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LUNAR PROSPECTOR ORBIT DETERMINATION RESULTS

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The orbit support for Lunar Prospector (LP) consists of three main areas: (1) cislunar orbit determination, (2) rapid maneuver assessment using Doppler residuals, and (3) routine mapping orbit determination.

The cislunar phase consisted of two trajectory correction maneuvers during the translunar cruise followed by three lunar orbit insertion burns. This paper will detail the cislunar orbit determination accuracy and the real-time assessment of the cislunar trajectory correction and lunar orbit insertion maneuvers.

The non-spherical gravity model of the Moon is the primary influence on the mapping orbit determination accuracy. During the first two months of the mission, the GLGM-2 lunar potential model was used. After one month in the mapping orbit, a new potential model was developed that incorporated LP Doppler data. This paper will compare and contrast the mapping orbit determination accuracy using these two models.

LP orbit support also includes a new enhancement - a web page to disseminate all definitive and predictive trajectory and mission planning information. The web site provides definitive mapping orbit ephemerides including moon latitude and longitude, and four week predictive products including: ephemeris, moon latitude/longitude, earth shadow, moon shadow, and ground station view periods. This paper will discuss the specifics of this web site.

INTRODUCTION

The Lunar Prospector mission, NASA's first lunar mission since Apollo, was launched on January 7, 1998 after a one day launch slip. Three trajectory correction maneuvers (TCMs) were planned during the 104 hour cislunar phase but only two were performed. LP was captured about the Moon on January 11 and placed into its 100 km circular polar mission orbit on January 15 via three lunar orbit insertion (LOI) maneuvers and one mapping orbit correction (MOC) maneuver (see Figure 1). The mission is scheduled for one year with a possible six month extended mission to follow. The Guidance, Navigation, and Control Center (GNCC), formerly Flight Dynamics, at Goddard Space Flight Center performs the orbit determination support for LP.

The cislunar phase objectives were accurate orbit determination for mission planning and rapid postmaneuver orbit determination in order to plan TCMs quickly. The lunar mapping phase objectives are high accuracy post-processed ephemerides for science processing. The GNCC Lunar Prospector Product Center (*fdd.gsfc.nasa.gov/lp*) provides definitive and current predictive products to a number of international customers from launch through the current lunar mapping orbit.

CISLUNAR PHASE

There were two primary goals during the cislunar phase: (1) provide predicted ephemerides for mission planning, and (2) provide near real-time assessments of maneuver performance. During this phase, the spacecraft would be continuously tracked by the Deep Space Network (DSN) tracking stations in Goldstone, California; Madrid, Spain; and Canberra, Australia. After each maneuver, range, Doppler, and XY angles (only for DSN 26 m stations) would be collected and processed to determine the new trajectory.

There were three planned TCM maneuvers during the cruise phase. The first was planned 4 hrs after the translunar injection (TLI). This first burn would be an

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energy correction burn to correct for launch vehicle errors. The second burn was planned at 28 hrs after TLI and the third at 24 hrs prior to lunar orbit insertion. The lunar orbit insertion would consist of three burns. The first would capture the spacecraft into a 12 hr elliptical polar orbit. Two periselenes later the second LOI burn would reduce the orbit period to 3.5 hrs. One day later, the third LOI burn would circularize the orbit at 100 km.

Covariance analysis was performed premission to determine the orbit determination (OD) capabilities during the cislunar phase. The time required to obtain an accurate converged solution would increase, during the cruise phase, as the maneuvers moved away from perigee due to the reduced dynamics on the spacecraft. Once captured in lunar orbit, the required time would be mostly a function of the orbit period. Table 1 shows the approximate time after each planned maneuver required to obtain a full state batch orbit estimation.

After an updated state was obtained following each maneuver, a preliminary maneuver plan would be developed based upon that state. The state would be updated several hours prior to the next maneuver and the maneuver plan would be fine tuned. In each case, the predicted velocity uncertainty at the time of the next maneuver was expected to be at least an order of magnitude less than the ΔV for that maneuver. This would ensure that the maneuver plan would not be corrupted by orbit determination errors.

The real-time maneuver assessments would be critical because of the direct lunar insertion. The more time spent determining the spacecraft state after a maneuver, the higher the ΔV cost to correct for an off-nominal burn later. Additionally, for the two critical maneuvers, TLI and LOI-1, contingency plans included emergency spacecraft maneuver commands based upon the assessment.

TABLE 1: POSTMANEUVER OD

Maneuver	Time for OD	Maneuver	Time for OD
TLI	30 min *	LOI-1	4 hrs
TCM-1	6 hrs	LOI-2	3 hrs
TCM-2	8 hrs	LOI-3	2 hrs
TCM-3	12 hrs		

* After TLI, tracking data was expected from the Tracking & Data Relay Satellite System (TDRSS). DSN tracking data would not be available until 19 minutes after TLI. Using tracking data from both TDRSS and the DSN would enable a solution within 30 minutes of TLI.

The real-time assessment would be made by monitoring the Doppler residuals from the DSN. Once the final maneuver plan was available several hours before the planned maneuver, the predicted finite burn ephemeris would be used to generate simulated Doppler measurements. These Doppler measurements would be processed through the orbit estimation software, compared to the nominal premaneuver or postmaneuver state, and the expected Doppler residuals plotted. Then additional finite burn ephemerides would be generated assuming a hot or cold maneuver. Expected Doppler residuals from these off-nominal cases would also be plotted. After the actual maneuver began, Doppler residuals would be available in near real-time. These residuals would be compared against the expected plots to quickly assess the maneuver performance. Premission analysis indicated that the residual

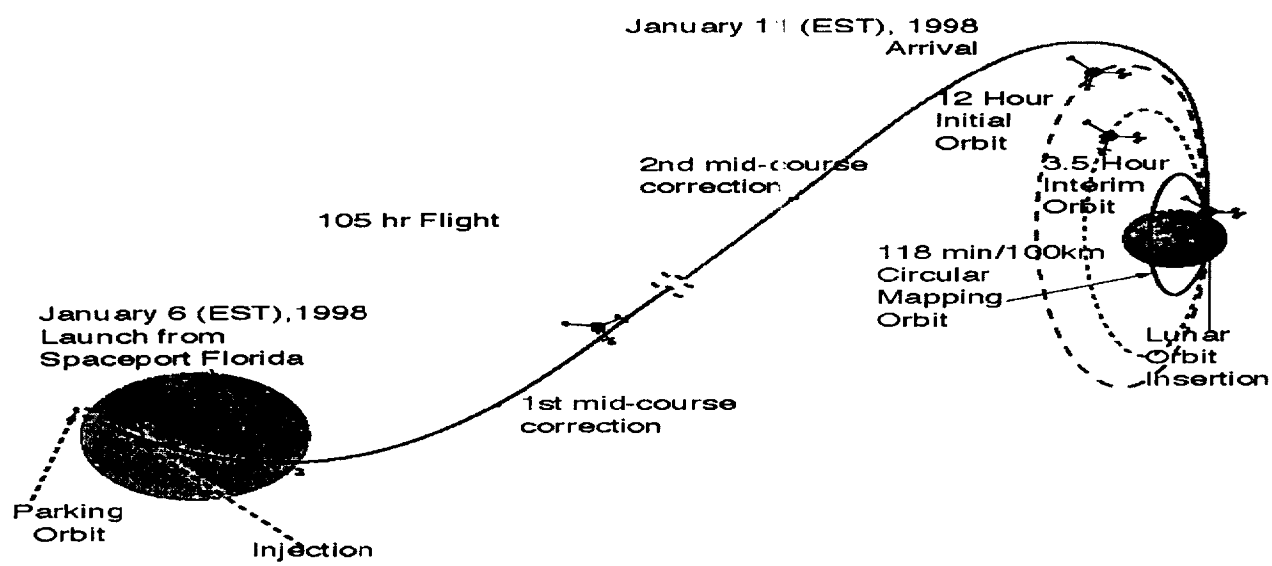

FIGURE 1: LUNAR PROSPECTOR PLANNED TRAJECTORY

differences between nominal and 5% off-nominal maneuvers was greater than the uncertainty in the residuals. The residual uncertainty is due to measurement and dynamic modeling errors. Thus, for all deterministic maneuvers, maneuvers off as little as 5% in thrust magnitude would be observable.

The actual cislunar phase of LP went better than planned. The third TCM was not needed and was cancelled. The dates and times of each LP maneuver through May 20, including attitude and spin maneuvers, are shown in Table 2. The support of the major maneuvers is discussed in detail in the following sections.

TABLE 2: LUNAR PROSPECTOR MANEUVERS[1]

Maneuver	Date	Start (GMT)	Stop (GMT)
Reorient	1/7	05:51:52	06:00:47
Despin	1/7	06:30:09	06:30:15
Spin-up	1/7	07:45:53	07:46:00
Reorient	1/7	09:22:57	09:30:57
TCM-1	1/7	11:55:23	11:56:19
TCM-1	1/7	12:00:45	12:23:33
TCM-1	1/7	12:25:55	12:27:47
TCM-2	1/8	08:25:22	08:25:28
TCM-2	1/8	08:36:23	08:39:55
Att. Trim	1/9	06:30:23	06:45:23
LOI-1	1/11	11:44:54	12:17:07
LOI-2	1/12	10:58:30	11:25:35
Spin Trim	1/12	12:03:29	12:03:34
LOI-3	1/13	11:37:38	12:04:40
Spin Trim	1/13	13:11:23	13:11:25
MOC-1	1/15	21:43:49	21:45:06
MOC-1	1/15	22:32:05	22:32:22
Att. Trim	1/15	23:57:25	00:08:55
Att. Trim	1/26	17:18:00	17:18:55
Spin Trim	1/26	17:54:01	17:54:02
MOC-2	3/8	03:49:37	03:50:24
MOC-2	3/8	04:53:40	04:54:26
Att. Trim	3/13	21:26:23	21:27:27
Spin Trim	3/13	21:50:22	21:50:23
Att. Trim	3/31	22:58:00	22:59:55
Att. Trim	4/24	15:31:00	15:31:00
Att. Trim	4/27	15:08:02	15:11:22
MOC-3	5/1	15:50:06	15:50:45
MOC-3	5/1	16:54:27	16:55:04
Spin Trim	5/1	17:35:00	17:35:01
Att. Trim	5/20	22:54:22	22:54:47

Launch & Early Orbit

Launch was from the Eastern Test Range in Florida. The spacecraft was placed into a low Earth parking orbit for a 42 min coast. Just off the coast of Australia, the TLI motor performed a 3142 m/sec burn to place the spacecraft into the cislunar phase. After TLI, the ground track of the spacecraft headed east over the Pacific Ocean before finally turning west after Hawaii (see Figure 2). Tracking support from the Tracking & Data Relay Spacecraft System (TDRSS) was planned during the first 20 min after TLI. However, due to the limited spacecraft transponder capability and the limited sweep capabilities of TDRSS, the signal never locked up.

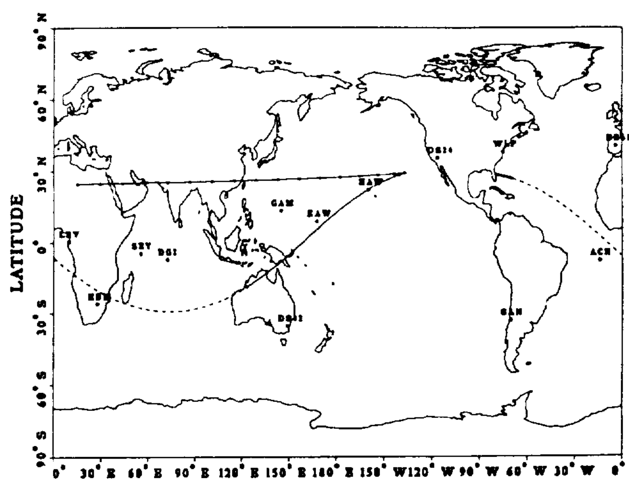

FIGURE 2: LAUNCH GROUND TRACK

The first duty of the orbit team was the assessment of the TLI maneuver. The loss of TDRSS data delayed that assessment. Coherent Doppler was received from the DSN station in Goldstone approximately 25 min after TLI. The expected residuals for several off-nominal cases and the actual residuals obtained are shown in Figure 3. The off-nominal cases shown are: -20 and -35 m/sec TLI magnitude errors and ±0.8 deg and -2.4 deg argument of perigee (AP) errors. The AP errors result from a timing error in TLI ignition. In the event of a 20 m/sec underburn, an emergency energy correction burn contingency would have been performed immediately following the assessment of TLI. In the event of a 35 m/sec underburn, a phasing loop contingency plan would have been implemented.

The residuals in Figure 3 indicate a slightly cold burn. Resolving the residuals into a TLI magnitude error or AP error was difficult, with only the differing residual signatures to differentiate. In the first few minutes after Goldstone acquisition, the TLI magnitude error was estimated to be approximately -5 m/sec. Ten minutes later, that assessment was changed to -11 m/sec. The actual calibrated TLI magnitude error was -9.6 m/sec. The AP error was less then 0.1 deg, though there was an additional 2 sec launch delay that added to the residual error.

The first full state estimate was not obtained until 1 hr after TLI due to the loss of TDRSS tracking data. With the TDRSS data, we expected to have a solution 30 min after TLI. The 1 hr solution was based only on Goldstone range, Doppler, and XY angles. Even though the 1 hr solution converged, we were not confident in its accuracy. Due to noisy telemetry data, spacecraft commanding was suspended until a better aspect angle was obtained, thus delaying TCM-1 until 8.5 hrs after TLI. This gave the orbit team more time to obtain a better orbit estimation.

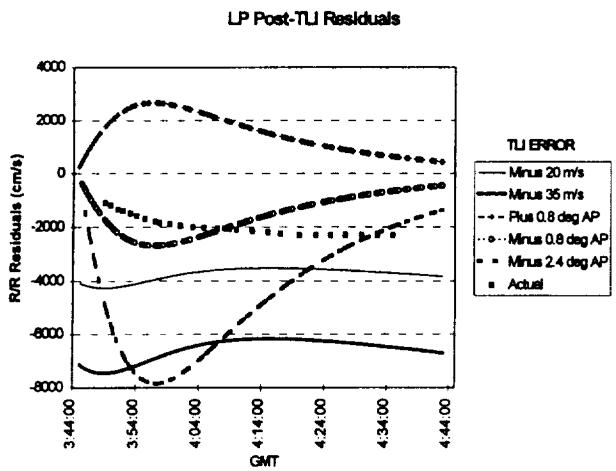

FIGURE 3: POST-TLI RESIDUALS

Figure 4 shows the post-TLI 1 hr, 2.5 hrs, and 6.5 hrs solutions. Position and velocity errors are propagated to the time of TCM-1. The solutions are compared against the post-processed best estimated trajectory (BET) prior to TCM-1. The 2.5h solution is expectedly better than the 1h solution and gives a velocity error at TCM-1 of less than 2 m/sec. TCM-1 had a magnitude of 50.2 m/sec, so the effectiveness of TCM-1 was not compromised significantly by orbit determination errors. The 6.5h solution was less accurate due to the two reorientation attitude maneuvers and two spin maneuvers performed between the 2h and 6.5h solutions. These maneuvers were not modeled and perturbed the orbit significantly.

<u>Trajectory Correction Maneuvers</u>

TCM-1 was performed on January 7 at 11:55 GMT, about 8.5 hrs after TLI. The burn was broken into axial and tangential thruster components. Each component of the burn was no more than 3 min long, not enough time to assess the maneuver during the burn. The Doppler assessments would be based upon the burnout spacecraft states.

Prior to TCM-1, off-nominal burnout states for both axial and tangential thrusters were generated and simulated to obtain off-nominal Doppler residuals. Because the tangential burn ΔV was an order of magnitude larger than the axial burn ΔV, the expected residuals from an off-nominal tangential burn were an order of magnitude larger than the axial. These simulated residuals, along with the actual residuals obtained, are shown in Figure 5. The actual residuals indicate a slightly hot burn, but less than 1%. The actual calibrated TCM-1 efficiency was 99%, or 1% cold. TCM-1 started about 1 min after the maneuver plan, creating the error in the expected residuals.

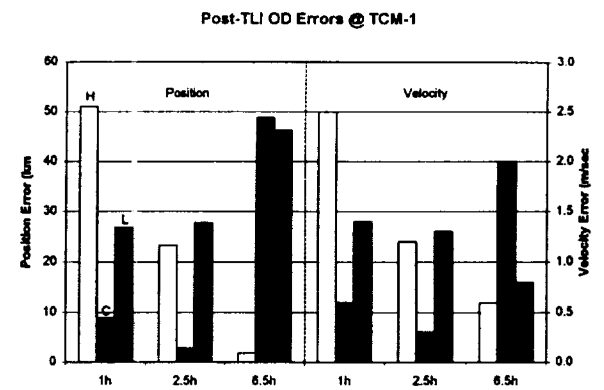

FIGURE 4: POST-TLI OD ERRORS

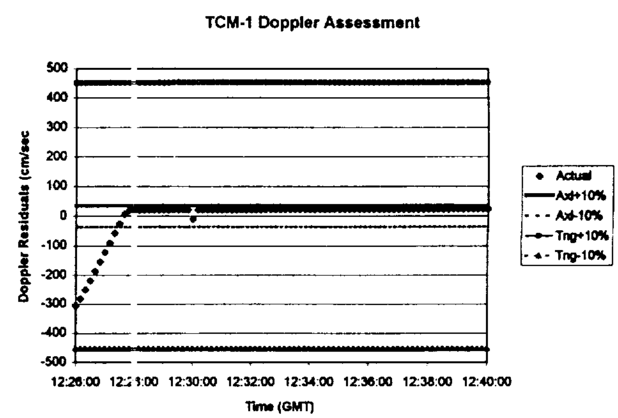

FIGURE 5: TCM-1 DOPPLER ASSESSMENT

The first orbit solution after TCM-1 was obtained after four hours. This solution was passed onto the maneuver team who determined that a TCM-2 maneuver would be needed.. Updates to the 4h solution after TCM-1 were provided. These solutions and their position and velocity errors propagated to TCM-2 are shown in Figure 6. The solutions are compared with the BET using all available tracking data between TCM-1 and TCM-2. With no spacecraft perturbations between TCM-1 and TCM-2, each successive orbit solution improved the estimate at TCM-2. The final post-TCM-1 maneuver gave a velocity error at TCM-2 of less than 17 cm/sec. TCM-2 magnitude was 7.4 m/sec, thus orbit determination errors did not impact the effectiveness of this maneuver.

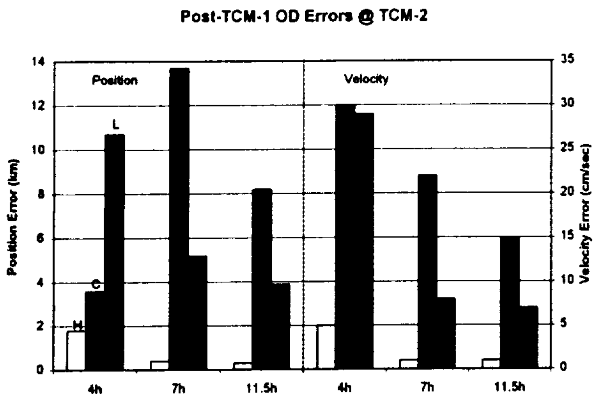

FIGURE 6: POST-TCM-1 OD ERRORS

TCM-2 was performed on January 8 at 08:25 GMT, 20 hrs after TCM-1. TCM-2 was also split into axial and tangential components, with each burn less than 4 min long. The Doppler assessment after TCM-2 also indicated about a 1% hot burn. The actual calibrated error was 1% cold. The difference was again due to incorrect timing of the start of TCM-2. The maneuver plans were generated several hours prior to the maneuver and the expected residuals generated at this time. The maneuver plan was then fine tuned by the Mission Operations Center (MOC) which changed the maneuver start times by up to a minute. The accuracy of the Doppler assessment could have been improved had the exact same burn plan been used. The TCM-2 actual and simulated Doppler residuals are shown in Figure 7.

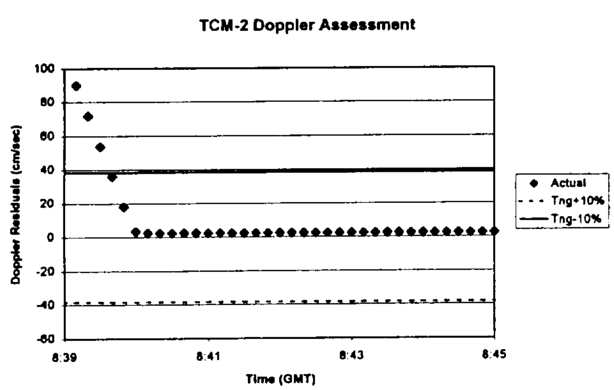

FIGURE 7: TCM-2 DOPPLER ASSESSMENT

After TCM-2, the first orbit estimate was available at eight hours. Because the post-TCM-2 state propagated to periselene met the lunar arrival conditions, TCM-3 was cancelled. The lunar arrival conditions were: arrival time on January 11 at 12:00 GMT ±1 min, 1819.7 km periselene ±10 km, and 89.8 deg inclination ±0.1 deg. The post-TCM-2 states and their propagated lunar arrival conditions are shown in Figure 8. Two days prior to periselene, the lunar arrival conditions were met.

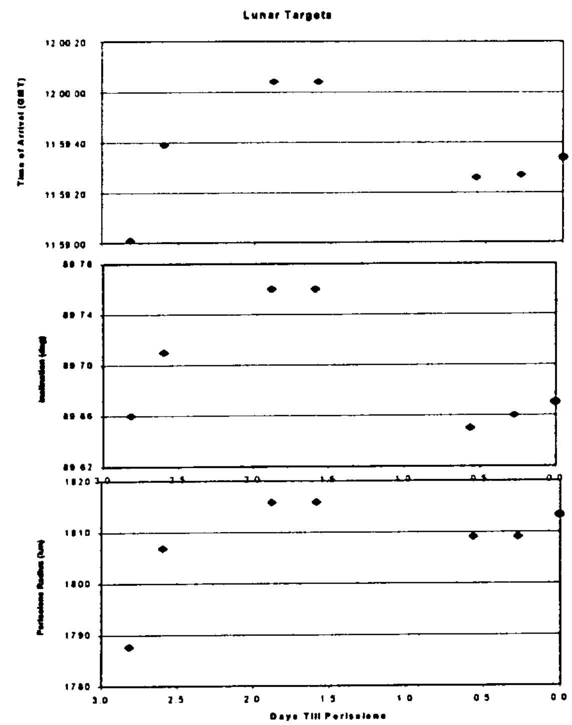

FIGURE 8: LUNAR ARRIVAL CONDITIONS

Lunar Orbit Insertion

The first LOI burn was performed on January 11 at 11:44 GMT. The first LOI burn was critical. Two thrusters were used for LOI-1. If one thruster failed completely and the other underperformed, the spacecraft would fail to capture into lunar orbit. Contingency plans did exist although at the loss of some mission objectives. As such, the Doppler assessment during the 30 min LOI-1 burn would be critical.

Just after LOI-1 burn start, at 11:45 GMT, the DSN station at Goldstone lost coherent lock on the spacecraft. It was later determined that the antenna predicts could not accurately model such a large spacecraft maneuver. As a result, no Doppler data was obtained until 12:04 GMT, 19 min into the burn. The Doppler data is received and stored at Goddard within 2-3 min. It then takes another 2-3 min to process the data and generated residuals. Thus, actual residuals were not seen at Goddard until almost 12:10 GMT, just 7 min from burnout. The limited residual data obtained confirmed that the burn did occur, in the proper direction, and was approaching the nominal burnout state. No accurate assessment of efficiency was possible with the short amount of time remaining in the burn and the limited amount of data, though a gross assessment of ±10% was determined. The LOI-1 burn terminated at 12:17 GMT. Residuals after burnout indicated the burn was within 1%. The actual calibrated maneuver error was 0.7%.

A full orbit state was obtained 1.5 hrs after LOI-1, which was a couple of hours before expected (recall Table 1). The solution was used to plan LOI-2, and was later fine tuned with an 11h solution. The accuracy of the 1.5h and 11h solutions is shown in Figure 9. The accuracy of the solutions is determined by comparing them to the BET using all available tracking data between LOI-1 and LOI-2. In addition, the BET solution used the updated lunar potential model derived from one month's worth of LP tracking data and is considered more accurate than the model used at the time (see next section for more details). An interesting effect is seen in Figure 9 (note the log scale). As the solutions are propagated to the next periselene, the 1.5h position accuracy degrades while the 11h position accuracy improves. This is due to the inaccurate estimate of the orbital period in the 1.5h solution.

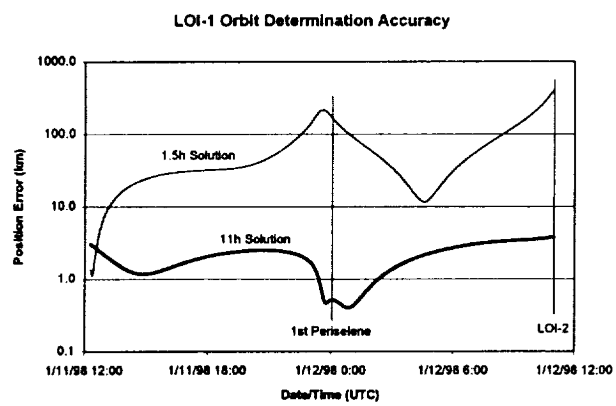

FIGURE 9: LOI-1 OD ACCURACY

The LOI-2 and LOI-3 burns were nominal and were performed one day and two days after LOI-1 respectively. Each of the burns was approximately 30 min in length. Doppler assessments were used during each maneuver to estimate the maneuver efficiency. In the case of LOI-3, had the maneuver been just 9% hot, the spacecraft would have crashed into the Moon! The actual residuals during the LOI-3 burn along with the nominal and off-nominal expected residuals are shown in Figure 10. The residuals were determined by comparing the states to the initial no-burn ephemeris. The accurate finite burn modeling was not available in the orbit estimation software, so residuals could not be generated versus the nominal finite burn ephemeris.

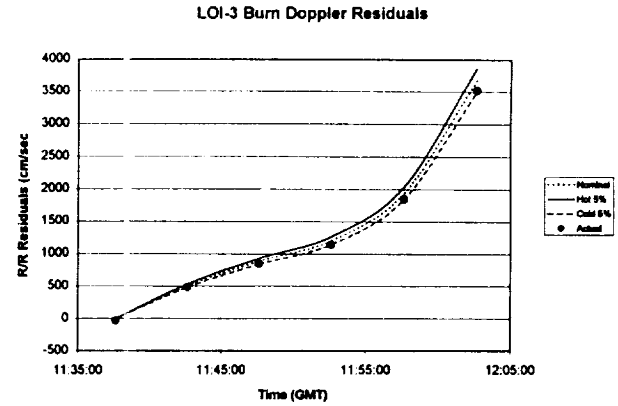

FIGURE 10: LOI-3 DOPPLER RESIDUALS

Full state estimates were available 2 hrs after LOI-2 and 3.5 hrs after LOI-3. The trend for amount of tracking data needed to converge after LOI-1,2, & 3 was exactly opposite of what was expected (recall Table 1). It has been determined that this is due to the inadequacy of the potential model used at lower altitudes (see next section for more details). This effect was not seen in the premission covariance analysis.

After LOI-2, the spacecraft was in a 3.5 hr elliptical orbit. The accuracy of the post-LOI-2 orbit solutions is shown in Figure 11. The accuracy is measured against the BET between LOI-2 and LOI-3 using the LP derived lunar potential model. The same trend is seen as in the LOI-1 solutions. The short arcs solutions, 1h and 2h, have inadequate period estimates and position errors increase at each periselene, while the long arc, 11h, solution has a good estimate of period and the position error improves at each periselene.

One day after LOI-3, a final mapping orbit correction (MOC) burn was done to optimize the initialization of the lunar mapping orbit.

LUNAR MAPPING ORBIT

The LP mapping orbit was achieved on January 15 at 22:33 GMT after the MOC-1 maneuver. The spacecraft began mapping in a 99.7 by 100.9 km near perfectly circular orbit. The first mapping orbit began with an ascending node at 222.6 deg east longitude. As of June 5, the spacecraft had nearly completed five complete mappings of the lunar surface. This mapping phase will continue until January 1999. An extended six month mission is likely at lower altitudes after that.

The objective of the orbit team during the mapping phase is the definitive orbit determination accuracy. The post-processed definitive ephemeris requirement is 1 km 1-sigma position accuracy in each of radial, crosstrack, and alongtrack. Covariance analysis indicated that the lunar potential model was the leading source of orbit estimation error. The lunar potential model used initially was GLGM-2 developed at Goddard by F. Lemoine[2] using tracking data from the 1994 Clementine mission. The covariance analysis indicated that the mission requirements could be only partially met using this model and only with extensive post-processing. When the orbit plane was parallel to the Earth-Moon line, and lunar occultation occurred, called the edge-on geometry, the mission requirements would likely not be met.

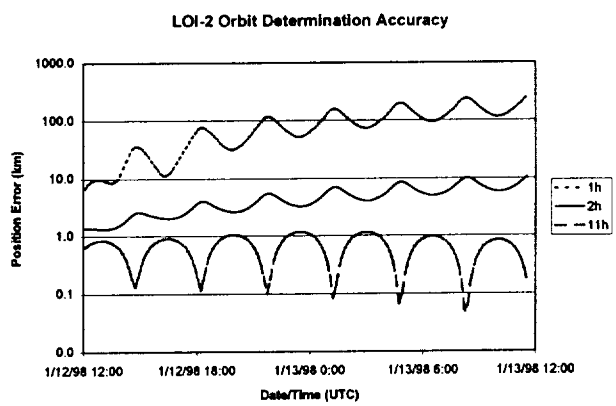

FIGURE 11: LOI-2 OD ACCURACY

One of the experiments for LP was the development of a new lunar potential model two months into the mission mapping phase. It was decided to switch to the new model once it became available and to regenerate the first two month's worth of definitive data using the new model to ensure that orbit accuracy requirements were met. The actual orbit accuracy obtainable using the new model would not be known until it was available.

Once the mapping orbit was achieved, different batch weighted least squares arc lengths were attempted with the goal of extending them as long as possible to reduce the amount of processing at this time since the definitive ephemerides would be regenerated with the new potential model later. A 14 hr tracking arc was chosen with a 2 hr overlap between two consecutive tracking arcs. Thus two 12 hr definitive ephemerides per day were generated for use by the mission control center and scientists.

The first new potential model was available after just two weeks in the mapping orbit. This model included LP tracking data over the entire surface of the visible Moon. The new model, LP75A, was developed by A. Konopliv[3] of the Jet Propulsion Laboratory. The final model, LP75D was available after one month.

With the improved potential models designed specifically for the LP mapping orbit, the batch arc lengths could be extended without degradation. The LP75A solutions were 26 hr arcs with a 2 hr overlap. The LP75D solutions are 55 hr arcs with a 7 hr overlap. The definitive orbit accuracy is measured by comparing the ephemerides over this overlap period. Figure 12 shows this concept graphically. This technique is more accurately a consistency measurement, but without independent tracking of the spacecraft, it is the best available technique. The Root Mean Square (RMS) of the position component differences, measured every 10 min during the overlap period, is considered the 1-sigma position component accuracy. All mapping orbit solutions are performed using Doppler measurements only.

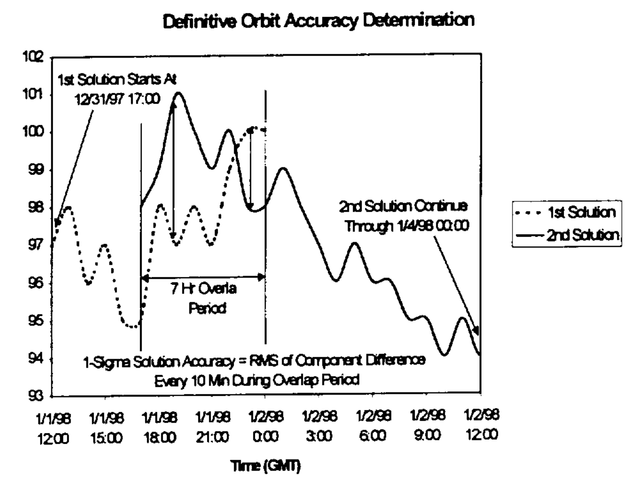

FIGURE 12: OVERLAP EXAMPLE

The orbit accuracy achievable with these three models is shown in Tables 2 and 3. The GLGM-2 results are obtained from the 12 hr solutions generated between January 15 and February 23, prior to the availability of the LP75A and LP75D models. The LP75A results were obtained from the 26 hr solutions generated between February 9 and February 23. These solutions were never used operationally. The LP75D results were obtained from the 55 hr solutions generated between January 15 and May 10. They include the regeneration of the first month's worth of definitive solutions.

Clearly the LP75D solutions meet the mission requirements. As of February 23, definitive ephemerides were being generated using the LP75D model. The entire lunar mapping orbit definitive ephemeris history is available on the GNCC Lunar Prospector Product Center. The definitive ephemeris accuracy for each solution, including position components, is shown in Figure 13. Note that no significant orbit plane effects are seen in the orbit accuracies. Covariance analysis seemed to indicate more unstable solutions in the edge-on geometry but real orbit estimates do not bear this out.

TABLE 2:OD COMPONENT ACCURACY

Model	Radial RMS	Crosstrack RMS	Alongtrack RMS
GLGM-2	475 m	4.0 km	4.4 km
LP75A	NA	NA	NA
LP75D	13 m	155 m	189 m

TABLE 3:DEFINITIVE OD ACCURACY

Model	Position RMS	Avg. Doppler Residual
GLGM-2	6.6 km	21 cm/sec
LP75A	1.9 km	5.5 cm/sec
LP75D	270 m	9.3 mm/sec

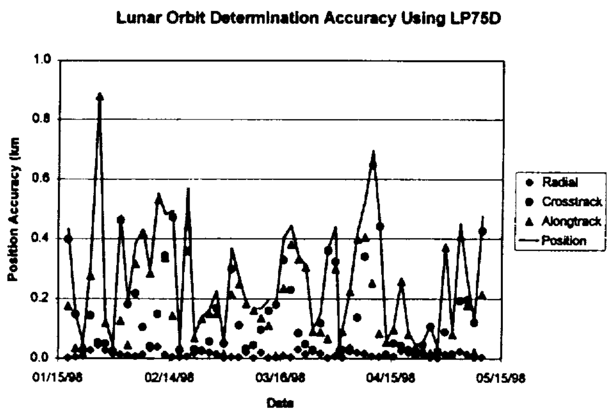

FIGURE 13: LP75D OD ACCURACY

A closer look at the definitive solutions reveals very stable weighted least squares solutions. The residuals are on the order of 9.3 mm/sec for the LP75D solutions. These residuals are consistent between each of the DSN tracking stations, indicating that no erroneous measurement modeling is impacting the solutions. Figure 14 shows the residuals from a sample solution of 55 hrs. A closer look at the residual pattern indicates a high frequency periodic pattern in the signature. This periodic signature sets the amplitude of residuals and limits the accuracy of the solution. Figure 15 shows a magnification of the same residual pattern over a shorter 6 hr time frame. From this graph, the period of the large amplitude residual signature is clearly seen. It is almost exactly the same as the orbit period, 118 min. This pattern is seen in all tracking passes regardless of tracking station or tracking geometry. The measurement noise of the DSN Doppler data is about 1 mm/sec. Thus, the residual pattern seen in Figure 15 is likely due to the lunar potential modeling errors.

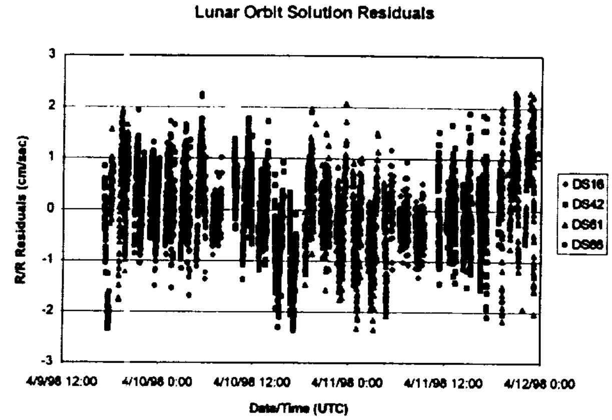

FIGURE 14: SOLUTION RESIDUALS

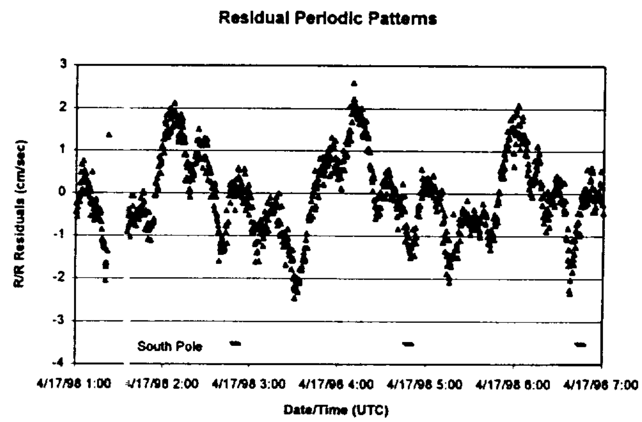

FIGURE 15: RESIDUAL SIGNATURE

Further inspection of Figure 15 reveals that the apparent noise on top of the potential error signature is larger than the expected 1 mm/sec DSN Doppler noise. Figure 16 shows another magnification of the same residual pattern over just a 2 min time frame. From this graph, another periodic residual pattern is noticed – this time with exactly a 5 sec period. This pattern is noticable only when receiving high rate Doppler data at one measurement per second from the DSN. LP is a spin stabilized spacecraft. The spin axis is within about 8 deg of the north ecliptic pole. And most importantly, the spin rate in the mapping orbit is 12 rpm. Clearly this residual signature is from rotation of the Medium Gain Antenna (MGA) on the spacecraft during receipt of the DSN signal[4]

The residual pattern is most likely from either a nutation in the spin axis or a misalignment of the MGA antenna on the spin axis. The spacecraft consists of a drum 50.3" in height with the center of gravity (CG) 23.7" from the base. The MGA antenna sits on top of the drum, centered on the spin axis, with a height of 38". The amplitude of the 2-way Doppler high rate residual signature is about 13 mm/sec. Thus the 1-way Doppler amplitude is 6.5 mm/sec and the deviation from the mean is 3.25 mm/sec. With a 12 rpm spin rate, the magitude of the antenna misalignment that would create such a residual pattern is 2.6 mm. Or it's possible that the residual pattern is due to a nutation of the spin axis. The nutation angle (assuming 45.6" distance from CG to MGA) would be 0.13 deg. It's impossible to determine from the residual signature which cause is in effect. Modeling the antenna motion would be possible and might improve orbit determination accuracy slightly but has not been tried yet.

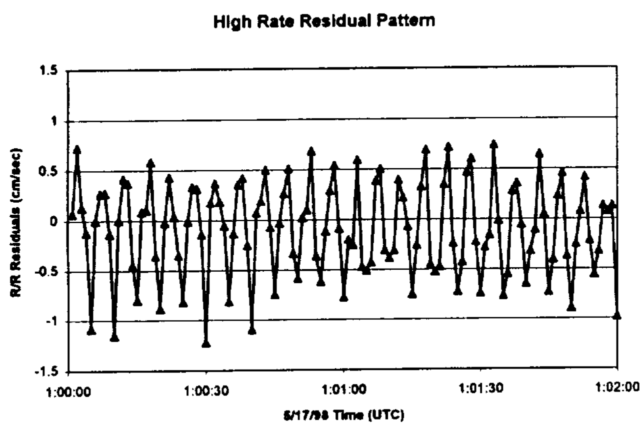

FIGURE 16: 1/SEC RESIDUAL SIGNATURE

Long term predicted products are generated for use by the mission control center, so it seemed appropriate to investigate the predictive capabilities of the different lunar potential models discussed thus far. The longest period in the mapping orbit with no spacecraft perturbations was 36 days. Figure 17 shows the 36 day propagation accuracy using four different lunar potential models. The accuracy is determined by propagating from the best definitive state (determined using LP75D) for 36 days and comparing to the new definitive (LP75D) over a 24 hr period. In addition to GLGM-2, LP75A, and LP75D, the LUN75A model is compared also. The LUN75A model was derived by Konopliv[5] in 1993 and was used during the Clementine mission. A 6 day propagation comparison is also shown in Figure 17. Because the 6 day propagation accuracies from GLGM-2 were not as accurate as the available LUN75A propagations, a switch was made to the use of LUN75A for the 4 wk long term products provided to the mission control center. When LP75D became available, all products were then generated using it.

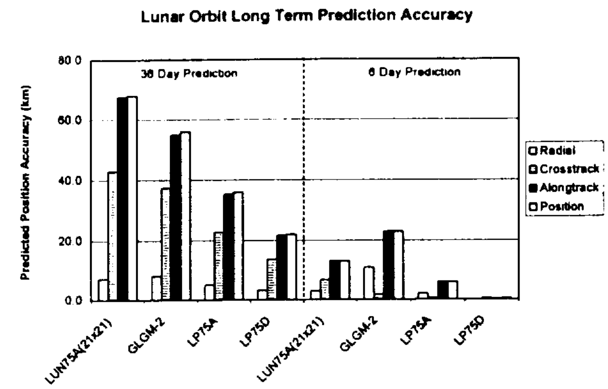

FIGURE 17: PROPAGATION ACCURACY

EXTENDED MISSION

The extended mission for LP entails dropping the altitude from the 100 km circular orbit to, initially, a 20x100 km elliptical orbit and, finally, to a 30 km circular orbit. Some initial covariance analysis has been performed to determine the orbit determination accuracy achievable during those mission orbits.

The first step was to verify the LP75D standard deviation model obtained from Konopliv. Figure 18 shows the 1-sigma position uncertainties from a 100 km circular orbit. The potential uncertainties from each harmonic coefficient are algebraically summed to obtain the complete uncertainty due to the potential model. Both extreme geometries are shown: edge-on and face-on, when the orbit plane is perpendicular to the Earth-Moon line. Note that, as in the premission analysis using GLGM-2, the covariance indicates a much higher uncertainty in the edge-on geometry. This effect is not seen in the actual orbit determination however, and needs further investigation. The face-on results are more indicative of the actual OD results obtained.

Figures 19 and 20 show the position uncertainties from applying the LP75D standard deviation error model to the 20x100 km and 30 km circular orbits respectively. Note that the 20x100 km orbit may actually improve the edge-on results, though those results are possibly unrealistic. The 30x30 km results indicate an increase in position uncertainty by approximately a factor of four, regardless of orbit geometry. Based upon that, we may expect OD accuracies in the range of 1.0 to 1.5 km in the final mission orbit. These results are preliminary however and need further refinement.

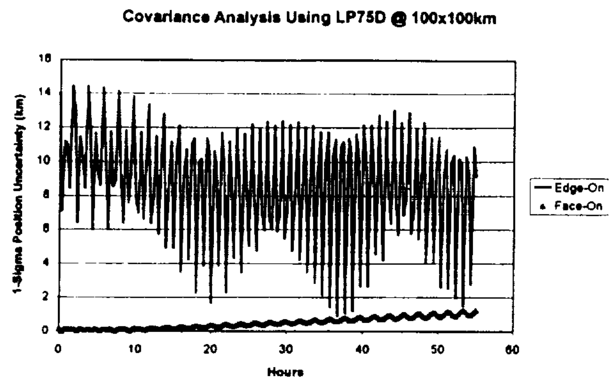

FIGURE 18: COVARIANCE ANALYSIS (100)

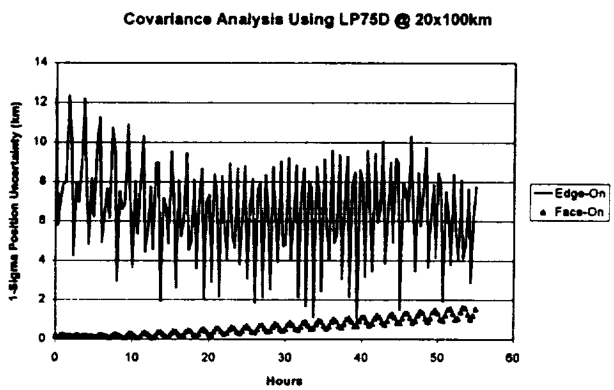

FIGURE 19: COVARIANCE ANALYSIS (20x100)

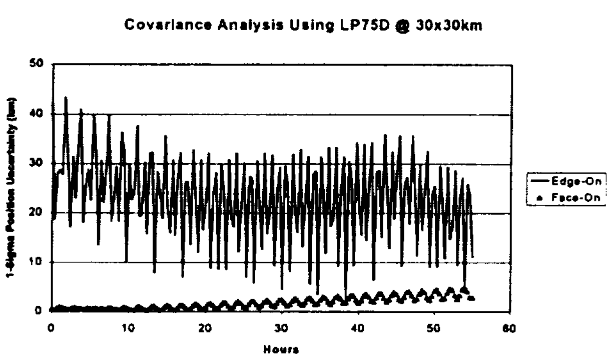

FIGURE 20: COVARIANCE ANALYSIS (30)

WEB PAGE

The GNCC Lunar Prospector Product Center (*fdd.gsfc.nasa.gov/lp*) is a world wide web site maintained by the Goddard LP team. Its purpose is to serve as a repository for the various flight dynamics products provided for the mission. This is the first Goddard supported mission where all products, including those for the MOC for mission event planning, maneuver planning, launch support, and simulations, were delivered primarily via a web site.

While Goddard provides a generic data products web server for all GSFC supported missions (*fdd.gsfc.nasa.gov/FDD_products.html*), the LP team custom designed the Product Center to suit the needs of various LP customers. These needs are ease of use, quick access, and specific, customized products. Instead of encountering multiple query interfaces, as would be necessary from the generic product server, the LP Product Center was designed to provide access to all products with no more than two mouse clicks from the welcome page. A frames based menu bar provides links to pages entitled for each product (see Figure 21).

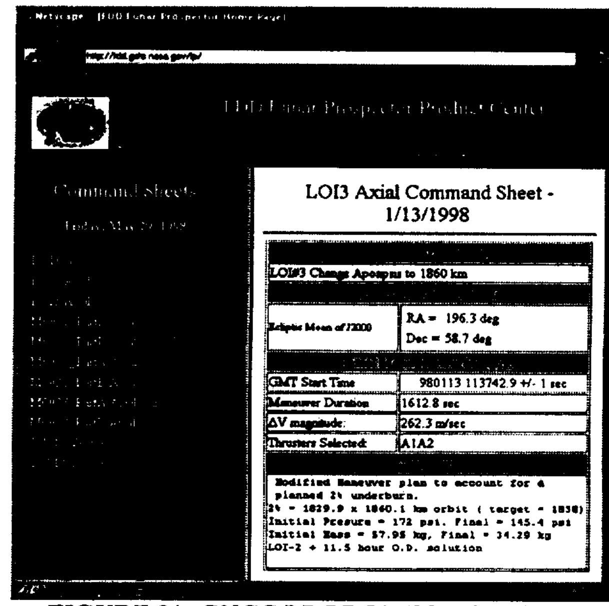

FIGURE 21: GNCC LP PRODUCT CENTER

Within each page the dynamic generation of links to available products is automated by command gateway interface (cgi) scripts written in perl. Thus, the user is guaranteed the most recent products. An added bonus of designing such a site is the unprecedented access for the world-wide community to real-time delivered products.

The LP Product Center delivers the following product menu: Maneuver Command Sheets, Mapping Orbit Definitive Ephemerides, Moon Definitive Latitude & Longitude, 4 Week Predicted Weekly Products, and Special Products. The following is a brief description of these products.

During the course of mission event planning, maneuver command sheets were generated by Goddard trajectory analysts using the LP Product Center. The command sheets were generated and archived using cgi scripts on the web server. Figure 21 shows the command sheet for the LOI-3 maneuver. The command sheets for each LP maneuver are available via the LP Product Center.

The LP Product Center provides the definitive history of the LP mapping orbit in two forms: (1) Cartesian ephemeris in the J2000 selenocentric coordinate system and (2) Moon latitude and longitude in a selenographic coordinate system. Each is available for each day of the LP mapping orbit. Figure 22 shows the Definitive Ephemerides page. A calendar of linked dates provides intuitive browsing. To the right of the calendar, the user may browse the file prior to or in lieu of downloading it. The Moon Lat/Lon page also uses this format.

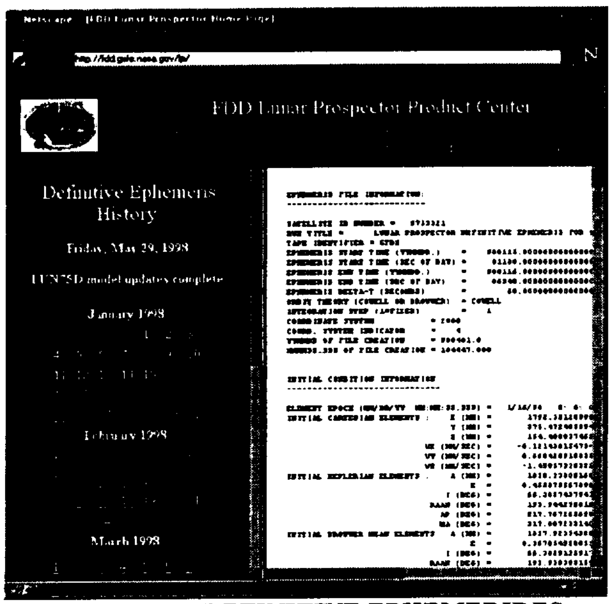

FIGURE 22: DEFINITIVE EPHEMERIDES

The following set of predicted products are generated weekly with a 4 week span: Earth Shadow Times, Moon Shadow Times, Station View Periods, a Merged Report of the above three, Moon Latitude & Longitude, and Predictive Ephemeris. The user has the option of retrieving the current or previous week's products. Figure 23 shows the Weekly Products page with the Merged Shadow Station Report in the output frame.

The Special Products page provides special requests or other non-standard products. Cislunar BETs and lunar potential models are examples of such products.

The LP Product Center has been very successful in providing the scientific, engineering, and educational communities timely access to orbit determination products generated by Goddard. Over the course of a typical 30 day period, the site averages 150 unique host accesses to the main page (in web parlance, "hits"). On average, 790 files representing over 300 megabytes of data each month are downloaded by various customers, with the definitive products as the most frequently accessed. Frequent vistors include: Goddard, Ames Research Center, Jet Propulsion Laboratory, Johnson Space Center, Los Alamos National Laboratory, US Air Force Academy, and UC Berkeley.

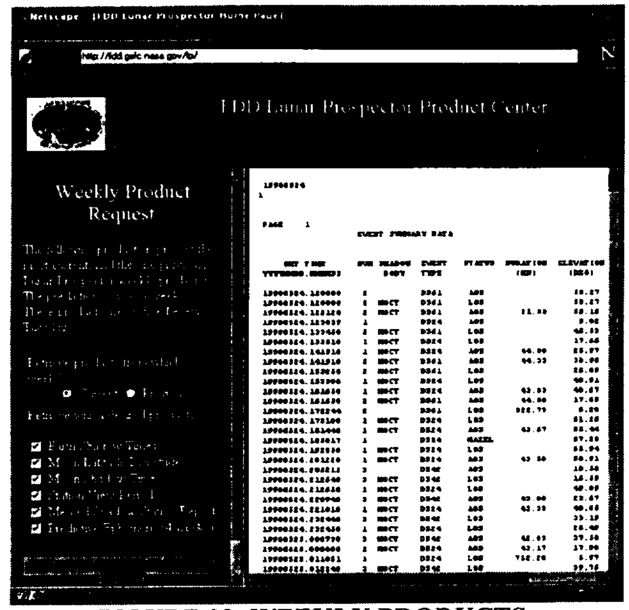

FIGURE 23: WEEKLY PRODUCTS

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