**GNSS For Lunar Missions**

# Introduction

GNSS provides a platform that can and has been used to provide continuous on board orbit determination, attitude determination, and positioning for spacecraft in low Earth orbit, and has been used above the GPS constellation [3]. This provides a layer of autonomy for spacecraft, and reduces cost that would be associated with ground tracking of the spacecraft. This is appealing to a lunar mission which need the improved accuracy in position and velocity estimates, while reducing mission costs. Lunar missions bring about many new challenges for GNSS positioning, including weak signals and poor satellite geometry [3,4,5,]. GNSS receivers capable of acquiring these weak signals are being developed, and solutions using new navigation constellations near the Moon, or adaptive filters to deal with the poor geometry [1], have been proposed.

# Lunar Mission Phases

Lunar exploration missions can be split into parts, or mission phases. These phases are split based off of their characteristics such as dynamics, distance, and mission requirements. Each phase has unique challenges associated with it. These phases were identified for ESA Moon-GNSS project, for both the European Student Moon Orbiter (ESMO), and the ESA Lunar Lander. ESMO was a proposed small satellite that would use a low thrust propulsion to take student payloads to lunar orbit. The lunar lander mission is a proposed to demonstrate precise autonomous planetary landing capabilities. Manzano [4] breaks the mission down into 8 phases. For this paper, the phases will be grouped under lunar transfer orbit, and lunar altitude, which includes LLO and surface operations.

## Lunar Transfer Orbit (LTO)

Lunar transfer orbit is the first phase for every lunar mission. It is the trajectory from LEO to the Moon’s sphere of influence. There are a few different Lunar transfer orbits, some of which are direct transfers, continuous spiral [3], and phasing loops. LTO can be further split into two parts: GTO like and outside the GPS constellation [3]. GTO or geostationary transfer orbit like, is the portion of LTO from LEO to geostationary orbit (GEO) altitudes. GNSS has been used extensively in this region, as much of the region is within the GPS constellation. Multiple studies have shown the feasibility of using GNSS above the constellation, and it has been used on a few spacecraft such as the Equatior-S mission, and the AMSAT Oscar-40 spacecraft [3,10]. Once outside the GPS constellation signals to noise ratios get lower, and geometry gets worse, increasing GDOP. As distance from the GPS constellation increases, occultation from the Earth increases, and the spacecraft must rely on the second and third lobes from the GPS Satellites. According to Carpenter[2], during LTO there are typically 2 or more GPS satellites in view out to about 18 Earth radii, after which it is rarely more than 2, and never more than 3 satellites. These effects and the challenges they bring are discussed further later on.

## Lunar Altitude

Lunar altitude includes all orbits inside the Moon’s sphere of influence, the descent/landing and surface operations on the Moon, as well as the Earth-Moon Lagrange points. Distance aside, use of GNSS at Lunar altitude can face interference from Lunar occultation [4].

# Challenges of GNSS for Lunar Missions

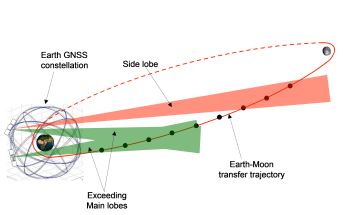


Figure 1:Visibility of lobes out of Earth Umbra [4]

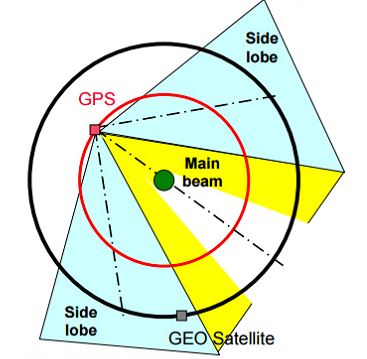


Figure 2: GPS signal lobes out to GEO, with Earth occultation [10]

For GNSS to be useable during a Lunar mission, poor satellite geometry, occultation from the Earth and Moon, and weak signal strength must be overcome. Figures 1 and 2 above, show examples of how signals spread from the GPS satellites out past the constellation. The Earth blocks a large portion of the main lobe, requiring use of the weaker side(secondary) lobes of the GPS signal when on a LTO. Palmerini [5] shows the consequence of this poor geometry in figure 3, that plots the geometric dilution of presicion (GDOP) across the distance from Earth’s surface to lunar altitude. The increase in GDOP amplifies the user ranging error. Capuano [1], saw a similar trend in GDOP, but with the inclusion of large spikes throughout. Capuano states that this may be attributed to the fact that the simulator used had a limited the number of channels supported to 12, selecting only the strongest signals, without considering the satellite geometry. It may have also been from signals being discarded by the positioning algorithm used in Capuano, which discards the signal when it crosses the ionosphere [1].

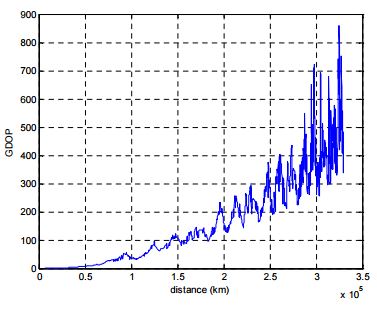


Figure 3:GDOP from Earth to Lunar altitude [5]

In a signal availability study done by Carpenter [2], the change in signal strength and satellite availability over a 3.5-day transfer to Lunar orbit, is observed for receivers with 3 different sensitivities using only L1 C/A code. The three sensitivities chosen are 25 dB-Hz (Navigator [6, 7]), 18 dB-Hz (just beyond state of the art to decode), and 11 dB-Hz (just beyond state of the art to acquire). The baseline case is the 25dBHz receiver, which has an approximate minimum receiver power of -174 dBW, with a 10 dB antenna. Carpenter plots the number of available GPS satellites to each of these receivers across LTO, shown in figure 4. It is clearly evident that increasing the sensitivity of the receiver significantly increases the number of available satellites, where with the 25 dB-Hz receiver, typically no more than one satellite is available past 20 earth radii, the 11 dB-Hz receiver has 2 available out to lunar altitude [2]. Figures 5 and 6 offer a comparison of the signal to noise ratios and ambient signal power for both the 25 db-Hz receiver and the 18 dB-Hz receiver. Figure 5 shows the power throughout the entire LTO, while figure 6 focus on the signal near the Earth-Moon L1 (EML1) point. As demonstrated in the figures, the signals from the side lobes are shown to be weaker, and only available to the 25 db-Hz receiver out to about 20 Earth radii, while for the 18 db-Hz receiver the side lobe signals are visible near EML1. The presence of these side lobe signals reduces the duration of outages that occur near EML1 [2]. Carpenter does not plot the signal power for the 11 dB-Hz receiver, as it is evident from figure 4 that it provides near continuous GPS coverage, but it is believed to be optimistic, as actual side lobe signal power may deviate from the modeled power at 60 degrees from GPS satellite nadir [2].

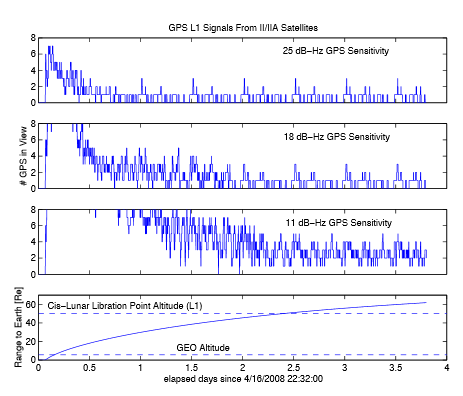


Figure 4: Satellites in view for different receiver sensitivities during LTO [2]

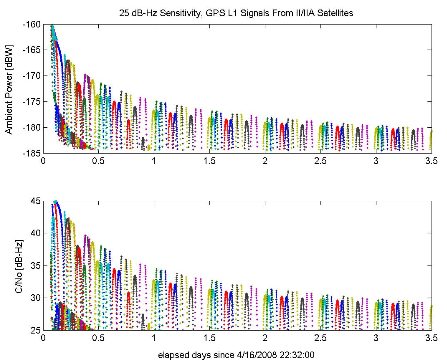


Figure 5: Signal power and signal-to-noise ratio for a 25 dB-Hz receiver on LTO [2]

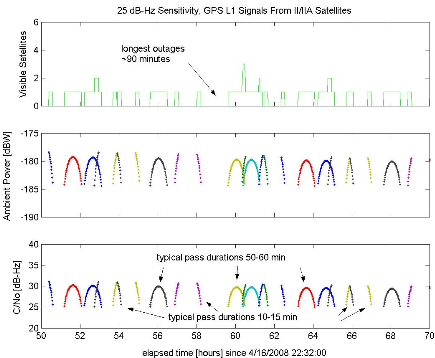
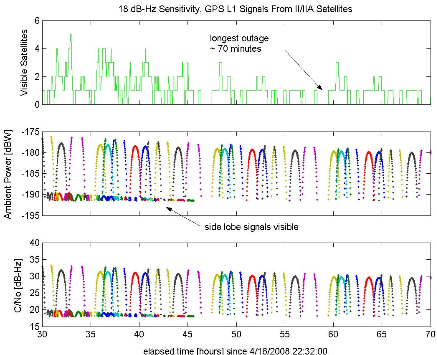
 

Figure 6: Signal power and signal-to-noise ratio for a 25 and 18 dB-Hz receiver near EML1 [2]

# Receivers for Lunar Missions

Manzano-Jurado [4] lays out requirments for Moon-GNSS receiver.

1. Should be able to reach sensitivities down to 15 dB-Hz or lower.
2. Have a high quality shielded front end to prevent interference from other spacecraft components.
3. Should have access to a high stability local oscillator.
4. Should have large data logging capabilities.

Manzano-Jurado [4] did a review of receivers (both developed and in development), capable of operating above the GPS constellation, and found that all the receivers reach down to sensitivities between 20 and 25 dB-Hz [4, 6, 7, 17], not low enough to meet the requirements [4]. As an option to acquire weak signals, Manzano-Jurado seeks to develop a snapshot architecture, similar to those used for indoor and urban environment navigation, for a Moon-GNSS receiver. This architecture provides robustness against signal attenuation and uncertain receiver dynamics, as well as allows for long coherent and non-coherent integration intervals [4]. Using assistance information and INS with a snapshot architecture reduces the time-frequency search range. A snapshot architecture also lends itself to use as a software defined receiver with hardware for parallel processing. Manzano-Jurado does point that this type of receiver is similar to the development of the Navigator receiver developed at NASA’s Goddard Space Flight Center. Palmerini [5], suggests that taking advantage of the snapshot receiver, and a knowledge of the spacecraft dynamics, the tracking of the signal can be left aside. This would require external aid to acquire the navigation message. The core portion of the navigation message can be provided externally from the GPS signal, such as from a ground station or a relay satellite [5].

Navigator is a space-borne receiver designed to operate effectively from LEO to outside the GPS constellation. It is currently in use on the Magnetospheric Multiscale (MMS) mission, and is the highest operating GPS receiver to date, able to position the MMS satellites to within 65 meters when compared to the orbit determination solutions from the Flight Dynamics Facility (FDF) at GSFC [18, 19]. The Navigator has fast acquisition capabilities providing a fast time to first fix (TTFF) without needing a priori receiver state or almanac information using Fast Fourier Transform (FFT). Navigator utilizes GSFC’s GPS-Enhanced Onboard Navigation System (GEONS), which provides estimates of the receiver state even when GPS is not available using high fidelity force and clock models [6]. As stated earlier, Navigator has a threshold of 22 to 25 dB-Hz for tracking.

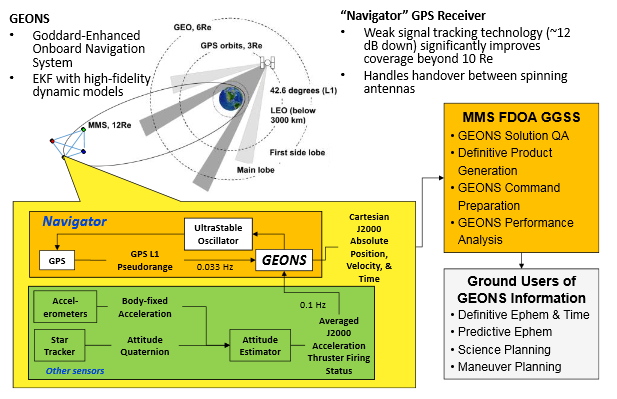


Figure 7: Overview of MMS navigation operations [19]

# Moon GNSS

A proposed solution to the poor geometry and low signal strength from GPS satellites at lunar altitude is to use a “GPS-like” system near the Moon [2, 4]. Carpenter [2] examines the cost of three different constellations: one with 6 satellites in circular orbits, another with 6 in elliptical orbits, and one with 4 satellites in large lissajous orbits at EML2. According to Carpenter, the orbiters at EML2 provide the best capability with minimal investment. Figure 8 contains the position and velocity errors in a local coordinate from of the combined GPS and EML2 orbiters indicating accuracies better than 1 km for position and 5 cm/sec for velocity [2]. Manzano-Jurado also investigates the use of a “GPS-like” constellation at the moon (MGNSS), but does not specify trajectories, but documents the results of its inclusion, an example of which can be seen in figures 9 and 10[4].

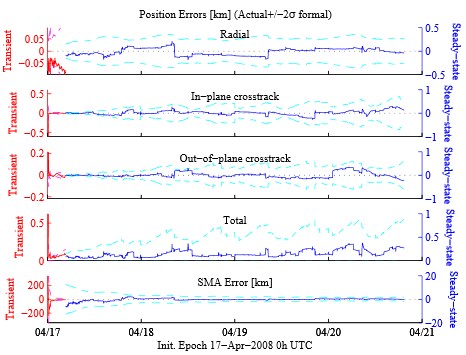
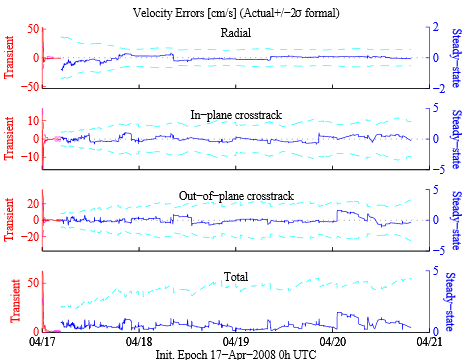


Figure 8: Position and velocity errors in a local coordinate from for LTO, inlcuding ranging satellites at EML2 [2]

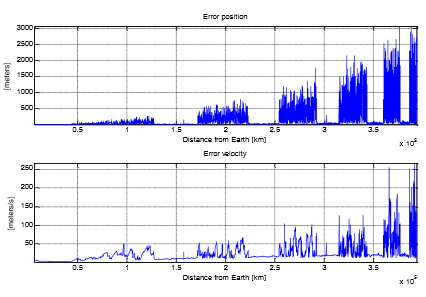


Figure 9: Position and velocity errors in ECI, using only GNSS, during LTO [4]

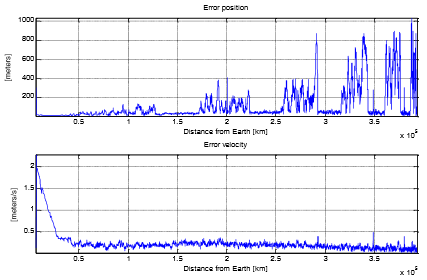


Figure 10: Position and velocity errors in ECI, using GNSS, MGNSS, and standard navigation sensors, during LTO [4]

# Navigation Filters

An effective technique for dealing with weak signals and poor geometry is to compensate with other sensor data or modeling of the dynamics of the spacecraft. As discussed earlier GEONS uses these models, as well as sensor data, in an extended Kalman filter (EKF) to provide position estimation when GPS becomes unavailable [6, 19]. There are three ways to integrate sensor data with receiver observations: loosely, tightly, and deeply integrated. Capuano, discusses the development of an adaptive filter that fuses GNSS observations with an orbital forces model on an LTO. The filter is adaptive in the sense that the measurement covariance matrix is tuned adaptively as a function of the GNSS measurement error [1]. The EKF used by Capuano fuses the prediction of the dynamics with the GNSS measurements to provide the navigation solution. GDOP adversely effects this solution, so Capuano has set a threshold, that if it crosses, to only use the dynamic model and ignore the GNSS measurements [1]. It is also possible to estimate the expected Doppler shift and the Doppler rate by using equations 1 and 2 [1]. Where *fT*is the transmitted frequency, *c* is the speed of light, and *ṙ* is the estimated range rate.

Equation : Expected Doppler shift as a function of estimated range rate [1]

Equation : Expected Doppler rate [1]

Manzano-Jurado looks at the trade-offs between complexity and performance and states that tightly coupled is preferred, as it allows the use of classical navigation filtering techniques while using every single GNSS measurement [4].

# Conclusions

The main advantage of using GNSS for a Lunar mission is increased autonomy of the spacecraft. This means that there would be less of a need for ground tracking and operations, potentially down to once per day [4], thus reducing cost. The benefits of this weak signal GNSS, is primarily seen during LTO, particularly closer to Earth. This is still important as all spacecraft have to perform some sort of correction burn during LTO, and an accurate position and velocity solution are essential to calculating those.

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