Orbit Determination for the Lunar Reconnaissance Orbiter Using an Extended Kalman Filter

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ABSTRACT

The Goddard Space Flight Center (GSFC) Flight Dynamics Facility (FDF) has performed orbit determination (OD) and related mission support for the Lunar Reconnaissance Orbiter (LRO) since LRO launched in June 2009. The LRO mission achieved an initial elliptical commissioning orbit after lunar orbit insertion. A series of descent maneuvers were performed to navigate LRO into a 50-km circular orbit around the Moon, where it remained until December 2011. In December 2011, LRO was returned to the elliptical commissioning orbit.

Since LRO launch, the FDF has employed the Goddard Trajectory Determination System (GTDS) for operational LRO OD. GTDS is a batch least-squares (BLS) estimator, employing high-order gravity modeling and a spherical spacecraft model for solar radiation pressure (SRP) as the primary forces for routine OD. Orbit determination definitive and predictive accuracy requirements for LRO were easily met using GTDS during the 50-km circular orbit mission phase. However, predictive accuracy has been observed to be poorer in the elliptical commissioning orbit, particularly during high beta-angle periods. Previous work has shown that use of a more detailed spacecraft area model, with definitive attitude modeling for the spacecraft and solar array, can greatly improve prediction accuracy in the commissioning orbit. However, use of the box and wing attitude-dependent area model implemented in GTDS is not currently practical for routine OD.

This paper examines the use of a commercially-available Extended Kalman Filter (EKF), the Orbit Determination Tool Kit (OTDK), for LRO OD. An EKF has a few natural advantages for LRO OD. For example, an EKF delivers faster OD processing than a BLS estimator, since an EKF only iterates on the residuals once rather than multiple times as is the case for a BLS estimator. In addition, the filter can provide a covariance estimate that is time-dependent and potentially more realistic than that achievable by GTDS. Furthermore, the propagation of the filter state and covariance from periods of favorable orbit geometry to poor geometry provides a natural means of ameliorating the effects of poor observability.

For the EKF to perform in an optimal manner, errors in the dynamical model must be properly accounted for through the addition of process noise. Whenever possible, the required process noise should be driven by characterizing uncertainty in the physical models used in the propagation of the spacecraft trajectory. When such “physically connected” process noise is used, the filter becomes more

robust to variations in orbital conditions, provides a realistic measure of orbit uncertainty and requires less operator intervention during operation. In the case of LRO, the main sources of dynamical model uncertainty come from the lunar gravity model and SRP. While the uncertainty in lunar gravity has been greatly reduced with the introduction of the Gravity Recovery and Interior Laboratory (GRAIL) derived gravity solutions, it is still important to model the remaining uncertainty in the gravitational acceleration to achieve optimal estimation performance. Accordingly, a process noise model based on the GRAIL gravity solution has been developed. The gravity process noise is generated based on the concept of averaging acceleration errors over a sphere where the radius of the sphere coincides with the location of the spacecraft. The analytical model implemented in the estimation software is driven by a set of precomputed inputs which are generated from the formal error covariance associated with the gravity field solution. The generation of the gravity process noise model inputs followed the same general procedure which has been used to generate gravity process noise models for numerous Earth gravity models, but required minor updates in the implementation to account for a much higher degree and order gravitational field. The resulting gravity process noise model was validated through trajectory simulations and the processing of operational tracking data. Uncertainty in the acceleration due to solar radiation pressure was addressed in two ways: by using a Gauss-Markov stochastic sequence to allow for variations in the magnitude of the acceleration along the sun line; and by implementing a more detailed physical model of the spacecraft.

It is natural to expect that an EKF will yield improved definitive accuracy over a BLS estimator, but this study also seeks to improve prediction accuracy by implementing a more capable box and wing spacecraft area model than currently available in GTDS. The box and wing SRP model applied is a multi-plate model in which the user specifies for each plate the area, specular and diffuse reflectivity, and normal vector in the body or sun frame. It then computes the reflectance vector and its partial derivatives and returns these to ODTK. Additionally, it can add state parameters, such as independent coefficient of reflectivity (Cr) values for the body and solar panel, into the filter state space for estimation. The SRP model computes the necessary partials in the body frame, allowing the SRP model to automatically use user-supplied attitude information. Since the attitude and solar panel motion is available as historical information and is somewhat predictable as a function of orbit geometry and solar beta angle, both potential definitive and predictive accuracy improvements are investigated.

The process of tuning the filter for LRO support is described, including examination of the relative importance of available observation types (Doppler and range), and methods of dealing with coarsely modeled momentum unloads. Definitive and predictive accuracy of the ODTK EKF solutions are assessed versus mission requirements and compared to the results obtained operationally using the BLS method in GTDS. The ODTK results are also compared to high-precision definitive orbits computed by the LRO science team. Lastly, the viability of using the EKF tool for operational LRO OD support in the future is assessed.