Uncommon Sense
in Orbit Mechanics

by
Chauncey Uphoff
Consultant - Ball Space Systems Division
Boulder, Colorado

Abstract:

This paper is a presentation of several interesting, and sometimes valuable *non-sequiturs* derived from many aspects of orbital dynamics. The unifying feature of these vignettes is that they all demonstrate phenomena that are the opposite of what our "common sense" tells us. Each phenomenon is related to some application or problem solution close to or directly within the author's experience. In some of these applications, the common part of our sense comes from the fact that we grew up on the surface of a planet, deep in its gravity well. In other examples, our mathematical intuition is wrong because our mathematical model is incomplete or because we are accustomed to certain kinds of solutions like the ones we were taught in school. The theme of the paper is that many apparently unsolvable problems might be resolved by the process of guessing the answer and trying to work backwards to the problem. The ability to guess the right answer in the first place is a part of modern magic. A new method of ballistic transfer from Earth to inner solar system targets is presented as an example of the combination of two concepts that seem to work in reverse.

Introduction

Perhaps the simplest example of uncommon sense in orbit mechanics is the increase of speed of a satellite as it "decays" under the influence of drag caused by collisions with the molecules of the upper atmosphere. In everyday life, when we slow something down, we expect it to slow down, not to speed up. Yet when a satellite is "retarded" by atmospheric drag, its orbital speed increases. What happened? A more subtle example is that of the vertical pendulum. How can a juggler balance a broomstick on his finger when we know from left-brain analysis of the vertical equilibrium that the solution is unstable? Why does the control response on some airplanes reverse when the plane exceeds the speed of sound? Why does a gyroscope move to the side when you push it forward with your finger? There must be more to these problems than meets the eye; there must be other forces at work.

The solutions to these questions seem to be sensible to people who understand the entire problem, but, to the astute novice or educated nonprofessional, the appearances of many physical phenomena are as if

Nature intended to misdirect us, like a good close-up magician. The scientist might take a valuable lesson from the magician; if a problem seems insurmountable, maybe we should look for the silk handkerchief in the other hand. If we have spent half a lifetime searching for proof of an incompressible ether, we can take one of two views: we have suffered from a lack of diligence and cleverness in unlocking the ether-box, or we have been searching for something that isn't. If our best efforts (particularly within the next few years when a positive or null result should be verifiable) are unable to detect gravitational radiation, perhaps we should look for a formulation of the field equations that does not require (spatial) gravitons. The first of these suggestions was considered heresy in 1893, the second is considered heresy in 1993. In this paper, the "uncommon sense" attitude is presented as an alternative to the front-to-back approach usually taught in our schools and as a reiteration of Professor Wiener's epithet to the establishment to "Encourage Your Mavericks."

This paper contains discussions of a number of backwards ideas that seem to be contrary to common sense. Of more importance is the suggestion that much of the controversy in scientific advancement comes from an unwillingness to accept ideas that are contrary to conventional "wisdom." Those who learn to look for the silk in the other hand will often have a distinct advantage in problems that seem to defy solution. A more immediately practical result of this paper is the "Triple Lunar Swingby," a device for near-optimal use of the lunar gravity for transfer from Earth to inner solar system destinations. The TLS is a combination of two ideas, derived from the work of others, that seem to work in reverse.

Orbital Speed Limits

The next time an orbital policeman pulls you over for speeding in your spaceship, you may have some difficulty with the conventional excuses for Earth-bound speeders. But you might get away with this one: " I'm sorry, officer, I tried to slow down, but for some reason, I started going faster." The officer will probably issue a warning and require that you attend three classes in orbit mechanics. For a spacecraft in a near-circular orbit, the effects of a retarding force combine with the laws of motion in such a way as to increase the orbital speed while lowering the average distance from the Earth.

This backwards concept is easy to analyze and is probably familiar to anyone who has tried to predict satellite lifetimes under the influence of atmospheric drag. The simplest way to think of the phenomenon is to imagine what would happen to a spacecraft if one removed a small amount of orbital speed, ΔV, from the circular orbit with semi-major axis, a. The decrease in speed will cause a decrease in the centrifugal acceleration for that altitude and the spacecraft will be in a slightly elliptic orbit with its perigee slightly below the initial circular orbit altitude. The gravitational force of the Earth will pull the spacecraft closer to the force center and the speed of the spacecraft will increase under the influence of the stronger gravitational pull.
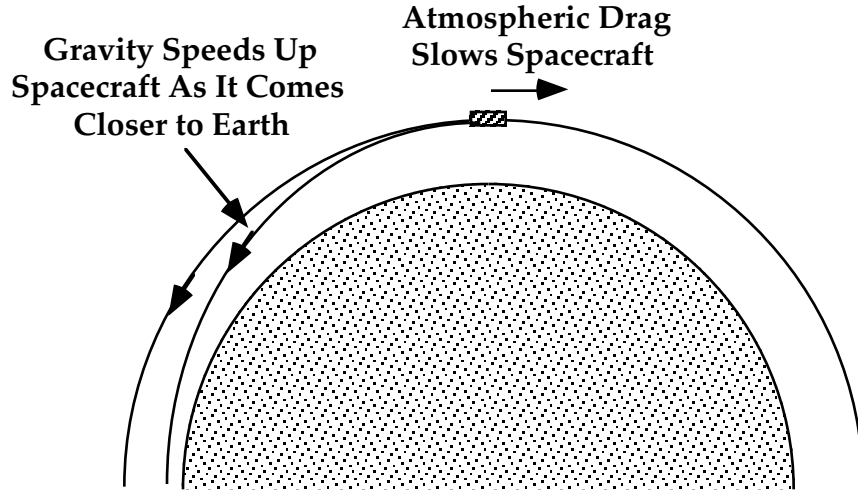
Fig. 1 Speeding Up by Slowing Down in Orbit

Of course, this effect does not happen immediately; if the initial orbital speed is $V_C = \{\mu a\}^{1/2}$ where μ is the gravitational strength (GM) of the central planet and a is the semi-major axis of the initial orbit, then the semi-major axis, a', after the (instantaneous) impulse ΔV, is given by

$$1/a' = (2/a - (V_C - \Delta V)^2/\mu) > 1/a,$$

which is to say that the new semi-major axis after the impulse is less than the original (circular) value as given above. The average speed of the spacecraft in this new elliptical orbit will be $V' = \{\mu/a'\}^{1/2}$ which is clearly greater than the original orbital speed. Thus, the effect of a small decrease in circular orbit speed causes an increase in the average orbital speed after the impulse. The result of a continuously applied retarding impulse is to increase the average orbital speed and to decrease the orbital altitude. This is the meaning of the expression "orbital decay" and the term refers to the decrease in average orbital altitude which is accompanied by an increase in average orbital speed.

Solar Sail Orbit Cranking

One of the most profound examples of uncommon sense in the author's experience is J.L. Wright's realization that the best way to change the inclination of a deep-space light-sailing vessel is to go inward toward the Sun. This "reverse" thinking allowed Wright[1] to define a realistic solar sail rendezvous trajectory with the Comet Halley in the 1985 apparition. Now, with 20/20 hindsight, many may declare that this was not such a laudable breakthrough because it is so obvious. At the time (1975) when ballistic and low-thrust optimization theory was in its heyday, it still required a reversal of thinking to identify the best use of the solar sail for rendezvous with Comet Halley.

To appreciate the difficulty of Mr. Wright's innovation, one must understand the context and convention of the time; one must recognize that conventional wisdom declared that inclination changes are best made near aphelion where the velocity vector is smallest and therefore easiest to change in direction. This is true if one is confined to conventional rocket propulsion that derives no benefit from proximity to the Sun. But this is not the case for Solar Electric Propulsion and the Solar Sail. Each of these propulsion mechanisms gains the advantage of an inverse square increase in propulsive capability as it goes inward toward the Sun. This inverse square increase in propulsive capability more than offsets the difficulty of bending the (larger) velocity vector to effect an increase in inclination. Wright's trajectory therefore began with an inward spiral from Earth's orbit to about 0.3 a.u., the smallest reasonable distance from thermal considerations. The trajectory was then "cranked" over the pole of the Sun by application of the greatly increased solar radiation pressure until the light-sail was going the "wrong way" around the Sun (opposite the direction of the Earth's motion), achieving, in about 3 years, the retrograde inclination of Halley's comet or about 163° with respect to the ecliptic.
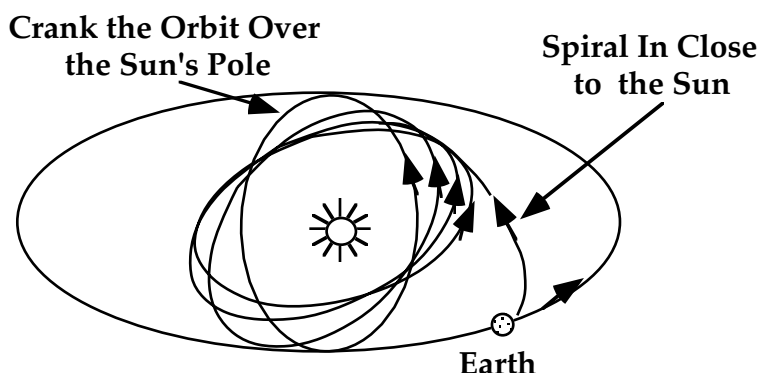

Fig. 2 Orbit Cranking with a Solar Sail

More conventional optimizations strategies were then used to increase the energy of the sail-craft's orbit to achieve rendezvous with the most famous comet in history. In spite of the valiant efforts of many[2], the project was canceled because it appeared that the mission uncertainty was too great. We now know that the Shuttle would not have been ready for the 1981 launch and it is probably for the best that the Halley Rendezvous Sail was not built. What is probably not for the best is that the solar sail and solar electric propulsion were both moved to the back burner as candidate propulsions systems for inner solar system exploration. On-going efforts by the World Space Foundation[3], U3P in France, and the Japanese Solar Sail Union have been up-staged recently by a Russian solar sail deployed from a Progress supply ship leaving the MIR space station. It is fitting, although frustrating to American proponents of the solar sail, that the first sail in orbit was placed there by the countrymen of Konstantin Edwardovitch Tsiolkovskiy and Friedrich Arturovich Tsander, almost certainly the independent inventors of solar sailing.

The Gyroscope: Spinning Magic

One of the most amazing of the many phenomena of Physics is the gyroscope or spinning wheel. Many young people are fascinated by the apparent ability of the toy gyroscope to defy gravity. As we become older and "wiser" we know to speak in terms of torque and time rates of change of angular momentum. But those are just descriptions of what may still appear to be magic to many observers. What really happens when one pushes on one end of the axle of a spinning wheel?
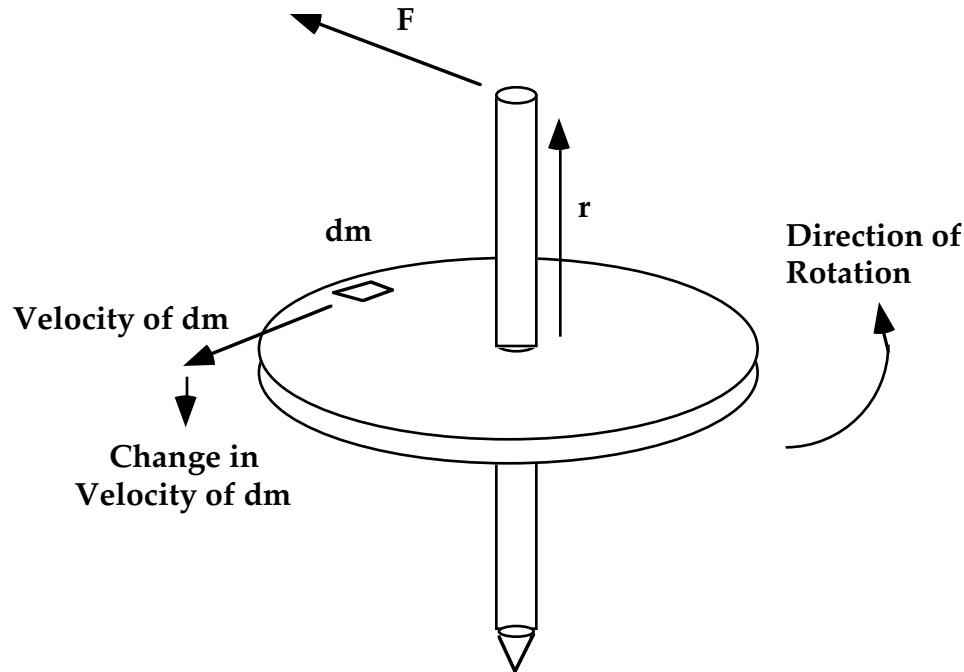
Fig. 3 The Strange Motion of a Gyroscope

Fig. 3 is a simplified diagram of the familiar toy gyroscope. Imagine an infinitesimal piece of the wheel lying in the plane formed by the axle and the applied force. The force, F, applied normal to the axle a distance, $|r|$, from the center, is transmitted through the (rigid) structure of the axle and the spokes and pushes down on the infinitesimal mass in the wheel. Now this force is normal to the circular motion of the mass particle and, therefore, does not change its speed, only its direction. But the mass particle is rigidly embedded in the wheel and the force is manifested as a change in direction of the spinning wheel itself. The entire structure above the point of suspension, therefore, moves to the left, in the direction of the cross product r x F as the wheel changes its orientation.

The simple explanation above was first given to the author by Dr. P.H. Roberts, another example of Roberts' clear and straightforward thinking, and his passion for understandable explanations of

physical phenomena. This understanding permits one to figure out which way a top or gyroscope will precess, even if one has forgotten the right-hand rule. Even so, when the author watches a gyroscope move around the center support, under the influence of gravity, it still seems like magic. Is it magic? No - - gravity itself would seem equally magical to a creature who had grown up on a small asteroid or space city. In this case, the magic is due to the environmental experience of the author. What is common sense to Earthies will someday be uncommon sense to Space people.

Reverse Thinking

Nicolas Copernicus provides one of the best examples of reverse thinking and its power to break a conceptual deadlock. It may seem easy for us, again with 20/20 hindsight, to downplay the importance of the transition from the geocentric to heliocentric thinking. But, for Copernicus, Galileo, and Kepler, it was truly a reversal of all that was "common knowledge." 2000 years of common knowledge, derived from the Aristotelian/Ptolemaic philosophy of a corruptible set of inner spheres and a perfect set of outer spheres, declared that the Earth was the center of the Universe, and that the orbits of the planets must be perfect circles. Yet the assumption of a heliocentric model solved so many of the problems of the early astronomers, like the limits of elongation of Venus and Mercury and the retrograde motions of the outer planets, that it could not long be denied.

The idea of a heliocentric Universe was not new; it had been suggested as early as the middle of the third century B.C. by Aristarchus of Samos. But Copernicus applied the concept to the motions of the planets with such success that only a few of the Ptolemaic epicycles had to be retained to save the (perfect) circular orbits of the planets. Copernicus rightly feared that the offering of the heliocentric theory as fact, rather than as a convenient device for calculation, would get him into trouble. His reluctance to be branded a heretic and other interests delayed the publication of his book until the year of his death.

Copernicus' reluctance was justified by the later troubles experienced by Galileo, perhaps the most outspoken, and certainly the most convincing , of the advocates of the heliocentric theory. But Galileo provided us with a more powerful example of reverse thinking in his famous refutation of Aristotle's law of falling bodies. Galileo knew that bodies did not fall at a rate proportional to their weights; he had tried the experiment many times. But he had no reliable way of measuring time and, much to the admiration of Einstein 300 years later, devised a thought experiment in which he worked the problem backwards. Galileo started with the "solution" that a cannonball will fall a certain distance in a given time. He then imagined that the cannonball were sawed in half and the experiment repeated with the assumption that the two halves would fall at half the rate of the full cannonball. But then, what if the two halves were tied together with a light piece of twine? Would the two halves

"remember" that they had once been a heavy body and fall quickly, or would they fall at half the rate because they are now light bodies? By this backwards argument, Galileo reduced the common knowledge law of falling bodies to an absurdity[4]. This, and his clever experiments with inclined planes, led Galileo to the brink of a full understanding of inertia. Galileo's work, and the great leap made by Johannes Kepler, from the common sense of perfectly circular orbits to the uncommon sense of ellipses, and his discovery of the three laws of planetary motion, set the stage for a different kind of thinking, to be discussed in the next section.

There have been many great thinkers who do things in reverse. They are the dyslexics, the reverse writers some of whom see written words backwards or sideways. Many have been called retarded because they were not recognized as dyslexic by their early teachers. Some of the greatest thinkers of all time were dyslexic. Those who learned to translate to "common" language were more successful than those who became lost, either through neglect or prejudice, in what to them must seem the quagmire of everyday life. Those lost people may have contributed much more to society than we might imagine at first thought. Such people are born with a different point of view. They may be able effortlessly to recognize solutions to problems that the rest of us consider intractable. The list of famous dyslexics or suspected dyslexics is long. It includes, Thomas Edison, Leonardo daVinci, Hans Christian Anderson, Winston Churchill, Albert Einstein, and many others who could not read the King's English (or Italian or German) the way others do but who provided the King's treasurer with great booty from the taxes on the sale and applications of their ideas and achievements.

Cosmic Thinking

This paper is not intended as a history of Science but, rather, as an exposition of the value of unconventional thinking. Every few centuries, on average, our civilization is honored by the appearance of a person with the capability of much more profound thinking than the rest of us. Compared with their achievements, the efforts of most scientists, however important they may seem at the time, are as mousetraps to starships. The author does not presume to classify the kind of thinking exhibited by Archimedes, Newton, Maxwell, Poincaré, Einstein, Eddington, Tesla, and Hawking in the same category as the examples given above; nor does he claim this list of supergiants to be complete or anything more than a personal opinion of awe-inspiring intellect. The point to be made is that, this kind of cosmic thinking, to which we all owe so much of our own comfort and well-being, is almost always contrary to current-day common sense. Usually, these supergiants are so far beyond everyday common sense that they have little to do with the petty squabbles of academia or politically spawned societies. Any one of the persons mentioned above has done more for our civilization than all the political heroes of all the nations combined. The Roman General Marcellus is remembered not for his conquest of Syracuse or other excellence in coercion, but because one of his soldiers

killed Archimedes. To Marcellus' credit, he was much upset by the arrogance of his soldier to kill Archimedes simply because he was too busy to see the General. In the long run, it is ideas and their inventors that will survive.

Newton's thinking was so unconventional that it took almost a century for ordinary scientists to apply his description of "the System of the World" to everyday problems of living and industry. Few people today realize that almost all of our power is distributed through a polyphase system of alternating current, devised, almost in an *augenblick*, by Nicola Tesla. Einstein's genius probably grew from his own stubbornness, born of a childhood of less than ordinary marks in school, and a "vote" of no confidence from his teachers at Eidgenössische Technische Hochschule, particularly from Heinrich Weber, Einstein's instructor in Electricity and Magnetism. No love was lost in either direction. Einstein called him "Herr Weber", in deprecation of Weber's professorship at ETH. This was the hallmark of a maverick who would probably end up a minor bureaucrat in a rigid and left-brain society.

But Einstein's genius would not wait for tenure. During his time of "paying his dues" at a Swiss patent office, the young Einstein published no fewer than four major papers in Physics.   The most famous of these is the 1905 paper "On the Electrodynamics of Moving Bodies.[5]" This apparently straightforward paper requires the reader to examine his most deeply ingrained "common" sense regarding the meanings of space, time, and simultaneity - - the fundamentals of Physics. The paper led to the foundation of modern cosmology and reconciled the most disturbing dichotomies between classical mechanics and the observations of Mssrs. Michelson and Morley on the constancy of the speed of light.

Einstein, like Newton, had little use for the literature.   This was probably a partial cause of their difficulties with others. Many of the same people who contend that Einstein proved Newton wrong have the same covetous intellect as those who sought to discredit Newton's ideas after the publication of Principia in 1687. Nothing could be more abhorrent to Einstein than to think that he had "proved" Newton wrong.   Einstein was more aware than anyone that his theory encompassed Newton's System of the World and expanded that System into a domain that Newton could not have known. No person in history is more worthy to stand on Newton's shoulders than Albert Einstein.

Common Sense and Modern Magic

What have these considerations to do with orbit mechanics?   They are to remind the reader, presumably an aspiring astrodynamicist or aerospace engineer, that the great bulk of human knowledge has come from mavericks who are more interested in making a long-term contribution to humanity than in acquiring great wealth.   It is the intention here to point out that the use of uncommon sense may often be the most sensible thing to do, especially if the thinker is up against the wall and has no more

common knowledge solutions to try in solving his problem. When common knowledge is wanting, or just plain wrong, the scientist may well take the attitude that Nature has placed a subtle obstacle in his way, rather like the misdirection of a good close-up magician, in order that the observer may gain a greater appreciation for the effect and the wonder of the magic. It is doubtful that the Almighty wishes to impress us with legerdemain, but there are almost certainly good reasons why humans have the gift of appreciation for the beauty, and the subtlety, of Nature's magic.

These discussions are descriptions of the concepts described here as Uncommon Sense, Magic, Reverse Thinking, or Maverickism. Natural laws are usually obvious, once articulated, but they seem to be inscrutable before discovery. This does not mean that Nature is malicious. Professor Einstein said:

"Raffiniert ist der Herr Gott, aber boshaft ist Er nicht."

"The Lord is subtle, but He is not malicious," said one of the greatest thinkers of our civilization[6]. Professor Einstein spoke of his own reluctance to accept an apparent experimental detection of an ether drift in 1921. He believed that Nature's subtlety came from profundity ("die Erhabenheit ihres Wesens") rather than intentional misdirection. He expressed his discomfort with quantum mechanics more colloquially in his famous phrase: " ... He does not play dice." Einstein considered the new quantum theory as useful but that it "hardly brings us closer to the secret of the Old One.[7] " He was not negligent in his efforts to understand the new theories; he just could not accept the conclusions of what he must have considered fuzzy Physics.

It was a time when the classical determinism of the late 19th and early 20th centuries was under fire from the young physicists of the late 1920s. Einstein was "the Man" in Physics. But there were things at the atomic level that Einstien's Physics would not admit. Niels Bohr had shown how the Hydrogen spectrum could be explained by quantizing the angular momentum of the electron and there was every hope that the Helium spectrum could be explained using the same principles, however great the computational effort may have seemed at the time. Schroedinger had recently formulated the equations of modern wave mechanics, and Heisenberg, after "many pangs of conscience" had come to believe in the necessity for indeterminism at the atomic level.

Quantum mechanics must have seemed like magic to Einstein who, probably more than anyone else, believed that the Universe was comprehensible. An indeterminism like that expressed by Heisenberg's Uncertainty Principle, embedded in the fundamental laws of Nature, must have seemed to Einstein as an insurmountable barrier to comprehension. What could be more absolute than the two basic precepts

of Einstein's Special Theory of Relativity; 1) that the speed of light was constant and 2) all uniformly translating coordinate systems have equal validity of form in the expression of natural laws?   This revolutionary and uncommon sense framework was foundation for Einstein's later General Theory of Relativity which incorporated the principle of equivalence between gravitational mass and inertial mass. But even the maverick Einstein could not accept the uncommon sense of quantum mechanics.

 Thus, many innovations, new methods, or points of view have a component of uncommon sense, something that breaks with tradition.   And many innovators, inventors, and theorists are mavericks, people who take issue with, or often rebel against, common knowledge.   The repeated success of mavericks in Science throughout history suggests that we might look for solutions to apparently intractable problems in the realm of the preposterous. Then if, *and only if*, one can work backwards from the apparently preposterous to the mainstream of scientific knowledge, one will have made a new step in the expansion of Mankind's knowledge.   The process of working backwards, even from an incorrect solution, will almost certainly reveal an important class of solutions that will *not* work and may point the way to the one that will.

The Triple Lunar Swingby

The concept of this section is not an example of reverse thinking or uncommon sense; it is a left-brain synthesis of two such concepts combined in such a way as to provide a useful mechanism for ballistic transfer to inner solar system objectives requiring a launch C_3 of 4 or 5 km^2/s^2.   The analysis came from a long-standing curiosity about the best use of lunar gravity assist for transfer to Venus and Mars.   The author was long aware of the great strength of the lunar gravity for modification of Earth orbits and for escape of the Earth-moon system altogether.   Recent studies[8] have shown that the most one might expect from use of the lunar gravity for launch into interplanetary space was a C_3 of about 3 km^2/s^2. This former "best' scenario included a lunar gravity assisted transfer "almost to Earth escape" followed by a second lunar swingby to a C_3 of about 3 km2/s2. But the analysis of Ref. 8 ignored something buried in the author's subconscious from many years ago. This buried concept came from David Ross[9], then a co-worker of the author at the Jet Propulsion Laboratory.   Ross's idea (later expanded by Dr. Bender[10]) was to capture a small asteroid into Earth orbit by use of a retrograde double lunar swingby.   After publication of Ref. 8, this author realized that it might be possible to gain an advantage from three gravitational boosts from the moon before escape from the Earth-moon system.

There was no question that the solar gravitational perturbations would be required; it is clear from analysis of Jacobi's integral that an increase in Earth-relative energy must be accompanied by an increase in the axial component of angular momentum.   Three prograde swingbys were out of the question. Because one swingby is sufficient to escape the Earth-moon system, a second must yield escape

so that the spacecraft cannot return for a third. One of three prograde swingbys would simply be a futile maneuver to establish an outgoing energy that could be achieved by two, straightforward, prograde swingbys. Only if one could arrange for a mechanism that reversed the angular momentum without increasing the energy beyond escape could one expect to gain an advantage from a third lunar encounter.

Then came the second "backwards" idea, gleaned from the work of R. Farquhar, D. Dunham, and E. Belbruno, helped by the author's own experience with trajectories to the transition region between the Earth-moon system and the Sun. If the first lunar swingby takes the spacecraft out to the transition region between the gravitational attraction of the Sun and that of the Earth-moon system, the solar gravity can change the Earth-moon relative Jacobian constant. That is to say that the Sun's influence can reverse the Earth-relative angular momentum without significantly decreasing the orbital energy. It occurred to the author that this mechanism might be used, after a first lunar swingby, to set up a subsequent *retrograde* double lunar swingby, *a la* Ross, that could take advantage of the lunar gravity without obviating future use of the lunar gravity because of the increase in angular momentum associated with energy-increasing encounters.

Preliminary calculations by the author indicated that a C_3 of 9 or 10 km^2/s^2 could be achieved by such a sequence of maneuvers. That would be enough to permit transfer to Venus and Mars for a launch requirement of -2.0 km^2/s^2, the energy required to reach the moon. Subsequent attempts to generate a realistic trajectory for such a transfer revealed that the author had made a mathematically trivial mistake in the initial calculations. This "trivial" error gave an estimate of the energy obtainable that was optimistic by a factor of two. If this mistake had not been made, the author would probably not have continued these studies. But the corrected analysis revealed that Earth escape energies of 4 to 5 km^2/s^2 could be achieved with launch-vehicle requirements of only the minimal Earth-moon transfer energy (about -2.0 km^2/s^2). Such an energy savings corresponds to about 20% increase in launch mass for the Delta II 7925 launch vehicle. Thus, if the deep-space transfer requires less than a C_3 of about 4.8 km^2/s^2, the same energy can be achieved using only a minimal energy Earth-to-moon transfer. For this reason, it seemed appropriate to publish the results even though they were not so spectacular as the author had hoped. In a later section, we shall consider what is actually required to achieve gravity assisted transfer from a minimal energy Earth-to-moon trajectory to Venus and Mars.

The First Swingby

The first gravity assist of the TLS is a straightforward energy boosting (pumping) swingby at the moon that takes the spacecraft from minimal Earth-to-moon energy (about -2.0 km^2/s^2) to an orbit that very nearly escapes the Earth-moon system ($C_3 \approx 0$.) The spacecraft must have enough energy, after the

swingby, here called S_1, to reach the transition region between the Earth-moon system and the solar gravitational perturbations. Furthermore, the transfer must take the spacecraft in the direction nearly perpendicular to the Sun-Earth line. Thus, the first swingby must occur a few days before the moon is in quadrature (1st or last quarter) so that the solar gravitational perturbations will subsequently have the desired effect of reversing the orbital angular momentum. The "uncommon sense" part of this maneuver is that one would expect such a reversal to occur in a region where the solar gravitational acceleration is strongest - that is, along the Sun-Earth line. But the reversal requires a moment along the Earth-spacecraft vector and the best place to achieve such a change is in the 1st and 3rd quadrant of the diagram of Fig. 4. Therefore, the first swingby should take the spacecraft ahead of (or behind) the Earth in its orbit around the Sun. As the spacecraft slows to return to Earth, the apparent motion of the Sun will bring the spacecraft into the region of maximum reversal of angular momentum while the spacecraft is still near its apogee.
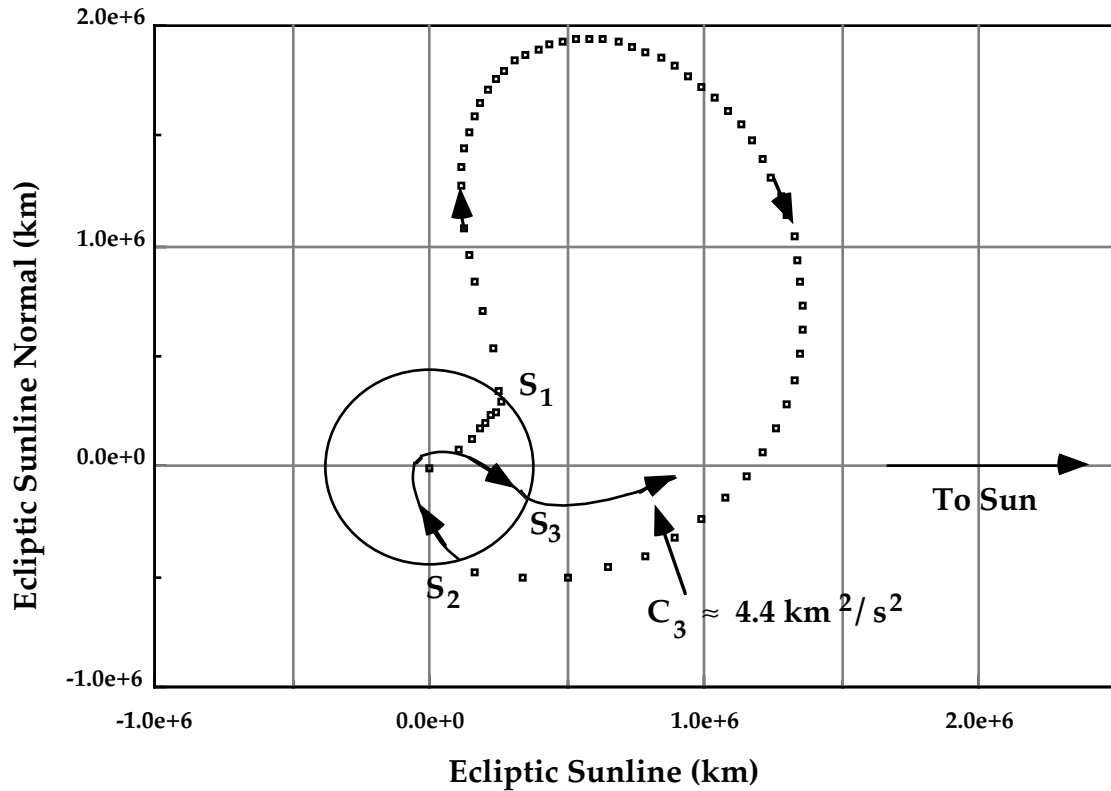
Fig. 4 Schematic Diagram of the Triple Lunar Swingby

Fig. 4 shows the geometry of the Triple Lunar Swingby with the basic encounters and the reversal segment shown in a rotating Earth-centered coordinate system whose x-axis points to the Sun and whose y-axis points in the prograde direction (opposite the Earth's heliocentric velocity vector) and with +z

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out of the page. Here we see the three fundamental segments of the TLS, the outbound "kick" to a region where the solar gravity will reverse the spacecraft's orbital motion; the return to the moon's orbit on a retrograde trajectory; and the retrograde double "kick", S_2-S_3, to escape from the Earth-moon system.

The first "trick" to the TLS is the reversal of angular momentum so that the spacecraft will return to the moon's orbit on a retrograde trajectory that will permit a retrograde moon-to moon trajectory after the second encounter with the moon. The second "trick" is that the transfer from the 2nd to the 3rd swingby is sufficiently retrograde that the perigee is above the surface of the Earth. Only then, can the transfer include two lunar swingbys during a single pass of a spacecraft, with positive energy, through the Earth-moon system. This second "trick", which actually preceded, chronologically, the angular momentum reversal maneuver, is the very best kind of reverse thinking. It reminds us that we tend to think along lines that are familiar to us. In orbit mechanics, we think in terms of two-dimensional diagrams like the ones in our books and we think in terms of prograde orbits like those of our planet around the Sun and our moon around our planet. It takes a maverick like Ross, to recognize that there might be an advantage to going the "wrong" direction in orbit.

The Retrograde Double Lunar Swingby

This powerful concept may someday provide the Earth with an abundance of precious metals, iron, and nickel. Someday, the space-borne industries of our civilization may rely on capture of small asteroids and cometoids for a life-sustaining supply of oxygen, hydrogen, and carbonaceous materials. Although future generations will probably devise fusion or anti-matter propulsion systems that will render these considerations obsolete, Mr. Ross and Dr. Bender have discovered and developed a mechanism that may outlive the propulsionists. No matter how great the power of your Starship, you must use reaction mass to stop at a planet. If the destination planet has a moon with substantial mass, why not target your approach to take advantage of the gravitational "retro" impulse provided by the momentum of the target planet's satellite(s)? One good reason is environmental. If the Starship's mass is a significant fraction of the swingby moon, that satellite's orbit might be so severely perturbed that the swingby would cause the satellite to crash into the planet. This would not be a politically correct maneuver. These worries are far in the future for our fledgling society. We can barely get enough mass in orbit to sustain life for a few months; it will be many generations in the future before we need worry about significantly disturbing our moon's orbit by the gravitational attraction of our tiny spacecraft.
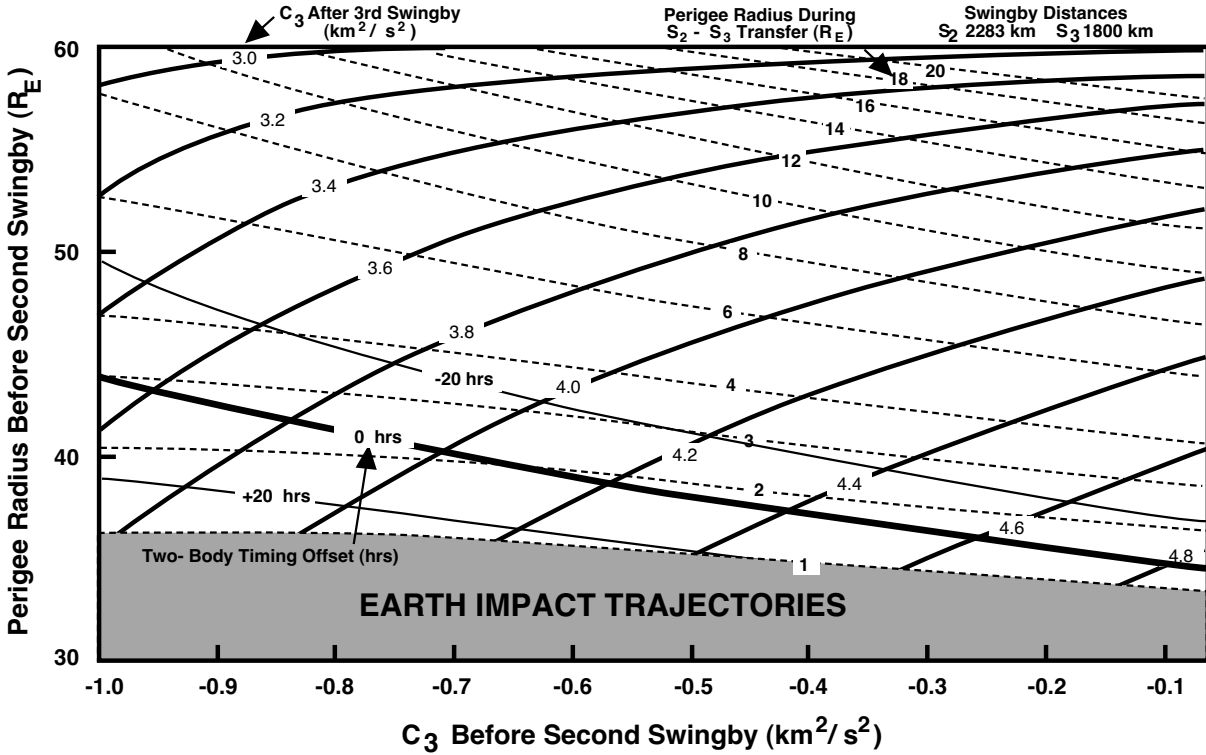
Fig. 5 Performance Chart for Retrograde Double Lunar Swingby

The essential features of the retrograde double lunar swingby (in the circular restricted three body problem) are shown in Fig. 5. The approach energy (C_3) and the perigee radius of the (retrograde) approach trajectory are represented along the x and y axes respectively. In this application, these parameters represent the energy and angular momentum of the spacecraft just before the second swingby, S_2. Contours of C_3 after the third swingby are plotted on this grid along with contours of perigee radius during the critical transfer from S_2 to S_3. Also shown on Fig. 5 are lines of constant two-body transfer time offset. This quantity is the difference in time between the spacecraft's (retrograde) transfer from S_2 to S_3 and the time required for the moon to go (in the prograde direction) from S_2 to S_3. Contours of ±20 hr timing offset are included to show the sensitivity of the transfers. Actual trajectories should never be more than a few hours from the curve of zero two-body timing offset.

The swingby distances at S_2 (2283 km) and S_3 (1800 km) were chosen to be compatible with the integrated trajectory[11] designed as a contingency transfer to the comet Giacobini-Zinner for the ISEE-3 spacecraft. Although this transfer was not used, it includes all the essential features of the TLS except the first swingby. The first swingby was not required for this application because ISEE-3 was already on station at the interior Sun-Earth libration point. But the angular momentum reversal maneuver, followed by a retrograde double lunar swingby, with S_2-S_3 perigee distance at 1.8 Earth radii (R_E = 6378.14 km) and an approach C_3 of -0.46 km²/s² are included in this very clever sequence to transfer

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from a geotail excursion to a real target. The design shows that these maneuvers are practical for real world applications. The design of Ref. 11 actually acquired more energy ($C_3 = 4.49$ km^2/s^2) than that shown on the curves of Fig. 5 ($C_3 \approx 4.39$ km^2/s^2) because the real-world design encountered the moon near its perigee. In practice, the S_2-S_3 sequence may sometimes have to occur when the moon is near apogee. In that case, one could expect to acquire only about 4.3 km^2/s^2 if all the other parameters are the same.

Mars and Venus by Lunar Gravity Assist

The use of the Triple Lunar Swingby can save considerable propellant for missions with launch requirements under about 5 km^2/s^2. The question remains, however, as to how many lunar gravity assist maneuvers are required to reach a C_3 of 9 or 10 km^2/s^2, the energy required to do a ballistic transfer to Venus or Mars. Bender[10] suggested the use of 1-year Earth return trajectories, using a single lunar swingby at each return, to increase the Earth-relative energy. After use of the TLS, which requires about 4 months, it should be possible to achieve a C_3 of about 9.5 km^2/s^2 using two more lunar swingbys. Indeed, another retrograde double lunar swingby is almost achievable but requires slightly subsurface passage at the Earth in order to achieve the bending necessary for the outbound lunar encounter. Perhaps a powered Earth swingby would make the transfer possible.

Another possibility is the use of out of the ecliptic Earth-to Earth transfers of about 6 months as suggested by Breakwell and Gillespie[12]. Such a scheme, if compatible with energy increasing lunar swingbys at each Earth return, could cut the time required for the encounters almost in half. Thus, it may be possible to achieve enough energy to travel to Venus or Mars within about 16 months using one TLS and two additional lunar swingbys at two separate Earth returns. The details of these transfers will have to be carefully checked to ensure their applicability for actual use. Of course, the TLS can be used with a powered Earth swingby at perigee of the S_2-S_3 leg to add more energy for more demanding missions. This technique could enable many missions that would otherwise not be possible with small launch vehicles like PEGASUS, Conestoga and others.

Conclusions

Several "backwards" concepts of orbit mechanics have been presented within the framework of a broad suggestion that the use of uncommon sense is often sensible. Historical precedent for the success of reverse and revolutionary thinking was presented. It was suggested that a particularly difficult problem may yield to the process of guessing a solution and trying to work backwards to the original problem and that the scientist might sometimes take the view that Nature has "hidden" the key to the solution in the least likely place, like a good magician. The Triple Lunar Swingby was identified

as a combination of two, somewhat reverse concepts in a straightforward way. The result is a technique for launching spacecraft to deep-space targets. When the launch requirements are about 4.6 km^2/s^2, for example, the technique can increase the payload of the Delta II 7925 vehicle by about 20%. Discussions of potential enhancements of the TLS included suggestions for 1-year and 6-month Earth-return transfers to enable additional energy boosting lunar swingbys.

Acknowledgments

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