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# THREE-DIMENSIONAL TRACKING OF A LUNAR SATELLITE WITH DIFFERENTIAL VERY-LONG-BASELINE-INTERFEROMETRY

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## ABSTRACT

Lunar gravimetry mission in the Japanese lunar exploration project SELENE (Selenological and Engineering Explorer) is characterized by inter-satellite tracking by means of a relay satellite in a high eccentric orbit, combined with differential Very-Long-Baseline-Interferometry (ΔVLBI) and conventional 2-way Doppler tracking. ΔVLBI provides information on the satellite position and velocity complementary to conventional range and range rate measurement, and allows us to measure lunar gravitational accelerations in all the three components. In this article, ΔVLBI and 2-way Doppler numerical simulation results are compared to those obtained from 2-way Doppler observations only, so that we can evaluate the contribution of ΔVLBI to the SELENE lunar gravimetry mission. 

## LUNAR GRAVIMETRY IN THE SELENE PROJECT

Deviation from spherical symmetry of the lunar gravity potential is described with coefficients of spherical harmonic functions, *e.g.*, modern lunar gravity models GLGM-2 (Lemoine *et al.*, 1997) and LP75G (Konopliv *et al.*, 1998) give coefficients complete to degree and order 70 and 75, respectively. Doppler shifts of the radio beacon signal from a lunar satellite reflect its line-of-sight velocity, and its temporal change provides information on the lunar gravity fields in that direction. The gravimetry mission in the SELENE project (Namiki *et al.*, 1999) to be launched in 2003, adopts such conventional 2-way Doppler measurements, but also includes several new features, namely, deployment of two satellites with different heights, relay of the Doppler signal to/from the low satellite via the high satellite, and three dimensional tracking of the satellites by ΔVLBI.

The satellite altitude needs to be as low as possible to enable sensitivity to a harmonic range as large as possible. The SELENE main orbiter takes a low circular orbit (100km x 100km); we can resolve gravity anomalies as small as 100km. However, it is equipped with instruments such as cameras and altimeters, which requires attitude control maneuvers as frequent as once per 18 hours. This makes it difficult to measure long wavelength gravity features with desired accuracy. In our project, the relay satellite keeps orbiting in a relatively high eccentric orbit (100km x 2400km) for more than a year without maneuvering, and offers a situation suitable for determining low order gravitational coefficients such as $J_2$ and $C_{22}$. Thus the two satellite strategy helps us determine low and high order gravity coefficients with relatively uniform accuracy. Direct measurement of the lunar farside gravity by 4-way Doppler tracking of the main orbiter via the relay satellite is another remarkable feature. Full selenographical coverage of the tracking data enables determination of the gravity coefficients that does not strongly depend on the assumed a-priori constraints (Matsumoto *et al.*, 1999), *e.g.* those based on the Kaula's (1966) rule of thumb. In this article we describe the last feature, introduction of ΔVLBI to the lunar gravimetry.

## ΔVLBI IN THE SELENE PROJECT

Accuracy of ordinary ground-based VLBI is limited by atmospheric refraction and its changes. Such effects are, however, effectively canceled by comparing the fringe phases of two sources close by in the sky. The differences between these delays therefore could be measured with resolutions one or two orders higher than the individual delays, or relative positions between the sources could be determined in extremely high accuracy (*e.g.* Asaki *et al.*, 1996). In the SELENE project, we will apply ΔVLBI for selenodesy using artificial radio sources on board the spacecraft (directions toward these radio sources are small enough for effective compensation of atmospheric scintillation) and nearby background quasars. The main ΔVLBI mission is to be started 1 year after the launch when the propulsion module of the orbiter is separated from the main body and land softly on the lunar surface. This landing module and the relay satellite are equipped with S- and X-band transmitters designed to transmit carrier waves in several different frequencies so that phase delays can be determined without ambiguities. The ΔVLBI data will be used to study lunar orbital motion, physical libration and lower order gravity coefficients (Hanada *et al.*, 1997).

In this article we emphasize another series of ΔVLBI observations to be performed during the first year after the launch between the signal from the relay satellite transmitter and the S-band data communication down link signal from the main orbiter (Figure 1). We can measure only delay rates (changing rates of the delays) in this period (*i.e.* we cannot solve the ambiguities), but simultaneous ΔVLBI and 2-way Doppler measurements constitute 3-dimensional velocity measurements of satellites, and benefit the gravimetry mission in several aspects. They include quick determination of the Keplerian elements of the main orbiter which has frequent attitude control maneuvers. It also means that we can measure lunar gravity-induced perturbations in directions to which 2-way Doppler measurements from the Earth are not sensitive.

## CONTRIBUTION OF ΔVLBI TO THE ORBIT DETERMINATION AND GRAVIMETRY

We use the software package GEODYNII (Pavlis *et al.*, 1997), for orbit generations and data simulations. ΔVLBI observations are assumed to be done along two Japanese domestic baselines, Mizusawa–Titijima and Titijima–Ishigaki (Figure 1 right). They are baselines of the VERA (VLBI Exploration of Radio Astrometry; Sasao *et al.*, 1996) network dedicated to ΔVLBI observations. Figure 2 shows root-mean-square (rms) differences of the epoch state vectors between the true orbit and the estimated orbits of the main orbiter as function of arc length. These orbits are estimated using tracking data of 2-way Doppler measurements only (solid symbols), and 2-way Doppler plus ΔVLBI delay rate measurements between the satellites (open symbols) under a known lunar gravity field. In the second case the relay satellite orbit is supposed to be known, a reasonable assumption considering its year-long arc length. Delay rate accuracy depends on several parameters, *e.g.* integration time, angular separation of radio sources in the sky and their zenith distances. Sasao *et al.* (1993), based on the model of temporal and spatial structure of the atmospheric water vapor by Treuhaft & Lanyi (1987), calculated

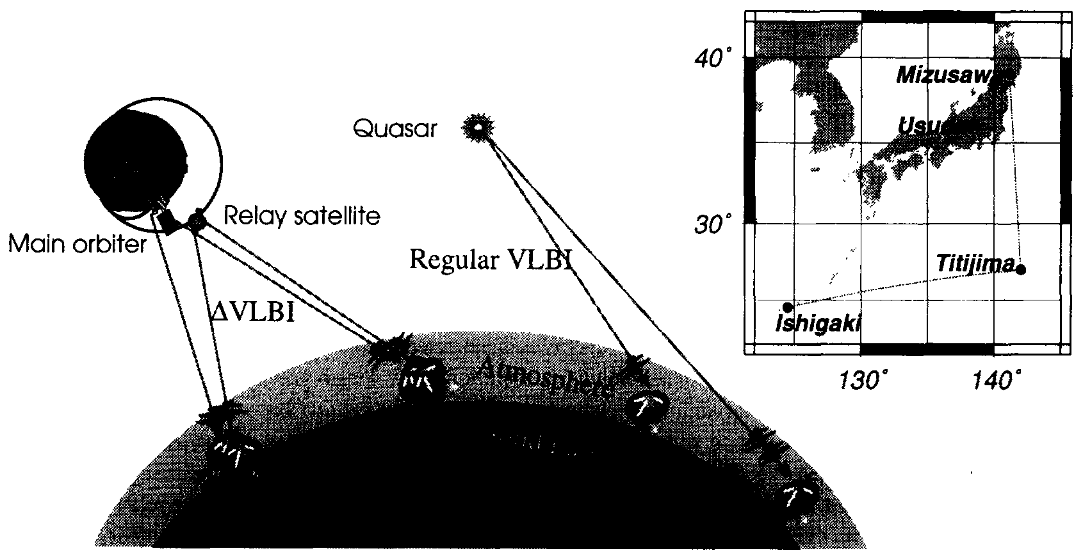


Fig. 1 Regular VLBI using natural radio sources such as Quasars and differential (Δ) VLBI using radio signals from two lunar satellites planned in the SELENE project. The inset shows the two baselines assumed for simulation studies.

Allan standard deviation of atmospheric scintillation as a function of these parameters. The between-satellites separation varies over 0°~0.9° and we assume 0.5° as the average. If the integration time is 30 seconds, and the elevations are ~60°, ΔVLBI delay rate accuracy would be around $10^{-14}$, i.e. 0.01 ps/s. For 2-way Doppler measurements, we presume an accuracy of 0.2 mm/sec, the same sampling interval (30 seconds), and one Japanese tracking station (Usuda). The ratios of amplitudes of signal variations due to the satellites' orbital motions to the observational errors are around $10^6$ to 1 both for the 2-way Doppler and the ΔVLBI data, that is, comparable amount of information on the orbits exist in these two data types. Figure 2 shows that degradation of the estimated orbit in along-track and cross-track components for short arcs in the first case (solid symbols; without VLBI) almost disappears in the second case (open symbols; with VLBI).

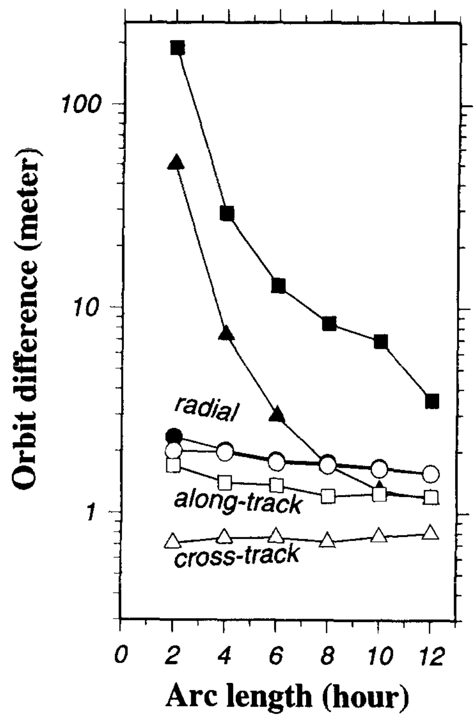


Fig. 2 Comparison of the rms differences of the epoch state vectors between the true and estimated orbits in three components. Solid symbols give values when only 2-way Doppler observations are performed. Open symbols indicate the case where ΔVLBI observations (delay rate only) by the two baselines (Figure1) are added.

Although lunar gravity fields accelerate satellites in every direction, 2-way Doppler measurements from the Earth are only sensitive to those in the Earth-Moon direction. Hence velocity measurements in a plane perpendicular to that direction by including ΔVLBI data, would not only increase the data quantity but also provide new information on the lunar gravity field. We compared the formal errors of the lunar gravity coefficients of degree and order up to 30 for two cases, namely (a) 2-way Doppler plus ΔVLBI and (b) 2-way Doppler only. Attitude control maneuvers are assumed to be performed once per day during the observation period as long as two weeks. Normal matrices generated by GEODYNII (parameters composed of lunar

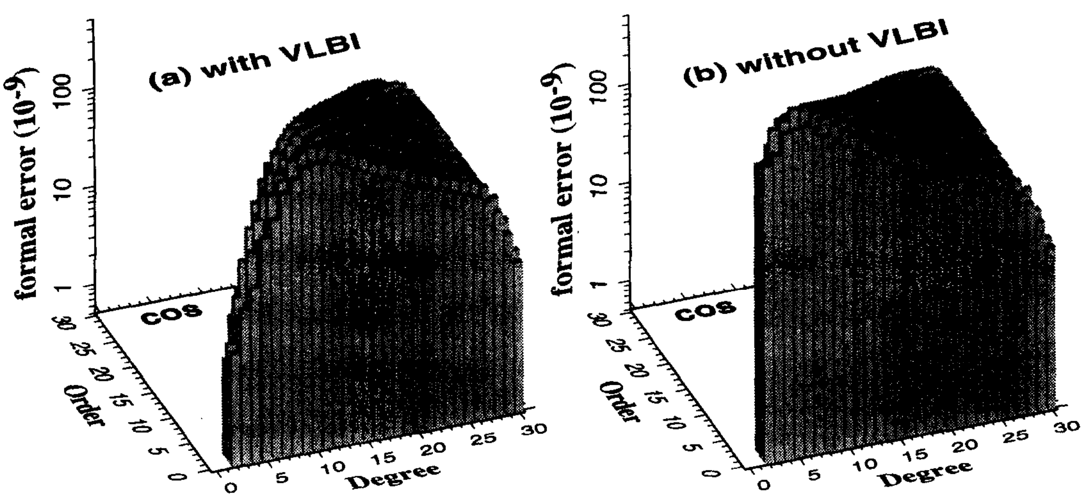


Fig. 3 Expected formal errors of the estimated lunar gravity coefficients (cosine terms with degree/order up to 30) for the cases (a) both ΔVLBI and 2-way Doppler data are used, and (b) only 2-way Doppler data are used.

gravity coefficients with degree/order up to 30, orbit initial values and solar radiation pressure coefficients for individual arcs) for 14 arcs as long as 1 day based on the same force models, were stacked and inverted with the program SOLVE (Ullman, 1994) to obtain the covariance matrix of global parameters for the two cases. The same measurement accuracy and sampling intervals as in Figure 2 are assumed. Results shown in Figure 3 suggest that improvements of formal errors by including ΔVLBI, especially for low degree and order coefficients, are more than expected from the increase of the data quantity. In fact, the formal errors of the coefficients $J_2$ and $C_{22}$ are improved by more than two orders of magnitude by introducing ΔVLBI. It would reflect not only the longer arc of the relay satellite, but also the addition of information on non-line-of-sight gravity fields and the improvements in orbit determination performance owing to ΔVLBI. On the other hand, formal errors of the coefficients with degree and order higher than 10 hardly decrease by ΔVLBI. This is due to the lack of the farside tracking data in this simulation study, and formal errors of high degree/order coefficients merely reflect a-priori constraints (Kaula type constraints are applied here) in such an ill-posed case. Theoretically estimated accuracy of ΔVLBI measurements used in this simulation study might be replaced by a more realistic value when we start to obtain real ΔVLBI data with VERA, whose construction is about to start in Japan. In any case the contribution of ΔVLBI would remain significant from the standpoint that it provides information complementary to the Earth-based 2-way Doppler measurements.

Lunar Prospector, an American lunar exploration satellite, is currently "globally" mapping lunar gravity fields (Konopliv *et al.*, 1998), but the data include information only on the Earth-Moon direction gravity field over the lunar nearside like those of past lunar satellites. Hence the SELENE gravimetry experiments are expected to yield the first measurements of lunar global (in the true sense) gravity field in every direction, and we expect that the lunar gravity model to be established using the SELENE data will bring about a considerable advance in lunar gravity studies. Such an advance will help us address selenophysical issues, such as the origin of the lunar dichotomy, lunar thermal history, lunar isostasy, and the lunar moment of inertia (*i.e.*, the existence of the metallic core).

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