GNSS SIGNAL UTILIZATION AND AUGMENTATION FOR A LUNAR MISSION NAVIGATION

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Abstract

Long duration missions such as a lunar mission typically involve multiple orbit raising and transfer maneuvers where orbit determination accuracy is a critical factor. Presently GNSS aiding is being effectively utilized to achieve such high accuracy levels in LEO missions. However, at higher orbits such as a trans lunar orbit, reduced signal strength and geometry constraints pose unique challenges. This paper discusses the challenges involved and techniques that can be adopted for successful GNSS aided navigation in such missions. India's Chandrayaan-1 mission profile has been taken as a case study and possible performance improvement by onboard GNSS aiding is presented. Augmentation of future GNSS constellations by satellite antenna beam steering to provide sufficient visibility to predetermined lunar trajectories is also proposed.

Keywords: GPS navigation, GNSS augmentation, Lunar Transfer Orbit, Chandrayaan-1, Beam steering

1 Introduction

GNSS satellite constellations typically consist of a number of satellites in Medium Earth Orbits (MEO), with earth nadir directed antennae main lobes, to provide a continuous visibility of more than four satellites enabling real time kinematic positioning to a near-earth user. Global Positioning System (GPS) signal aided on-board navigation is now a proven and cost effective means of achieving high levels of orbit determination accuracy for Low Earth Orbit (LEO) missions[1]. However at higher orbits, only a part of the GNSS main lobe and side lobe signals beyond the earth shadow region are available for positioning (Fig. 1). Hence two major challenges arise: (i) signal strength reduction and consequently (ii) low satellite visibility.

A quantitative assessment of signal strength by link budget analysis for various orbital altitudes is presented in the paper. Typical GPS signal visibility with a high sensitivity receiver for Chandrayaan-1 mission profile is also studied. The results show that as the orbital distances increase, the task of GNSS signal utilization becomes tougher and the minimum number of satellites for real time kinematic positioning is not met majority of the time.

There are techniques to deal with the above challenges using which good orbit determination accuracy has been reported even in Geosynchronous Transfer Orbit (GTO)[2] and Highly Elliptical Orbit (HEO)[3] missions. A discussion on these techniques and their applicability to higher orbits with near lunar apogee distances is considered in this paper.

Future space transportation systems will require reliable onboard navigation, with minimal ground based operations, at various high altitude orbits. A novel method of augmenting future GNSS constellations by satellite antenna beam steering to provide sufficient visibility to predetermined trajectories is also proposed in this paper.

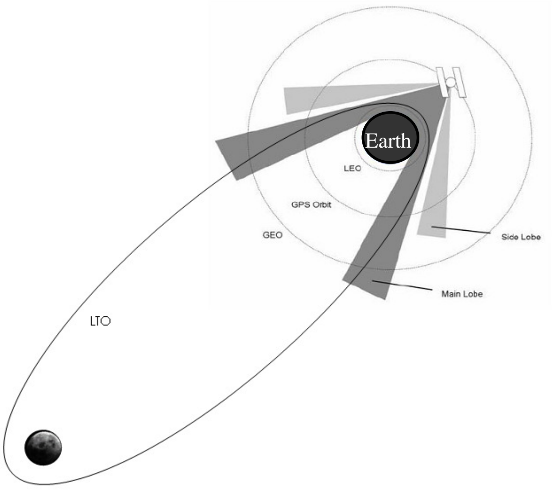

Figure 1: GNSS signal availability in various orbits

2 GPS visibility : Geometry and link budget

Link budget and GPS Space Vehicle (SV) to User spacecraft geometry are the primary factors affecting visibility. The link budget presented here considers the effect of transmitting satellite antenna gain, free space path loss, and receiving antenna gain on the radiated power. Losses due to other effects such as noise figure of components in the RF chain etc are clubbed together as miscellaneous losses. The transmitting antenna gain pattern of Block IIR satellites[6] (Fig. 2) is used for all calculations. On the receiving end, a high gain antenna of 10dB, and a high sensitivity weak signal GPS receiver that can acquire and track signals from 15dBHz is assumed. Considering the capabilities of present day weak signal indoor GPS receivers, this is an assumption presently feasible, or at least in the near future.

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Taking earth's atmospheric altitude as 1000km, to avoid ionospheric errors in measurements, the best transmitting gain of 11dB (considering main lobe alone) is possible when the signal skirts the atmosphere, subtending a half angle of 16.1^0 w.r.t. nadir[7], at the satellite. The geometry for the situation is shown in Fig. 3. Link budget calculations for this case, shown in Tab. 1, under all the above assumptions, allow a maximum path length of 3,55,000 km which correspond to an altitude of 3,23,675 km from the earth's surface.

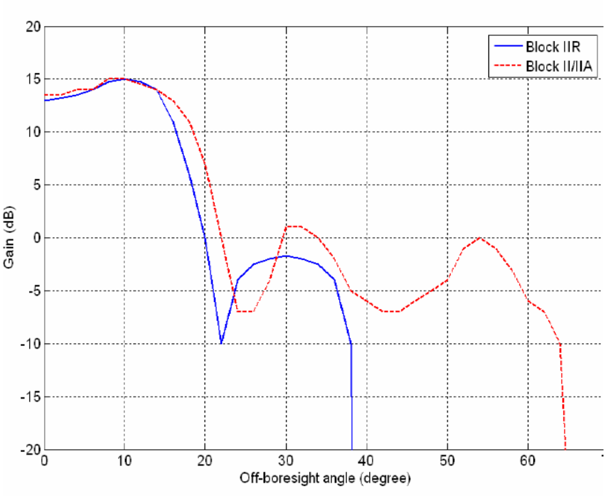

Figure 2: Transmitting antenna Gain pattern[6]

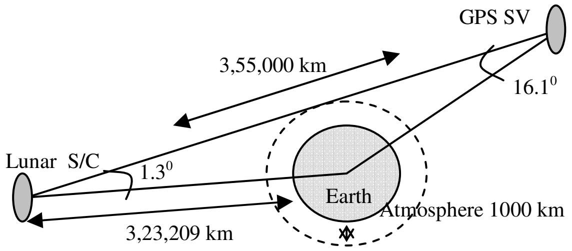

Figure 3: Max user altitude: Best SV gain case

From the transmitting antenna gain pattern, it can be seen that beyond 19^0 half angle from nadir, the gain drops rapidly (considering main lobe alone). For all practical purposes, the worst usable transmitting gain can be taken as 1.4dB at 19^0 half angle. The geometry for the situation is shown in Fig. 4 and the relevant calculations are presented in Tab. 1.

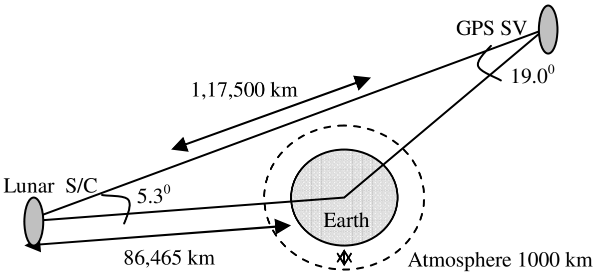

Figure 4: User altitude: Worst SV gain case

Table1: Link budget calculations

Parameter	Units	Transmit antenna gain	
		Best	Worst
Frequency	MHz	1575.42	1575.42
Transmit Power	dBW	14.31	14.31
Transmitter Loss	dB	-1.50	-1.50
Antenna Gain	dB	11.00	1.40
Satellite EIRP	dBW	23.81	14.21
Receive G/T	dB/k	-19.00 (10dB Antenna)	-19.00 (10dB Antenna)
Range	Km	355000.00	117500.00
Path Loss	dB	207.39	197.79
Miscellaneous Loss	dB	1.00	1.00
Boltzman Constant	dBW/k	-228.60	-228.60
Received Power	dBW	-184.58	-184.57
Received PFD	dBW/m^2	-158.18	-158.18
Resultant C/N_o	dB	25.02	25.03

3 GPS visibility : Chandrayaan-1 Mission

The mission profile of the first Indian lunar mission, Chandrayaan-01 is chosen as a sample for this study. The Chandrayaan-1 space craft was launched atop a PSLV rocket from Sriharikota launch complex at 6:22:11 on 22nd October 2008. The space craft was injected into an initial elliptical orbit of 256.1 km X 22863.2 km at an inclination of 17.88^0. Through a sequence of earth bound maneuvers (earth burns), the orbit was raised to near lunar apogee, and a lunar orbit insertion maneuver followed by a series of lunar burns took the space craft to its final orbit around the moon. A simulated trajectory of the mission profile is shown in Fig. 5.

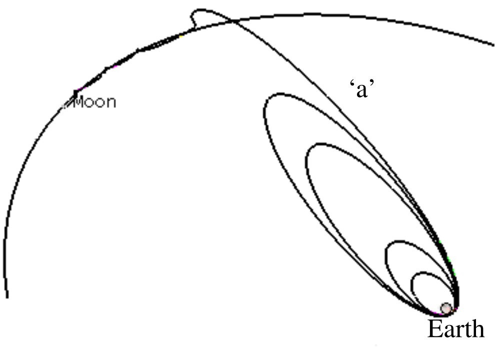

Figure 5: Chandrayaan-1 simulated trajectory

3.1 Line of sight visibility

The portion of the highly elliptical orbit (marked 'a') from the final earth burn point to the lunar orbit insertion point is considered here for a geometrical line of sight (LOS) visibility simulation of an imaginary receiver placed in the space craft. The 'Astrogator' propagator module of the STK® simulation tool has been used for this study. The results are presented in Fig. 6.

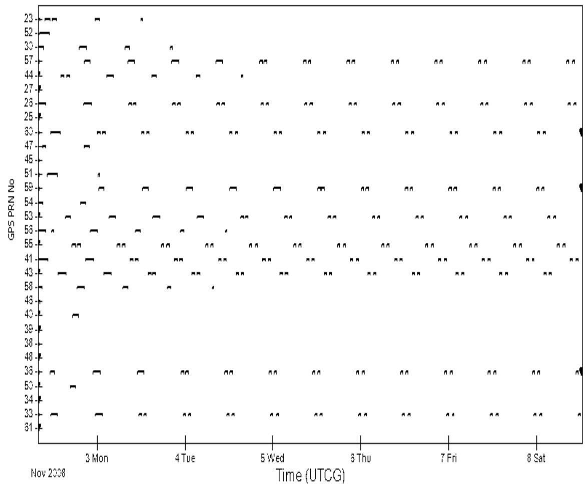

Figure 6: LOS visibility in Chandrayaan-1 orbit

In the Fig. 6, the X axis shows the time in days from 2nd November 2008 to 8th November 2008 when Chandrayaan-1 traversed the orbital section marked 'a' in Fig. 5. The Y axis shows the GPS satellite ID numbers. It can be seen that times when more than four satellites are simultaneously visible is very less and still decreases as the spacecraft altitude increases.

3.2 Visibility with link budget

When the link budget considerations are applied, the visibility further reduces from the theoretical line of sight maximum, and the results are shown in Fig. 7.

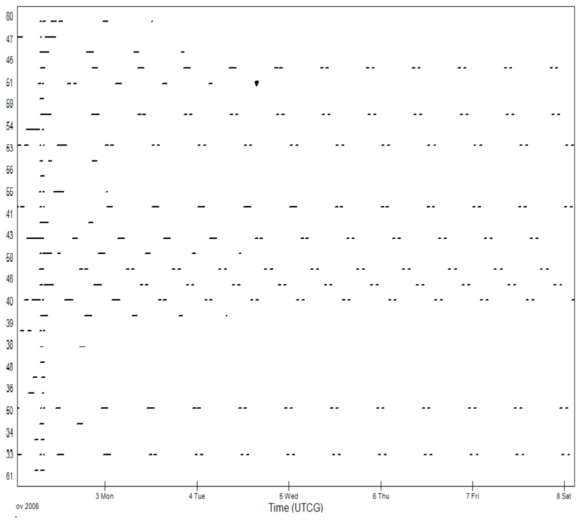

Figure 7: Visibility with link budget considerations

4 GPS Navigation scheme for higher orbits

The results of the visibility study in Chandrayaan-1 mission trajectory indicate that, even with a high sensitivity weak signal receiver and a high gain receiver antenna, the minimum number of satellites for real time kinematic positioning is not met majority of the time. The visibility situation is somewhat similar, but less pronounced in GTO, GEO cases. Orbital mechanics have traditionally been used to good advantage in such cases, since orbits can be accurately predicted and propagated for reasonably short durations. Several studies have reported successful real-time orbit determination using observation filters such as Extended Kalman Filter[7,8].

These methods require a model of the user spacecraft dynamics and knowledge of the process and measurement noise covariance[11]. The spacecraft motion dynamics may be represented by the following model[9]:

$$\ddot{\mathbf{r}} = -GM \frac{\mathbf{r}}{|\mathbf{r}|^3} + f(t, \mathbf{r}, \dot{\mathbf{r}}, \mathbf{r}_0, \dot{\mathbf{r}}_0, p_0, p_1, ...) \qquad (1)$$

where t-time, r-current vector of satellite position, r_0-initial conditions, GM-Earth gravitational constant, p_i-parameters of radiation pressure and atmosphere drag models[9]. The first term on the right hand side is the standard two body term and the second one describes perturbing accelerations due to effects such as earth gravity potential, lunar and solar gravitational attraction, radiation pressure, atmosphere drag, solid earth tides, ocean tides, and relativistic effects[9]. The model is valid for all types of earth satellites: LEO, GTO, GEO and HEO, albeit with differing complexities of the right hand side equations[9]. The process noise is generally considered to be associated with the GPS receiver clock quality and is modeled accordingly. The pseudo range and delta pseudo range from the GPS receiver usually comprise the measurement inputs to the Kalman update algorithm whose noise characteristics are pre-evaluated by independent receiver tests.

In the initial phases of a Chandrayaan-1, as the orbit is similar to a GTO or HEO, the sequential filtering approach can give onboard orbit determination with good accuracies, but as the orbit approaches near lunar apogee distances, the large outage times limit the applicability of these methods. The clear solution is to improve the GNSS satellite visibility through out the lunar space-craft trajectory. A means to achieve this, by GNSS augmentation, is proposed in the next section.

5 GNSS augmentation: a conceptual study

There has been a renewed interest in lunar exploration in the recent years, with many ongoing and proposed missions by a number of space fairing nations. This indicates that, the possibility of lunar missions becoming a frequent affair, in the near future, is very tangible. In such a situation the cost and time benefits offered by an autonomous navigation to moon, i.e. without relying on ground station tracking aids, must easily outweigh an investment in GNSS infrastructure augmentation. A novel method of augmenting future GNSS satellites, by providing an additional space looking beam, can phenomenally improve GNSS visibility to predetermined trajectories.

The concept is to provide a steerable space looking antenna to the GNSS satellite, in addition to the regular earth nadir pointing one. The idea is depicted in Fig. 8 where a satellite in GNSS orbit steers its space looking beam to provide constant access and visibility to targeted vehicle except the earth blocked outage times. It can be clearly seen that GNSS signal availability to the target vehicle is increased considerably.

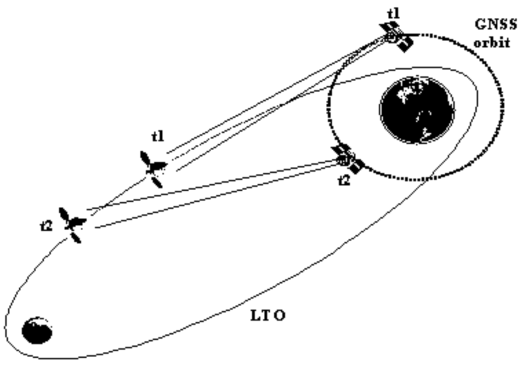

Figure 8: Improved LTO visibility by GNSS augmentation

In order to validate the concept, a simulation study was undertaken for two cases: (i) A fixed space looking antenna (ii) A steerable space looking antenna, in all the GPS satellites, that follows the target vehicle.

5.1 *Case (i) : Fixed space looking antenna*

An additional fixed space looking antenna, with a beam width of 30^0 was simulated for all the GPS satellites, on the face opposite to the earth nadir pointing face. The line of sight visibility for the portion of the Chandrayaan-1 trajectory 'a' (marked in Fig. 5) is shown in Fig. 9. It can be seen that there is a marked improvement in the visibility situation in comparison to Fig6. The * in figure indicates the additional beam.

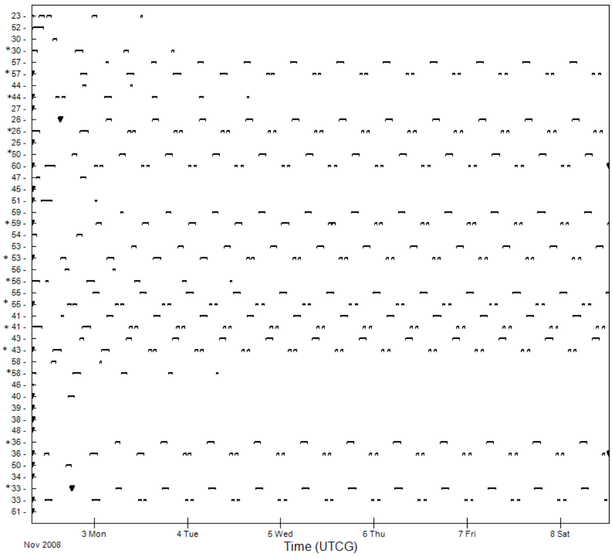

Figure 9: Improved visibility in Chandrayaan-1 orbit section with fixed space looking antenna in GPS satellites

5.2 *Case (ii) : Steerable space looking antenna*

The additional space looking antenna, in case (i), was simulated to be beam steerable to follow the target lunar spacecraft. The resulting line of sight visibility for the same portion of the Chandrayaan-1 trajectory is shown in Fig. 10. It indicates near 100% visibility of all GPS satellites that are not in the earth shadow. This is the theoretical maximum visibility with unconstrained beam steering.

In order that the simulation be realistic, a constraint was added to limit the steering angle within a cone of 60^0 from the line joining the lunar space craft and GPS satellites as shown in Fig. 11. The resulting line of sight visibility for the same portion of the Chandrayaan-1 trajectory is shown in Fig. 12. It can be seen that there is still a marked improvement in the visibility situation in comparison to Fig. 9, with each available GPS satellite being visible for more than 6 hours continuously. There are more than four satellites simultaneously visible most of the time allowing real time kinematic positioning. Outage times are minimal and sequential filtering methods can very well be applied at these times for accurate orbit determination.

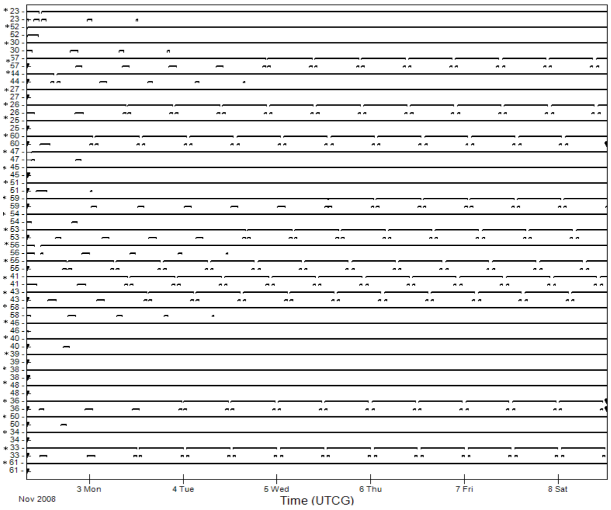

Figure 10: Theoretical maximum visibility with steerable space looking antenna in GPS satellites

6 Future work

The present work considered visibility from GPS satellites only. With multiple GNSS usage such as GLONASS and GALELIO, the visibility to LTO will be better even if all these systems have earth pointed antennae. IRNSS constellation with earth and space pointing beams is also a topic of future study. If the orbits of future GNSS satellites, equipped with additional space pointing beams, are designed optimally taking into consideration both the terrestrial user and the lunar probe trajectories, it must be possible to get a better GNSS visibility situation than what was demonstrated in this paper with GPS orbital constellation as a case study.

7 Conclusions

The paper discussed the challenges involved in GNSS signal utilization for a lunar mission navigation. Methods of dealing with them in the present scenario were outlined. A novel method of GNSS augmentation for better satellite visibility was proposed. The simulation results indicate a dramatic improvement over the current scenario.

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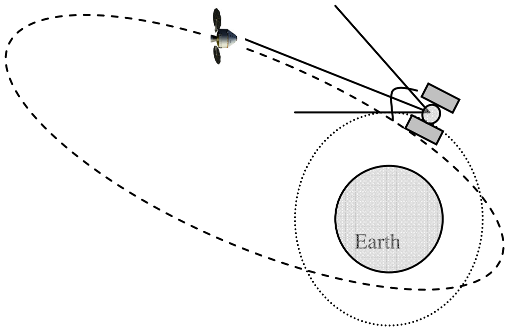

Figure 11: Antenna steering angle constraint

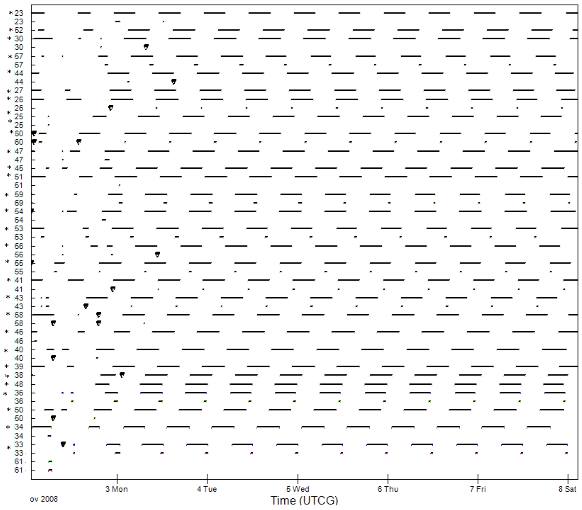

Figure 12: High visibility in Chandrayaan-1 orbit section with constrained steering of space looking antenna

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