SMALL SPACECRAFT CONCEPTUAL DESIGN FOR A LUNAR POLAR MAPPING/EDUCATIONAL SPACECRAFT

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Abstract

The Lunar Educator is a Phase A mission definition and development activity being undertaken by the University of Colorado's Space Grant Consortium. The scientific objectives of the mission are to provide greater than 50 meter resolution visual images of the Lunar polar regions from various lighting angles in order to discover permanently shadowed craters, and, if spacecraft lifetime allows, to digitally map the entire lunar surface. Of equal importance is the program's educational objective to use this mission as a platform to educate and excite people of all ages in math, science, engineering, and space exploration. The Lunar Educator program intends to accomplish these goals with a simple, low cost spacecraft built and operated entirely by undergraduate and graduate level students.

Introduction

The Lunar Educator is a scientific and educational mission being undertaken by the university of Colorado. It is an on-going effort that began in January of 1992 and is currently in a phase A/B design mode in which a conceptual design has been developed and some flight hardware has been selected. The scientific objectives of the mission are to provide comprehensive visual images of both lunar poles at a pixel resolution of greater than 50m. Once the poles are completely mapped at several different solar lighting angles, the imaging system will then be used to map as much of the lunar surface as spacecraft lifetime will allow. The polar Images will aid in the search for lunar ice and the lunar surface maps will contribute to the body of knowledge of planetary science. The Lunar Educator will also provide valuable data on the lunar gravity field simply from its own tracking. The lunar educator can also act as a beacon for a second sub orbiting spacecraft to provide gravity modeling information for the far side of the moon.

The educational aspects of this mission extend from the current design effort through the construction and operations phase into the data reduction and analysis work. The current spacecraft design was developed entirely by graduate and undergraduate students at the university of Colorado. The fidelity of the design effort was achieved by using a mentor system in which the students drew heavily from the experience of academic and industry professionals to understand the real issues behind the design and construction of spacecraft systems. Future hardware development and construction efforts will be undertaken in the same fashion as Space Grant's successful sounding rocket and Get -Away-Special programs. The spacecraft will be operated out of the University of Colorado much as the Solar Mesosphere Explorer (SME) was with the help of additional universities and educational institutions around the globe. The data acquired by this mission will be distributed by a variety of means to K-12 level to allow teachers to use this data to educate their students in science, math and engineering.

Design Approach

The design of the Lunar Educator spacecraft and mission has been driven by four requirements that derive from its dual scientific and educational nature;

1) The spacecraft must be simple enough for students to design, build, and operate.

2) The mission must be scientifically worthwhile.

3) The program cost must be low enough to be managed within the university system.

4) The spacecraft development time must be within a student's career.

The first requirement derives from the educational aspects of the mission. The primary educational thrust of this mission is to get the next generation of engineers and scientists hands-on experience in the realities of designing, building and flying a scientific space mission. Making the program too large or complex for a student organization would eliminate this educational benefit.

The second requirement is to provide a real benefit to the planetary science community. In order for the program to appeal to the students as well as the scientists it cannot be simply a flag-waving endeavor, real science must be performed.

The third requirement is a concession to the pragmatics of funding and program management. If a program gets too large and costs too much, greater restrictions and overhead costs are placed on the program management.

Additionally, the required simplicity of the program dictates a relatively simple science mission. To keep the dollars to science ratio on a par with larger missions, the cost must be correspondingly modest. The funding level anticipated for this effort is under $10 million.

The fourth requirement enables continuity through out the design and construction process. Previous experience at the Colorado Space Grant College has shown that students learn a great deal more if they are able to watch their design efforts go through the growing pains of becoming a reality.

These four requirements can be summed up as Simple, Good, Cheap, and Fast. The combination of these requirements results in a quickly developed, simple mission that provides a modest science return for a low cost. The four different requirements complement each other quite well. The short development time reduces the total overhead costs. The low level of complexity reduces both the development cost and time. The low cost allows the relatively simple science to have as much "bang for the buck" as larger, more complex, and expensive missions. And the good science in a short time brings in the interest of the planetary exploration community as it provides an early precursor to future lunar exploration.

These seemingly contradictory requirements are met by employing design philosophies that are a departure from standard scientific mission practices. These departures can be summed up as follows;

1) Use surplus hardware wherever possible *even if it affects the overall mission plan.*

2) Use only existing designs and technology.

3) Do not build anything specialized unless absolutely necessary.

4) Do not add to the basic science capabilities of the mission unless there are minimal design and cost impacts.

The specific impacts of this design philosophy to this mission will be described in the "Design History" and "Current Baseline Design" sections. The generalized impacts are quite clear. The resulting spacecraft and mission are not optimized for high performance or to serve a broad scientific community. Instead, the mission is optimized for cost and simplicity. Using surplus hardware and existing technology results in spacecraft systems that are over-built for the specific mission. However, by using surplus and off-the-shelf hardware, long procurement cycles are avoided, thus cutting development time and cost.

The spacecraft and scientific mission that result from these design requirements and philosophy is a quick, simple mission that provides a modest science return for a minimal cost. The education and experience that the students receive while designing, constructing and operating the spacecraft is unparalleled.

Science

The science the Lunar Educator performs is separated into two basic categories, visual imaging and gravity model refinement. The visual imaging is accomplished using a high resolution Charged Coupled Device (CCD) camera that produces gray scale images of the lunar surface. Both poles of the moon will be completely mapped from different sun angles to provide detailed information on these unexplored regions and to identify those crater areas that are permanently shadowed. The discovery of permanently shadowed craters would be a first step in the search for lunar ice. The lunar gravity model would be much refined simply by tracking a spacecraft in a lunar polar orbit. In addition, the Lunar Educator will carry an Ultra Stable Oscillator (USO) to act as a beacon for a second spacecraft in a lower orbit for gravity modeling of the far side of the moon.

Lunar Imaging

The lunar poles are of interest for two reasons, first because they are the least researched area of the moon and secondly because of the possibility of discovering frozen volatiles such as water or carbon dioxide (Refs. 1-2). The lunar poles were not mapped in detail during the initial race to the moon since they did not contain viable landing sites. Maps that do exist are from the Ranger, Surveyor and Lunar Orbiter missions, none of which ever got above 85° inclination or 100 m resolution. The Lunar Orbiter took only limited images of the polar regions. Additional images of the polar regions would thus be of interest to the planetary science community.

The possibility of permanently shadowed craters acting as a thermal trap for volatile interplanetary volatiles has been debated for some time. Since the moon's axis is nearly perpendicular to the ecliptic plane, it is possible that the rim of a crater on the north or south pole could block any sunlight from ever reaching certain areas internal to the crater (see Figure 1).

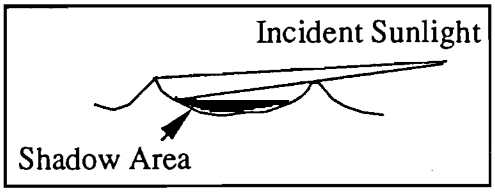

Figure 1. Permanently Shadowed Polar Crater

These areas would be extremely cold (~3° Kelvin) and may act as a trap for volatile materials such as water, carbon dioxide, etc. Such frozen "lakes" of material would be of tremendous value both as a selenological record akin to Earth's polar ice caps and as a valuable resource for future lunar missions.

By imaging the lunar polar craters throughout a complete cycle of sun angles, the Lunar Educator program would be able to identify which craters were permanently shadowed, thus paving the way for future moon missions. Time-lapse photography of these regions would be accomplished from a "frozen" orbit that stays fixed as the moon rotates underneath it, thus providing different lighting angles over a long time periods. This orbit is described in detail in the following sections.

Lunar images are obtained by a 1024 by 1024 pixel array looking through a 10 cm diameter Catoptic telescope. Each image is 51.2 km by 51.2 km, with a pixel resolution of 50 meters. The images are then compressed and transmitted back to Earth at a rate of one every 0.5 to 1.5 hours depending on the data compression rate. If continuous telemetry coverage is available, both poles will be completely imaged from 80° North and South latitudes to the poles themselves within one month. The spacecraft will then continue to image craters of interest to see if specific regions remain permanently shadowed over the course of six months.

Once the polar regions are completely imaged, the spacecraft will begin imaging the rest of the lunar surface. Given the low data rate, this process could take as long as 1.5 years, but since the spacecraft is in a stable orbit, very little propellant is needed. The only limitation then is the lifetime of spacecraft sub systems such as solar arrays, batteries, radiation sensitive components, etc.

Various strategies for imaging have been suggested. The simplest is to compress all images equally and send them all down at the same rate. A second strategy uses two data compression schemes, a high compression ratio with high data losses and a low ratio, low loss scheme. An area would first be imaged at the high rate to get as much area covered as possible and then features of interest would then be imaged and transmitted using the slower, higher fidelity scheme.

Lunar Gravity Modeling

The gravity field of the moon is not at all uniform and therefore has a large impact on any lunar orbiter mission design. The existing gravity models are based on satellite data from primarily equatorial orbits, and no data is available from the back side, since it is always out of site (Ref. 3). Additionally, there is a fair amount of disagreement between the different existing gravity models. By tracking a polar orbiter over one to three years, it will be possible to at least quantify the fidelity of the existing models.

The Lunar Educator will also be equipped with an Ultra Stable Oscillator that can act as a beacon for other spacecraft to develop lunar gravity models for the far side of the moon. The ultra stable signal will be broadcast from the known orbit of the Lunar Educator to the more perturbed orbit of a low lunar orbiter. The Doppler shift in the ultra stable signal will indicate how the sub spacecraft's orbit is perturbed by the irregularities in the moon's gravitational field. This will allow scientist to produce a new gravity field that includes data from the far side and the polar regions.

Education

One of the primary purposes of the Lunar Educator mission is to provide an educational tool for K-12 as well as higher education. This goal can be accomplished in a number of ways throughout the lifetime of the mission.

Development/Construction Phase

During the early phases of the mission, students can be shown how the spacecraft is developed by the distribution of mock-ups and models of both the spacecraft and the cis-lunar environment it will operate in. Many of the problems of space flight provide demonstrations of how math and science are used in the modern world. The concepts of shadowing, imaging, spacecraft visibility, power, and communications all can offer a context for the teaching of basic concepts in geometry and science. The relating of these concepts to a real mission, as well as interaction with the university students actually working on the mission, can also provide younger students with a feeling of ownership, which can spark their individual interests in science and engineering.

Operations

During the actual operating lifetime of the spacecraft, portable workstations that tie into the main ground control for the Lunar Educator can be taken to schools to allow the students to actually see some operations in real time at their school. A system of image distribution that allows each school to build its own "Lunar Map" as the images are collected by the spacecraft will allow the schools to participate in their own "science" mission - they can identify shadowed regions, craters, etc.

The development of an "Educational Infrastructure" to perform these types of activities is as important to the Lunar Educator mission as the actual spacecraft itself. Once such an infrastructure is in place, it is trivial to adapt it to any other mission that is available. Obviously, such an infrastructure does not require a lunar mission in order to be implemented.

Design History

The Lunar Educator project began as an engineering study to explore what lunar missions could be accomplished by a student group and what scientific uses could be found for a series of "frozen" orbits recently rediscovered by C. Uphoff (Ref. 4). These orbits balance Earth perturbing effects against lunar gravitational anomalies (mas-cons). The resulting orbit has an inclination of 90.25° with an orbital period of 3.9 hours and a perilune altitude of 1013 km. The orbit is considered "frozen" because the argument of perilune and perilune altitude stay relatively constant over time. In such a stable orbit, reboost and orbit trim maneuvers are minimal. Due to the altitude of the orbit, its stability is not sensitive to which of the several lunar gravitational models are assumed.

The original Lunar Educator proof of concept design was a two stage spacecraft designed to be launched in Low Earth Orbit (LEO) off of a Pegasus size launch vehicle. The original spacecraft was a 150 kg spin stabilized spacecraft that was boosted from LEO to a trans-lunar trajectory by a Star 24 solid rocket motor. A bipropellant engine then braked the spacecraft into a lunar polar capture orbit and then trimmed the orbit to the desired frozen orbit.

This original spacecraft design, while feasible, was undesirable for three reasons, all related to the requirements described in the preceding Design Approach section. The spacecraft had extremely tight mass and power margins, requiring all systems to be highly optimized. This optimization and particular part design was expensive and required a long procurement cycle. It was also considered that multiple stages, bipropellant propulsion, and extremely tight mass margins would be make the design process more difficult than practical for a student developed mission. Additionally, surplus parts for such a specific, inflexible design were unable to be found.

The design team then took a different approach to the same general mission plan. Using the original, more complex design as a starting point, students canvassed the aerospace industry and government institutions for surplus and bench test hardware that could be used to provide some of the capabilities needed to perform the scientific and education missions.

The resulting search brought forth two major findings, first that there is indeed a fair amount of surplus flight hardware available to anyone willing to search diligently, and secondly that the engineering community is extremely supportive of small, low cost missions such as the Lunar Educator.

Many spacecraft developed in the last two decades have bought spare parts either as flight spares or as ground test equipment. Also there have been several programs that have purchased hardware and then been terminated. The result is that there is a fair amount of space flight hardware sitting on shelves around the nation that needs only a minimum of refurbishment to be flight worthy. The difficulty in using this hardware lies in finding it in the first place and then getting permission to use it.

In both these tasks the aerospace community as a whole was extremely helpful. Engineers, management and staff at all levels were overwhelmingly supportive of this educational and scientific effort. The enthusiasm for space exploration and education cut across institutional and corporate boundaries and since the proposed budget is so small, monetary competition was not an issue.

The Lunar Educator program was able to find a Ball Star Scanner, a series of high resolution CCD's, an 8648 cubic inch capacity propellant tank, three 40 lb. thrust hydrazine engines, and a set of flight ready batteries. This equipment has a total value of over $2 million. Additional donations of solar arrays, a flight computer, and communications hardware are also being pursued. On a larger, $100+ M program, these donations would have little or no impact, but on a $10M program, these donations are a significant cost savings, and thus well worth the performance impacts.

The performance impacts of using this hardware and the simplicity dictated by the low cost and student production have resulted in a number of design changes. The spacecraft is now to be launched into a Geosynchronous Transfer Orbit (GTO) and from there the spacecraft is a single stage vehicle to its final lunar orbit. The propulsion system became a monopropellant blow-down system with the Nitrogen ullage pressurant also used for attitude control. The spacecraft now carries additional attitude control propellant to adjust the spin rate so that the donated star scanner is effective.

Additional concessions to the simplicity and cost requirements include an omnidirectional antenna, and spin stabilization. The omnidirectional antenna reduces the data downlink rate but it is extremely simple and less expensive and complex than a articulated directional antenna. The spin stabilized spacecraft puts additional demands on the speed and sensitivity of the camera but eliminates the need for such expensive active attitude control measures as CMG's or momentum wheels.

The impacts of the hardware donations and the requirements imposed by this program's educational nature have had large impacts on the spacecraft and the mission design. In some cases, the changes have reduced the spacecraft performance over the original design but in all cases, have reduced the spacecraft's cost, complexity and development time. These reductions have placed this program within the reach of a student run organization, providing a unique educational experience.

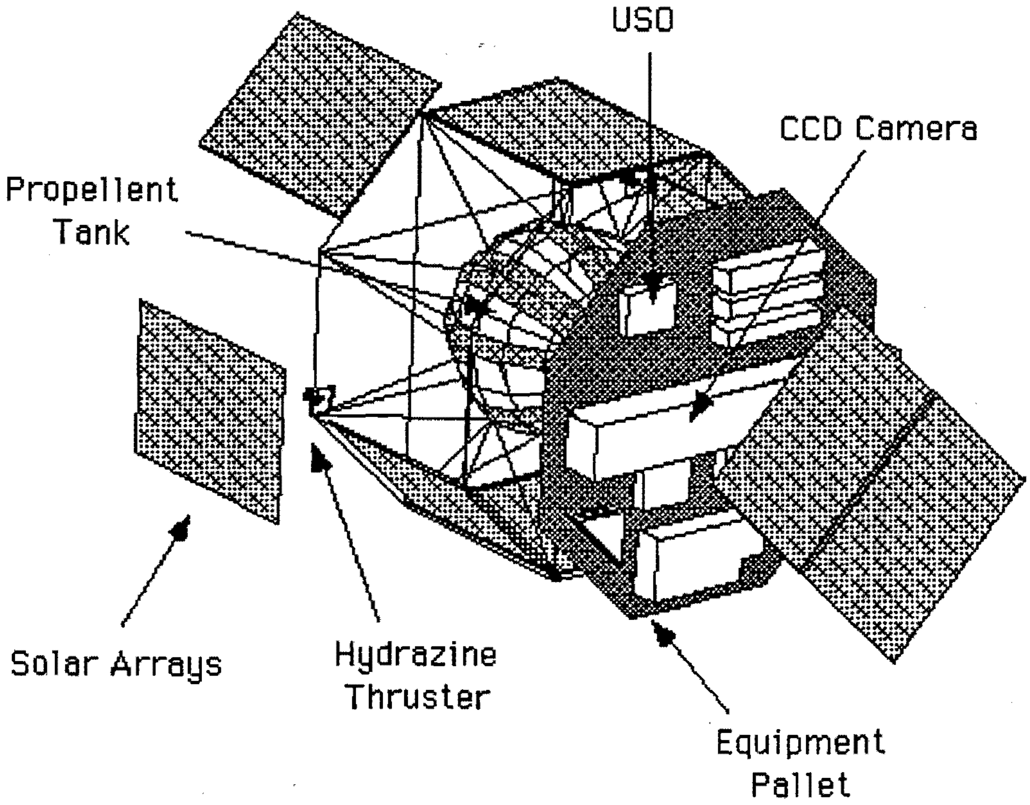

Figure 2. Lunar Educator Spacecraft

Current Baseline Design

Spacecraft

The Lunar Educator is a octagonal, spin stabilized spacecraft 1.5 meters wide and 1 meter tall. Figure 2 illustrates the general layout of the spacecraft. The central section contains a 71 cm diameter hydrazine tank and the spacecraft batteries. It also acts as the support for eight solar array panels. The bottom of this central section is covered by passively controlled louvers for thermal control. The top of the central section is covered by the payload support pallet. This upper pallet contains all the instruments, control electronics, and communications equipment. The spacecraft's dry mass is 90 kg and can be loaded with 110 kg of propellant and pressurant for a total launch mass of 200 kg. The spacecraft generates an average of 130 Watts of power and can downlink data from the moon at a rate of 500 bits per second.

The spacecraft is separated into two sections to ease assembly, integration and testing. The large lower section contains all the elements of the propulsion system as well as the batteries and power conditioning equipment. The upper equipment plate contains the imaging equipment, the star scanner and sun sensors, the command and control electronics and the communications equipment. This separation allows all the electronics of the satellite to be tested as an integrated unit while the propulsion system is being filled and tested.

The upper section consists of a honeycombed aluminum plate with all components supported on top. The components are then covered with multilayer insulation and then with two solar array panels. The lower section is a truss framework that supports the central propellant tank with aluminum tubing. The framework also provides support for eight solar array panels around the spacecraft's circumference. The bottom of this section is covered by a series of passively controlled louvers that provide thermal control for the spacecraft.

The spacecraft is commanded by a radiation tolerant 68030 microprocessor with 2 Bytes of memory for code, processor memory and stack space. This microprocessor controls all spacecraft functions through a series of 20 relays that activate the various spacecraft systems. The image data is compressed and stored in a 2 Byte solid state data storage system and downlinked at a later time. The microprocessor is programmed in the NASA developed Spacecraft Command Language (SCL).

The baseline imaging system consists of a 10 cm diameter Catoptic telescope pointing out of the side of the spacecraft. The spacecraft spin axis is perpendicular to the orbit plane so that the telescope scans the lunar surface once per spacecraft revolution. The telescope images are recorded on a 1024x1024 pixel Charged Coupled Device (CCD) camera. These images are then compressed at a rate of between 3:1 and 10:1 and stored for later transmission. This system achieves a pixel resolution of 50 meters in a square image 51.2 km on a side.

The power generation system on the Lunar Educator consists of ten 80 x 39 cm silicon solar arrays. Two of these arrays are on the top of the spacecraft, the remaining eight each are attached to a side of the spacecraft octagon. This arrangement produces between 100 and 155 Watts of power depending on the spacecraft orientation. This power is distributed throughout the spacecraft by a relay control board commanded by the Command and Control microprocessor. The excess power is stored in a series of banks of battery cells for use during the brief periods when the spacecraft is in shadow. The longest shadow period anticipated is 1.3 hours, thus the batteries are sized to provide 235 Watt-Hrs at an 80% depth of discharge.

The spacecraft communicates with the Earth ground stations using two omnidirectional S-band patch antennas. These antennas are located on the top and bottom of the spacecraft providing full spherical coverage. The antennas are driven by a transponder that performs all of the transmitter, receiver, modulator, and amplifier functions. The transmitter has an EIRP of 10 Watts and a corresponding data rate from the moon of 500 bits per second (bps). The uplink frequency is 2110 MHz, the downlink frequency is 2290 MHz.

The propulsion for the spacecraft is provided by a monopropellant hydrazine blowdown system. A central, 71 cm diameter tank provides a total capacity of 142 liters of hydrazine and is pressurized to 380 psi by a nitrogen pressurant contained in an elastomeric diaphragm. The hydrazine is fed to two 40 lb thrust hydrazine engines for orbital maneuvers or alternated between the two engines for a coarse turning capability. The engines are located at the bottom of the spacecraft and are pointed out along the spin axis.

The spacecraft attitude is determined by a star scanner in concert with a sun sensor. Rate gyros and accelerometers will provide additional data and act as a back up if the spacecraft is rotating at a rate out of the range of the star and sun sensors. Data taken from the above instruments will be taken with time stamps and downlinked for ground calculation of the spacecraft's state.

The spacecraft attitude is controlled by a series of six attitude control thrusters. These thrusters are cold gas jets that use the ullage nitrogen from the propellant tank as reaction mass. They can provide a coupled torque about the spacecraft to turn 0.1° per spacecraft revolution. Any resulting nutations are then damped out by a passive nutation damper. The spacecraft can also be turned in a coarse mode by the primary, hydrazine engines.

The spacecraft's temperature is maintained within operational limits by multilayer insulation and emissive coatings. Louvers on the bottom of the spacecraft are used to control the emitting area and thus the spacecraft temperature. These louvers are passively controlled using a series of bimetallic springs. When the spacecraft temperature starts to rise, the bimetallic springs begin to unwind, opening the louvers and exposing part of the spacecraft to deep space, thus cooling it off.

These spacecraft systems are designed for simplicity, ease of integration, and low cost. The technologies used are all proven designs that have been used many times in the past. The upper payload plate allows the complex electronic components to be integrated and tested apart from the chemically active hydrazine propellant and the magnetically noisy power conditioning equipment. The level of complexity of all these systems is within the capacity of undergraduate and graduate level students, affording them a unique educational opportunity.

Mission Design

The nominal mission profile consists of five separate phases:

1. Geosynchronous Transfer Orbit (GTO)

2. Phasing Orbit

3. Trans-Lunar Trajectory

4. Operational Lunar Orbit.

C. Uphoff (Ref. 5) has correctly pointed out that Lunar transfer from GTO can be not only efficient, but also affordable, given the relatively high traffic Geosynchronous orbit. Figure 3 shows the entire mission profile.

For an efficient transfer from GTO to Lunar Injection, the GTO orbit must be allowed to rotate (rotation is caused by oblateness effects of the Earth) until the line-of-apsides falls in the Earth-Moon plane. Once this geometry is established, a phasing orbit is chosen for the spacecraft to wait in until the Moon has swung into position for the Trans-Lunar trajectory. The period of the phasing orbit is chosen to put the spacecraft at perigee when it is time for the TLI maneuver. Once the TLI maneuver is complete, the duration of the mission is like any other Lunar mission. The necessary waiting time in GTO, and the

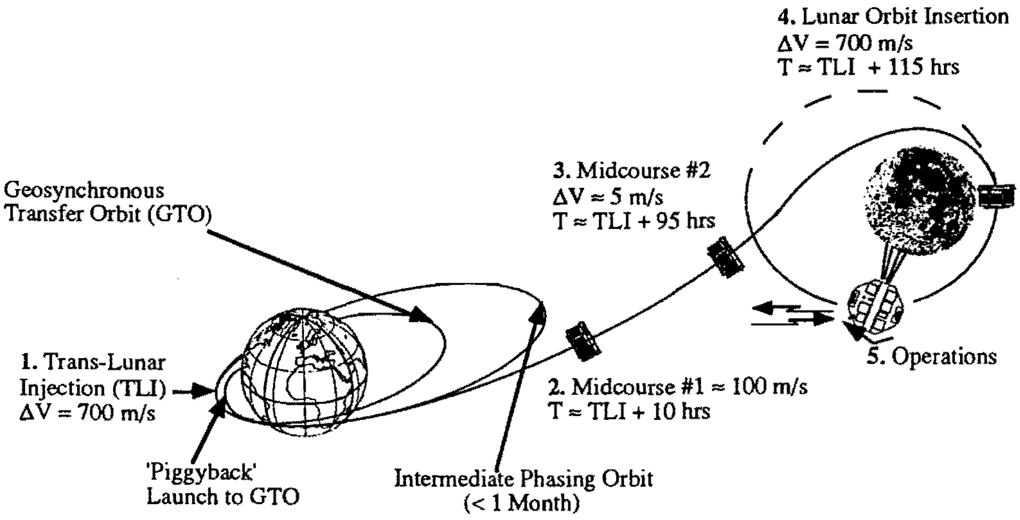

Figure 3. Lunar Educator Mission Profile

parameters of the Phasing orbit, are all functions of the original GTO orbit and the time of year (and of the Month) that launch occurs.

The trans-lunar trajectory is actually an elliptical Earth-orbit that is perturbed near apogee by the Moon's gravity. The TLI burn combined with the burn to the phasing orbit requires a ΔV of only 700 m/s. The nominal mission statement shows two midcourse maneuvers. We estimate a need for 100 m/s of midcourse ΔV that can be split in two or used in one burn. Given the difficulty and length of attitude maneuvers on the Lunar Educator spacecraft, it is likely that only one midcourse maneuver will be used, and any further corrections will have to be dealt with in Lunar Orbit. It is also likely that an intermediate Lunar parking orbit will be used for the initial orbit capture.

The final orbit has been chosen to be a 'frozen' orbit, i.e. one whose argument of perilune and perilune altitude stay constant over long periods of time. Although there are various Lunar gravity fields currently in use, this orbit has been found to be essentially 'frozen' in all of the fields. This, in addition to the relatively high altitude of the orbit, provides a good probability for a long orbital lifetime. The orbital parameters are: $a = 2905$ km, $e = 0.053$, $i = 90.25°$, $\Omega = 0$, $w = 357°$. The orbital period is 3.9 hours and the perilune altitude is 1013 km. We have used a baseline of 2 years for the operational lifetime of the spacecraft in this orbit, although the orbit should be stable for much longer.

Operations and Ground Systems

Polar reconnaissance is the top scientific priority for this mission and thus is the primary mission for the first cycle (1 year). The imaging strategy has been developed to acquire complete coverage of the polar regions during all possible lighting conditions given a relatively low downlink rate (500 bits/sec)

The polar regions will be imaged in swaths as the spacecraft "rolls" over its orbit with each swath consisting of thirteen 1 megabyte images that are 51.2 km square regions of the lunar surface.

At this point, we have assumed that the only ground station available a modified station that uses the two 60 foot dishes north of Boulder, Colorado owned by the U.S. Dept. of Commerce. This allows us approximately 8 hours each day of communications with the Lunar Educator. Given this downlink time, and assuming an achievable compression rate for images of 10:1, we can 47 images per month. This is clearly a low estimate, and can be improved by increasing the ground visibility time by adding additional ground stations or by improving the data rate.

Due to this low downlink rate, a large onboard data storage unit is required. We will use a 2 Gigabyte solid state unit for this purpose.

Spacecraft operations are designed to be minimal once lunar orbit is achieved. Small periodic attitude maneuvers may be necessary to maintain the right spin axis orientation with respect to the nadir. In addition, switching between the two omnidirectional antennae will be required every 15 days to keep the active antenna facing the Earth.

Ground operations will be modeled after the highly successful Solar Mesosphere Explorer spacecraft, using the Project Operations Control Center (POCC) at the University of Colorado and could be complemented with additional POCCs in international locations if they become available.

Current and Future Activity

The Lunar Educator program is currently developing a comprehensive software model of the operational characteristics of the spacecraft. This model will be used to walk through the end-to-end operations of the mission. These operations walk-throughs will test the overall spacecraft systems performance under nominal and contingency situations and determine if the spacecraft design is robust enough to perform the desired mission.

Future activity of the Lunar Educator program will include the construction of a ground test prototype to simulate the actual hardware interfaces between the different subsystems and to perform similar "shake down" mission simulations. As the flight hardware is developed and acquired, this hardware will be incorporated into the flight prototype to ensure smooth integration and proper performance.

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References

1) Cordell,B., *Search for the Lost Lunar Lakes* , Astronomy Magazine, March 1993.

2) Light, D.L., *Moonsat: An Orbital Imaging System for Mapping the Moon*, (ISSSR F-04), Presented at the International Symposium on Spectral Sensing Research, November 15-20, 1992, Maui, Hawaii.

3) Bills, B.G., and Ferrari, A.J., "A Harmonic Analysis of Lunar Gravity," Journal of Geophysical Research, Vol. 85, pps 1013-1-25, Feb., 1980.

4) Uphoff, C.W., Personal Communication, 1991.

5) Uphoff, C.W., "Practical Aspects of Transfer from GTO to Lunar Orbit," Presented at the Flight Mechanics /Estimation Theory Symposium, May 5-7, 1992, Greenbelt, MD.