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Chapter 7

Ary Sternfeld and Modern Cosmonautics*

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Abstract

This chapter is devoted to one of the cosmonautics pioneers, Ary Sternfeld, whose 105th Birth Anniversary was marked in 2010. The first part of this chapter presents the scientist's life and career (1905–1980). An analysis of Sternfeld's significant contribution to astronautics is presented. First, there was his work for many years as a science popularizer of astronautics. Sternfeld's scientific achievements were important, too. Of prime importance was his discovery of bi-elliptic trajectories for an approach to a central celestial body from an initial orbit and for transfers between orbits. Next discussed is Sternfeld's achievement in his monograph, *Introduction to Cosmonautics* (1937). For many space engineers, scientists, and cosmonauts, this monograph was a textbook during the early years of space research. The second part of this chapter analyzes the connections among Sternfeld's works and modern cosmonautics. It is shown that his ideas of bi-elliptic trajectories became part of the modern theory of space maneuvers. It is also shown that the linkage of this idea with the concept of gravity assistance provides the basis for some new and interesting solutions to several important space problems.

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Sternfeld and His Contribution to Cosmonautics

Ary Abramovich Sternfeld (1905–1980) lived a bright, vital, and creative life. The prime of his life was in the 1920s–1950s, a time when engineers and scientists had sharply increased their interest in the problems of spaceflight. During this period pioneer theoretical and experimental studies in cosmonautics were performed by K. E. Tsiolkovsky, R. Esnault-Pelterie, R. H. Goddard, H. Oberth, W. Hohmann, Yuri V. Kondratyuk, F. A. Tsander, S. P. Korolev, V. P. Glushko, M. K. Tikhonravov, and other scientists, engineers, and specialists, who can be considered the pioneers of rocket and space science and technology.[1-16]

These studies put cosmonautics on a firm footing of scientific theory and real technology. They turned humankind's ancient dream of spaceflight into reality. Ary Sternfeld made a remarkable contribution to the formation and development of cosmonautics, devoting his creative life to problems of space research. His ideas and works have passed the most difficult test—that of time—and have not lost their importance even today.

Sternfeld recalled that he commenced serious studies in cosmonautics after 20 years of age,[17] although some of his ideas were born during his school years and later developed, to be included to his book, *Introduction to Cosmonautics*, in particular. He found his calling in cosmonautics. Cosmonautics absorbed Sternfeld all his life. In 1927 he graduated from the Institute of Electrical Engineering and Applied Mechanics of Nancy University (Institute d'Electrotechnique et de Mécanicue applliquée, Université de Nancy), France. He worked for some companies, but then decided to continue his education at the Sorbonne for a Doctorate. For this, he took the investigation of cosmonautics problems as the subject of his Doctoral Dissertation.

Sternfeld learned the works of Tsiolkovsky, Oberth, Hohmann, and Esnault-Pelterie and carried out some original studies in cosmonautics theory. However, the path that he chose was thorny, as the supervisors of his Doctoral Dissertation did not agree with the problem he chose. Nevertheless, Sternfeld continued his work and began to correspond with K. E. Tsiolkovsky.[17-19] In 1930, Sternfeld published in the Paris newspaper, *L'Humanité*, a popular science article on cosmonautics.[20] In it, he recounted Tsiolkovsky's pioneer work on rocket flights to other planets, including a portrait of Tsiolkovsky, and prophetically wrote: "Only a socialist society will open a way to the exploration of space."[17] Figure 7–2 shows an excerpt from this article.

From that time, Sternfeld became a prolific and lifelong popularizer of ideas in cosmonautics and this is, undoubtedly, his great contribution to world cosmonautics.

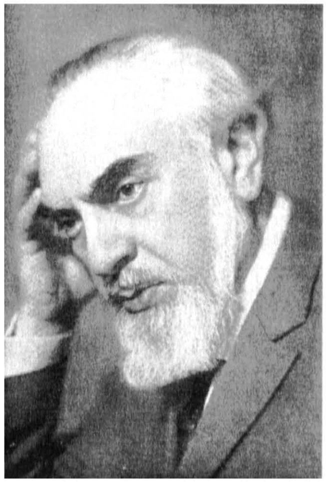

Figure 7–1: Ary Abramovich Sternfeld (1905–1980).

Utopie d'hier, possibilité d'aujourd'hui

PEUT-ON ALLER DE LA TERRE AUX AUTRES PLANÈTES ?

Les anticipations audacieuses de Jules Verne et de Well font place aujourd'hui à des prévisions scientifiques

La possibilité des voyages interplanétaires est si contestée en général qu'on n'y prête aucune attention. Cette possibilité est pourtant démontrée scientifiquement.

On a même commencé à faire des expériences pour prouver la justesse des déductions théoriques, et on peut espérer, sans témérité, que, dans les années qui viennent, le problème sera pratiquement résolu.

Que faut-il pour s'arracher à la terre ?

C'est bien la force de l'attraction terrestre qui nous tient prisonniers du globe. C'est elle qui rappelle au sol tout objet lancé vers le haut.

Mais la grandeur de cette attraction diminue sensiblement à mesure qu'on s'élève au-dessus du sol. La loi de Newton nous enseigne que l'intensité de cette force diminue proportionnellement au carré de la distance de l'objet au centre de la Terre. Ainsi, un objet qui pèse 1 kilog au niveau du sol ne pèse plus qu'un quart de kilog à une hauteur de 6 371 kilomètres.

K. E. CIOLKOWSKY
savant russe, un des pères de la science astronautique

Ainsi, pour lancer un projectile sur contre cette force et à choisir le moyens les plus efficaces.

Il est évident que le développemen de l'aviation, basée sur ses principe actuels, ne peut pas aboutir à la con quête des espaces interplanétaires. E effet, le « plus léger » et le « plu lourd » que l'air utilisent cet air com me milieu d'appui. Or, la densité d l'atmosphère diminue très vite et une hauteur de 100 kilomètres elle es déjà pratiquement négligeable. L hauteur accessible même pour l'avio le plus perfectionné est donc très l mitée.

La première idée qui nous vient l'esprit c'est de tirer sur la Lune l'aide d'un très long canon, un projec tile habitable, comme l'a proposé Ju les Verne (*De la Terre à la Lune* e *Autour de la Lune*).

L'obus de l'illustre écrivain ne ré siste pourtant pas à la critique de l science et de la technique. Entre au tres objections, il faudrait souligne qu'un tel obus ne pourrait certaine ment pas être habitable. En effet, a moment de l'explosion, les voyageur

Figure 7–2: Part of Sternfeld's article in *L'Humanité,* 1930.

In 1932, after an invitation from the Union of Soviet Socialist Republics (USSR), Sternfeld went there to establish a project to develop a robot android that he had recently invented, for remotely carrying out dangerous works. Figure 7–3 shows a schematic for this robot.

Later, it became obvious that this robot could also be used in the future for space operations. This project demonstrated that Sternfeld could solve both theoretical and engineering problems. It also showed that he had broad interests. Sternfeld carried out several projects in this area.[21-23,24(pp.74-87)]

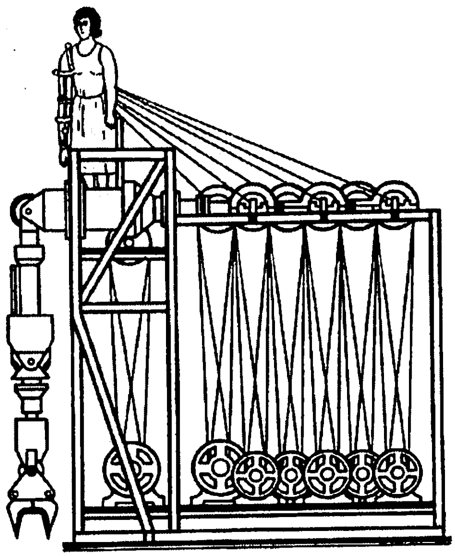

Figure 7–3: Schematic diagram of Sternfeld's robot android.

Ary Sternfeld then returned to his parents at Łódź, where, in 1933, with the help of his wife and his older sister, he finished the manuscript of his book *Introduction to Cosmonautics*. In December 1933, he presented his manuscript to the Astronomical Observatory of Warsaw University. Although it was not found to contain any scientific errors, Sternfeld's work was nevertheless received coldly, because his some ideas seemed to be too fantastic.[17,25-27]

Sternfeld presented to J. Perren and E. Esclangon his two original scientific studies, and at the beginning of 1934 they presented these studies to the French Academy of Sciences. These papers were soon published by the French Academy.[28,29]

In the first paper, the author suggested an original idea and a scheme for a device for an autonomous navigation, "Method of Determination of the Space Trajectory of a Body Moving in Interplanetary Space by an Observer Who is Connected with a Moving Coordinate System."[28] In that paper, it is suggested that the distance to the Sun is to be determined by a measurement of temperature from an onboard thermometer. An optical device provides an angle of flight. This allowed determination of the space trajectory.

In the second paper, "On the Trajectories of Approach to a Central Attracting Body from an Initial Keplerian Orbit,"[29] the author analyzed the problem of approaching a celestial body. It was Sternfeld who first showed that, under some conditions, a bi-elliptic detour approach to a central body (with initial flight away from the body) was better from an energy point of view than the usual direct approach along the arc of a half ellipse. Figure 7–4 gives a diagram and some characteristics of this flight.

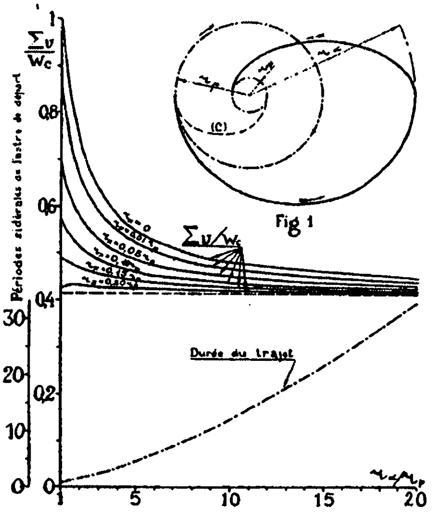

Figure 7–4: Figures from Sternfeld's paper "On the Trajectories of Approach to a Central Attracting Body from an Initial Keplerian Orbit."

It is this author's opinion that the solution demonstrated in Sternfeld's "Trajectories" paper is his main scientific achievement. Because of this discovery, Sternfeld's scientific contribution to cosmonautics is important and undoubted.

In May 1934, at the Sorbonne, Paris, Ary Sternfeld repeated the presentation of his manuscript "Introduction to Cosmonautics." Some well-known scientists were present, including R. Esnault-Pelterie, in particular.[19, 27] The audience warmly received this presentation and positive reviews of the study were given by R. Esnault-Pelterie, H. Oberth, W. Hohmann, J. Perren, and P. Langevin.[17] In June 1934, the Astronautics Committee of the France Astronomical Society gave its International Encouragement Prize for Astronautics (the REP-Hirsch Prize, presented 1928–1939) to Ary Sternfeld for his paper. In a letter to Sternfeld, A. Louis-Hirsch wished him to find a publisher for the book as soon as possible. This wish was eventually fulfilled in the Soviet Union.

Sternfeld "was sure that the Soviet Union would be the first country to explore space."[17] Because of this, in 1935, he moved to the Soviet Union and became a Soviet citizen. Sternfeld worked in the famous Jet Scientific-Research Institute (RNII) (see Figure 7–5), as a Senior Engineer, with other pioneers of cosmonautics, who became well-known scientists, in particular, S. P. Korolev, M. K. Tikhonravov, V. P. Glushko, Ju. A. Pobedonostsev, and G. E. Langemak.

He added new results to his manuscript and, in 1937, his book *Introduction to Cosmonautics* was published in the USSR.[30]

Figure 7–5: The house in Moscow where RNII was in the 1930s.

Figure 7–6: Cover of *Introduction to Cosmonautics*, 1937.

Some Soviet specialists who studied the problems of spaceflight gave the book good reviews,[17,31] and it played a great role in spreading knowledge about cosmonautics in the Soviet Union, which opened a new space era in the history of humankind. Thus this book, *Introduction to Cosmonautics*, became another of Sternfeld's important contributions to cosmonautics, and it is worth noting that it was Sternfeld who first introduced some important terms, such as "cosmonautics" and "first space velocity" (orbital velocity), which have now become part of the standard lexicon of cosmonautics.

After 1938, Sternfeld did not take any direct part in the development of rocket-space systems, nevertheless, for the rest of his career he actively continued his investigations in the theory of cosmonautics. In 1938–1946, he applied for, and received, several patents for inventions that developed his android idea, in particular.[21-23,24(pages74-87)] In 1945, he published in *Doklady Academii Nauk SSSR* (a main journal of the USSR Academy of Sciences), his paper on fuel mass consumption for the intersection of the Earth's atmosphere by a space rocket.[32] Following this, Sternfeld also published additional books and articles, mainly on spaceflight dynamics.[33-37,17]

In 1956, shortly before the launch of the first artificial satellite *Sputnik* from the USSR, which was the beginning of the space era, he published an interesting book *Artificial Earth Satellites*. In 1958, its Second Edition, *Artificial Satellites*, was published. In this book Sternfeld develops his old idea of the "detour" trajectory from the problem of an approach to a central body (for example, to the Sun) to a problem of inter-orbital transfer. In 1975, his *Introduction to Cosmonautics* was republished in a Second Edition.[17]

Sternfeld's works were published about 100 times in many languages and in many countries. His scientific activity was acknowledged in the Soviet Union and in many other countries around the world. In the USSR, the scientific degree of Doctor (Honoris Causa) in Scientific Techniques and the title of Honored Worker in Science and Techniques of the RSFSR* (USSR) were awarded to him. A memorial plaque was erected at the house where he lived in Moscow (Figure 7–7, where the scientist's daughter M. A. Sternfeld and the author are shown, too), and he was elected as an "honored citizen" of his native city, Seradz, where he was born. Nancy University and the National Polytechnic Institute of Lotaringy awarded him the degree of Doctor (Honoris Causa) in physics and mathematics. In 1963, he was awarded a second international prize, the Galaber prize in astronautics. On his Memorial, his scheme of optimal flight is shown, see Figure 7–8.

Figure 7–7: The house in Moscow where A. Sternfeld lived, near a pond "Patriarshy Prudy."

Figure 7–8: Sternfeld's Memorial on his grave, at the Novodevichy cloister where he was buried in 1980.

Sternfeld and His *Introduction to Cosmonautics*

In this author's opinion, Sternfeld's monograph *Introduction to Cosmonautics* was the most important product of his creative work. Using this book for a basis, here is a brief analysis of Sternfeld works.[38-40] What are the characteristics of this work? First, there is the breadth of analysis of the problems connected with the investigation of spaceflight. This book became a singular encyclopedia

* Russian Soviet Federative Socialist Republic.

of rocket-space techniques at a time when the theory and technology of rocket-powered spaceflight were being elaborated. Second, it is necessary to note Sternfeld's deep analysis of various aspects of the problems he was considering, and his wish to connect a solution of theoretical questions with practical questions of cosmonautics. Of course, not all his hypotheses and ideas were confirmed by subsequent developments in rocket-space techniques. Nevertheless, some his studies have passed the test of time. Third, there are some original, bright ideas in Sternfeld's work, especially in the area of spaceflight trajectories. The bi-elliptic trajectories of approach to a central body that he discovered have become classics that have entered into the canon of cosmonautics.

Here is a summary of the book's content. In the first part, the author states his ideas on the scientific importance of space investigations. He emphasizes their importance for the investigation of the Earth's atmosphere and the characteristics of the other planets of the solar system, and living conditions on them, and also their importance for astrophysics experiments. Sternfeld then outlines the laws of motion for the celestial bodies in the solar system, the properties of the Earth's atmosphere, and some of the physiological phenomena that a cosmonaut would expect to experience during spaceflight. He also gives an analysis of some methods of spaceflight that cannot be implemented, and so are without prospect, from his point of view. It should be noted that in the Second Edition of the book, the author adds the use of solar light pressure to the methods without prospect, but removes his former note that electric rockets are in that same category.

In the second part of Sternfeld's book, a theory of rocketry is developed. The author gives a review of the history of rocket studies—both in theoretical studies and experimental ones. Then the theory of rocket propulsion is discussed (including the electric rocket engine in the Second Edition) and the physical and chemical processes in the rocket engine are described. A special chapter is devoted to an analysis of the ways in which rockets can be used and rocket testing methods. In particular, the space rocket is described: its engine, control methods for active and passive flight, measuring, and regulating devices. Although today the parameters of spacecraft motion are determined by methods that differ from those suggested by Sternfeld, nevertheless, that he even addressed those important problems wins great respect. The author then describes the life-support conditions for a spacecraft and possible principles for the design of life-support systems.

The third part of the monograph ("The Path of a Space Ship") is devoted to an analysis of rocket flight dynamics problems. The author considers spacecraft orbits in the frame of a two-body problem, such as the problems connected with the launch of artificial Earth satellites (geostationary satellites, in particular). He examines the problems of flight to the Moon, and to other planets of the solar system. In this analysis, he proposes using an orbit that is close to the Earth and intermediate between the launch from the Earth and the final trajectory to the target body (in other words, a parking orbit prior to final orbital insertion). Analyzing flights to the planets, the author also studies the question of spacecraft returning to the Earth. Sternfeld introduces, for this, some bi-elliptic trajectories, with the spacecraft making a preliminary pass of an apocenter ("aphelic point" in the book), and considers the trajectories that give a return to the Earth over any whole or rational number of years. It was perhaps in connection with these trajectories, that he conceived his pioneering idea of the bi-elliptic trajectory for approach to a central body. The author develops this idea in the book and it is considered in more detail later in this chapter.

Following K. E. Tsiolkovsky, Sternfeld considers inclined and vertical takeoff in a gravity field and a rocket launch into the atmosphere from the Earth's surface and a return to the Earth. He provides some examples of the determination of rocket trajectories using numerical calculations. An analysis of compound (or multistage) rockets is carried out. Sternfeld considers a hypothetical possibility of decreasing energy loss during acceleration by using a "vertical tunnel." This helps to explain an interesting and important property of rocket flight dynamics: the greater the rocket velocity, the greater the energy change under acceleration. Sternfeld also provides other examples of interesting peculiarities of rocket flight, which he calls "rocket paradoxes." Sternfeld often returned to this theme of "paradoxes" in cosmonautics.[41]

Figure 7–9: Sternfeld with cosmonauts A. Nikolaev and P. Popovich in 1962.

In the last chapter, in order to improve the accuracy of the trajectory calculations, the author considers such exotic (for that time) problems as using the theory of relativity in an analysis of interstellar flight. In the appendix, he also discusses the problem of the inhabitability of other planets, and the universe in general, and looks at the connection of some cultures' legends and stories with ideas of interplanetary voyaging.

From this brief review of the book, it is obvious that Sternfeld's work was undoubtedly important for cosmonautics. In fact, in the 1950 years, at the "dawn" of cosmonautics, *Introduction to Cosmonautics* was the textbook, the guidebook, for some young specialists in space research and cosmonauts. [42(p.264)]

Sternfeld's Work on Space Trajectories

Investigation of spaceflight trajectories is a central point in Sternfeld's studies. Many of his results in this area are presented in the third section of *Introduction to Cosmonautics.* The discovery and investigation of the bi-elliptic "detour" trajectory is the major research finding disclosed.

Based on the pioneer studies of German scientist Hohmann (1880–1943)[5,8] and Soviet scientist Tsander (1887–1933),[2,7,11,12] it had previously been supposed that a two-impulse trajectory along a tangential half-ellipse was optimal for the classic problem of transfer between circular coplanar orbits in a central Newtonian gravity field (see Figure 7–10). The term "Hohmann–Tsander trajectory" will be used for this trajectory. The optimal approach to a body was supposed to be a similar direct one-impulse trajectory (see Figure 7–11).

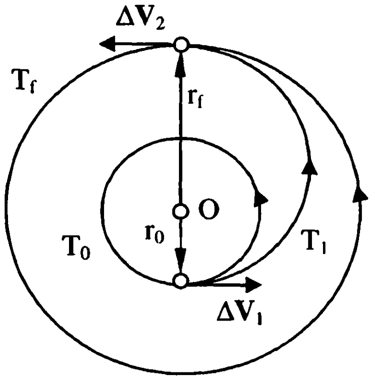

Figure 7–10: Two-impulse trajectory of the Hohmann–Tsander type for a transfer between circular coplanar orbits.

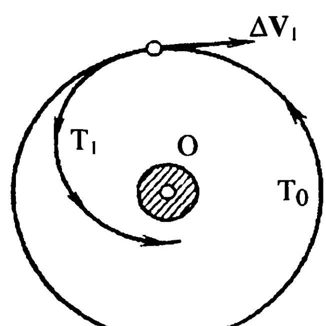

Figure 7–11: Direct approach to a central body for a Hohman–Tsander trajectory.

Analyzing the problem of an approach to a central body, Sternfeld carried out a very interesting study.[29,30,17,43] He first showed that the direct one-impulse approach to the central body (Figure 7–11) could be worse from an energy point of view than an indirect "detour" flight along a bi-elliptic trajectory, with initial flight away from the body (see Figure 7–12). Then, a decelerating impulse was applied at the apocenter of a transfer orbit, and it was only after that impulse, that the spacecraft approached the central body.

Sternfeld used this "detour" scheme for the analysis of a flight from the Earth to the Sun and for approaching Jupiter from its satellite Callisto.[17(p.133)] It is interesting that Sternfeld performed the comparative analysis of direct and indirect schemes not only with the usual Delta-V criterion but also with the criterion of useful mass, taking into account that some losses increased with increasing the flight duration (such as the food for a manned flight).

Already, in his early paper of 1934,[29] the author had paid attention to "detour" flights with orbits whose velocities in the contact points form small angles; this case may be more interesting and important. Below, in the next section, confirmation of this idea is discussed. Later.[35,37] Sternfeld developed his idea of the "detour" trajectory flight, applying it to the problem of a spacecraft launch to a satellite orbit and also to the problem of transfer between circular orbits (see Figure 7–13).

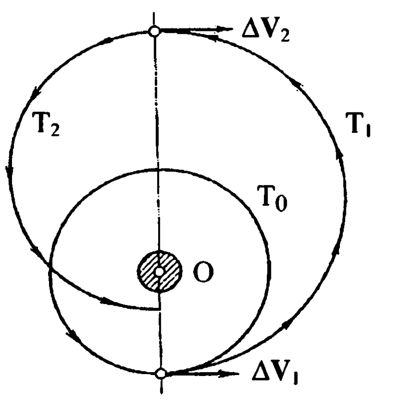

Figure 7–12: Sternfeld's "detour" trajectory for indirect approach to a central body.

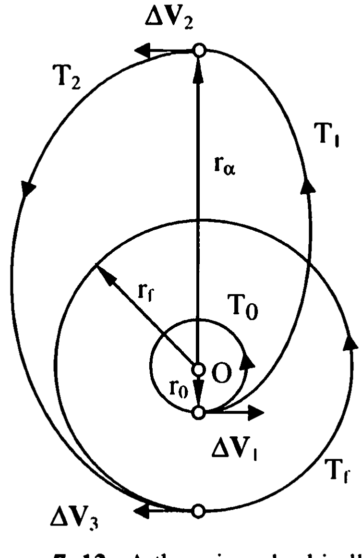

Figure 7–13: A three-impulse bi-elliptic transfer of the Sternfeld type.

It is also very interesting that the author, in 1956–1958, prophetically noted good prospects for using the "detour" scheme in flights to the Moon.[35(p.98),37(p.103)] This will be further discussed in the next section. Summing up this brief review of Sternfeld's development of his "detour" idea, in the 1930s, in RNII, there was the real possibility of uniting Tsander's results on gravity assist and interplanetary flights with Sternfeld's results on "detour" trajectories, and on this basis to design some space projects on the modern level: for example, a flight to the Sun with gravity assist near Jupiter, or a flight to geostationary orbit with gravity assist near the Moon. More about these projects is below.

Sternfeld carried out, in addition, some other interesting studies in space trajectories, such as the investigation of interplanetary expeditions with the trajectories Earth–planet (Mars, Venus)–Earth and planet–Earth–planet. Analyzing an approximate model of a flight, the author discovered the possibility of sharply decreasing the expedition duration, if the initial velocity increases to some critical value. Sternfeld paid close attention to an analysis of civil rocket trajectories for sending passengers, mail, and cargoes between points on the Earth's surface, etc.[44-47]

The Connection of Sternfeld's Results with Modern Cosmonautics

Theory of Space Maneuvers

Let us briefly consider the evolution of Sternfeld's ideas connected with orbital transfers of the indirect detour bi-elliptic type. The evolution of the theory for optimal multi-impulse orbital transfers was carried out in many directions, though only some are discussed in this chapter. The classic results of Hohmann, Tsander, and Sternfeld in two-impulse transfers and three-impulse bi-elliptic transfers between circular coplanar orbits were developed to more general cases, particularly, to energy optimal transfers between elliptic orbits, between elliptic and hyperbolic orbits, and between hyperbolic orbits.

Let us firstly consider, for example, transfers between coplanar elliptic orbits with free relative orientation, free transfer time, and limited distance to the attraction center ($r_{min} \leq r(t) \leq r_{max}$). Studies by Hoelker and Silber, Ting, Marec, Marchal, Gurman and Ivashkin[48-61] have shown that when the orbits are aligned and satisfy the limitations in distance above, the optimal transfers are two-impulse and three-impulse that are generalizations of the classic Hohmann–Tsander trajectory and Sternfeld trajectory.

In a two-impulse scheme, the transfer is performed between the more distant apocenter of a given orbit and the pericenter of another orbit (Figure 7–14).

In the three-impulse scheme, when the first cotangential accelerating velocity impulse is applied at initial pericenter π_0, it increases the spacecraft velocity. After that, the spacecraft moves away from the attraction center. At the apocenter α_1 of the first transfer orbit, at the maximal distance $r=r_{\alpha 1}=r_{max}$, the second cotangential velocity impulse is applied, $r=r_{\alpha 1}=r_{\alpha 2}$. The pericenter of the second transfer orbit received is equal to the final pericenter, $\pi_2=\pi_f$. Here, the third cotangential decelerating impulse is applied (see Figure 7–15).

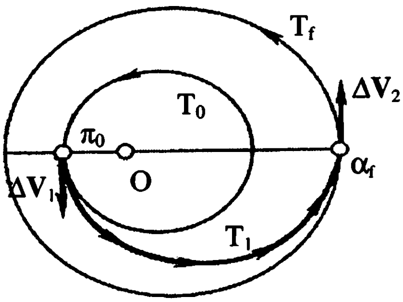

Figure 7–14: Two-impulse transfer between elliptic orbits.

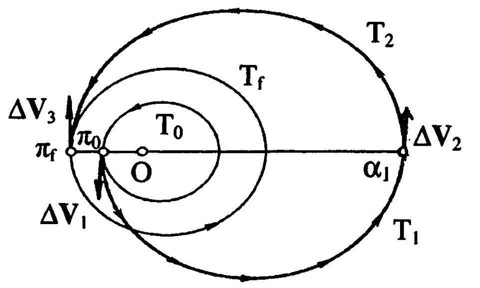

Figure 7–15: Three-impulse transfer between elliptic orbits.

If there is no limitation on the maximal distance to a central body $r_{min}\leq r(t)<\infty$, an energy optimal three-impulse transfer will, in this limit case, use two parabolic orbits and a flight "through infinity." This is a so-called bi-parabolic transfer (see Figure 7–16). Of course, this cannot be realized in practice, and it would not be received, if increasing some losses with time had been taken into account. Sternfeld noted this in his *Introduction to Cosmonautics.*

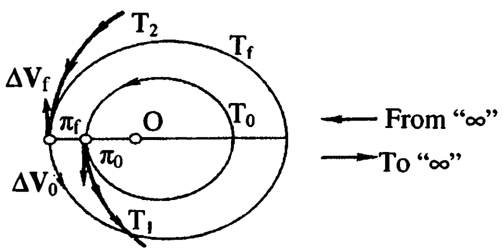

Figure 7–16: Bi-parabolic flight "through infinity."

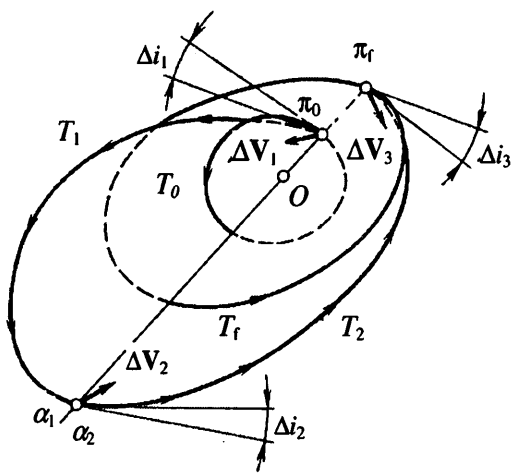

Figure 7–17: Non-coplanar three-impulse transfer between elliptic aligned orbits.

If there is limited jet thrust of the engine, and impulse control cannot be performed, the optimal trajectories shown can be realized exactly enough—by some number of small active arcs around the pericenters or apocenters shown, that are separated by approximately whole (or half) revolutions of the orbital passive motion.

Coplanar transfers, particularly Sternfeld's transfer, are generalized (by the studies of Rider, Marshal, Marec, Winn, Gobetz, Doll, Ivashkin, and Tupitsyn, etc.[57-64]) for the case of a transfer between non-coplanar elliptic aligned orbits. In the three-impulse case, every impulse is also applied at the apsides (pericenter or apocenter), but in any angle to an orbital plane (see Figure 7–17).

A domain where three-impulse transfers are optimal and better than two-impulse ones is now bigger than in the coplanar case. Thus, an optimal rotation of the circular orbit is always a three-impulse transfer (and a bi-parabolic one if $r_{max}=\infty$).[57,58]

For a flight from a low Earth circular orbit of radius r_0=6,630 km to a geostationary equatorial orbit (GEO) of radius R=42,164 km, Figure 7–18 gives the characteristic velocity w_f, (the sum of all impulses values) of the three-impulse transfer, depending on a parameter $k=R/r_{\alpha 2}$. $0 \le k \le 1$.[60,63,64] A case k=1 corresponds to $r_{\alpha 2}=R$ when the three-impulse case, N=3, became a two-impulse one, N=2. A case k=0 corresponds to the bi-parabolic case. The transfer N=2 is worse than the transfer N=3, if the initial inclination is more than ~39°. This is correct for spacecraft launched from cosmodromes at Baikonur and Plesetsk. In the next section, the development of these results will be considered.

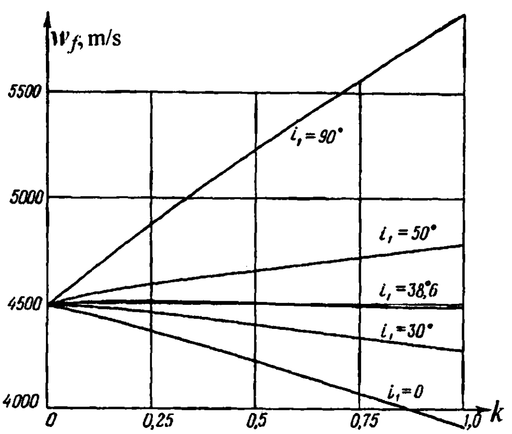

Figure 7–18: Characteristic velocity for three-impulse transfer from low Earth circular orbit to geostationary orbit.

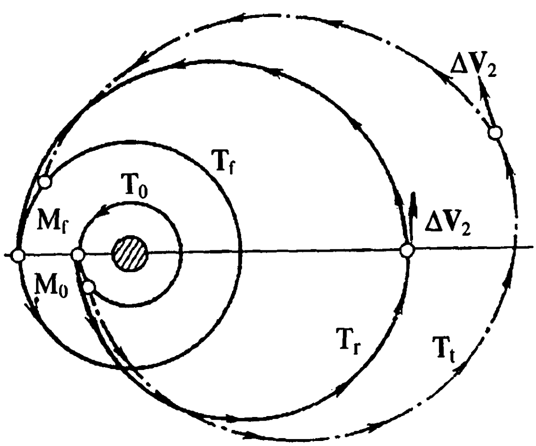

Figure 7–19: Optimal trajectories T_r and T_t, for limitations at distance and flight duration.

There are many other generalizations about Sternfeld's "detour" transfer. Here is one more result that is connected with Sternfeld's solution. A modification of the optimal trajectory T_r is investigated[65] if the upper limitation on the distance $r \leq r_{max}$ is changed to a limitation on the transfer duration $t_f - t_0 \leq t_{max}$. In the latter case, an optimal trajectory T_t is defined numerically, using the theory of optimal impulse maneuvers (see Figure 7–19).

From a geometry point of view, this trajectory T_t differs from Sternfeld's apsidal trajectory T_r. Its impulses are applied near the apsides and with some angles to velocities vectors, it has greater maximal distance. But, from an energy point of view, these trajectories are close if the flight duration is the same for the both trajectories. The characteristic velocity for the trajectory T_t is less than that for T_r, but this decrease is small, less than about 1 percent if the ratio of the final and initial radii is less than 100. Therefore, Sternfeld's apsidal trajectory can give a good approximation of the optimal transfer for limited flight duration. Thus, Sternfeld's "detour" trajectory concept had future prospects and naturally entered into modern spaceflight dynamics.

Next, three projects are considered where the "detour" idea is well exemplified. The first is the case of a spacecraft to be launched to geosynchronous equatorial orbit (GEO).

Spaceflights between Earth and Geosynchronous Equatorial Orbit

The two-impulse scheme (N=2) is usual for a spacecraft launch to geosynchronous equatorial orbit (GEO). However, as has been shown, the three-impulse scheme is, from an energy point of view, better than the two-impulse one if the initial inclination is large enough (i_0 >39°). For i_0=50°, $w_f \approx$4,780 m/s if N=2, and $w_f \approx$4,485–4,530 m/s if N=3, and $r_{\alpha 2}$>400×10^3 km. If $r_{\alpha 2} \approx$400×10^3 km, the second intermediate impulse is large enough—its value is $\Delta V_2 \approx$300 m/s.

The idea arises to replace this velocity impulse by lunar gravity assist.[60,63,64] In this case, the characteristic velocity for the launch will decrease and be equal to about ~4,250 m/s.

In Figure 7–20, the line w_f^I gives the characteristic velocity for the launch without lunar gravity, while the line w_f^{II} corresponds to taking into account the lunar gravity assist.[60,64] The latter case is better for an initial inclination more than ~28°. Figure 7–21 gives a typical "detour" trajectory for a spacecraft launch to GEO with a close flyby of the Moon.[63]

In 1997–1998, the satellite AsiaSat 3/HGS-1 was launched from the Baikonur cosmodrome to GEO using this type of trajectory.[66-68] The usual two-impulse trajectory could not be used due to an accident with the Proton launcher. As a result, using the more economic "detour" trajectory, employing lunar gravity assist, enabled the satellite to be placed in the correct orbit. This flight was referred to as "the most spectacular 'must mention' item" in 1998.[67]

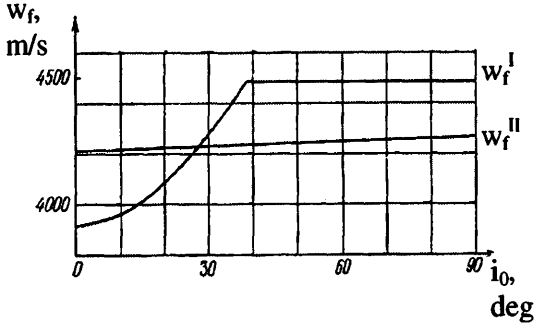

Figure 7–20: Characteristic velocity of the two schemes for a spacecraft launch to GEO.

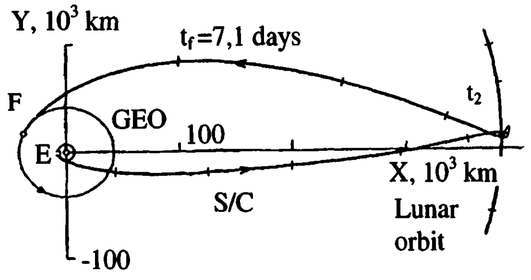

Figure 7–21: Spacecraft "detour" trajectory from Earth to GEO.

So, for a spacecraft launch to the GEO from a cosmodrome with a high enough latitude, an optimal flight path is not the direct Hohmann–Tsander type trajectory, but the indirect "detour" trajectory with the lunar gravity assist that typifies Sternfeld's scheme.

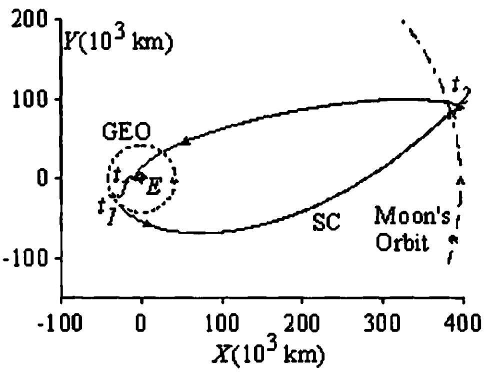

Figure 7–22: The XY geocentric view for a GEO–Earth trajectory of "detour" type with lunar gravity assist.

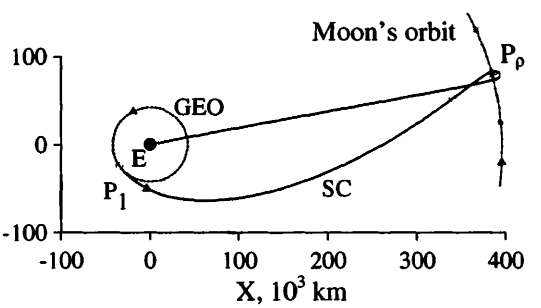

Figure 7–23: Geocentric trajectory for a "normal" reentry with lunar gravity assist near the ascending node of the Moon's orbit.

Similarly, for the case of a spacecraft return from GEO to the Earth, it is also more effective, from an energy point of view, to use, not a direct flight with decreasing velocity (at ~1,490 m/s), but a "detour" trajectory with acceleration (at ~1,100 m/s), with a flight to the Moon, utilizing lunar gravity assist, and a following flight to the Earth.[69-71] Figure 7–22 gives a trajectory of this reentry to the Earth, commencing from GEO on 29 December 2000 (with a total flight duration of about 9.4 days), in projection on the geo-equatorial plane. Here, reentry to the Earth's atmosphere is performed along a tangential trajectory, with the altitude of osculating perigee $H_{\pi f} \approx 50$ km, and final osculating perigee distance $r_{\pi f} \approx 6420$ km. Figure 7–23 gives a trajectory for spacecraft reentry from GEO to the Earth with a "normal" reentry to the atmosphere, at a final osculating perigee distance $r_{\pi f} \approx 0$. The energy advantage of the indirect flight versus the direct trajectory is better in this normal case $r_{\pi f} \approx 0$ than in the tangential case.

Lunar Flights

Direct Lunar Flights

Investigations of trajectories between the Earth and the Moon are of great importance for both celestial mechanics and cosmonautics. From the first flight to the Moon, in 1959, until now, "direct" trajectories have been used for almost all lunar flights.[72-74] Figure 7–24 shows the trajectory of the Soviet spacecraft Luna-9, which performed the first soft landing on the Moon.

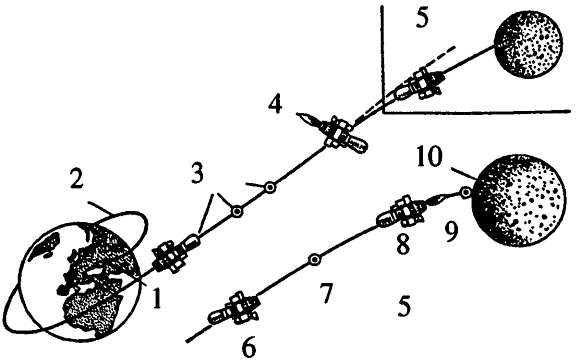

Figure 7–24: Trajectory of the spacecraft Luna-9: 1. launch; 2. intermediate orbit; 3. measurements; 4. course correction; 5. deceleration; 6. spacecraft orientation along lunar vertical, $\rho \approx 8{,}500$ km; 7. radio-altimeter switch-on; 8. deceleration engine switch-on; 9. deceleration engine cut-off; 10. soft landing.

The usual lunar trajectories of the direct type, with chemical rocket engines, have a small flight duration (several days) between the Earth and the Moon. In practical terms, the spacecraft moves in frame of a three-body problem (spacecraft, Earth, and Moon), because the Sun creates a small perturbation only. Near the Moon, a motion to the Moon, and a flight from it, are performed along hyperbolic selenocentric orbits, with velocity at "infinity" of ~1 km/s. This results in significant fuel consumption for spacecraft decelerating and accelerating near the Moon for these trajectories. Therefore, it is important to find low-energy lunar trajectories for spacecraft.

"Detour" Earth–Moon Flights

Sternfeld said[35,37] that using a "detour" trajectory would be in prospect for a flight to the Moon. For Sternfeld's bi-elliptic scheme, if the maximal distance to the Earth is large enough, about several million kilometers, then the "detour" trajectory is better than the usual direct flight. But, in this case, the Sun's gravity has to be taken into account. Considering the "detour" bi-elliptic scheme of Earth–Moon flight in the gravity field of the Earth–Moon–Sun–particle system, it is possible to derive new "detour" types for the Earth–Moon trajectories (see Figure 7–25).[75-83]

From the point of view of an external appearance, these trajectories are similar to Sternfeld's bi-elliptic flight. However, from a dynamic point of view, they are different:

- the Sun's attraction increases the perigee distance, unless a velocity impulse is provided by a rocket engine;
- the approach to the Moon is performed along an elliptical orbit, determined by the Earth's gravity, and there is lunar orbit capture (at point C on Figure 7–25).

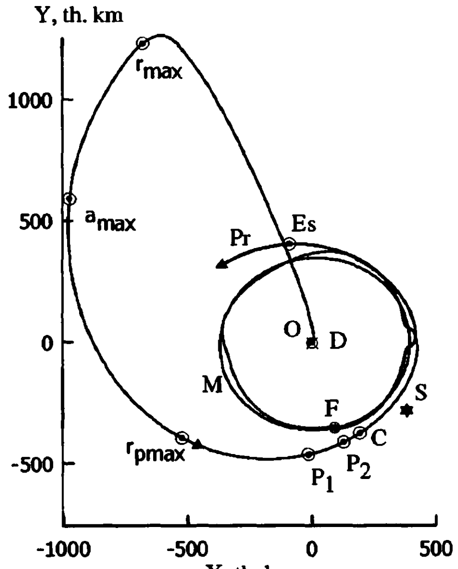

Figure 7–25: Geocentric "detour" Earth–Moon trajectory with lunar capture and its passive continuation Pr in the Earth–Moon–Sun–particle system.

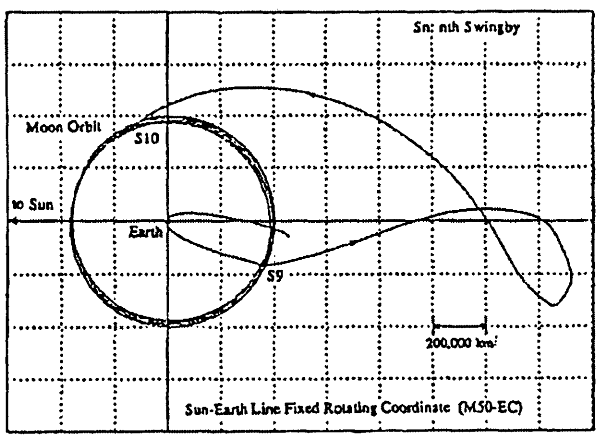

Figure 7–26: Flight path of the Japanese Hiten spacecraft.

This results in decreasing the deceleration velocity impulse near the Moon for a transfer to a lunar satellite orbit. This type of flight trajectory was utilized for the Japanese Hiten mission, 1990–1993.[78,84,85] (see Figure 7–26).

"Detour" Moon–Earth Flights

"Detour" trajectories for a flight from the Moon to the Earth were constructed in the frame of the four-body system Earth–Moon–Sun–particle.[77,86-88] These trajectories use a passive escape principle. They use, first, a flight from the Moon and from the Moon orbit away from the Earth's sphere of influence; only after that is there a flight to the Earth. Figure 7–27 gives a typical "detour" trajectory for a Moon–Earth flight.[86]

From an external appearance point of view, this trajectory is similar to the Sternfeld bi-elliptical trajectory. Again, as for the Earth–Moon flight, this "detour" trajectory for a four-body system, although it is similar to the Sternfeld bi-elliptical trajectory, is dynamically far more complicated.

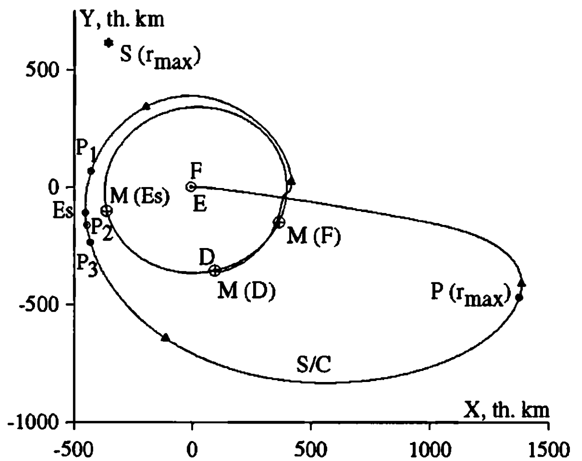

Figure 7–27: Geocentric "detour" trajectory for a flight from the Moon to the Earth.

Flight to the Sun

For another example of a space project using the "detour" trajectory, consider the flight of the international (National Aeronautics and Space Administration, NASA, and the European Space Agency, ESA) spacecraft Ulysses. Its main goal was the investigation of the solar polar regions outside the ecliptic. To perform the great inclination of the trajectory to the ecliptic plane, allowing the spacecraft to attain the out-of-ecliptic domain, a method similar to that of the transfer to GEO via a close flyby of the Moon was used. First, the spacecraft was launched into a trajectory heading away from the Sun, removing itself from the vicinity of the Earth and the Sun and traveling out to the orbit of Jupiter. A flyby of Jupiter changed the spacecraft's orbital inclination and perihelion radius. Thus, there was a "detour" of the Sternfeld type: but this change of orbit was performed using Jovian gravity assist, rather than the velocity impulse of a rocket engine. The spacecraft was launched in October 1990. Figure 7–28 shows the spacecraft trajectory for its flight to Jupiter and the spacecraft motion at its first revolution after the Jovian gravity assist in February 1992.[89] For the spacecraft heliocentric orbit, its inclination is ~80°, perihelion and aphelion radii are ~1.35 A.U., ~5.4 a.e.[90] Ulysses finally ended its operations on 30 June 2009.[91]

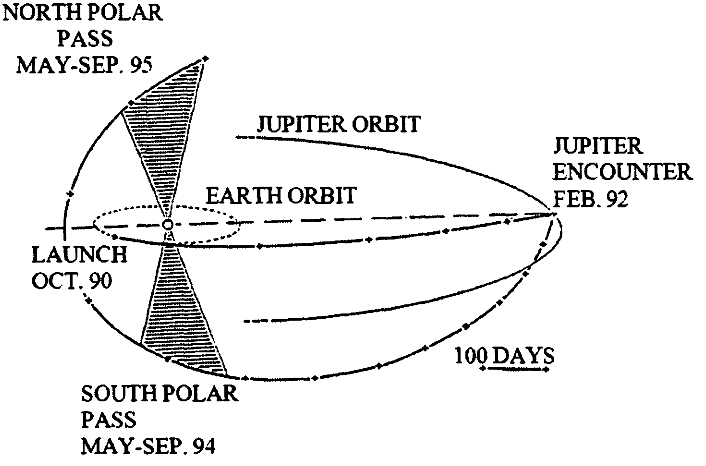

Figure 7–28: The trajectory of the Ulysses spacecraft.[89]

Conclusion

An analysis of the Sternfeld works performed allows one to draw the conclusion that Ary Sternfeld, through his scientific work and science popularization activity made a remarkable contribution to the development of cosmonautics. Sternfeld's ideas for indirect, bi-elliptic, and "detour" trajectories have entered naturally into both the theory and practice of the modern cosmonautics.

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