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NASA GSFC Lunar Reconnaissance Orbiter (LRO) Orbit Estimation and Prediction

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LRO launched on June 18, 2009 and successfully entered lunar orbit following the first orbital insertion maneuver on June 23, 2009. The NASA Goddard Space Flight Center (GSFC) Navigation and Mission Design Branch (Code 595) provides orbit estimation and prediction support to the LRO project via their Flight Dynamics Facility (FDF) at NASA GSFC. Since the main goal of this robotic mission is to definitively map all aspects of the lunar environment as a precursor to later NASA follow-on manned missions, the FDF has evaluated and implemented many new force modeling and estimation improvements to the FDF ground system to achieve the high-precision navigation goals for this mission. Among these improvements are upgrades for enhanced lunar gravity modeling, the addition of a lunar solid tide model, improvements to solar radiation modeling that includes a new n-panel macro spacecraft model with the ability to model both specular and diffusive radiation, a self-shadowing model, a new lunar albedo model, and a laser one-way forward measurement model.

This paper details the upgrades performed and also provides an overview of the performance of these upgrades during the actual support of the mission. Also presented are details of the integration of the software tools and automation implemented, including an overview of the integration of government legacy orbit estimation tools and automation with two commercial off-the-shelf (COTS) tools used in the support. The paper also presents the navigational approach for different phases of the mission including the Earth-centered cislunar phase, the lunar orbital insertion maneuvers, and the lunar environment.

Nomenclature

Cr	=	solar radiation pressure coefficient
CRD	=	Consolidated Laser Ranging Data Format
Delta-H	=	momentum unload maneuver
Delta-V	=	orbit adjustment maneuver
DSN	=	Deep Space Network
FDF	=	Flight Dynamics Facility
GMSEC	=	Goddard Mission Services Evolution Center
GTDS	=	Goddard Trajectory Determination System
HGA	=	High gain antenna
IAU	=	International Astronomical Union
ILRS	=	International Laser Ranging Service
LOI	=	lunar orbit insertion maneuver
LOLA	=	Lunar Orbiter Laser Altimeter

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MAX	=	maximum position or velocity differences
MCC	=	mid-course correction
MOC	=	Mission Operations Center
MOI	=	mission orbit insertion maneuver
OD	=	orbit determination
PDS	=	Planetary Data Services
RMS	=	Root Mean Square
RSS	=	Root Sum Square
SCN	=	Space Consolidated Network
SK	=	Station Keeping
SOC	=	Science Operations Center
SPICE	=	Spacecraft Planetary Instrument Pointing Events information datasets
STK	=	Satellite Tool Kit
USN	=	Universal Space Network
WRMS	=	Weighted Root Mean Square

I. Introduction

The Flight Dynamics Facility (FDF) at the NASA Goddard Space Flight Center (GSFC) hosts the navigation support for the Lunar Reconnaissance Orbiter (LRO). LRO is one of over 30 missions supported from this multi-mission facility in all orbital regimes. The FDF has previously supported several other lunar missions: the NASA Apollo missions of the 1960s and 1970s, the NASA/NRL DSPSE/Clementine mission in 1994, and the NASA Lunar Prospector (LP) mission of 1998-1999.

A. Navigation Goals for LRO

LRO differs from these previous missions in terms of the navigation requirements and goals. Orbit determination (OD) accuracy is a function of the accuracy of the tracking measurements, tracking geometry, and the tracking schedule as well as the force and measurement models used in the OD processing. The navigation goals for the earlier lunar missions required definitive position knowledge necessary to maintain successful spacecraft acquisition. The achieved accuracy for the DSPSE and LP missions was approximately 1 km[1]. LRO navigational goals are a definitive position requirement of 500 meters RMS and a predictive accuracy requirement of 800 meters over a prediction period of 84 hours[2]. The radial accuracy requirement is 18-meters[2]. These requirements are meant to support daily on-going mission estimation and prediction necessary to support the spacecraft operations and also supply definitive and predictive products for the seven different science teams with instruments on-board the spacecraft.

Later post-processing of orbital tracking data will be performed when updated gravity models are available using both the S-band radiometric tracking data, and the new 1-way forward normal point laser measurements being used for the first time by any mission. The 1-way forward measurement is returned in LRO telemetry first to the LRO MOC and then routed to the LOLA SOC at Bldg. 33 at GSFC. After further preprocessing, this data is forwarded to the FDF via the LRO MOC for inclusion in high precision orbit determination in the FDF. SPICE ephemeris files are created based on this improved state estimation process and will be stored at the PDS science data archive at JPL[3] for use by science teams.

Goals for the laser reprocessing are orbital positional knowledge of 50 meters horizontal and 1-meter radial combining definitive attitude data for improving the spacecraft perturbation modeling and utilizing both the S-band and laser tracking data[4]. Additionally, this goal requires the incorporation of a new lunar gravity model that will be produced by Frank Lemione and members of his Planetary Geodynamics Lab at GSFC by processing of the LRO tracking data with high precision perturbation modeling.

This paper focuses on early day-to-day results achieved with the S-band tracking data since it is still fairly early in this on-going mission. However, an overview is given of the enhancements already made to the FDF ground network to help achieve the laser reprocessing goals.

B. LRO Orbit Overview and Timeline

Table 1 below displays an overview of the LRO early mission timeline.

Table 1. LRO Early Mission Timeline Events

Event	Approximate Start (GMT)
Launch	6/18/09 21:32
Spacecraft Separation	6/18/09 22:16
Thruster Tests	6/19/09 0:13
Momentum Unload	6/19/09 0:47
MCC-1	6/19/09 22:17
LOI-Engineering Orbit Adjust	6/23/09 3:05
LOI-1	6/23/09 9:47
LOI-2	6/24/09 10:29
LOI-3	6/25/09 10:33
Momentum Unload	6/25/09 13:00
Momentum Unload	6/26/09 12:25
LOI-4	6/26/09 12:25
LOI-5	6/27/09 12:36
Momentum Unload	7/2/09 21:14
Momentum Unload	7/27/09 12:00
Momentum Unload	8/14/09 12:15
Phasing Maneuver for Chandryaan-1 Bi-Static Radar Test	8/19/09 22:15
Momentum Unload	8/31/09 12:15
Momentum Unload	9/11/09 17:30
MOI-1	9/15/09 19:32
Momentum Unload	9/25/09 15:45
MOI-2	9/25/09 18:28
MOI-3	9/26/09 17:55
Momentum Unload	10/5/09 21:55
LCROSS Phasing Maneuver	10/7/09 19:15

LRO employed a direct transfer trajectory from its launch site at Kennedy Space Center to the Moon[5]. A mid-course correction (MCC-1) was performed at 24 hours after launch,. A thruster engineering burn (LOI-E) was performed prior to lunar orbit insertion. The early lunar orbit was achieved after 5 LOI maneuvers spaced approximately 24 hours apart. This initial commissioning orbit around the Moon was designed to be a higher orbit with a 30 km periselene and a 216 km aposelene meant to serve as a stable holding phase while instrument checkouts were performed. The achieved commissioning orbit was 33 km x 198 km altitude. The official mission orbit began with the final descent to the 50 km circular mean altitude orbit on September 24, 2009. It is necessary to maintain this orbit approximately every 27 days with a pair of orbit adjust stationkeeping (SK) maneuvers. Additionally, since LRO is three-axis stabilized, it is also necessary to unload excess momentum with thruster firings (delta-H) maneuvers every two weeks, one of which is paired with the monthly SK burns. These are all orbit disturbing events for OD and must be incorporated into predictions for science and network planning accurately.

During the translunar phase of the mission, the spacecraft was tracked continually while in view of scheduled Earth tracking antennas. This phase of the mission was the most difficult due to the critical orbit adjust maneuvers that had to be planned and performed accurately to reach the target insertion conditions at the Moon.

C. Tracking Volume

For both of the lunar phases (commissioning and mission science phase), LRO is tracked when in view of a scheduled Earth station, for 30 minutes per orbit (2 hour period). It is generally out of view for 1 hour per orbit except for the ”face-on” periods every 13 days. In the “face-on” view the orbit is completely visible from Earth for a brief period. In the “edge-on” geometry part of the orbit is occulted by the Moon from an Earth observer. Orbit solution WRMS is lowest during periods that LRO is near the face-on view relative to the Earth. LRO will go from face-on to edge-on within a period of approximately 7 days.

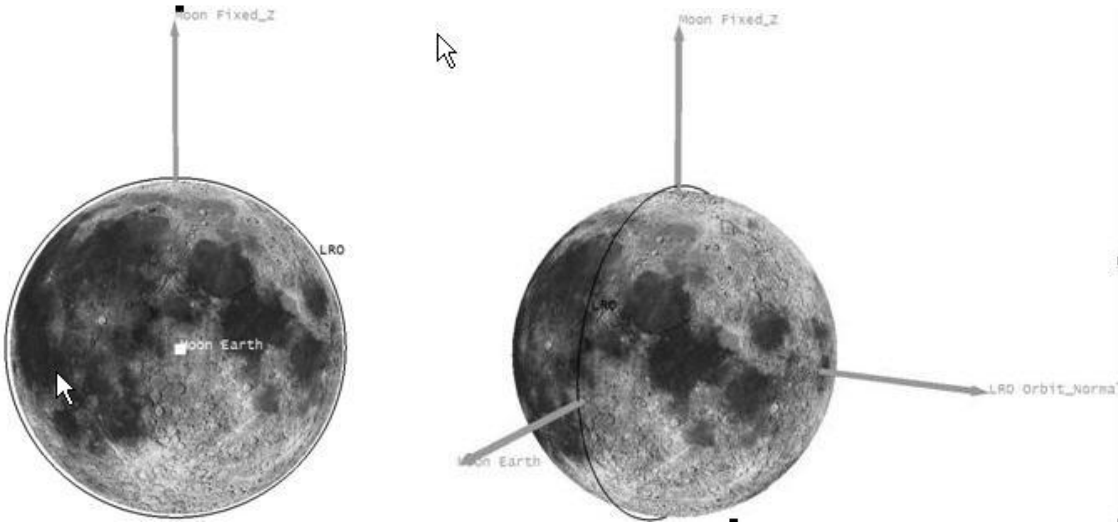

Figure 1. LRO Geometry, "Face-On" (left) and "Edge-On" Geometry (right)

II. Navigation Ground System Overview

The LRO navigation ground system consists of several different S-band tracking networks, in addition to the Flight Dynamics Facility. All navigation related products are sent to the LRO MOC via the Flight Dynamics Product Center. Figure 2 below displays all the S-band tracking sites supporting LRO:

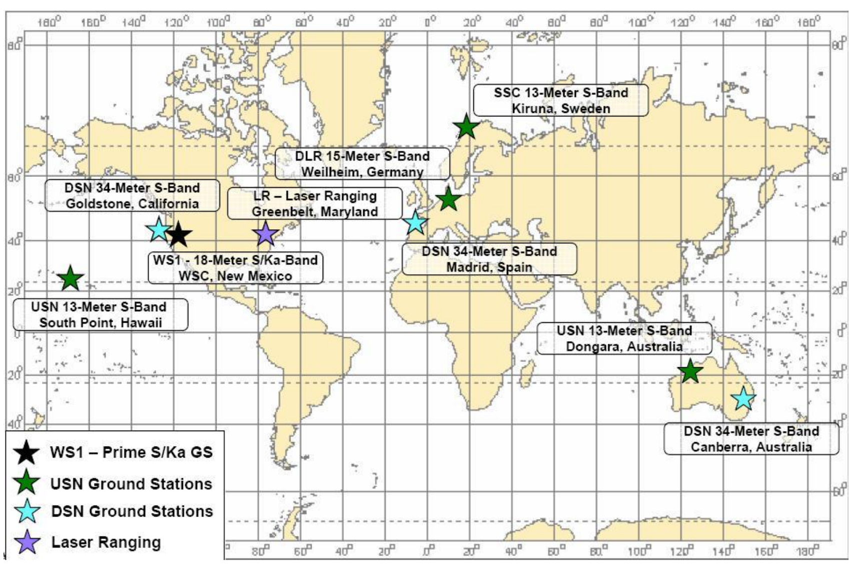

Figure 2. LRO S-Band Tracking Sites and Main Laser Site.

A. S-band Networks.

The S-band network for LRO is composed of the following elements:

Table 2. LRO S-band Antenna and Measurement Accuracy Requirements

Network Element	Location	Range Error 1-sigma	Doppler Error 1-sigma
DSN DS24, 27, 34-meter	Goldstone, California	10 m	1 mm/s for 5 second Doppler integration
DSN 34, 45, 34-meter	Canberra, Australia	10 m	1 mm/s for 5 second Doppler integration
DSN 54, 65, 34-meter	Madrid, Spain	10 m	1 mm/s for 5 second Doppler integration

Network Element	Location	Range Error 1-sigma	Doppler Error 1-sigma
NASA WS1S, 18 meter	White Sands, New Mexico	10 m	1 mm/s for 5 second Doppler integration
USN USPS, 15-meter	Dongara, Australia	10 m	3 mm/s for 5 second Doppler integration
USN WU2S, 13-meter	Wilheim, Germany	10 m	3 mm/s for 5 second Doppler integration
USN USPS, 13-meter	South Point, Hawaii	10 m	3 mm/s for 5 second Doppler integration
USN KU1S, 11-meter	Kiruna, Sweden	10 m	3 mm/s for 5 second Doppler integration

The Space Communications Network (SCN) that supports LRO is composed of the NASA White Sands antenna and the USN commercial antennas. The USN antennas and White Sands antennas were built and/or enhanced specifically to meet the performance requirements for LRO support with CORTEX XL units as outlined in Table 2 above. The White Sands antenna is the prime LRO antenna, which also support Ka-band downloads.

The SCN and NASA DSN antennas were used on the trans-lunar phase, as well as during the early mission lunar orbit. In the mission orbit, the NASA antennas and USN antennas are used with the spacecraft HGA antenna. Since it is necessary to use the spacecraft Omni antennas during orbit adjust maneuvers, DSN antenna coverage is required during these periods to close the communications link.

B. Laser Sites.

The laser sites were also augmented to support LRO. A new one-way forward measurement was designed and new lasers installed at GSFC. Also, collaborative sites from around the world were drafted to support LRO (see Figure 3 below). The laser network supporting LRO has the following elements:

Table 3. LRO One-Way Forward Laser Sites

Station	Location	Range Error 1-sigma
GO1L	Greenbelt, MD, USA	10 cm at 5-second rate
HARL	Hartebeesthoek, South Africa	10 cm at 5-second rate
HERL	Herstmonceux, England	10 cm at 5-second rate
MDOL	McDonald Observatory, Ft. Davis, Texas, USA	10 cm at 5-second rate
STL3	Mt. Stromlo, Canberra, Australia	10 cm at 5-second rate
WETL	Wettzell, Germany	10 cm at 5-second rate
YARL	Yarragadee, Australia	10 cm at 5-second rate
ZIML	Zimmerwald, Bern, Switzerland	10 cm at 5-second rate

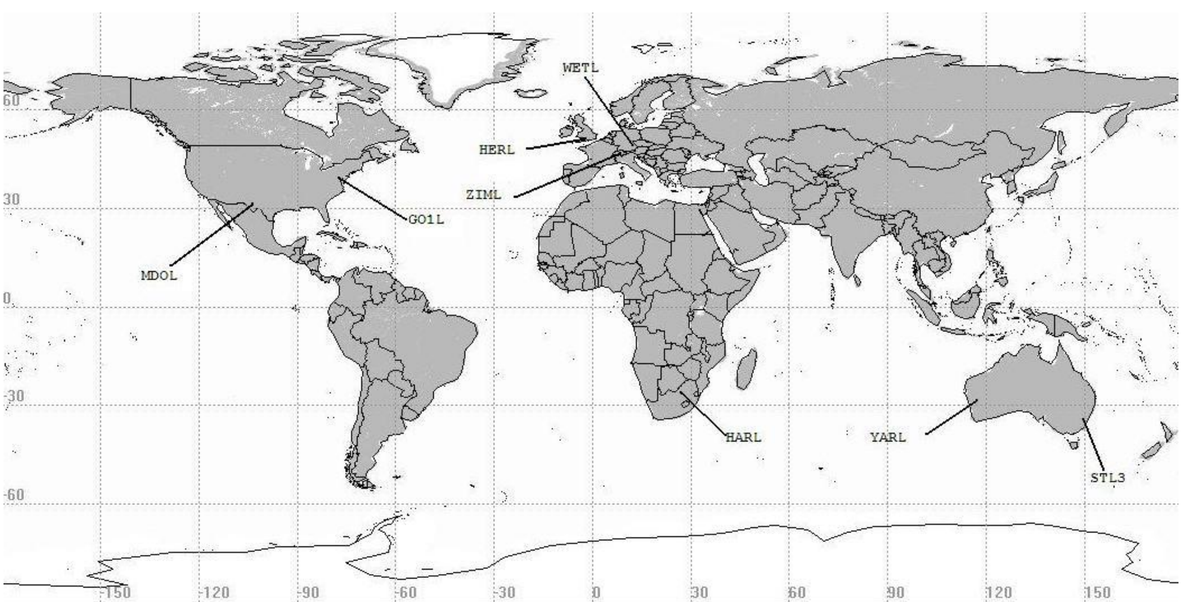

Figure 3. LRO Laser Sites.

C. FDF Ground System Automation Overview.

The main navigation components of the LRO FDF ground system combine existing orbit determination and data collection systems, along with new systems required for LRO hosted on either UNIX or Windows operating systems. Executive control of the automation manages all the OD and orbit prediction processes from the UNIX system (see Figure 5 below). The automated executive manages the process flow for LRO OD, definitive and predictive product generation across both the UNIX and PC platforms, going to each subsystem as needed in the proper controlled sequence. The automation begins with controlling the updating of the orbit determination for LRO using GTDS, then re-propagates the latest orbit determination vector considering the latest maneuver plans in STK, creates updates of the definitive products, creates all the required prediction products, automatically quality assures all OD and predictions results, logs the results, and delivers the products to the required recipient. The automation detects anomalies in the processing, and alerts the FDF mission team by email. The FDF mission team also receives an email when the products are successfully delivered. LRO receives 5 definitive products, and over 25 predictive products that are generated on a regular basis.

This system was installed prior to any of the mission tests and simulations prelaunch to ensure adequate vetting and reliable test support. During the prelaunch testing and during the actual early mission phase, the automation was used to create standard products at the direction of a user through a User Interface (UI). This permitted concentration on quality orbit determination while minimizing likelihood of predictive product errors. For several months after launch the automation was run in a quasi-light out mode as OD results were always reviewed significantly, although the products were automatically created and delivered once the OD had been formally approved interactively. The mission moved to full lights-out operations in November 2009. Maneuvers are treated as special events, mainly to adjust the orbit solution arc from the standard length to exclude the orbit adjust period.

Figure 4 below presents an overview of the processing within FDF to support LRO along with the interfaces, subsystems, and data. Also shown are the external interfaces, which includes the tracking networks, the MOC, the SOCs (via the MOC), and the final destination for all LRO data the PDS repository at JPL.

D. FDF Ground System Components.

All of the support is executively driven by pre-existing automation tools available in the FDF, the Operational Products Automation System (OPAS), and the Quality Assurance Tool (QATool). OPAS in combination with QATool can be used interactively through a user interface (opasUI) or used in a lights out mode where all the support including OD, product generation, full quality assurance, and delivery is performed automatically without user intervention. Should one of the quality assurance criteria detect a non-compliance in a product generation or product, the system will automatically notify by email the LRO FDF team members for further assessment. OPAS will deliver products that have passed successful Quality Assurance (QA) checks and will not deliver the products that have not passed QA checks until the mission team assesses and addresses any product failures or QA tolerance checks. LRO support is currently routinely performed in the lights-out mode.

To support LRO, FDF is using a government legacy (GOTS) orbit determination system called GTDS. It is currently used to support low-Earth, high-Earth, libration-point, and deep-space missions as well as previous lunar missions. GTDS employs a batch estimation weighted least squares method. As necessary, measurement biases are also estimated along with the state parameters during the OD processing for LRO.

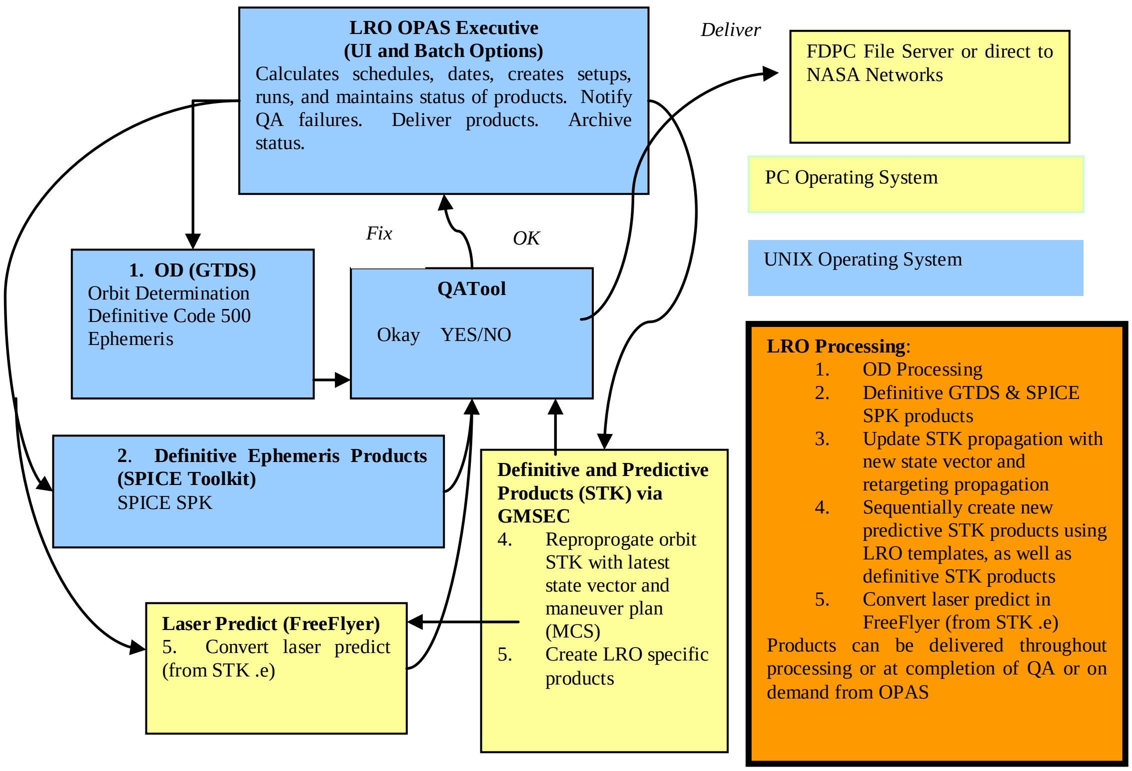

Figure 4. Overview for LRO Orbit Determination and Prediction Processing

GTDS version 2008.01 was upgraded to support the S-band laser ranging measurements (SLR) as well as further force modeling upgrades for a lunar environment. The laser measurements are not used in the day-to-day support of the mission, but for post-facto high precision solutions using updated gravity models. While many of the force modeling enhancements are targeted for use in the laser reprocessing, some of the force modeling enhancements support the day-to-day operations on LRO, principally the enhanced lunar gravity model and the solid lunar tide model enhancement. The LRO force modeling upgrades are detailed in Section III.

FDF is using the Analytical Graphics Inc. system STK version 8.1.3 with the Astrogator and Connect modules to support product generation for LRO. The STK system with lunar enhancements and force modeling upgrades performed consistently well in comparisons against GTDS in all pre-mission testing, achieving ephemeris propagation consistencies of under one meter in three days. This pairing of major components has worked well for use in support of LRO. The force modeling is kept strictly consistent between the two systems. The OPAS executive for support is driven from the UNIX OS where the OD process is the first step in new updates. Again, the OPAS executive can be run interactively or in a lights-out mode via the UNIX *cron* scheduler. The automation also utilizes STK Connect calls to create mission specific products using customized report templates inserted into STK. For some of the orbital products, PERL scripts have been used to perform further formatting or combining of some intermediate orbital products info into desired final product formats for the MOC's Mission Planning System. Also, the LRO mission is the first mission in FDF to use the Goddard Mission Services Evolution Center (GMSEC) architecture within the FDF to support communications protocols between any available STK-enabled PC and the UNIX systems. Each product is automatically delivered upon successful quality assurance checks with a seamless integration of the two operating systems to support LRO.

JPL's SPICE Toolkit components are used to create both predictive and definitive SPICE SPK kernels for use by the DSN scheduling and planning team as well for use by the LRO science teams for definitive product formatting. STK also has embedded SPICE Toolkit functionality, which is utilized also for predictive ephemeris products.

Ephemeris data for laser acquisition data is created based on STK's Astrogator propagations but is reformatted to the output and coordinate frame conventions requested by the Laser Ranging Ground team. This reformatting is performed by the ai Solutions Inc. system FreeFlyer utilizing a special mission script.

The S-band tracking measurements are processed within existing data collection systems in FDF, no changes were required for LRO. These systems are a combination of data preprocessors that identify tracking measurements by data type (with over 20 variants), perform engineering conversions, then further separate the data by mission, and add them to an Oracle database. The data is then retrieved by a client/server architecture that retrieves the data on demand by mission and time, and converts the data from the raw converted data to a special format compatible with GTDS. All of the tracking data collections subsystems are UNIX based. A new PC-based data preprocessor was created in Matlab to independently ingest the new SLR data measurement separately from the normal tracking data path. The SLR measurements are pre-processed in Matlab, where they are combined with the archived S-band tracking data residing on the UNIX.

III. Navigation Ground System Enhancements

Preparation for LRO built on results accumulated by FDF and others on past NASA lunar missions, principally Lunar Prospector and DSPSE/Clementine and the earlier Apollo missions. To achieve LRO goals (see section 1), the following enhancements to the FDF ground system were required[6]. These enhancements were aimed at reducing the dynamic modeling and measurement modeling errors in the OD processing.

Pre-mission assessments of the upgrades were performed in GTDS using historical archived tracking data from Lunar Prospector along with the latest lunar gravity models (LP100K, LP150Q). A series of solutions were performed with each upgrade to judge the effectiveness of the upgrade. The GTDS results were also validated using results from the GEODYN program. GEODYN is used by the NASA GSFC Geodynamics Branch to perform high precision orbit determination for further gravity potential determination.

This paper summarizes the specifications for the upgrades used in the day-to-day navigation that includes the lunar Principal Axis (PA) Frame, the expanded lunar non-spherical gravity potential, and the solar lunar-tides perturbation model. The other enhancements specifications will be presented with the results in a future paper but the upgrades are summarized briefly here[6].

A. Principal Axis Frame (PA)[7]

The prior FDF supported lunar missions, including Lunar Prospector, used a selenographic frame corresponding to a mean frame based on analytical expressions approved by the International Astronomical Union (IAU) conference of 1991. Since the LP100 and LP150Q gravity models were determined based on an instantaneous principal axis frame, an enhancement was performed to FDF processing to allow use of the instantaneous PA frame in GTDS. In order to achieve this frame, the Euler angles resident on the DE 400 series of JPL files must be read and used to compute the rotation from the mean of J2000.0 Lunar-centered inertial (LCI) frame to the instantaneous true selenographic (SG) frame[6].

$$\bar{r}_{SG} = T_{SG \leftarrow J2000_{LCI}} \bar{R}_{J2000_{LCI}} \qquad \text{(Eq. 1)}$$

The rotation matrix $T_{SG \leftarrow J2000_{LCI}}$ is computed as follows using the Euler angles of the lunar principal axes relative to the J2000.0 reference frame

$$T_{SG \leftarrow J2000_{LCI}} = R_Z(\psi) R_X(\theta) R_Z(\phi) \qquad \text{(Eq. 2)}$$

$$T_{SG \leftarrow J2000_{LCI}} = \begin{bmatrix} \cos\psi\cos\phi - \sin\psi\sin\phi\cos\theta & \cos\psi\sin\phi + \sin\psi\cos\phi\cos\theta & \sin\psi\sin\theta \\ -\sin\psi\cos\phi - \cos\psi\sin\phi\cos\theta & -\sin\psi\sin\phi + \cos\psi\cos\phi\cos\theta & \cos\psi\sin\theta \\ \sin\phi\sin\theta & -\cos\phi\sin\theta & \cos\theta \end{bmatrix} \qquad \text{(Eq. 3)}$$

During pre-mission testing with archived LP tracking, this enhancement demonstrated an improvement to the definitive OD performance of 600 meters compared to OD performed using the same tracking data from LP using the mean selenographic frame instead of the instantaneous selenographic frame, as measured by definitive ephemeris overlap comparisons.

B. Expanded Lunar Non-Spherical Gravity Potential[6]

Expansion of the GTDS lunar non-spherical gravity model from previous maximum of a 100x100 model to 200x200 was necessary in order to gain the full benefit of the accurate laser measurement data. Pre-mission testing with this upgrade showed an approximate 30-meter improvement in the OD consistency using LP150Q 150x150 modeling versus LP100K 100x100.

C. Solid Lunar Tides Perturbation Model[6]

The solid lunar tides model provides constant and periodic corrections to the coefficients of the lunar gravitational acceleration due to small periodic deformations of the solid body of the Moon caused by the Earth and the Sun acting on the Moon. Section 6.3 of Reference 2 explains that the degree 2 zonal tide generating potential has a mean (time average) value that is nonzero. This time-independent potential produces a permanent deformation and associated time-independent contribution to the geopotential coefficient $C_{2,0}$. In formulating the gravitational potential model, two approaches may be taken:

- If the time-independent contribution is not included in the adopted value of $C_{2,0}$, the value is termed "tide free." This is the case with the EGM96 and LP-derived (i.e., LP100K, LP150Q, LP165P) models.
- If the time-independent contribution is included in the adopted value of $C_{2,0}$, the value is termed "zero tide." This is the case with the JGM-3 geopotential model and the GLGM2 lunar potential model.

The following is the full lunar solid tide acceleration including the second and third order frequency-independent solid tidal effects of the Sun (j=1) and Earth (j=2) on the Moon based on the function TIDAL from GEODYN:

$$\ddot{r}_{Tides} = \sum_{j=1}^{2} \left\{ \begin{array}{l} \dfrac{3k_2\mu_j R_M^5}{2r_j^3 r^4}\left[\dfrac{\bar{r}}{r} - 5\left(\dfrac{\hat{r}_j(\lambda_t)\cdot\bar{r}}{r}\right)^2 \dfrac{\bar{r}}{r} + 2\left(\dfrac{\hat{r}_j(\lambda_t)\cdot\bar{r}}{r}\right)\hat{r}_j(\lambda_t)\right] \\ -\dfrac{5k_3\mu_j R_M^7}{2r_j^5 r^5}\left[r_j\left(7\left(\dfrac{\hat{r}_j(\lambda_t)\cdot\bar{r}}{r}\right)^3 - 3\dfrac{\hat{r}_j(\lambda_t)\cdot\bar{r}}{r}\right)\dfrac{\bar{r}}{r} - r_j\left(3\left(\dfrac{\hat{r}_j(\lambda_t)\cdot\bar{r}}{r}\right)^2 - 0.6\right)\hat{r}_j\right] \end{array} \right\}$$

(Eq. 4)

where

k_2, k_3 = second and third order Love numbers for the Moon that is associated with the lunar nonspherical gravitational model

R_M = the mean Equatorial radius of the central body (i.e. the Moon)

$\bar{r}$ = the position vector of the spacecraft relative to the Moon's center of mass, referenced to the mean of J2000.0 frame

r_j = magnitude of the position vector of the disturbing body relative to the Moon

$\hat{r}_j(\lambda_t)$ = the unit vector to the disturbing body from the Moon's center of mass in the means of J2000.0 frame, $\hat{r}_j$, rotated by a phase shift (λ_t) about the Moon's axis of rotation

$$\hat{r}_j(\lambda_t) = \begin{bmatrix} \cos\lambda_t & -\sin\lambda_t & 0 \\ \sin\lambda_t & \cos\lambda_t & 0 \\ 0 & 0 & 1 \end{bmatrix}\hat{r}_j \qquad \text{(Eq. 5)}$$

μ_j = the gravitational constant of the disturbing body (equal to the product of universal gravitational constant and the mass of the disturbing body)

During pre-mission testing with archived LP tracking, this enhancement demonstrated an improvement to the OD performance of 20 meters compared to OD performed using the same tracking data from LP where the solid lunar tide model was not employed.

D. N-Plate Model[6]

Solar radiation pressure enhancements were also made with a more sophisticated n-plate model than was previously available in GTDS. This plate model allows for individual plate specular and diffusive radiation modeling.

For the LRO spacecraft, the area model consists of the spacecraft bus (a box composed of six plates), the solar array front and back (2 plates), and the front and back of the high gain antenna (2 plates), for a total of 10 plates. Definitive spacecraft bus attitude and high-gain antenna (HGA) and solar array (SA) pointing information is down linked from the spacecraft, and further processed within the LRO Attitude Ground System located in the LRO MOC. This data is collected, processed, and later sent to FDF. Since it is not available to support the on-going day-to-day orbit estimation of the mission, the N-plate model for use with LRO will be used with the laser reprocessing only.

E. Lunar Albedo[6]

Another upgrade made for improving the solar radiation estimation was a new model for the planetary radiation pressure due to the Moon's albedo and thermal emissions. Previous estimates found that the lunar surface accounts for 10 - 20% of the solar radiation pressure at the Moon[2]. For the Lunar Prospector nominal and extended mission orbits, the effect of the Moon's radiation pressure was found to contribute 1-2 meters radial and 5-10 meters RSS over a 7 day time span. At each integration step, the part of the lunar sphere seen by the satellite is divided into a user-selected number of rings and each ring is again subdivided into equal area surface elements (with centers located at specific "spots"). For lunar albedo modeling, 5 rings is the baseline used for LRO.

The implementation in GTDS followed methods outlined in Knocke and Marshall[8,9,10]. The radiation pressure acceleration in the planet-body-fixed (PBF) frame of the central body for each flat plate in a box-wing spacecraft model, including different specular and diffuse reflectivity for each plate, and summing over the part of the lunar sphere seen by the satellite.

The lunar albedo model is very computationally intensive, increasing computation times by several hundred percent. This model will only be used with the laser reprocessing.

F. Other Updates

Other updates were also performed prior to LRO's launch[6]. These updates will be used in the laser measurement post processing not yet performed (not in the day-to-day navigation of LRO). Therefore for completeness, these models are simply summarized here but actual results are not presented.

The self-shadowing model considers the shadowing of spacecraft surfaces due to spacecraft structures upon itself. FDF is utilizing a model developed by NASA GSFC Code 698 by Erwan Mazarico and Frank Lemione and other associates in the Planetary Geodynamics Lab[11].

The HGA antenna offset correction to the computed S-band Doppler consists of modifying the spacecraft position vector used in the computation of the range at the beginning and end of the Doppler averaging interval to include the offset of the HGA antenna phase center from the spacecraft center-of-mass. This enhancement improves Doppler data fitting by at most approximately 1 mm/sec, with the greatest effect being for geometries where the LRO orbit is view edge-on from the Earth.

FDF implemented two troposphere model enhancements, the Marini model for the laser data, and the Modified Hopfield model for radiometric tracking[6]. These models will be used during the post processing of the laser measurements.

The laser measurement model was developed based on the new 1-way forward measurement type. Pulses from ground laser trackers are recorded on board LRO by the LOLA instrument, utilizing a receiver telescope mounted on the LRO high-gain antenna. Pulse receipt timings are returned to Earth in spacecraft telemetry. The LOLA science team will receive and process the spacecraft telemetry and provide the laser observations to FDF in the Consolidated Laser Ranging Data (CRD) format[12].

G. Other Updates Not Implemented

Other modeling upgrades were identified but not implemented as the effects were projected to be sub-centimeter in OD processing so not likely to contribute significantly to OD performance accuracy[6]. These include perturbation modeling for effects such as tectonic plate movement, station displacement due to solid Earth tides, and station displacement due to pole tides. These updates will be revisited if need be during the laser post processing phase.

IV. Navigation Performance

A. Prelaunch Phase

The LP mission of 1998-1999 supported by the FDF was used as a target of opportunity for testing the effectiveness of the various force model upgrades. Archived LP tracking data stored at the FDF was recovered and reprocessed using the enhanced models. Results showed that the most important enhancement is the use of PA lunar librations from the JPL DE file and associated updated lunar gravity models instead of the IAU 1991 lunar librations. This update alone improved LP definitive accuracy by approximately 600 meters. Use of a 150x150 gravity model with a 5-second integration step-size improved definitive accuracy an additional 30 meters versus a

100x100 model, and finally incorporation of solid lunar tides added another 20 meters of definitive accuracy. As a result, the expected definitive accuracies for LRO based on the LP reprocessing were expected to be on the order of 31 meters RSS, 3 meters radial. The effect of other enhancements such as lunar radiation pressure, spacecraft antenna motion correction, the Hopfield troposphere model, a box-wing spacecraft area model, relativity, and self-shadowing, were not specifically evaluated using the Lunar Prospector data. The majority of these other upgrades were tested against the GEODYN system for accuracy.

B. Translunar Phase.

LRO was launched into a direct lunar transfer trajectory, as depicted in Figure 5 below. Following spacecraft separation, thruster performance tests and delta-H momentum unloads were executed, all with orbit thrusting disturbances. A single MCC-1 maneuver was executed to set up the large (40-minute) LOI-1 burn. Due to the criticality of the LOI-1 burn, prediction accuracy of orbit solutions used for LOI maneuver planning between MCC and LOI-1 was a key concern.

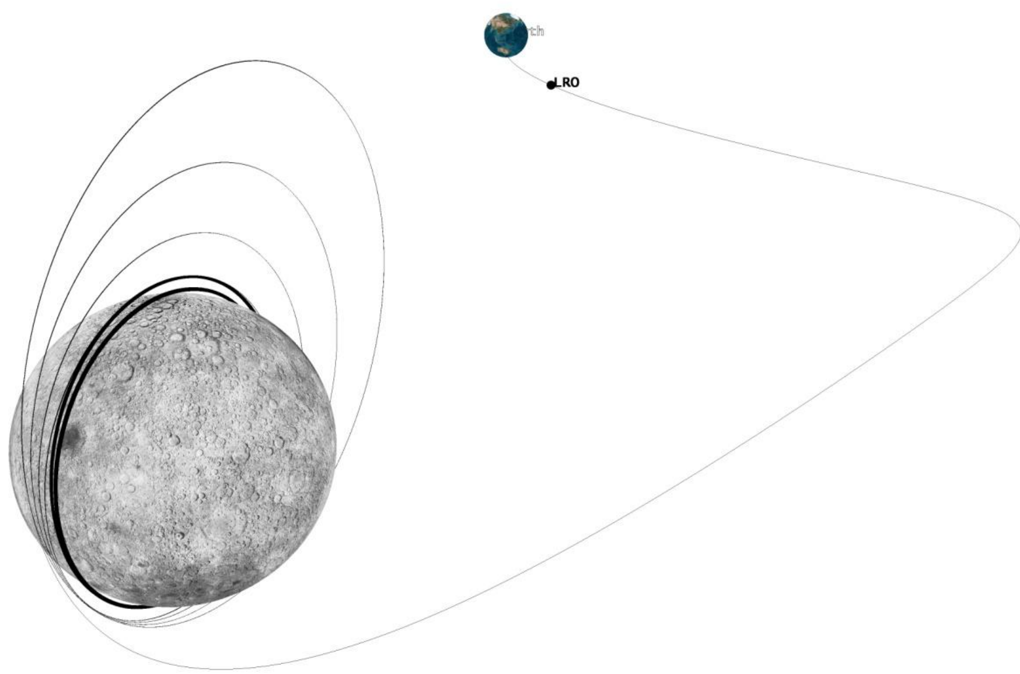

Figure 5. Overview of the LRO Translunar and Lunar Orbit Insertion Insertion Trajectory

Table 4 below summarizes the prediction accuracy of LOI planning solutions. The solutions delivered 41 hours after the MCC1 maneuver had a measured accuracy of 835 meters. The solution delivered 72 hours after MCC1 accuracy is estimated to be accurate to 400 meters.

Table 4. Prediction Accuracy of LOI Planning Solutions

OD Tracking Arc Length (hours)	Prediction Span to LOI-E (hours)	Position Error at LOI-E (km)	Velocity Error at LOI-E (mm/sec)
41	35	0.835	6
63	13	0.402	3
72	4	0.399	3

OD accuracy during the translunar orbit phase is difficult to assess due to the frequency of spacecraft maneuvers, momentum unloads and other orbit-perturbing activity. The longest largely unperturbed arc during translunar flight was the 76 hour span from MCC1 to the LOI-E. Orbit determination during this phase was complicated by numerous Doppler biases, the most severe of which was an intermittent sudden -4.7 cm/sec bias induced by the spacecraft Numerically Controlled Oscillator (NCO) when the difference between the spacecraft receive frequency and the nominal receive frequency was negative. This was mitigated in the first few weeks of support by instructing stations to use an uplink frequency with a positive bias large enough to avoid any Doppler shift of the receive frequency into values less than the nominal. In addition to the NCO bias, the USN stations at Dongara and Hawaii each displayed a 5.8 cm/sec Doppler bias. As a result, GTDS batch-least squares solutions frequently sigma-edited a substantial amount of valid Doppler tracking, reducing solution accuracy.

FDF tracking data analysts were later able to post-process the LRO tracking data to correct the majority of the biases. Comparison of various MCC-1 to LOI-E solutions using the corrected tracking data to the operational OD indicates that definitive orbit knowledge during this portion of the translunar orbit was approximately 700 meters RSS position and 5 mm/sec RSS velocity, so the 63- and 72-hour LOI planning deliveries were well-determined solutions, essentially at the limit of definitive error.

C. Lunar Phase (S-Band).

Operational batch-estimated orbit determination for LRO is performed daily using a 60-hour tracking data arc starting at 00:00 UTC of the second prior day and ending at 1200 UTC of the run day. The OD solve-for epoch is anchored at 00:00 UTC of the run day. The full 150x150 series of the LP150Q gravity model is used along with the time-dependent lunar tide perturbation. The DE421 ephemeris is used for perturbing bodies and lunar librations. Earth orientation parameters and UT1-UTC timing coefficients are updated daily. The spacecraft area is modeled as a simple ballistic sphere. Solutions model solar radiation pressure, but do not estimate a coefficient of solar radiation pressure. Lunar radiation pressure is not modeled. Doppler observations are used in the solution,

Solutions estimate multiple Doppler biases for each station across the tracking data arc. White Sands (WS1) and DSN tracking typically exhibits a Doppler bias close to zero, but USN tracking commonly has a Doppler bias of approximately -1 cm/sec. Some of the detailed force modeling upgrades described in previous sections are not employed for daily OD as most are necessary only for the high-accuracy laser data OD processing, and require inputs (such as definitive spacecraft attitude data) which are not available on a timely enough basis for the daily OD.

Table 5. LRO Mission Orbit OD Modeling

Parameter	Value
Lunar Gravity	150x150, LP150Q
Planetary Ephemeris	DE421
Integration Step Size	5 sec
Non-central Bodies	Earth, Sun, Jupiter
Solar Radiation Pressure (SRP)	Applied, not estimated, Cr = 1.0
Spacecraft Model for SRP	Spherical, 14 m^2 area
Lunar Tide Modeling	K2 = 0.0248, K3 = 0. Phase Shift = 0 degrees
Solar Irradiance	1358 W/m^2 at 1 AU
Tracking Data Arc	60 hours
Data Types Included	Doppler
Average Number of Observations Used	Approximately 1680

In accordance with standard FDF practices, definitive ephemeris overlap compares are used to assess performance against definitive accuracy requirements. The definitive portion of an ephemeris is defined as that span which is covered by the tracking data in the solution used to generate the ephemeris. A definitive overlap compare measures the difference between consecutive OD ephemeris over a common overlapping definitive span. Predictive ephemeris accuracy is assessed by comparing the predictive portion of an ephemeris (that span of ephemeris data outside the definitive arc) against a subsequent definitive ephemeris span. Predicted comparisons results are routinely collected and trended to measure the on-going performance of each prediction created for LRO.

LRO entered its mission orbit in late September 2009, following completion of the MOI burns. During its nominal science mission phase, LRO orbits the Moon in a polar orbit, with an average periselene height of 41 km, an average aposelene height of 60 km, and a period of about 1.9 hours. The following tables show results obtained over the time span September 27, 2009 through February 4, 2010 from operational LRO OD using only S-band tracking data. Predictions crossing delta-v events (momentum unloads or maneuvers) have been removed from these statistics.

Definitive RMS consistencies achieved during the on-orbit mission phase are shown in the histogram below in Figure 6 for 116 cases. The on-orbit average RMS compare from consecutive solutions is 35 meters with a standard deviation of 28 meters, well within the 500-meter requirement.

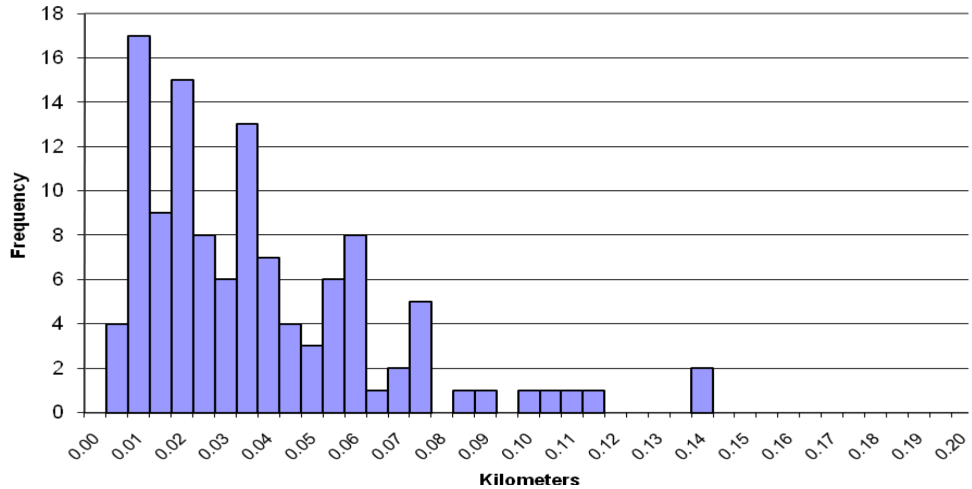

Figure 6. Definitive overlap RMS delta-R

Figure 7 below displays the radial component of the definitive overlap RMS differences between two consecutive solutions. Currently, with the force modeling in place the average difference is 1.9 meters with a 1.5 meter standard deviation. This is much below the stated requirement of 18 meters and is a large improvement over the LP-era results.

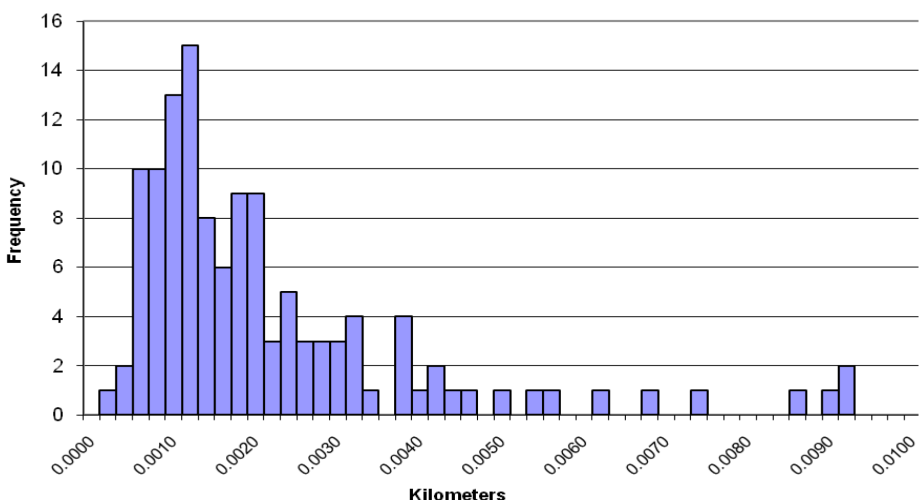

Figure 7. Definitive overlap RMS radial component.

Figures 8-9 below display maximum comparison differences between predictions measured at 36 hours and 84 hours respectively against the relevant new definitive solutions. This permits an assessment of the previous predictions accuracy. The 36-hour predictions performed to 55 meters with a 42-meter standard deviation during non-thrust disturbed periods for 116 cases. At 84 hours, the maximum position consistency is 127 meters with a 66 meter standard-deviation for 99 cases, well within the specific accuracy of 800-meters.

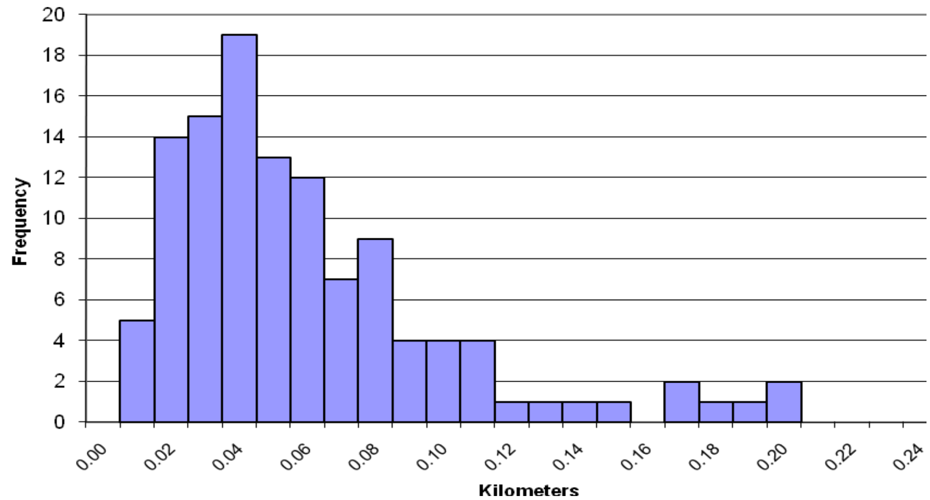

Figure 8. 36-hour Prediction accuracy.

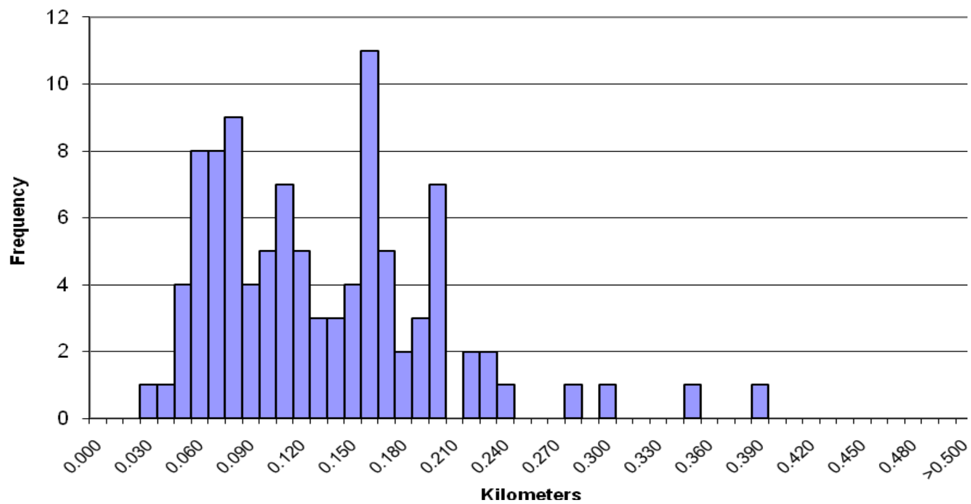

Figure 9. 84-hour prediction accuracy

V. Conclusions

The many navigational enhancements made for the LRO mission required upgrading of tracking assets as well as the ground system in the FDF. The FDF ground system updates included numerous force models changes, a new measurement model type in GTDS, two new data preprocessor systems for the new laser one-way forward model, a new methodology to create laser predict data. Collectively, these upgrades have been successfully implemented and have resulted in achievement of the LRO accuracy goals. Further, the force modeling improvements for daily navigation almost achieve the high precision post mission processing goals, which are 50 meter horizontal knowledge with a 1-meter radial knowledge. Current operational orbit determination for LRO using S-band tracking only achieves definitive apposition knowledge of on average 35 meters, with a 28-meter standard deviation. The current definitive radial accuracy is measured as 1.9 meters with a 1.5 meter standard deviation.

Current prediction performance is also well within the mission guidelines. The average 84-hour prediction has an accuracy of approximately 127 meters mean error with a standard deviation of 66 meters during non-thrust disturbed time periods. The actual performance requirement is 800-meters so the performance is quite good.

At a later date, the FDF will collect the laser CRD measurements, and use the enhancements prepared for improving the solar radiation pressure perturbations, principally the N-plate spacecraft area model and the lunar albedo model along with definitive attitude data to recompute the LRO orbit and also utilize the updated lunar gravity model based on LOLA measurement processing. Other measurement model upgrades will also be employed.

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