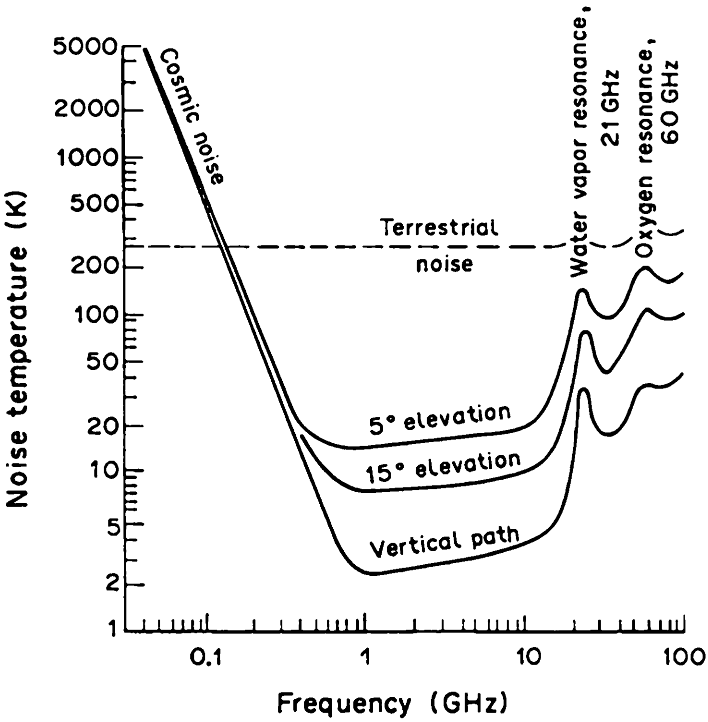


Figure 10 A Composite Noise Diagram. The solid lines show typical noise received by an Earth antenna, excluding the effects of rain, fog, and clouds. The dotted line shows the noise received at the satellite, caused mainly by the Earth [22].

To support the Apollo Program, NASA installed 9-meter USB antennas at nine tracking stations, and 25-meter USB antennas at three further stations. The basic configuration of a former Gemini primary station modified to support Apollo with Unified S-band 9-meter dish, is shown in Figure 11 [23].

Apollo Communications

The New Requirements. The Apollo requirements for centralization of flight control and increasing quantities of data had a significant impact on the NASCOM network [8].The USB system required transmission of three basic data streams—telemetry and tracking information from the stations to the control center and command data from the control centers to the stations. In addition, the need to relay voice messages between MCC Houston and the Apollo crew required voice/remote keying capabilities. It was clear at the outset that the quantity of data to be handled via the NASCOM network was far in excess of the capability of the teletype-based communications network of the Mercury and Gemini eras. NASA had therefore to design and engineer a world-wide network of high-speed data transmission facilities connecting nearly 30 overseas locations and five locations in North America.

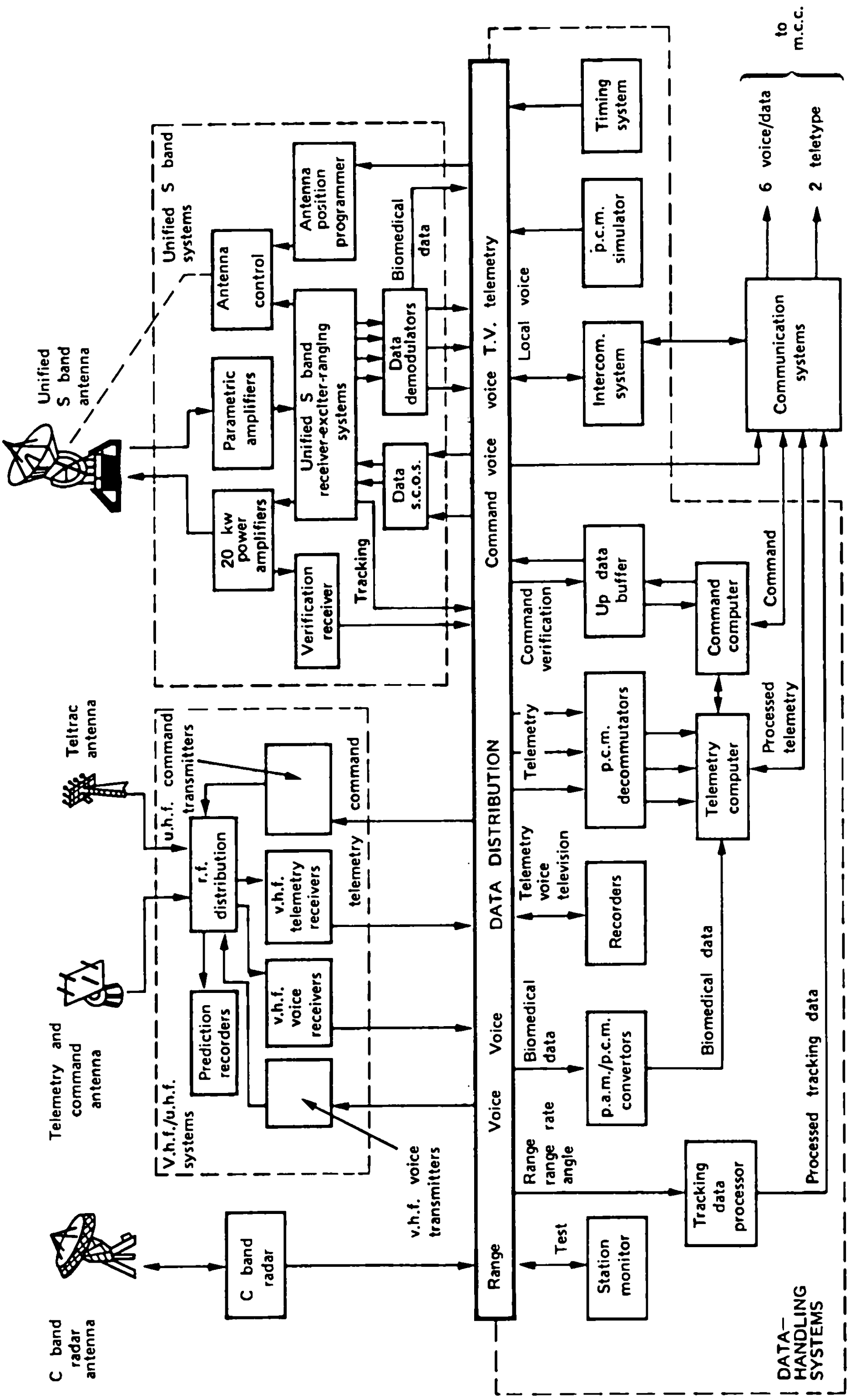


Figure 11 Manned Space Flight Network: Functional Block Diagram of Station (Modified GEMINI Primary Station).

These facilities consisted of voice-bandwidth channels, derived initially from combinations of landline, microwave radio, submarine cable, and high frequency radio systems. The initial planning for Apollo foresaw the provision of a minimum of two duplex data circuits to each USB site, with 600/1200 bps operations available to all sites and 2400 bps operations achieved at same.

At this point, it would be useful to consider two comments made by senior NASA officials. The first, was this comment made by John Hodge (Chief of Flight Control Division, MSC, at the Gemini Mid-Program Conference, Feb. 1966 [16, p.187]:

> Communications satellites are effective systems in the accomplishment of manned space flight operations. During the combined *Gemini VIA/VII* Missions, the *Coastal Sentry Quebec* tracking ship never lost communications while being supported by the communications satellite "Syncom III" (over the Pacific).

Secondly, this comment made, the previous year, by Ozro M. Covington, Deputy Assistant Director, OTDS, GSFC, at the conclusion of the USB conference at GSFC, 14 July 1965 [8, p.293].

> "HF communications and data error correction!" - "Quite frankly, I don't see any answer to really centralized flight control, until we can depend on satellite communications for all the stations which are not now tied to main trucks on cables and hardware lines." (i.e. the radio circuits).

HF radio was finally on its way out, and the communications satellite was needed. Fortunately, NASA had made provision with COMSAT, as early as June 1965, to obtain communications satellite circuits. In January, 1967, Intelsat placed Pacific 1 on station and, in March, 1967, Atlantic 2 was launched. These met Apollo requirements, and provided circuits to NASCOM throughout 1969 [Ref. 6a]. The communications quality was of such a high level that NASA subsequently decided to maintain all flight controllers at the MCC in Houston. The days of the on-site flight control team were over; the remote site would now be called in MCC-Houston parlance an "un-manned site." The fact that as many as 130 people were working on each unmanned site did not appear to be noticed. It is quite clear that without the availability of these communications satellite circuits in both the Atlantic and Pacific Ocean regions, the lunar landing mission of *Apollo 11* would have been infinitely more difficult, and the Rescue Mission of *Apollo 13* may have ended in disaster. (See Figure 12 for overview of NASCOM network - Aug 1970) [10].

The MSFN Network Data-Flow

We shall quickly review the on-site processing functions, which fulfilled the requirements for real-time data transmission to the control center.

The two basic processing functions at the MSFN station were real-time *telemetry data processing* and *command data processing* [Ref. 24]. To accomplish these tasks, two computers (UNIVAC 642B) were installed at each site, one assigned to each processing function, although one alone could support both functions in reduced mode. But, in addition, two other important functions must be mentioned: tracking and voice communications. A review of the Apollo On-site Data Processing and Communications System follows:

The Remote Site Data Processor (RSDP). As mentioned above, the RSDP consisted basically of two UNIVAC 642-B computers interfaced with the up-link and down-link sub-systems of the Apollo station (see Figure 14). But this is an oversimplification; Figure 13 [24] provides a representation of data flow between the elements of the RSDP itself.

Both computers had a main memory of 32,768, 30-bit words plus and an expanded memory unit (EMU) of 32,768 words, and each computer mainframe was equipped with 16 I/O channels. The I/O word rate of each system was 1 MHz to accommodate the PCM telemetry data at rates up to 72 Kbs. Each PCM interface channel accepted the demodulated serial PCM bit stream from the USB system, and provided a parallel digital 8-bit format to the computer.

Telemetry Data Processing [24]. Telemetry (TLM) data at 51.2 Kbs, 72 Kbs, or 1.6 Kbs (low speed data) was inputted to the TLM 642-B computer on a continuous basis. The entire telemetry data stream was stored in core memory, forming a continuously updated data pool.

TLM data output from the TLM data processor in 600-bit blocks, consisting of data plus synchronization and error-protection codes, was transmitted at 2.4 Kbs to GSFC via data-link and then to Houston MCC via wide-band link.

Command Data Processing [23]. Commands (CMD), originating at the Mission Control Center, were transmitted to the remote sites for further transmission to the spacecraft. Two types of commands were used in Apollo for each spacecraft, and they served two purposes:

1. To initiate immediate action in spacecraft systems; and,
2. To update the memory of the spacecraft guidance and navigation computer.

These were known as "Real-Time Commands" (RTC) or "Command Loads," respectively.

Both types of command were transmitted to the spacecraft only after an "execute command request" was received from the MCC at the remote site. This request was transmitted from the MCC in a protected command format. Upon receipt of the request, the CMD computer assembled the command in correct format, performed a validation of data format, and routed the command word via the Up-Data Buffer (UDB) to the Unified S-Band system, where it modulated a sub-carrier and was transmitted to the relevant spacecraft. It should be noted that for Apollo there were three space vehicles, the Command and Service Module (CSM), the Lunar Module (LM), and the S-IV B Rocket, which could all be commanded via the remote sites.

Tracking Data Processing [8/23]. The USB system at each station contained a subsystem designated as the Tracking Data Processor (TDP). This device converted the ranging information derived from the USB Ranging System (the Mark-1 System) into the formats needed for transmission to Houston. The data could be transmitted either as digital data (high-speed data) or in low-speed (teletype) format. Both methods were used for Apollo ranging measurements.

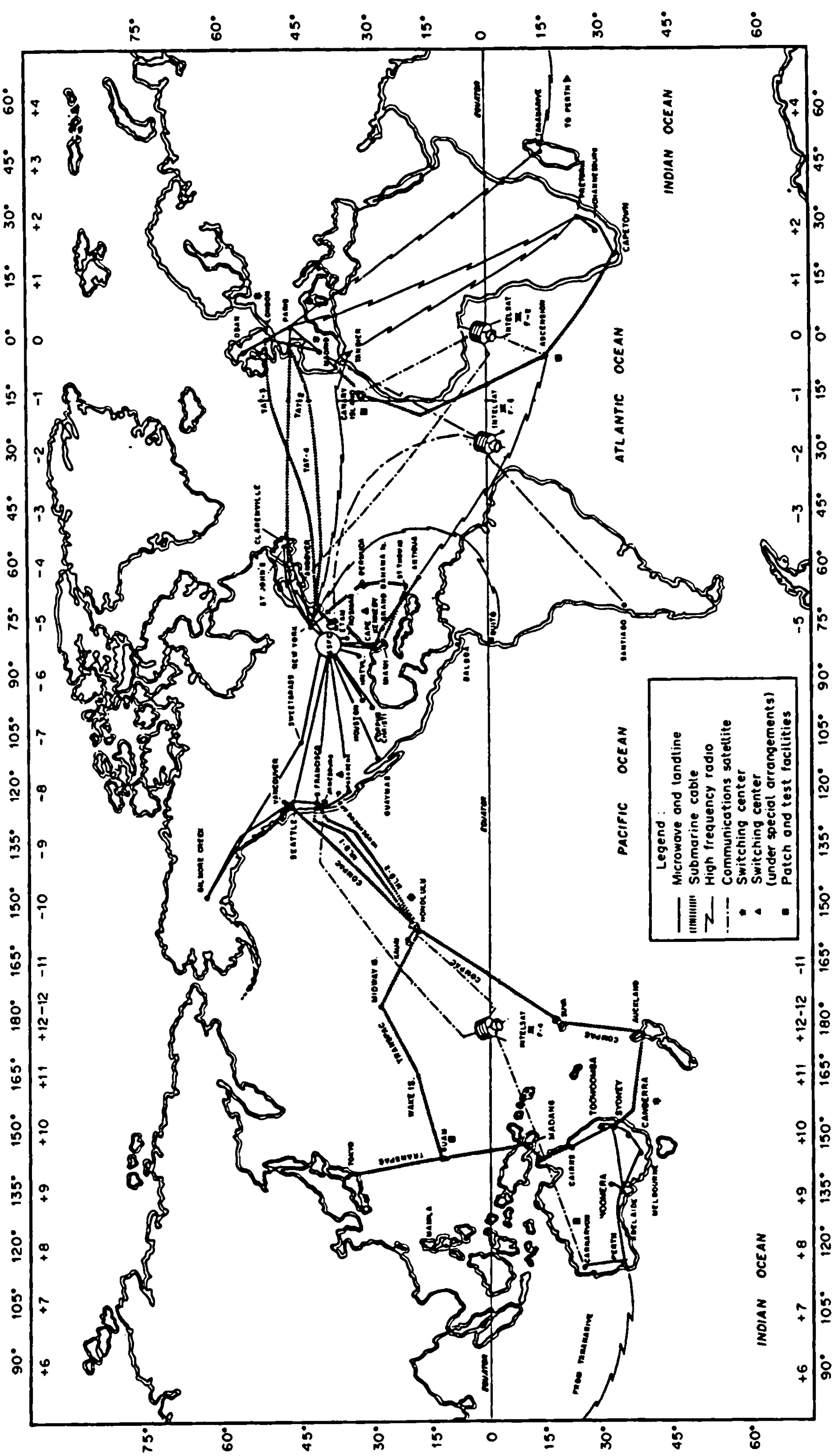


Figure 12 The NASCOM Network (As of August 1970).

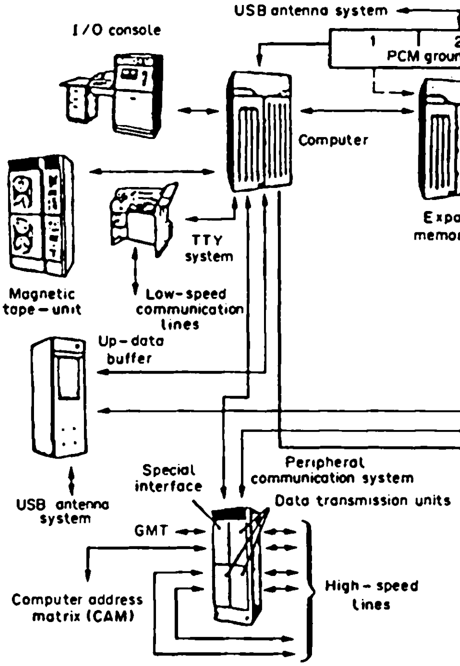
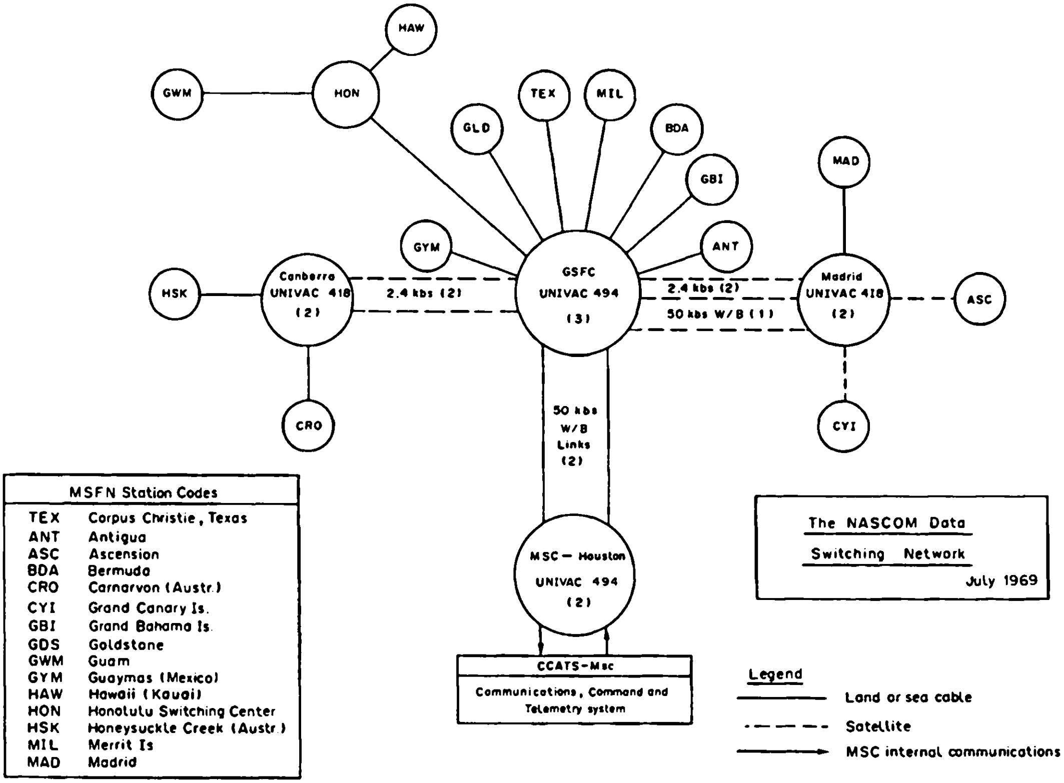


Figure 13 The Apollo Remote Site Data Processor (RSDP).



MSFN Station Codes

TEX	Corpus Christie, Texas
ANT	Antigua
ASC	Ascension
BDA	Bermuda
CRO	Carnarvon (Austr.)
CYI	Grand Canary Is.
GBI	Grand Bahama Is.
GDS	Goldstone
GWM	Guam
GYM	Guaymas (Mexico)
HAW	Hawaii (Kauai)
HON	Honolulu Switching Center
HSK	Honeysuckle Creek (Austr.)
MIL	Merrit Is.
MAD	Madrid

Figure 14 The NASCOM Data Switching Network (July 1969).

The above data, transmitted at either 10 characters per second (TTY) or 2.4 Kbs (Data-link), combined with X-Y angles from the USB antenna shaft encoder, and GMT, provided both GSFC and Houston with all the data needed to compute the spacecraft orbit and radial velocity. This method proved to be highly successful, and it was instrumental in the successful lunar landing of *Apollo 11* and, more especially, in navigating *Apollo 13* back to Earth after the near disastrous explosion.

Extremely high precision was achieved in measuring Doppler shift and range. Systematic errors in spacecraft velocity were within ±5 mm/s, or about 1 part in 10^6, of the velocity. Range determination errors were within ±25 meters. At lunar distance, this corresponds to an error of 1 part in 1.5×10^7 [Ref. 23].

Voice Communications. Voice communications at the remote sites were of three types:

1. Internal voice coordination circuits for operations management and coordination between the various operating positions on station.
2. External voice circuits between the site and GSFC via the SCAMA system for network coordination and also to Houston for coordination.
3. External voice circuits to Houston for remote keying and modulation of the USB voice up-link sub-carriers by flight controllers to communicate with the Apollo astronauts in orbit. Down-link voice communications from the astronauts was received, demodulated, and routed directly, via the same dedicated voice circuit, to MCC at Houston. High quality voice communications were provided throughout the Apollo program.

The two latter off-station communications circuits formed part of the six voice/data circuits and two telex circuits which interfaced each Apollo station with the NASCOM network and to Mission Control. Voice circuits could be used for either voice or data as required.

The NASCOM Network

General. From each Apollo USB tracking station, as many as six voice/data circuits and two teletype circuits were connected to the NASCOM network, which at the time of *Apollo 11* launch, consisted of approximately 3 million circuit miles of voice, data wide-band, and TTY circuits [10 & 24].

From Figure 12, it can also be seen that as late as August, 1970, the NASCOM network, while employing satellite and cable circuits to service the USB stations, still relied on HF radio to communicate with Tananarive in Madagascar (and as back-up to South Africa). But, with this exception, the essential mission data of voice, tracking, telemetry, and command were all routed via cable or satellite circuits to GSFC, thence to Houston.

How did NASA manage the enormous quantity of data being transferred between the Mission Control Center and the MSFN tracking stations? Basically this was done by establishing remote NASCOM switching centers at Canberra, Australia; Honolulu, Hawaii; London, England; and Madrid, Spain. The primary switching center at GSFC, in Greenbelt, Maryland, provided centralized communications and control and, in conjunction with the remote switching centers, enabled primary circuit sharing on long-haul circuits.

These five switching centers provided the interface between the multiple communications trunks used by the remote sites and the high-speed, multiple, diversely routed trunks connecting with GSFC. The centers at Canberra and Madrid employed dual UNIVAC 418 computers, in redundant configuration, to connect the low speed and medium speed data emanating from the remote sites with the circuits routed to GSFC, where UNIVAC 494 computers served as the central communications processor.

In addition, all four switching centers, using voice switching consoles similar to the SCAMA consoles at GSFC, enhanced NASCOM performance by expediting circuit restoration, by segmenting a circuit and isolating the faulty section and by reducing the number of long-haul voice circuits required. The four centers also exercised control over all communications facilities in their region, permitting the interconnecting trunks and tributary circuits to be placed under a single leasing agency. Each point in the system was connected by at least 2 trunks to provide back-up in case of circuit degradation or loss [24].

The remote switching centers provided message switching capability by regenerating incoming messages, converting the format to the format used by the terminal equipment of the outgoing trunk, and by performing data rate conversion correspondingly. Where many low-speed teletype circuits entered a switching center, a considerable savings in cost was realized by use of Voice Frequency Telegraph Systems (VFTG). These systems enabled signals from several (up to 16) low-speed teletype circuits to be multiplexed and re-transmitted as a composite signal over one high-speed voice-data circuit. This system was used between GSFC and Houston, GSFC and Honolulu, and GSFC and Kennedy Space Center. The system was designed to provide system error control for an end-to-end undetected bit-error rate of less than 1 bit in 10^9 [24]. This, coupled with the flexibility of line switching and diverse routing, established a very high degree of reliability of high-speed circuits. Mission Control at Houston was provided, at all times, with a high quality data path to the remote sites and, thereby, to the Apollo spacecraft.

The Real-Time Computer Switching System. The heart of the NASA Apollo communications system was the computer network located at GSFC, Houston, Canberra, and Madrid (see Figure 14). This system of real-time computer switching utilized three UNIVAC 494 computers at GSFC, with two each UNIVAC 418 computers at the Canberra and Madrid switching centers. The system provided the real-time interface with the two UNIVAC 494 computers at MSC, Houston. Two of the GSFC 494 computers were on-line at all times to process incoming data simultaneously (one prime, the second in stand-by). The third computer was off-line for development work, but it was rotated with the other two machines to permit regular maintenance [24, 10].

CONCLUSIONS

This paper has traced the development of communications from the birth of the Space Age at the time of the *Sputnik 1* launch (4 October 1957) until the lunar landing of *Apollo 11* on 20 July 1969. This was a period of somewhat less than 12 years.

Yet, in that time, man had not only placed astronauts (and cosmonauts) into Earth orbit, but he had achieved the goal of placing a man on the Moon by the end of the decade (the 1960s). It was an era of continuing developments in space, with lunar orbiters, lunar landers, Earth satellites and planetary probes all being launched to investigate the Earth's environment and the solar system.

Although not as apparent to the layman as space developments, the communications field expanded remarkably. It would not be until the late 1970s that microcomputer and LSI developments would revolutionize the computer industry and lead to networks of computers, linked by data communications systems, being installed throughout the world. But between 1957 and 1969, the NASA Space Program in particular forced the communications industry to develop new RF transmission techniques, new modulation methods, new error-protection and correction codes, new data transmission methods, and ever more sensitive low-noise amplifiers, which were all incorporated into the Manned Space Flight Network and Deep Space Network systems.

In 1957, and as late as 1959, no world-wide real-time communications system existed. The world relied on HF radio circuits for most transoceanic voice and teletype traffic. But in 1969, the world listened as a man took that "giant leap" for mankind on to the lunar surface. They later saw, "direct from the lunar surface," television images of Neil Armstrong and Buzz Aldrin relayed, via the MSFN Commercial Communications Satellites, to the entire world. In ten short years, the world's communications systems were changed beyond all recognition. Today, as we are faced with a future geostationary orbit over-crowding problem because of the proliferation of communications satellites, we accept world-wide voice, data and video transfer via satellite as the norm. Frequencies in the 20/30 GHz band are in use for satellite links (e.g. Japanese CS-2 series), and research on 40/60 GHz satellite links is progressing rapidly.

Figure 15 graphically illustrates the communications system established first in July 1969, as the first astronauts walked on the lunar surface after they had erected the 3 meter high-gain S-Band antenna for direct communications to Earth.

Telemetry, tracking and command data plus voice and television channels, were available between Moon and Earth for the first time. This shows clearly the vital contribution of the complex MSFN and NASCOM systems to the success of the NASA manned space flight program. It is interesting to compare this with Figure 2, and to realize what great developments in communications were achieved between October 1957 and July 1969.

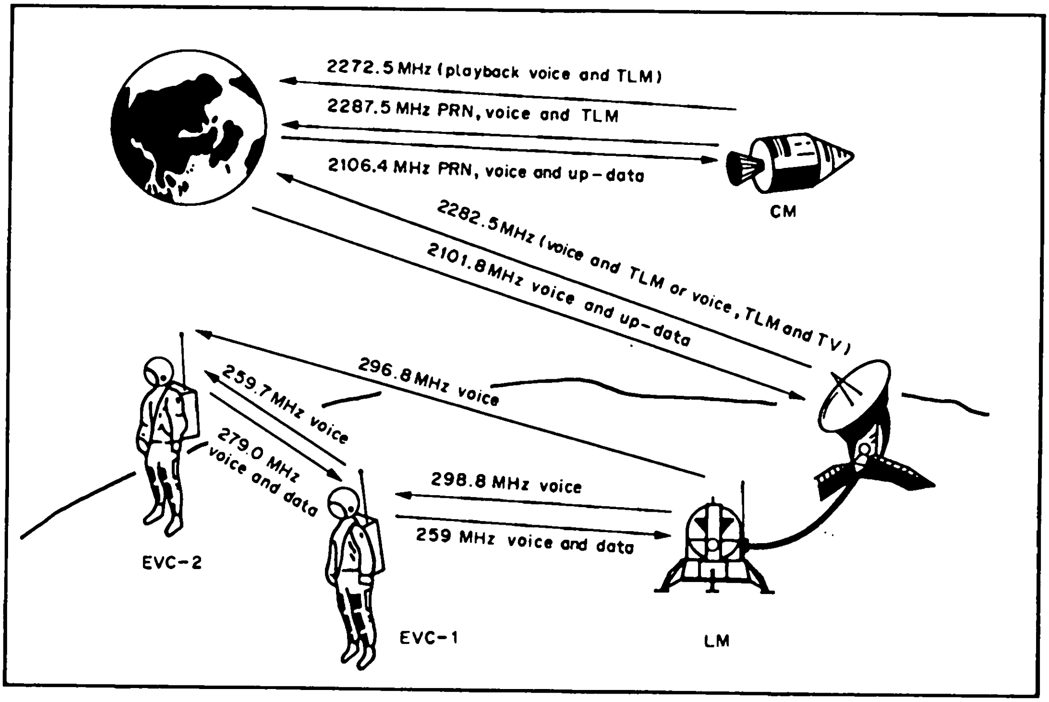


Figure 15 Communications During Lunar Surface Operations on the **Apollo 11** Flight.

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