ESTABLISHING A NEAR TERM LUNAR FARSIDE GRAVITY MODEL VIA INEXPENSIVE ADD-ON NAVIGATION PAYLOAD

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Abstract

The Space Communications and Navigation, Constellation Integration Project (SCIP) is tasked with defining, developing, deploying and operating an evolving multi-decade communications and navigation (C/N) infrastructure including services and subsystems that will support both robotic and human exploration activities at the Moon. This paper discusses an early far side gravitational mapping service and related telecom subsystem that uses an existing spacecraft (WIND) and the Lunar Reconnaissance Orbiter (LRO) to collect data that would address several needs of the SCIP. An important aspect of such an endeavor is to vastly improve the current lunar gravity model while demonstrating the navigation and stationkeeping of a relay spacecraft. We describe a gravity data acquisition activity and the trajectory design of the relay orbit in an Earth-Moon L2 co-linear libration orbit. Several phases of the transfer from an Earth-Sun to the Earth-Moon region are discussed along with transfers within the Earth-Moon system.

We describe a proposed, but not integrated, add-on to LRO scheduled to be launched in October of 2008. LRO provided a real host spacecraft against which we designed the science payload and mission activities. From a strategic standpoint, LRO was a very exciting first flight opportunity for gravity science data collection. Gravity Science data collection requires the use of one or more low altitude lunar polar orbiters. Variations in the lunar gravity field will cause measurable variations in the orbit of a low altitude lunar orbiter. The primary means to capture these induced motions is to monitor the Doppler shift of a radio signal to or from the low altitude spacecraft, given that the signal is referenced to a stable frequency reference. For the lunar far side, a secondary orbiting radio signal platform is required. We provide an in-depth look at link margins, trajectory design, and hardware implications. Our approach posed minimum risk to a host mission while maintaining a very low implementation and operations cost.

Introduction

The Space Communications and Navigation, Constellation Integration Project (SCIP) is tasked with defining, developing, deploying and operating an evolving multi-decade communications and navigation (C/N) infrastructure including services and subsystems that will support both robotic and human exploration activities at the Moon.

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This paper describes a proposed innovative design of an early far side gravitational mapping service and related telecom subsystem that uses an existing spacecraft and the Lunar Reconnaissance Orbiter (LRO) to collect data that would vastly improve the current lunar gravity model. An accurate lunar gravity model is critical to the needs of the Vision for Space Exploration (VSE) and the Constellation Program (CxP). Current lunar architecture goals include exploration sites located on the far side of the Moon, vehicles in low altitude lunar orbit and other landers with operations that will be impacted by the lunar far side gravity field [Ref-1]. Both mission planning and operations will benefit from an improved model of the lunar far side gravity field.

Our current knowledge of the gravity field on the lunar far side is minimal since no direct Doppler Line-Of-Sight (LOS) measurements exist. Current gravity models are derived from observing the integrated effect on the Doppler shift as an orbiting spacecraft entered and exited occultations as seen from Earth. Given this, the uncertainties in the far side gravitational acceleration are as large as 100 milligal, or 100 times larger than the uncertainties on the near side gravity model. While a dedicated lunar gravity science mission can achieve a factor of 100 or greater improvement in the far side gravity model it will do so at a much higher price than a proposed add-on payload scheme. The add-on payload described here elevated the far side gravity model accuracy to the nearly the same level as the near side model. Beyond this, there are numerous operational and experience benefits that would have been derived from this gravity science mission. Near term benefits include:

- Improved gravity model for all future robotic and CxP planning activities
- Accurate planning and execution of lunar descent and landing trajectories
- Improved ΔV / fuel mass budget planning and management
- Longer range and more accurate science operations schedules based on better orbit propagation modeling.
- Experience and insight gained from coordinating operations of multiple spacecraft at the Moon.
- Experience and understanding of operating a lunar relay spacecraft
- Experience working with and processing radiometrics from multiple lunar spacecraft for the purpose of navigation and cross-link telecom.
- Experience and understanding of Earth-Moon transfer orbits that are essential for manned lunar flights and rendezvous operations.

The science of lunar geophysics benefits from a more accurate gravity model. Correlating gravity information with topographical information, inferences can be made about the lunar interior structure and ultimately its thermal history. For example, gravity models of large lunar impact basins, "provide insight into the impact processes that formed the basins as well as the volcanic filling history which many of these basins experienced."[Ref-2] Going deeper, an improved gravity model provides insight into the lunar core size and metallic content. [Ref-3] This information could assist in the selection of far side and polar sites of interest for either scientific investigation or resource utilization.

S-band Gravity Science Data Collection Scheme

As shown in Figure 1, we proposed a gravity data acquisition activity as an add-on to the Lunar Reconnaissance Orbiter, LRO, which is scheduled to be launched in October of 2008. LRO provides an example of a host spacecraft against which we designed the science payload and mission activities. From a strategic standpoint, LRO would be a very exciting first flight opportunity for gravity science data collection. What we describe here is an approach that poses the **minimum risk** to the host mission while maintaining a very **low implementation and operations cost**.

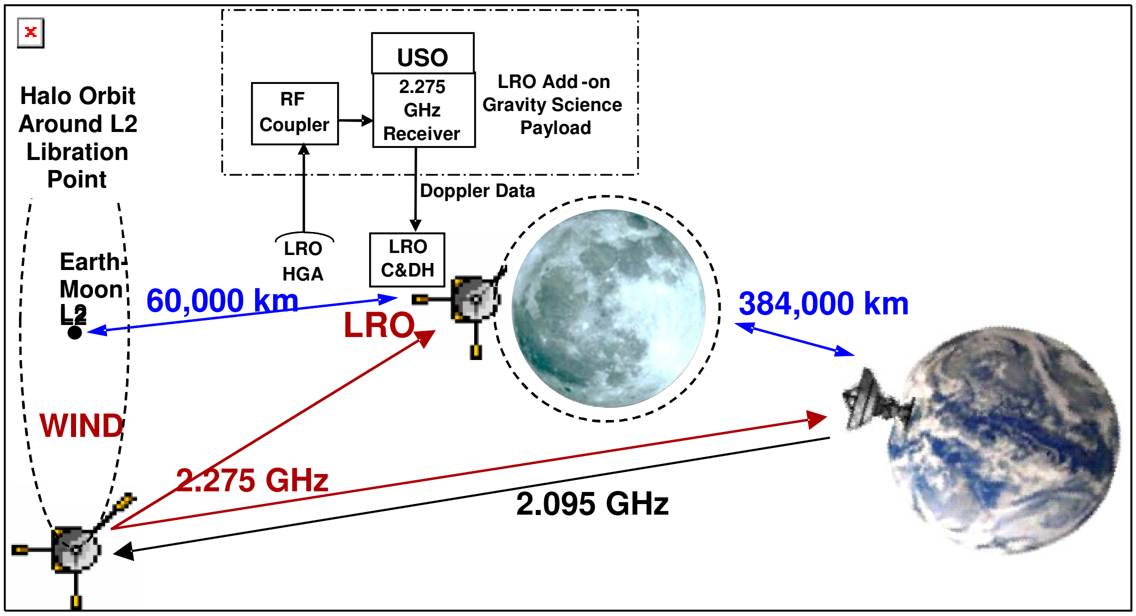


Figure 1 - Lunar Far Side Gravity Data Collection with WIND or WMAP in an Earth-Moon Libration L2 Orbit

Gravity Science data collection requires the use of one or more low altitude lunar polar orbiters. Variations in the lunar gravity field will cause measurable variations in the orbit of a low altitude lunar orbiter. The primary means to capture these induced motions is to monitor the Doppler shift of a radio signal to or from the low altitude spacecraft, given that the signal is referenced to a stable frequency reference. For the lunar near side, this can be achieved with Earth based observations. For the lunar far side, a secondary orbiting radio signal platform is required, such as WIND or The Wilkinson Microwave Anisotropy Probe (WMAP) in an Earth-Moon Libration orbit. Figure 1 depicts such a scheme.

L2 Relay Platform

The secondary signal relay platform for this proposed initiative is the WIND spacecraft. The WIND spacecraft is currently orbiting the Sun-Earth co-linear L1 libration point and will be maintained there for the foreseeable future. [Ref-4] This orbit is the final phase of the WIND mission design and science operations may cease by FY09. The proposed WIND relay orbit at the Earth-Moon co-linear L2 libration point can be easily achieved by redirecting the spacecraft from its current libration orbit onto a trajectory that will traverse Earth-Moon regions to be used by Exploration missions. The WIND spacecraft has a moderate amount of fuel left onboard, estimated to be equivalent to 100 m/s. Through judicious fuel use, one can achieve the desired relay orbit, perform stationkeeping, move to alternate relay orbits and possibly re-establish and maintain another Sun-Earth libration orbit.

Transfer Trajectory Analysis

There are many possible orbit designs; the goal of attaining and maintaining an Earth-Moon libration orbit was the priority of our trajectory analyses. Figure 2 shows a sample transfer in a Sun-Earth Rotating coordinate system. The simulation starts with WIND's orbit state from late November, 2005. WIND remains in its orbit around L1 for another 2.5 years until a departure maneuver is executed to send WIND on a transfer to the Moon in June, 2008. Four months later (near the proposed launch date of LRO), a trajectory correction maneuver (TCM) is performed to further target conditions at the Moon. Finally, a maneuver is required to insert into an orbit around the Earth-Moon L2 (EML2) libration point. The total ΔV required for this trajectory is less than 35 m/s. Additional analysis could help to optimize the required ΔV.

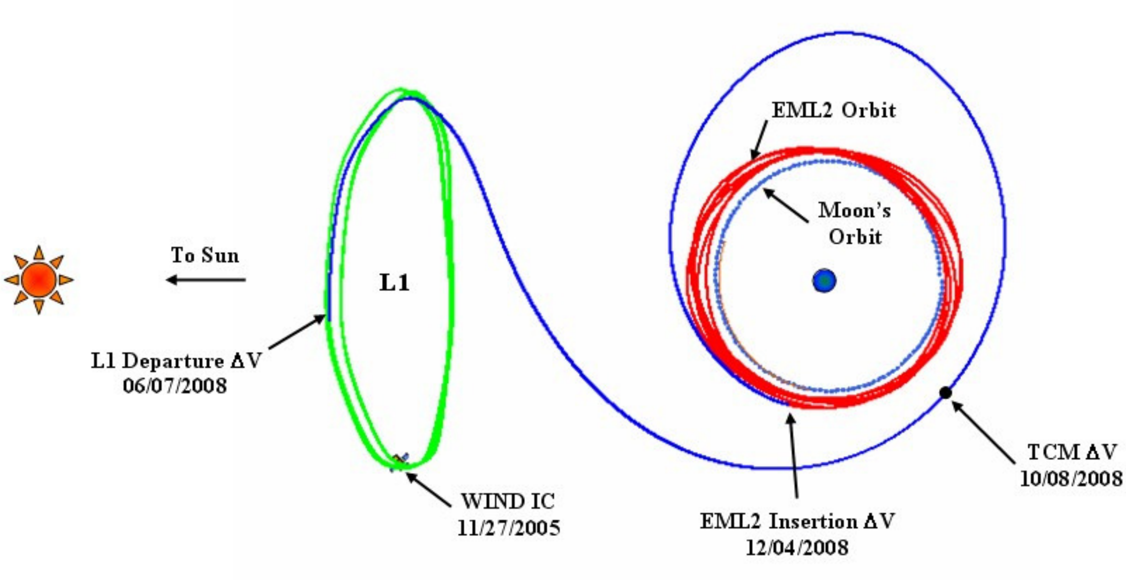


Figure 2 - Transfer from Sun-Earth Libration L1 Orbit to Earth-Moon Libration L2 Orbit

Earth-Moon Libration Halo Orbit

After achieving the transfer back to the Earth-Moon system, an insertion into the Earth-Moon L2 Libration orbit is performed. Figure 3 shows the WIND spacecraft in its EML2 orbit for 6 months (12 revolutions). The orbit is visualized in Earth-Moon rotating coordinates. Important in this segment is the test and verification of stationkeeping and the ground tracking resources required to perform navigation in order to maintain the orbit. We have investigated stationkeeping requirements using GSFC's Flight Dynamics Analysis Branch (FDAB) operational methods from SOHO, WMAP, ACE, etc., but the dynamics of the Earth-Moon region are much more unstable, resulting in higher perturbations and the associated fuel (ΔV) and operations cost. Navigation and stationkeeping in the Earth-Moon libration orbit have never been verified, as there have been no missions in these regions. GSFC has vast experience in traversing these regions (ISEE-3, WIND, SOHO, WMAP, ACE) and going to the Moon (Clementine and Lunar Prospector), but the models haven't been verified in their application to stationkeeping in the Earth-Moon Libration orbits.

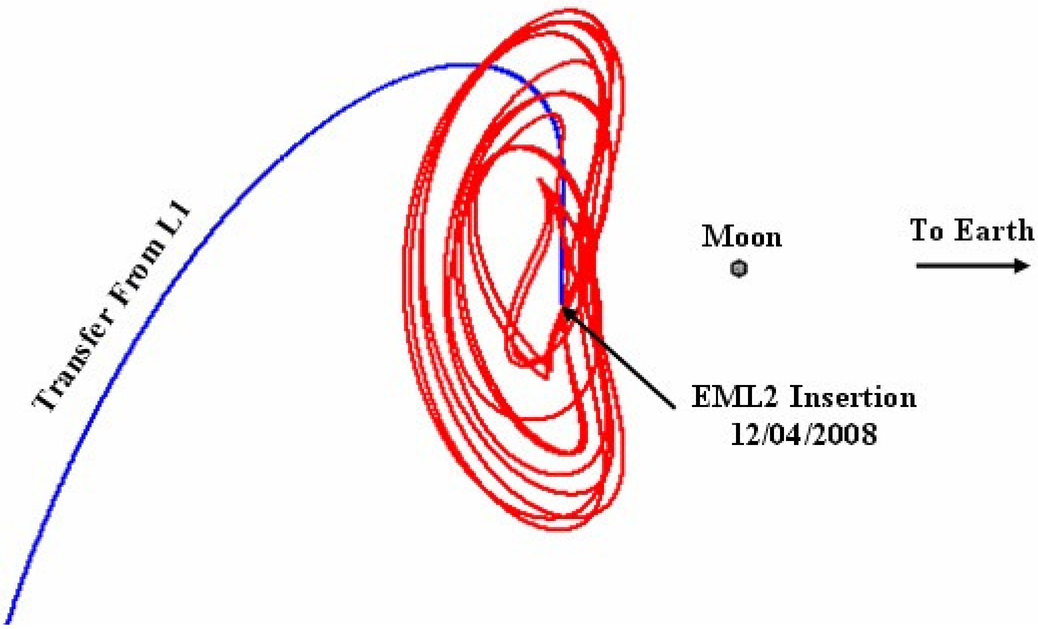


Figure 3 - Transfer of WIND to Earth-Moon L2 Orbit

Preliminary contact analysis revealed nearly 300 candidate passes (greater than 10 minutes) per month where WIND has both DSN coverage and line-of-sight contact with LRO on the far side of the Moon. The average length of these passes was 37.5 minutes. The WIND to LRO range varied from 33,000 km to 85,000 km with an average of 65,000 km. while the range-rate varied between ±1.9 km/s. All DSN coverage analysis assumed a minimum elevation of 10º. Further analysis will be required to include the attitude profile of WIND and its antenna patterns. These results will likely reduce the number of potential opportunities.

WIND Telecom Hardware

The WIND spacecraft is equipped with an S-band transponder. This transponder is connected to a medium gain antenna that provides a peak gain of roughly 2.6 dBi, but DSN link budgets carry the gain as -0.9 dBi, "including circuit losses". The transponder is capable of producing a downlink signal that is phase coherent to the uplink signal with a frequency transponding ratio of 240/221. Nominal WIND uplink frequency is 2094.896 MHz and the downlink is 2275.000 MHz. Spacecraft design documents describe an end of life RF transmit power of 28 watts but DSN link budgets carry a transmit power of 19 watts. [Refs – 5 and 6]

With WIND positioned in a halo orbit around the Earth-Moon L2 point, the range to Earth would roughly be 455,000km and the range to the LRO spacecraft would vary between 35,000 km and 85,000 km. The WIND spacecraft attitude is maintained to produce maximum Tx antenna gain toward the LRO spacecraft. Currently the attitude of this spinning spacecraft is kept to +/-1 degree off the North Ecliptic Pole. With this orientation, Earth appears no more than 8 degrees off the boresight of the WIND Medium Gain Antenna (MGA).

LRO Gravity Sensing Platform

The current LRO mission plan calls for three on-orbit mission phases and three corresponding orbits. During the first month after arrival the spacecraft will be in a commissioning phase for calibration of the science instruments. The commissioning orbit is a 30 km x 216 km lunar altitude frozen orbit with periapsis over the south pole. Mission navigators will also use this first month to better characterize the stability of the frozen orbit, which is a strong candidate orbit for an extended LRO mission phase. During the primary science phase, the spacecraft will be lowered to a 50 km circular orbit. At the end of the 1 year science phase a decision will be made whether to leave the spacecraft in the low altitude circular orbit for one more year of science data collection or to return the spacecraft to the frozen orbit that will allow for a much longer orbit lifetime. In all cases, LRO is in an excellent orbit for gravity science data collection. That is, both of the low altitude orbits make the LRO spacecraft sensitive to the detailed variations of the lunar gravity field. In addition, the polar nature of the orbits force the LRO spacecraft to cover all lunar far side longitudes twice during one 28 day period of the Moon's orbit around the Earth.

Gravity scientists typically require 1 month of continuous daily far side Doppler measurements to obtain a global field with good reliability [Ref -7]. A second month of observation provides flexibility to fill-in coverage gaps. The daily observations over 1 month would provide a full complement of LRO orbit geometry over the Moon. If LRO operations restrictions prevent this there are alternatives. In our proposal, we would collect Doppler passes as LRO's operations schedule allowed and/or schedule the gravity science data collection for an extended mission phase. In all cases the goal was to collect Doppler data over a "good" distribution of LRO orbits over the lunar surface.

The current lunar gravity model is constructed up to a degree and order of 165 with a near side component uncertainty of 1 milligal and a farside component uncertainty of up to 100 milligal. [Ref-7] For practical purposes, the existing field model is physically valid with high reliability to degree 130 on the near side and degree 15 on the farside. The model uncertainty is depicted in Figure 4. The proposed LRO gravity experiment would reduce the far side component uncertainty to the 1 milligal level, making the far side model accuracy equivalent to the current near side gravity model accuracy.

As stated in the introduction, this improved gravity model will enhance mission planning, and mission operations for all future lunar orbiters, landers and ascent vehicles.

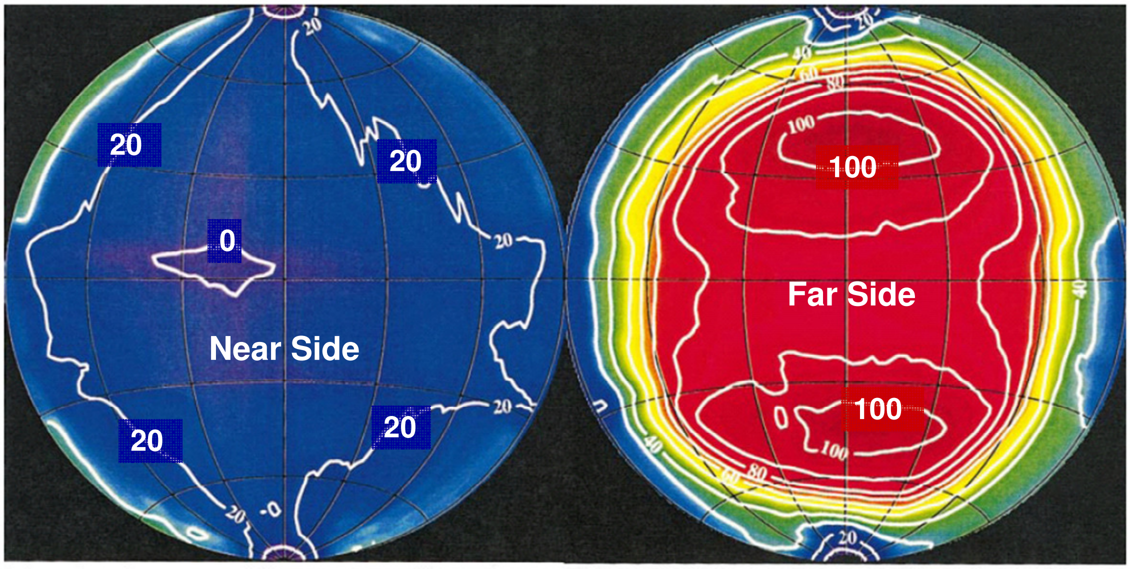


Figure 4 - Current Gravity Model Uncertainty, (contours in milligal, smaller is better)[+]

[+] A milligal is a convenient unit for describing variations in gravity over the surface of the Moon or Earth. 1 milligal = 0.00001 m/sec^2. Thus, a milligal is about 1 micro-g or 1 millionth of the 9.8 m/sec^2 acceleration found at the Earth's surface.

LRO Gravity Science Payload

With WIND in a halo orbit around the Earth-Moon L2 point the range between WIND and the LRO spacecraft would vary between 33,000 and 85,000 km over the 28 day lunar cycle. In order to close the S-band Doppler link at this long range, LRO must utilize its High Gain Antenna (HGA) S-band signal path to capture sufficient signal power. Nominally, both the WIND and LRO spacecraft have S-band systems that are designed to transmit RCP in the 2265 MHz to 2275 MHz band. Since we can't change WIND, the RF challenge was to propose a simple, low risk modification to the LRO S-band HGA signal chain that allows it to capture the WIND signal and pass it to the add-on Doppler payload. Figure 5 shows one scheme we call option 1.

LRO RF Modification and Operations to collect data

The S-band signal path between the Tx path transfer switch and the HGA should be bidirectional at 2275 MHz. Between the switch and the diplexer a circulator was added that provided directional coupling of the outgoing LRO Tx signal or the incoming WIND signal. When LRO transmits S-band telemetry over the HGA path, the Tx signal experiences an extra 0.3 dB of path loss due to the circulator and extra RF connectors. The circulator provides 20 dB of isolation to the Doppler receiver when LRO is transmitting. An RF switch in the Doppler payload provided an additional 60 dB of protection to the Doppler payload when the LRO S-band amplifier is powered up.

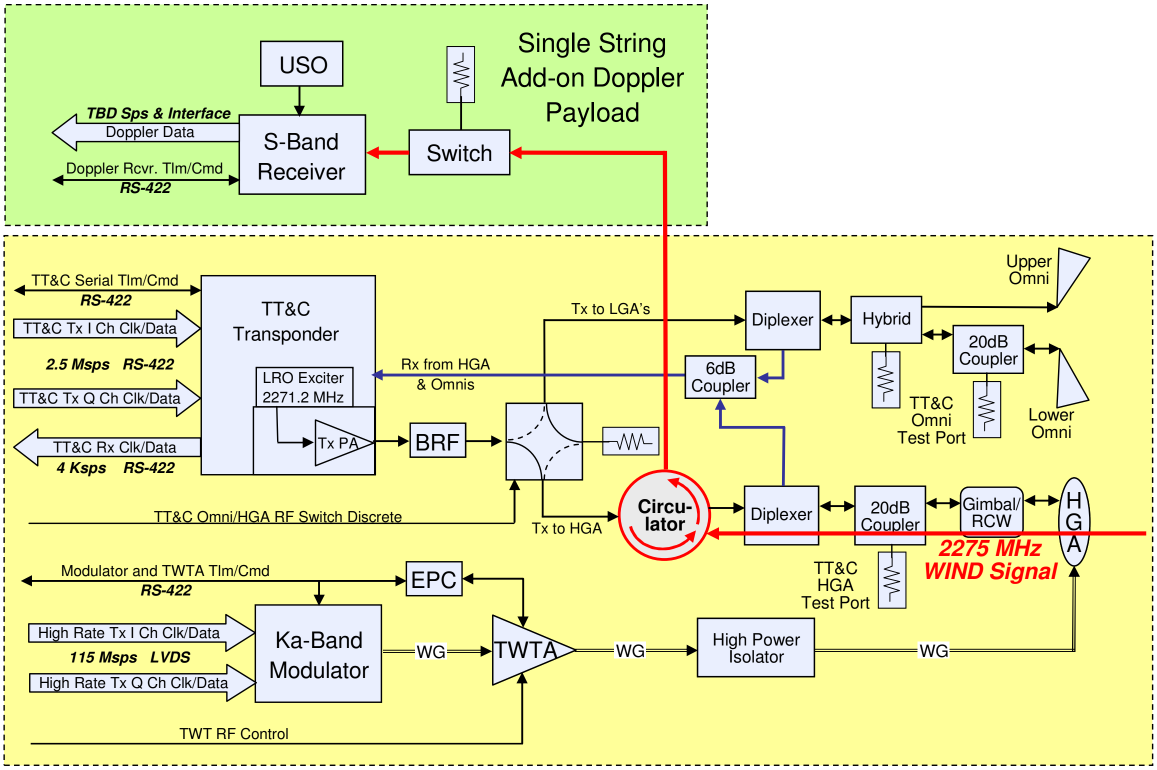
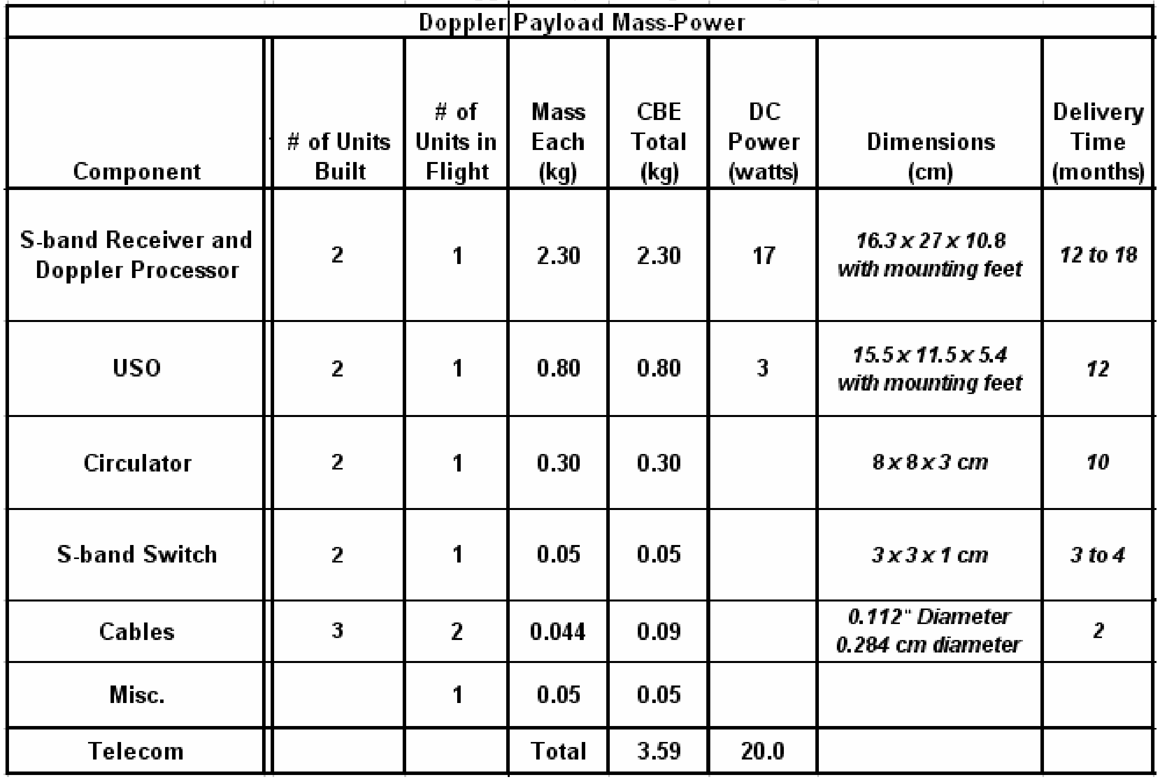


Figure 5 – Option 1: Integration of Doppler Payload with LRO Telecom Subsystem.

When LRO is operating its S-band link, the Doppler receiver is either powered down or in a standby state. In the standby state, the Doppler receiver front end is powered down. Since the USO takes many days post power up to reach its design frequency stability, we assumed that the USO stayed on all the time during weeks of gravity science activity. Also, since the USO is the basis for a very accurate local time base, it was useful to keep the USO on and the Doppler Payload in standby so that periodic clock correlation information could be exchanged with the host spacecraft and with the ground. During farside transit Doppler collection, LRO powered down the S-band exciter and transmitter to prevent interference from the LRO telemetry link from getting into the Doppler receive path. Discussions with LRO staff in December of 2005 produced assurances that this was operationally feasible without impacting LRO operations. The operational sequence would be to, 1) power down the LRO S-band transmit, 2) power up the Doppler payload front end and 3) switch the Doppler payload switch to close the RF receive path to the HGA. With the LRO HGA pointed at WIND, the 2275 MHz receive signal would travel in the reverse direction back through the diplexer and through the circulator which directionally coupled the signal to the Doppler payload. Table 1 provides Doppler Payload equipment list characteristics.

Table 1 - Add-On Doppler Payload, Option 1 Equipment List



Doppler Payload Mass-Power							
Component	# of Units Built	# of Units in Flight	Mass Each (kg)	CBE Total (kg)	DC Power (watts)	Dimensions (cm)	Delivery Time (months)
S-band Receiver and Doppler Processor	2	1	2.30	2.30	17	*16.3 x 27 x 10.8 with mounting feet*	*12 to 18*
USO	2	1	0.80	0.80	3	*15.5 x 11.5 x 5.4 with mounting feet*	*12*
Circulator	2	1	0.30	0.30		*8 x 8 x 3 cm*	*10*
S-band Switch	2	1	0.05	0.05		*3 x 3 x 1 cm*	*3 to 4*
Cables	3	2	0.044	0.09		*0.112" Diameter* *0.284 cm diameter*	*2*
Misc.		1	0.05	0.05			
Telecom			Total	3.59	20.0		

One of the key challenges is whether the flight Doppler receiver would be available for integration and testing on the LRO spacecraft. A delivery schedule that takes approximately 18-months makes this a difficult proposition for the scheduled October 2008 launch date. More discussion of this is contained in the Programmatics section that follows.

Substituting LRO Local Oscillators for the USO

There are perhaps numerous other telecom equipment variations. One additional option that begs consideration used of the LRO ovenized oscillator as the reference for gravity science Doppler collection. The current LRO design proposes to use a Symmetricom 9600 oscillator. Table 2 compares the Allan deviation stability of this oscillator with the proposed USO.

Table 2 - Allan Deviation vs. Stability Interval

Time Interval	Symmetricon 9600	Range-Rate Error	USO	Range-Rate Error	LRO orbital travel in along-track direction
1 second	2e-12	0.6 mm/sec	2e-13	0.06 mm/sec	1.7 km
10 seconds	2e-12	0.6 mm/sec	1e-13	0.03 mm/sec	17 km
100 seconds	5e-12	1.5 mm/sec	1e-13	0.03 mm/sec	170 km
1000 seconds	1e-11	3.0 mm/sec	2e-13	0.06 mm/sec	1700 km

The far right column shows how far the LRO spacecraft travels in its orbit over the Doppler integration period. We see from this table that the 1 second and 10 second oscillator stability numbers played into the finer scale details of the gravity map while the 100 second and 1000 second measurements fold into the larger scale gravity components. [Ref-7]

The Gravity science goal was set at 0.3 mm/sec of range-rate error. So using the Symmetricom oscillator for the gravity science experiment would compromise the data quality and final gravity field results. Detailed impact of this option would have to be further worked with the scientists.

Technical Challenges

We assumed that DSN 26m network would be revived to provide support to WIND and thus would be the signal source for the S-band reference signal relayed to the LRO spacecraft. If the DSN 26m stations were not available, then the DSN 34m network provided coverage but scheduling use of the 34m antenna resources is more difficult.

The uplink budget to WIND shows that the 26m antenna provided at least 45 dB Carrier Loop SNR signal margin on the uplink. One key value of the DSN sites is their use of a 1e-15 stability MASER frequency reference for the uplink. The WIND transponder and its Tx signal to LRO would be phase locked to this uplink MASER signal providing a high quality reference signal from which to track and extract LRO orbit motions.

Low Received Signal Level at LRO

A close look at the WIND to LRO link budget showed one of the key technical challenges. This link produced a received Carrier signal level of only -138 dBm. To achieve good quality Doppler data collection required a narrow carrier-tracking loop, e.g. 10 Hz. This was achieved by direct closed loop tracking in the Doppler receiver or via Open Loop capture of the base band signal followed by software processing on the ground. The proposed Doppler receiver was capable of either tracking mode.

Closed Loop Tracking Approach

Closed Loop Tracking mode had the advantage of producing a much lower data volume for down link to Earth. In an example implementation, each Doppler sample consists of a high accuracy 56 bit time stamp running off of the USO and a 63 bit combined Phase and Power level sample plus 9 bits of overhead for a total of 128 bits per sample. Assuming a Doppler sample rate of 1 sample per second this yields a raw data collection rate of 128 bps. Over a 40-minute pass this yields 38 kbytes of data.

The challenges with the closed loop approach are initial acquisition of the signal in the narrow tracking loop bandwidth and then tracking in the presence of potential EMI and noise. The first problem of carrier signal acquisition requires accurate Doppler predicts. The knowledge of the frequency of the transponded MASER signal and the USO added less than 3 Hz uncertainty to the initial receive frequency uncertainty. Our navigation experts believe that they would be able to predict the WIND and LRO orbits and orbit timing sufficiently that they could predict the initial Doppler profile vs. time to the order of 100 Hz accuracy. Given an accurate clock derived from the Doppler payload USO used to time the initial signal acquisition sequence, the acquisition frequency uncertainty would be roughly 200 Hz. Thus with careful predicts and acquisition sequencing the problem of carrier signal acquisition could be handled.

Open Loop Record Approach

The use of Open Loop recording of the base band Doppler signal removed the need to track that carrier altogether. Digital I/Q samples are collected and relayed to the ground where they are processed via software tools capable of sub-Hertz tracking loop bandwidths. In addition much more complex filtering was applied to remove unwanted signals and finally the signal was processed in both forward time and reverse time to obtain maximum signal recovery around difficult signal conditions where interference or multipath may have existed. Thus the Open Loop record method is more robust in a difficult low signal level environment.

The down side is an increase in data volume relative to the Closed Loop approach. The Doppler shift ranged over +/- 13,000 Hz or a total of 26 kHz. Thus if we collect complex open loop samples at a 32 kHz sample rate we could effectively bracket the total signal bandwidth. If each sample is 32 bits, this is equivalent to a bit rate of (32,000 * 32) = 1.0 Mbps. Over a 40 minute pass this equates to a data volume of (1e6 * 40 * 60 / 1e6) = 2.4 Gbits. This data volume is collected on each Doppler far side pass and it is passed to the LRO data system. If Doppler data is collected on each far side pass and there are 12 passes per day the maximum open loop record data volume would be 12 x 2.4 Gbits = 28.8 Gbits. This is roughly

5% of the planned 600 Gbit/day download from LRO and could impact their data management and mission operations.

Tone Electromagnetic Interference

This still leaves the challenge of operating in the presence of Electromagnetic Interference (EMI). At the low received signal level of -137 dBm, it is possible that there existed LRO generated EMI tones that could temporarily corrupt or mask the intended signal. In general these EMI tones are overtones of clocks, switching power supplies or digital data lines. As such, their frequency is fixed or drifts at a slow rate. The intended Doppler signal on the other hand moved over a range of 26 kHz. Thus, if an EMI tones exist within the +/- 13 kHz range of the Doppler tone, the intended signal appeared to pass by them and interference effects will be vary over time.

LRO HGA Pointing to WIND

In all these scenarios and in the link budgets we assume pointing of the LRO HGA toward the WIND spacecraft. Initial discussion with the LRO project returned a positive response to the possibility of pointing the LRO HGA to WIND.

The nominal orientation of the LRO HGA is in the zenith hemisphere while the science instruments point nadir. On LRO orbits, when far side Doppler data was collected, we expected the following scenario. While traversing the near side, if LRO was scheduled to perform an Earth link, it would point its HGA toward Earth at a range of 385,000 km. While traversing the far side, LRO would point its HGA to the WIND spacecraft. The first task is to turn the HGA from Earth point to WIND point. This is a sweep of roughly 180 degrees. LRO engineers tell us that the HGA maximum sweep rate is 30 deg/min. This means it would take 6 minutes to reorient the HGA for gravity science measurements and then 6 minutes at the end of the pass to reorient the HGA to Earth point. That is 12 minutes out of a total 40 minute far side or 30%. One alternative is to steal the 12 minutes from the near side pass time. This may be a possibility if the gravity science data is collected in an extended mission phase. The other alternative is to forfeit the data in these first and last 6 minutes.

After the sweep is complete there can be residual spacecraft motion effects that last for minutes. These motions add to the Doppler noise. A reaction wheel ACS system could probably handle this additional complication but it should be included in gravity science analyses.

During a 40 to 60 minute far side pass, WIND will only move 1 to 5 degrees in its L2 Halo orbit and thus appears relatively “fixed” in position compared to the more rapid angular motion of the LRO spacecraft. The LRO engineers tell us that the maximum tracking rate (for fine pointing) is 3.2 deg/min and initial analysis shows that this fine pointing rate is more than fast enough to track WIND.

LRO Antenna Unwind

Apart from the WIND gravity experiment, the LRO spacecraft plans to perform an HGA “unwind” operation during the far side portion of the orbit so that it is ready to perform Earth-point when it re-emerges from occultation.

Under our proposal, on orbits collecting far side Doppler gravity measurements there would effectively be two “unwind” operations. The first unwind would slew the HGA to point at the WIND spacecraft. This would be followed by WIND tracking ops. These first two operations were additions to the nominal LRO orbit operations plan. The second unwind would occur at the end of the WIND pass and bring the HGA to a position ready to point at Earth. This second unwind operation is roughly equivalent to the unwind operation that LRO already plans to perform.

LRO S-band Transmitter Shutdown

As discussed earlier, the S-band SSPA and exciter were turned off. If this was not possible or was too risky during the LRO prime mission, it was considered as an approach for Doppler data collected during an extended mission phase.

Alternate WIND Orbits

Analysis of alternate WIND orbits is ongoing. This includes options such as high-inclination elliptical orbits, circular orbits, and butterfly orbits (Figure 6). [Ref-8] Currently, efforts to achieve such orbits given the remaining 100 m/s ΔV capability of the WIND spacecraft have proved troublesome. Further attempts to find alternate orbits are ongoing. While these orbits might reduce the range to LRO for the far-side passes, the angular tracking rate to WIND may be faster than the 3.2 deg/min rate supported by the LRO spacecraft. Furthermore, capturing WIND into a lunar orbit (rather than an L2 or butterfly orbit) might preclude its return to a Sun-Earth libration point orbit to resume normal operations.

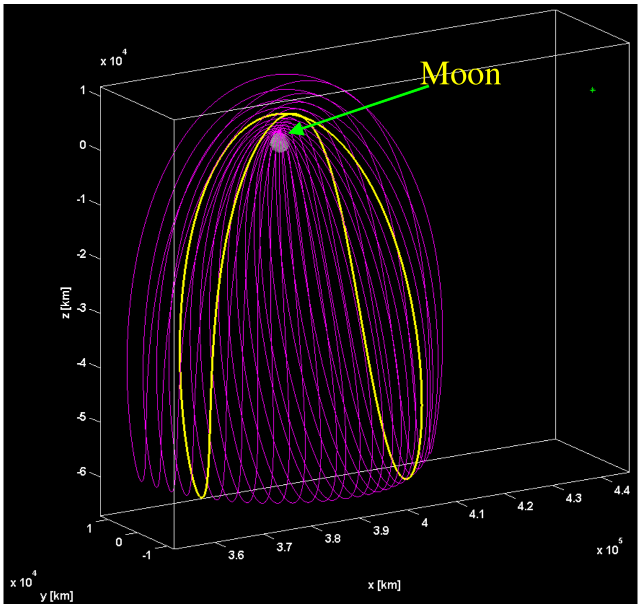


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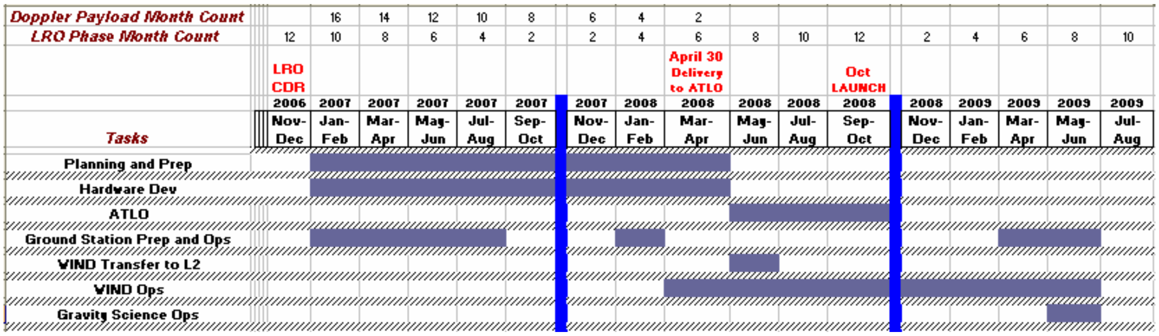
Figure 6 – Earth-Moon Butterfly Orbit

Programmatics

The primary schedule challenge associated with the LRO add-on payload was the building and delivery of the hardware. The LRO development schedule showed a need for payload delivery to ATLO in mid October of 2007, see Figure 7 below. To give us a full 16 months to bring together the add-on navigation payload, meant a payload start of no later than January of 2007.



Doppler Payload Month Count		16	14	12	10	8	6	4	2								
LRO Phase Month Count	12	10	8	6	4	2	2	4	6	8	10	12	2	4	6	8	10
	LRO CDR								April 30 Delivery to ATLO			Oct LAUNCH					
	2006	2007	2007	2007	2007	2007	2007	2008	2008	2008	2008	2008	2008	2009	2009	2009	2009
Tasks	Nov-Dec	Jan-Feb	Mar-Apr	May-Jun	Jul-Aug	Sep-Oct	Nov-Dec	Jan-Feb	Mar-Apr	May-Jun	Jul-Aug	Sep-Oct	Nov-Dec	Jan-Feb	Mar-Apr	May-Jun	Jul-Aug
Planning and Prep		▨	▨	▨	▨	▨	▨	▨	▨								
Hardware Dev		▨	▨	▨	▨	▨	▨	▨	▨								
ATLO										▨	▨	▨					
Ground Station Prep and Ops		▨	▨	▨	▨			▨							▨	▨	
WIND Transfer to L2										▨							
WIND Ops									▨	▨	▨	▨	▨	▨	▨	▨	
Gravity Science Ops																▨	

Figure 7 - Gravity Science Experiment Schedule

Apart from a schedule aspect, all other portions are less challenging. The ground station equipment exists in the form of Deep Space Network stations, GSTDN stations or commercial ground stations that can handle S-band 2-way space communications. Planning for their use would begin in 2007 but actual usage would not occur until 2009. Similarly, the relay spacecraft WIND is already operational in space and both its operation and navigation are well understood. Transfer of the WIND spacecraft to a lunar or L2 Halo orbit would not occur until mid 2008. Plans and preparations for WIND transfer and operations support would be accomplished in 2007. The schedule above shows the gravity science measurements scheduled for a 1 to 2 month period of time during the prime LRO mission. This could be delayed until after the LRO prime mission.

A draft staffing and cost breakdown was generated for the hardware development and work effort, but is not shown herein. It included all hardware, test equipment and staffing needed to develop, test and deliver the payload and staffing to assist in the spacecraft design accommodation, integration, test and operation of the payload. The ground stations, planning, navigation and operations support needed for the WIND spacecraft is also included.

Additional work/staffing needed on the LRO spacecraft side for tasks to accommodate the add-on Nav payload was required. These would include:

- Mechanical, thermal and interface changes
- C&DH software modifications
- Operations planning and software changes
- Ground data systems changes

WIND Spacecraft

While no formal agreement with WIND was made, discussions with their project management and technical staff were favorable and informative. Based on these discussions, WIND support of the gravity science experiment required no new procedures. The maneuvers required to leave the Sun-Earth L1 point, correct the trajectory, and insert into the Earth-Moon L2 point are no different in procedure than those that have been supported in the past. The current trajectory design has WIND maneuvering (~m/s) to leave its Sun-Earth L1 orbit on June 7, 2008. Four months later (October 8, 2008) a second maneuver is used to target the correct conditions at the Moon. Finally, a small insertion maneuver is required to enter an Earth-Moon L2 orbit on December 4, 2008 – two months after the nominal LRO launch date [Refs -9 and 10].

During this gravity science experiment the WIND team planned to manage the spacecraft with approximately one civil servant FTE of GSFC personnel and one FTE of contractor support for WIND design and navigation, and 3 FTEs for WIND operations. This work would include navigation support, mission design, maneuver support, tracking data V&V, and documentation, and assuming that the WIND Project continued to provide operational support for the spacecraft. The effort provided by the project covered the flight operation and ground tracking cost. The cost associated with the flight dynamics work was for the planning and execution of the trajectory, the navigation, and low-level technology development. Using the GSFC Flight Dynamics Facility (FDF), we provided all related operational support to the flight operations team. The FDF would support the processing of the navigation data and the generation and dissemination of any products, such as maneuver command generation.

No software upgrades or modifications were anticipated for this effort. Both the FDF and the vast libration and lunar expertise resident in the Flight Dynamics Analysis Branch (FDAB) of the Mission Engineering and Systems Analysis Division would be tapped to support this effort.

Proposed Management and Teaming

There are several options for partnerships and management for the build, integration, and operations of a Doppler payload experiment. For this proposal, it was recommended that, for purposes of building the LRO Doppler payload hardware, the current SCIP team at JPL work directly for (or with) the LRO Project. The LRO Project would then be responsible for integration of the Doppler Payload onto the LRO spacecraft with assistance of the build team. We recommend this approach due to the schedule challenge of developing the payload and the fact that the payload needs to be tightly coupled with the LRO communications system. It would be possible for SCIP to develop the Doppler payload and deliver it to LRO in a typical Instrument-to-Mission relationship, but the integrated approach offered a higher probability of success.

For operations, the SCIP Project would coordinate scheduling of the experiment with the LRO operations center, and with the WIND operations center. SCIP would work with LRO pre-launch to develop all procedures and processes required for operation of the Doppler payload. SCIP was to be responsible for coordinating the repositioning of the WIND spacecraft with the Science Mission Directorate and establishing the required processes and procedures for Wind with the Wind Operations center and the DSN.

The SCIP would have been responsible for the refinement of the gravity model using the data generated during the experiment. Also, the SCIP would need to form a multi-center Gravity Science team to advise the SCIP during the planning phase and prepare for receiving and processing the data. This team would be responsible for developing the revised Lunar Gravity model for distribution to other NASA elements and to vet other potential uses of the experiment.

Conclusion

We describe a proposed, but not integrated, add-on approach to the LRO spacecraft to collect data to improve the lunar gravity model. Our approach posed minimum risk to a host mission while maintaining very low implementation and operations costs. LRO was chosen because it provided a real host spacecraft against which we could design the science payload and mission activities. From a strategic standpoint, the LRO mission design also provided a first flight opportunity for gravity science data collection since it maintains a low lunar polar orbit.

Although it was not implemented for a variety of reasons, it demonstrated how an existing NASA asset (WIND) and design of a low lunar orbiter (LRO or any similar spacecraft in the future) could be used to derive gravity model information. Analysis regarding link margins, trajectory design, and hardware implications to collect this data was shown that this idea was feasible. An improved far side gravity model could have enhanced planning and execution of future Constellation and Exploration missions to the Lunar far side and Lunar poles. The experience gained in trans-lunar trajectories, libration orbits, and relay spacecraft design would also be highly valuable for future lunar mission activities.

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