"GRAVITY'S OVERDRIVE"

a critique

by Michael A. Minovitch

Tom Reichhardt's article "Gravity's Overdrive"[1] deals with the invention of gravity propulsion, also known as gravity assisted trajectories, and the history behind it. Since this invention made it technically possible to explore the entire solar system with instrumented spacecraft using conventional rocket propulsion and relatively small launch vehicles, it represented an important breakthrough in the history of space travel. Prior to this invention it was believed that the exploration of most of the solar system was physically impossible without very large launch vehicles and advanced nuclear and electric propulsion systems. Since these advanced propulsion systems were found to be beyond engineering feasibility, the exploration of most of the solar system was the direct result of the invention of gravity propulsion and could not have been achieved without it. Although Reichhardt recognizes these facts, his article contains many errors, due to the fact that this invention is highly technical and requires a knowledge of physics, advanced mathematics and astrodynamics before it can be accurately understood and described. This critique is intended to point out these errors so that future historians of science and technology will have a more accurate understanding of this invention.

Basically, gravity propulsion is a means for changing the direction and accelerating a spacecraft through the solar system to high velocities relative to the sun by substituting traditional propulsive forces generated by expelling mass at high velocity (reaction propulsion) by natural gravitational forces generated by passing one or more planets. Unlike reaction propulsion, these forces F automatically increase with vehicle mass m via the equivalence principle $F = ma = Gm\,M/d^2$ and do not require the expulsion of any mass. Consequently, after a spacecraft is launched to the first acceleration planet, it does not matter how massive the spacecraft is. Since it is relatively easy to reach a nearby planet, relatively little launch propulsion is required to initiate a voyage, and travel essentially anywhere through the solar system. Thus, most of the energy required to explore the solar system is provided by the planetary orbital energy of the solar system itself, instead of using chemical energy stored in large amounts of propellant or nuclear energy stored in a reactor.

In beginning this critique, it is important to mention the fact that most scientific discoveries or technological breakthroughs involve a phenomenon in nature that has been previously observed and studied. However, if a researcher fails to recognize how the phenomenon can be used to create the scientific breakthrough (i.e., if he or she fails to "discover it") and regards the phenomenon as having little relevance to a basic problem, the person can obviously not be credited for discovering the breakthrough. This is a well-established tradition in scientific research. It is part of the established ground rules.

In the case of gravity propulsion, the underlying phenomenon is gravitational perturbations. As Reichhardt correctly points out on page 74 of his article,[1] both Tsander,[2] working in the 1920's, and Lawden,[3] working in the 1950's, pointed out that gravitational perturbations could, in principle, be used to reduce the propulsion requirements for space travel. But these researchers did not recognize how gravitational perturbations could be used to open the solar system with relatively small launch vehicles and conventional rocket propulsion. This is not a matter of subjective interpretation. It can be proved by examining their published papers. However, to understand this fact requires some technical knowledge of astrodynamics.

In 1925 the German architect, Walter Hohmann, discovered an elliptical trajectory that would take a spacecraft from one planet to another planet which was believed to require the minimum amount of launch energy. Assuming that the planetary orbits are circular and coplanar (which is approximately true for all the planets except Pluto), this trajectory is a semi-ellipse, tangent to the orbits of the launch planet and the target planet at the periapsis and apoapsis points. This transfer ellipse became the most famous of all trajectories in the history of space travel and is known as the "Hohmann Trajectory." Unfortunately, the energy requirements for interplanetary space travel are so high that, unless the orbits of the launch and target planets are relatively close, such as the orbits of Earth and Venus or Earth and Mars, the Hohmann minimum launch energies are still very high, and the required trip times are very long.

Although both Tsander and Lawden pointed out the possible benefits of utilizing gravitational perturbations, they both regarded Hohmann's interplanetary trajectories as the trajectories requiring the minimum amount of launch energy for traveling between any two planets. Tsander actually called Hohmann's minimum energy trajectory a fundamental "Law" of space travel (see page 246, Ref. 2). Additional historical facts concerning Tsander's ideas about space travel and how he regarded gravitational perturbations are given in Ref. 4.

Lawden called Hohmann's minimum energy trajectory the "optimal" minimum energy trajectory for interplanetary space travel between two planets.[5,6] In some publications, Lawden calculated the Hohmann minimum launch velocities (hyperbolic excess velocities) and trip times required for traveling from one planet to any other planet in the solar system.[7] These papers were written several years after his 1954 paper on the possible use of gravitational perturbations.[3] But the most accurate picture of how Lawden regarded the possibility of utilizing gravitational perturbations to reduce the propulsion requirements for exploring the solar system can be found in a book he authored in 1963 on the minimum energy requirements.[8] He omits any discussion of this possibility in this book and "proves," with many mathematical demonstrations, that the absolute minimum energy requirements for exploring the solar system are those represented by Hohmann trajectories. His view of space travel was based so firmly on rocket propulsion that the search for optimal trajectoris became known as "Lawden's Problem of Optimal Rocket Flight."[9] During the 1950's and early 1960's, Lawden was considered by many to be the world's leading theoretical astrodynamicist. Reichhardt does not mention any of these facts which are crucial in questions regarding who was responsible for the gravity propulsion breakthrough in exploring the solar system. The "breakthrough" is, in fact, the discovery that it is possible to explore a distant planet with an instrumented spacecraft with launch energies significantly below the theoretical Hohmann minimum energy limit by the gravity propulsion concept. More specifically, it is the discovery that any region in the solar system can be explored with a spacecraft by sending it initially to Venus with very low launch energy and using gravity propulsion. The launch energy required to reach Venus is the lowest for any of the planets. This was a radical discovery in the early 1960's, contrary to the most well established principles of space travel. (Low launch energy trajectories to Venus have less energy relative to the sun than the earth's orbit.)

Perhaps the most important facts for understanding the history of the gravity propulsion breakthrough in space travel occurred in 1959. This is the year when Samuel Herrick[10] and Krafft Ehricke[11] investigated the possibility of utilizing gravitational perturbations for reducing the propulsion requirements of space travel. These studies are important because they presented quantitative and theoretical demonstrations showing that this possibility is not viable (i.e., practical). Although these studies were aimed primarily at utilizing relatively small perturbations generated by the moon, Ehricke's work was more general and included the possibility of utilizing planetary perturbations. Both Herrick and Ehricke were also among the world's leading astrodynamicists. These rejections (with mathematical demonstrations) confirmed the long held belief that Hohmann trajectories really do represent the minimum energy requirements for exploring the solar system and these minimum energy requirements cannot be circumvented. By the beginning of the 1960's, the Hohmann minimum energy interplanetary trajectory was universally regarded as one of the most firmly established energy principles for exploring the solar system.[12-27]

All of the astrodynamicists who investigated the possibility of utilizing gravitational perturbations (Tsander, Lawden, Herrick, and Ehricke) accepted the Hohmann minimum energy requirements for interplanetary space travel and published detatiled mathematical analyses "proving" that this is true. Therefore, the suggestion that the gravity propulsion breakthrough in space travel was an "evolutionary development" prior to Minovitch's work in 1961 is without foundation. In fact, the literature proves that the contrary is true. All of the research on gravitational perturbations after Lawden's initial work in 1954[3], and prior to Minovitch's initial work in 1961, resulted in mathematical analyses demonstrating why they were impractical as a means for space propulsion. This was a rejection on theoretical grounds. Thus, there was no "evolution."

As pointed out above, the Hohmann minimum energy requirements for sending spacecraft to all the planets except the closest planets (Venus and Mars) are very high, and the corresponding trip times to the outer planets are very long. Consequently, it became apparent in the 1950s and early 1960s that the exploration of most of the solar system was beyond the reach of chemical rocket technology. It was believed that the exploration of the solar system could only be achieved by developing advanced nuclear and/or electric propulsion systems using very large launch vehicles.[28-42] This is an indisputable fact clearly stated in the technical literature of that time. But the basic engineering feasibility of these exotic systems did not have a strong technical foundation. After spending more than a billion dollars in large scale research and development programs, it became apparent that such systems could not be achieved.[43-46] Thus it was believed that most of the solar system would remain out of reach. The invention of gravity propulsion changed the entire situation.[47,48] The very large technical effort put into the development of those advanced propulsion systems also demonstrates that this invention was not the result of any "evolutionary development." It was simply believed that there was no other means for exploring the solar system.

Besides mentioning the work of Tsander and Lawden in an attempt to suggest that gravity propelled space travel was not a new idea in 1961, Reichhardt also uses science fiction. In particular, on page 74 of his article,[1] Reichhardt points out that in 1939, the science fiction author Lester del Ray wrote a story[49] in which Jupiter's gravitational field is used to change the direction of a space vehicle without rocket propulsion. He cites a specific passage: "That's what I'd been looking for, something to catch hold of out in space to swing me around without loss of momentum, and that's what I'd found: Jupiter's gravity pulled me around like a lead weight on a swing rope." But the phrase "without loss of momentum" does not state that the vehicle's momentum can be increased by the encounter, which is the basis of gravity propulsion. The important observation here however, is not the fact that the cited story does not use the principle of gravity propelled space travel, but rather that Reichhardt attempts to use a science fiction story to support a position that cannot be supported by the scientific literature.

There is a deeper reason why the concept of gravity propelled space travel was not recognized as a means for breaking the Hohmann minimum energy limit and exploring the solar system without rocket propulsion prior to Minovitch's work in 1961. In fact, this reason made the concept virtually impossible to discover because it made it essentially impossible to investigate.

To quantitatively investigate the possibility of catapulting a free-fall spacecraft around the solar system from planet to planet without rocket propulsion by precisely designing each encounter trajectory such that the resulting gravitational interactions catapults the vehicle to the next planet (gravity propulsion) requires a numerical solution to the famous N-body problem of classical physics (i.è., analytical mechanics).[50] Prior to 1961, no such solution existed for free-fall space vehicles moving through the solar system on interplanetary trajectories. Although numerical solutions were developed to solve this problem for non-stop free-fall round trip trajectories to the moon by numerical iteration/integration techniques in the early 1960's,[51-59] the problem for round-trip interplanetary trajectories was much more difficult.[60,61] Consequently, since accurate interplanetary round-trip trajectories were beyond numerical computation in the early 1960's, the idea of utilizing a series of gravitational perturbations to propel a vehicle around the solar system form planet to planet was not something ready to be discovered because it was beyond the possibility of even being investigated. Minovitch developed the first general solution to the N-body problem for round-trip interplanetary trajectories, and he used this solution to propose his idea of gravity propelled space travel using a series of successive planetary encounters. He did this by developing a new mathematical approach using vector analysis, which was a relatively new mathematical tool in astrodynamics in 1961.[62] This is at the core of the history.

Unfortunately, Reichhardt omits any discussion of the N-body problem and the fundamental role it played in the invention of gravity propulsion.[47,48] He condenses this important part of the history with a brief passage on page 75 where he writes: [Minovitch] "began playing around with vector analysis of spacecraft trajectories, which led him to a realization."

Reichhardt's failure to understand this important technical part of the history is also evident when he describes the 1970 Earth-Venus-Mercury gravity propelled trajectory computations of Cutting and Sturms in 1964. He implies that Minovitch's computations (two years earlier) did not give launch dates, launch energies, flight times, and aim points required for a specific mission. But Minovitch did produce this data for the 1970 launch window. Moreover, he also computed these parameters for the 1965-66, 1967, 1969, 1972, and 1973 Earth-Venus-Mercury launch windows as well.[63] Although this data was based on 3-dimensional conic approximations, it was sufficiently accurate for mission planning. This date made it possible to calculate the exact aim points and distances of closest approach via a converging series of numerical iteration/integrations required for an actual mission (see pages 9, 10, 16, 17, Ref. 48). The 1973 window was the one actually selected for the Mariner 10 mission. But the most important fact ommitted by Reichhardt is that the detailed aim points at the Venus encounter that Cutting and Sturms gave in their 1964 paper (that would send the spacecraft to Mercury) were computed from a FORTRAN program incorporating Minovitch's solution to the N-body problem.[64,65] At that time Minovitch's vector techniques represented the only means JPL had for solving this problem (i.e., there was no other analytical method for calculating the aim points).

Some of Reichhardt's quotations involving Roger Bourke are misleading. For example, Bourke is quoted as saying that he remembers Minovitch as being very secretive about what he wanted to reveal. Minovitch does not recall being secretive about what he wanted to reveal. (However, it is true that he usually published and discussed specific trajectory profiles after he performed extensive numerical investigations.) He gave two technical seminars describing his ideas for exploring the solar system without rocket propulsion at JPL in April 1963, and he answered all questions put to him (see page 21, Ref. 48).

The quoted remarks made by Sturms on page 78 can be better understood if one knew that, in 1971, Sturms approached Minovitch with a proposed award nomination. The award was for the Earth-Venus-Mercury mission to be shared jointly among Cutting, Sturms, and Minovitch. Minovitch turned down the proposed joint award nomination because the Cutting and Sturms 1964 work involved more numerical analysis of a previously proposed and previously studied mission made possible by a solution to the N-body problem that Cutting and Sturms did not participate in or find. Although the 1964 work by Cutting and Sturms was excellent engineering, it was the type of work that had to be started in detailed mission analysis studies of gravity propelled trajectories where guidance was a critical factor. Minovitch asked JPL to begin carrying out these detailed studies in 1962.

On page 77, Reichhardt asserts that Minovitch never addressed the question of guidance. This is not true. In 1963, Minovitch did address this problem. He developed a general mathematical technique for guidance analysis applicable to any gravity propelled trajectory, and he used this technique to numerically investigate and develop an optimum strategy for corrective maneuvers. He presented this work in another paper specifically addressing this problem.[66]

On page 78, Reichhardt appears to describe Minovitch as being overly sensitive on the subject of who really invented gravity propelled interplanetary space travel. But he does not mention the fact that for many years, JPL has been publishing (or submitting) erroneous accounts. Refs. 67-69 represent a small example. However, perhaps part of the problem is the fact that Minovitch was never able to publish a detailed account of his gravity propulsion research.[70] Consequently, only a few people at JPL and UCLA really knew the details (parts of the details). When some of these details were uncovered in 1989 by William Kosmann, a JPL Voyager 2 mission analysist at the US National Archives, JPL did give Minovitch full credit in their book, <u>Voyager Neptune Travel Guide</u>.[71]

In closing his critique, Reichhardt also claims that Minovitch got into a dispute with Arthur Kantrowitz over who should get credit for laser-powered rocket propulsion. This is not true. Minovitch never communicated with Kantrowitz. An examination of the technical literature in this field will show that Minovitch wrote his first paper on this propulsion concept several months before Kantrowitz and was granted the first patent.[72] The fact that several American aerospace societies published papers giving credit to Kantrowitz does not make it true. Reichhardt has evidently viewed Minovitch's effort to call attention to these errors[72] a "dispute."

It is often the case that the history of a scientific discovery or breakthrough is related to the personalities and human circumstances behind it. In the case of gravity propulsion, Minovitch entered into a field of research (astrodynamics) and quickly developed a solution for one of its most difficult unsolved problems, and he used this solution to propose a new method for interplanetary space travel with physical principles that were regarded by the professionals at the time as either theoretically impossible or, at most, impracticable. But Minovitch showed through persistent research over a period of three years that these ideas made it technically possible to reach and explore any target in the solar system with relatively little conventional rocket propulsion which was believed (at that time) to be physically impossible without new propulsion systems so advanced that they were beyond technical feasibility.[28-46] He therefore opened up the entire solar system to direct exploration with instrumented spacecraft resulting in many new discoveries. This may have created some unintended animosity between those professionals and Minovitch, which is understandable.

Regarding the two IAF papers describing the details of the invention that Reichhardt mentions, it should be pointed out that that project was originally suggested by Richard Dowling (an IAF historian) and William Kosmann, not Minovitch. The goal was to uncover and document the history with as much detail as possible. Much of this work was done during tape-recorded weekly meetings[73] between Dowling, Kosmann, Rex and Ning Ridenoure (two other JPL analysts) and Minovitch during the spring and summer of 1990 in Los Angeles, California. The IAF papers cited 225 verifiable unpublished documents and published articles, the collected weight of which gives a fairly accurate history apart from any statements by

Minovitch. Finally, it should also be noted that Lowell Wood, Gary Flandro, and others interviewed by Reichhardt confirms several key parts of the published history[47,48] in statements which were unknown to Minovitch and were never solicited by Minovitch.

REFERENCES

1. Reichhardt, T., "Gravity Overdrive," Air and Space Smithosonian, Vol. 8, No. 6, February/March 1994, pp. 72-78.

2. Tsander, A.F., Problema poleta pri pomoshchi reaktivnykh apparatova: Mezhplanetnve polety (Problems of Flight by Jet Propulsion: Interplanetary Flights --Nasa Technical Translation F-147, 1964, Sec. 7, Flight-Around Planet's Satellite for Accelerating or Decelerating Spaceship, pp. 290-292.)

3. Lawden, D.F., "Perturbation Maneuvers," J. of The British Interplanetary Society, Vol. 13, No.6, November, 1954, pp. 329-334.

4. Minovitch, M.A., "Tsander's Work and Conclusions on Determining the Minimum Launch Energies Required for Traveling to Other Planets," June 1, 1990.

5. Lawden, D.F., "Transfer Between Circular Orbits," Jet Propulsion, July 1956, pp. 555-558.

6. Lawden, D.F., "Optimal Transfer Between Two Planets," Section XI in "Interplanetary Rocket Trajectories," Advances in Space Science, Vol. 1, Academic Press, 1959, pp. 1-53.

7 Lawden, D.F., "Interplanetary Orbits," Chapter 9 in Space Research and Exploration, ed. D.R. Bates, William Sloane Associates, New York, 1958, pp. 174-175.

8. Lawden, D.F., Optimal Trajectories for Space Navigation, Butterworth and Co., Ltd., London, 1963.

9 Kelley, H.J., "Singular Extremals in Lawden's Problem of Optimal Rocket Flight," AIAA Journal, Vol. 1, No. 7, July 1963, pp. 1578-1580.

10. Herrick, S., "Earth Satellites and Related Orbit and Perturbation Theory," Chapter 5 in: Space Technology, John Wiley and Sons, Inc., New York, 1959, pp. 5-01 to 5-30.

11. Ehricke, K.A., "The Hyperbolic Encounter," Sec. 8-4-5, Chapter 8 in: Space Technology, John Wiley and Sons, Inc., New York, 1959, pp. 8-65 to 8-73.

12. Barrar, R.B., "Analytic Proof that the Hohmann-Type Transfer Is the True Minimum Two-Impulse Transfer," Astronautica Acta, Vol. 9, 1962, pp. 1-11.

13. Smith, G.C., "The Calculation of Minimal Orbits," Astronautica Acta, Vol. 5, 1959, pp. 253-265.

14. Buchheim, R.W., "Interplanetary Flight," Chapter 3 in Space Handbook: Astronautics And Its Applications, Random House, New York, 1959, pp. 31-34.

15 Vertregt, M., "Interplanetary Orbits," Chapter 9 in Principles of Austronautics, 1960, pp. 158-161.

16. Ehricke, K.A., "Hohmann Transfer Between Co-Planar Circular Planet Orbits," Sec. 9.3 in Space Flight II, Dynamics, D. Van Nostrand Co., Inc., 1962, pp. 968-984.

17. Roy, A.E., "Minimum Energy Interplanetary Transfer Orbits," Chapter 10, Sec. 3 in: The Foundations of Astrodynamics, The Macmillan Co., New York, 1965, pp. 309-316.

18. Blasingame, B.P., "Minimum-Energy Interplanetary Trajectories," Sec. 1.9 in Astronautics. McGraw-Hill Book Co., New York, 1964, pp. 47-50.

19. Stearns, E.V.B., "Interplanetary Orbits," Sec. 6.1 in: Navigation and Guidance In Space, Prentice-Hall, Inc., 1963, pp. 202-207.

20 Munick, H. and McGill, R., "Analytical Estimates for Optimum Transfer Paths," ARS Journal, January 1960, pp. 120-122.

21. Munick, H. and McGill, R., "Analytical Solutions to Several Optimum Orbit Transfer Problems," The Journal of the Astronautical Sciences, 1961, pp. 73-77.

22. Ehricke, K.A., " Cotangential Transfer Between Coplanar Circular Orbits," Sec. 8-3-3 in Ref. 10, pp. 8-25 to 8-27.

23. Godwin, F., "Outer Planet Voyage Times and Velocities," Table 19 in, The Exploration of the Solar System, Plenum Press, Inc., New York, 1960, p. 158.

24. Ruppe, H.O., "Minimum Energy Requirements For Space Travel," in 10th International Astronautical Congress, London 1959, pp. 181-201.

25. Moekel, W.E., "Interplanetary Trajectories With Excess Energy," in 9th International Astronautical Congress, Amsterdam 1958, pp. 96-119.

26. Bryson, A.E. and Ouellette, G.A., "Optimum Paths to the Moon and Planets," Astronautics, September 1958, pp. 18-82.

27. Hazard, A.B., "The Space Mission Planning Chart," in Proceedings of the IAS Meeting on Large Rockets, Institute of the Aerospace Sciences, New York, 1962, pp. 5-11.

28. Langmuir, D.B. "Electric Spacecraft-Progress 1962," Austronautics, June 1962, pp. 20-25.

29. Spencer, D.F., et al. Nuclear Electric Spacecraft For Unmanned Planetary and Interplanetary Missions, JPL Technical Report 32-281, April 25,1962.

30. Stearns, J.W., "Electric-Propulsion Systems Applications," Astronutics, March 1962, pp. 22-80.

31. Beale, R.J. et al, The Electric Space Cruiser for High-Energy Missions, JPL Technical Report, 32-404, June 8, 1963, p. 13.

32. Seifert, H.S., "Propulsion For Space Vehicles," Chapter 8 in Space Logistics Engineering, John Wiley and Sons, Inc., New York, 1962, pp. 222-227.

33. Von Kármán, T., "Introductory Remarks On Space Propulsion Problems," in Advances In Astronautical Propulsion, Casci, C. (ed), Pergamon Press, New York, 1962, pp. 3-10.

34. Newgard, J.J., and Levey, M., "Nuclear Rockets," Scientific American, May 1959, pp. 46-51.

35. "Nuclear-Powered Engines Urged For Space Vehicle Upper Stages," Space Technology, July 1960, p. 21.

36 Sutton, G.P., "Rocket Propulsion Systems for Interplanetary Flight," J. of the Aero/Space Science, Vol. 26, October 1959, pp. 609-625.

37. Haviland, R.P., "Consideration of the Solar Probe," in 9th International Astronautical Congress, Amsterdam, 1958, pp. 44-53.

38. Breakwell, J.V., "Mission Normal to the Ecliptic," Astronautics, September 1962, pp. 59-61.

39. Burley, R.R., "Out-of-Ecliptic Trajectories," ARS Journal, July 1962, pp. 1104-1105.

40. Hunter, M.W. II, "Space Nuclear Propulsion," Chapter 12 in Space Exploration, ed. D.P. Le Galley and J.W. McKee, McGraw-Hill Book Co., New York, 1964, pp. 350-385.

41. Stever, H.G., "The Technical Prospects," Chapter 7 in Outer Space, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1962, pp. 7-30.

42. Wyatt, D.D., "The National Program for the Exploration of Space," Proceedings of The Conference On Space-Age Planning, NASA SP-40, 1963, pp. 9-17.

43. Yaffee, M.L., "Electric Rocket Program Being Reshaped," Space Technology International, April 1964, pp. 14-19.

44. "Nuclear Rockets: Flight Systems Deferred," Spaceflight 1964, pp. 93-94.

45. "Nuclear Flight Programs Canceled as President Trims FY'65 Budget," Space Technology International, 1964, p. 24.

46. "Electric Propulsion, "Aerospace America, December 1987, p.38.

47. Dowling, R.L. et al, "The Origin of Gravity-Propelled Interplanetary Space Travel," 41st Congress of The International Astronautical Federation, October 6-12, 1990, Dresden, Germany, IAA Paper No. 90-630.

48. Dowling, R.L. et al, "Gravity Propulsion Research at UCLA and JPL 1962-1964," 42nd Congress of The International Astronautical Federation, October 5-11, 1991, Montreal, Canada, IAA Paper No. 91-677.

49. del Rey, L., "Habit," Early del Rey, Lester del Rey, Doubleday and Company, Inc. Garden City, NY, 1975, pp. 46-57.

50. Whittaker, E.T., "The Reduction of the Problem of Three Bodies," Ch. 13 in, A Treatise on the Analytical Dynamics of Particles and Rigid Bodies, Dover Publications, New York, 1944, pp. 339-357.

51. Message, P.J., "Some Periodic Orbits in the Restricted Problem of Three Bodies and Their Stabilities," The Astronomical Journal, Vol. 64, Aug. 1959, pp. 226-236.

52. Kooy, J. M. T. and Berghuis, J., "On the Numerical Computation of Free Trajectories of a Lunar Space Vehicle," Astronautica Acta, Vol. 6, Nos. 2-3, 1960, pp.115-143.

53. Huang, S., "Preliminary Study of Orbits of Interest for Moon Probes," The Astronomical Journal, Vol. 67, June 1962, pp. 304-310.

54. Arenstorf, R.F. and Davidson Jr., M.C., "Solutions of Restricted Three-Body Problem Represented by Means of Two-Fixed-Center Problem," AIAA Journal, Vol. 1, No. 1, Jan. 1963, pp. 228-230.

55. Lagerstrom, P.A. and Kevorkian, J., "Matched Conic Approximations to the Two Fixed Force-Center Problem," The Astronomical Journal, Vol. 68, March 1963, pp. 84-92.

56. Lagerstrom, P.A. and Kevorkian, J., "Earth-to-Moon Trajectories in the Restricted Three-Body Problem," Journal de Mécanique, Vol. 2, June 1963, pp. 189-218.

57. Lagerstrom, P.A. and Kevorkian, J., "Numerical Aspects of Uniformly Valid Asymptotic Approximations for a Class of Trajectories in the Restricted Three-Body Problem," in Celestial Mechanics and Astrodynamics, ed. Szebehely, V.G., (Progress in Astronautics & Aeronautics Series, Vol. 13), 1964, pp. 3-33.

58. Choudkhari, R.K., "Series Solution of the Problem of Two Fixed Centers," AIAA Journal, Vol. 1, Sept. 1963, pp. 2218-2221.

59. Lagerstrom, P.A. and Kevorkian, J., "Nonplanar Earth-to-Moon Trajectories in the Restricted Three-Body Problem," AIAA Journal, Vol. 4, Jan. 1966, pp. 149-152

312-348, September 9, 1963.

67. Parker, P.J., “Grand Tour Spacecraft Computer,” Spaceflight, Vol. 13, No. 3, March 1971, pp. 88, 120.

68. "Mariner - Venus 73 Flight Genesis," NASA Press Release No. 70-112, July 5, 1970.

69. Bane, D., “First Stop: Jupiter,” Los Angeles Herald Examiner, September 10, 1969, pp. A12.

71. Kosmann, W., “Slingshot Magic,” Chapter 7 in The Voyager Neptune Travel Guide, Jet Propulsion Laboratory Publication 89-24, June 1, 1989, pp. 103-108.

72. Minovitch, M.A., “Laser-Propulsion History,” (letter-to-the-editor), Astronautics and Aeronautics, October 1980, pp. 7, 69.

73. Letter from W. Kosmann to M.Minovitch, August 27, 1990.