NUMERICAL SIMULATIONS OF THE NETLANDER IONOSPHERE AND GEODESY EXPERIMENT (NEIGE): LANDING SITE POSITIONS DETERMINATION FROM DOPPLER TRACKING BETWEEN AN ORBITER AND LANDERS

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ABSTRACT

The objectives of a geodesy experiment performed on the basis of a network of landers, such as NEIGE (Netlander Ionosphere and Geodesy Experiment) are to measure variations of Mars' orientation and rotation in space with a precision of a few centimeters over annual and sub-annual periods. The lander positions are not well known upon landing, depending on the technical solution chosen for the entry-descent-landing phase, and thus need to be accurately determined to achieve the scientific objectives of a geodetic experiment. We performed numerical simulations of the NEIGE experiment to evaluate our ability to recover the lander positions from Doppler shifts measurements between an orbiter around Mars and those landers, with a precision of a few centimeters.

1. INTRODUCTION

Mars' deep interior (state, size, density of the core) and its atmosphere (CO_2 seasonal cycle) are not well known and are difficult to measure with traditional space geodesy experiments (like orbiter or lander tracking from the Earth). To improve this situation, a geodesy network science experiment such as NEIGE (Netlander Ionosphere and Geodesy Experiment) has been proposed [1]. The idea is to use both Doppler radio tracking between landers on Mars' surface and an orbiter around the planet and between the Earth and this orbiter in order to measure Mars' rotation parameters (the precession, nutations, rotation rate and polar motion) with a precision of a few milli-arc-seconds (or mas) [1]. Such an experiment is within reach of current technology [1] and recent analytical simulations [2] have shown that this lander-orbiter Doppler signal can achieve a precision of a few mas (or centimetres at Mars' surface) on Mars' rotation parameters estimates. Numerical simulations have also been performed, in which the link between the orbiter and the Earth was additionally included [3]. These simulations confirmed the results obtained with the analytical approach, however, they assumed that the lander positions are perfectly known. Unfortunately, the lander positions are not well known upon landing, depending on the technical solutions chosen for the entry-descent-landing phase. The uncertainties on the landing site positions can correspond to areas of 250x50 km around the nominal landing position on Mars' surface. Such uncertainties generate large errors on the orbiter-lander link that must be removed to achieve the NEIGE objectives. Therefore, we have performed numerical simulations in order to establish a strategy for the Doppler data analysis, allowing for an accurate determination of the lander positions after landing.

2. NUMERICAL SIMULATIONS OF A MARS' GEODESY NETWORK EXPERIMENT

We used the GINS (Géodésie par Intégrations Numériques Simultanées) software developed by the French space agency (CNES) to simulate both lander-orbiter and Earth-orbiter Doppler radio links, involved in the NEIGE experiment. This software numerically integrates the equation of motion of the orbiter around Mars on the basis of a force model and simulates both Doppler shifts measurements. It also calculates partial derivatives of these measurements with respect to some parameters of the force model, and also to the lander positions, allowing least squares adjustment of these parameters.

2.1 Modeling of the force budget of the spacecraft

The gravitational forces acting on the spacecraft are modelled by using both a spherical harmonic expansion of the Martian gravity field GMM-2B [4] and a point mass representation of the Sun and other planets given by the JPL DE403 ephemeris. The atmospheric drag and the solar radiation pressure are also taken into account but, as for the gravitational

forces, are considered as perfectly known such that the orbit of the spacecraft is accurately determined. The albedo and thermal infrared emission of Mars' surface are not included in the force budget (or equivalently considered as perfectly known). The integration of each force is performed every 100 seconds over 100 weeks of data arcs of one week each (corresponding to a total period of one Martian year). The spacecraft is considered to have a near-polar orbit with an inclination of 93.2° and an altitude of 500 km (near-circular, eccentricity of 0.001, and Sun-synchronous) corresponding to the orbit of Mars Global Surveyor (MGS) spacecraft currently in orbit around Mars.

2.2 Modeling of Doppler tracking data and Mars' rotation

A network of four landers on Mars' surface (three landers around the area called Tharsis, and one near the area called Hellas basin, at antipodal position) is chosen for the simulations. The two simulated Doppler shifts measurements correspond to a two-way X-band radio link between the Earth and the orbiter (DSN tracking performed by the Deep Space Network antennas) and a dual frequency (UHF/S-band) link between this orbiter and each lander (NEIGE tracking). This study assumes that DSN and NEIGE Doppler data are integrated over 60 and 20 seconds intervals respectively with an instrumental noise budget of 0.1 mm/s [5, 1]. But, to account for the possible limitation of landers' power supply, we have assumed a limited number of NEIGE measurements. The rate of the UHF data has been fixed to one pass per lander per week, each pass lasting about 15-20 minutes. To simulate these Doppler shifts measurements, the six main harmonics in nutations of Mars, induced by the Sun, have been taken into account [6]. The nutations induced by the two satellites of Mars, Phobos and Deimos, are several orders of magnitude smaller and have not been included. The nutations of Mars that have been calculated in the assumption that the planet behaves rigidly are very accurately known from celestial mechanics. Here, we include an additional contribution from Mars' non-rigid response to the gravitational attraction of the Sun. In particular, we have considered the effects of a possible liquid core by modelling the induced amplification of the nutations with a transfer function depending on two parameters F and $2\pi/\sigma_0$ [7], which are related to the core physical state, size and flattening. The value of F is zero if the core is solid and 0.02 if the core is liquid with a radius of 1,468 km (taken as initial value in our simulations) [8]. We have used 240 days as initial value for $2\pi/\sigma_0$, the period of the Free Core Nutation (FCN), which is a rotational normal mode of Mars related to the fluid core [9]. The initial polar motion (denoted by X and Y and representing the motion of Mars' rotation axis in a frame tied to the planet) has been modelled by 12 parameters corresponding to the amplitudes of the cosine and sine polar motion terms of annual, semi-annual [10], and Chandler periods (200 days, [9]). Four parameters are used for the initial rotation rate or length-of-day (LOD) variations, which have been modelled as a sum of cosine and sine terms of annual and semi-annual periods (derived from amplitudes and phases of the Table 2, solution 1 of [11]).

3. STRATEGY OF LANDER POSITIONS ESTIMATION

We now try to recover the initial values of Mars' rotation parameters and the initial positions of the landers, which have been used to generate the simulated Doppler shift measurements. We perform a classical least squares adjustment of these data, which is initiated by taking a priori values, different from initial ones, for the parameters to be recovered. A zero LOD variations and a zero polar motion are considered as a priori knowledge of Mars' orientation and rotation. The a priori values for the parameters of the transfer function for nutations are taken as 0.05 for the core momentum factor F (0.02 as initial value) and 280 days for the FCN period (240 days as initial value). The a priori lander positions are taken by changing the initial positions by 500 km in longitude and latitude and 100 meters in altitude, in order to take into account the large errors on landing site positions due to the entry-descent-landing phase. However, these errors are too large to obtain Mars' rotation parameters by using the NEIGE data. Therefore, we have developed a strategy into two phases. The first one consists in improving the lander positions alone by using the first few passes of the spacecraft over the landers. From these improved positions, the second phase consists in estimating accurately both positions and rotation parameters over a period of one Martian year (or 100 weeks).

3.1 Phase 1: Improving the lander positions from a few NEIGE Doppler data

The orbit is classically determined by adjusting the DSN Doppler shift measurements of each one-week data arc. The starting position and velocity of the spacecraft at the beginning of each arc are adjusted. From the least squares adjustment, we obtain a normal matrix that contains, for each arc, the information about the orbit coming from the DSN tracking. Another normal matrix for each arc is obtained from the NEIGE data and stacked to the DSN one. Since the a priori positions of the landers are much different from the initial ones, the information contained in this NEIGE normal matrix degrades the precision on the orbit determination. Mathematically, stacking both NEIGE and DSN matrices yields a normal matrix that

is singular, and the lander positions cannot be estimated. To avoid this problem, we apply a weight factor to the DSN matrix, which allows for accurate determination of the orbit. A suitable value for this weight factor is 10^8. Once the orbit has been determined, the NEIGE matrix is next weighted by a similar factor, as was done for the DSN data, and then stacked to this DSN matrix to be inverted in order to recover the information about the lander positions. From several tests it has been found that stacking five data arcs (or 5 weeks of data) permits to improve the error (difference between adjusted and initial values) on the lander positions from 500 km to about 200 km. Stacking more data arcs does not decrease this error. The adjusted values of this first estimation are then used as a priori values for a second iteration of the least squares adjustment, which decreases the errors down to 50 km. Finally, 5 successive iterations yield the errors on the positions, which are shown on Fig. 1. The largest error is about 5 meters in longitude. It corresponds to the signal induced by the LOD variations, which have not been correctly modelled since the rotation parameters have not been adjusted yet. In other words, the error mainly corresponds to the effect of the difference between a priori and initial LOD variations on the lander positions. The errors in latitude and altitude are only a few centimetres and also result from the difference between the a priori values and the initial values introduced for the other rotation parameters.

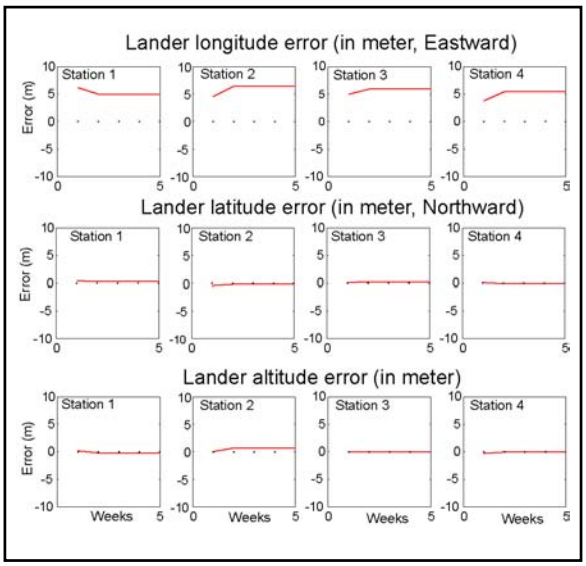

Fig. 1. Improvement of the Lander positions on the basis of 5 successive iterations of the least squares adjustment of the orbiter-lander Doppler shift measurements. Each iteration is performed over 5 passes per week per lander, each pass lasting 15-20 minutes. Stations 1 to 4 denote the lander positions. The Mars rotation model has not been adjusted.

3.2 Phase 2: Accurate estimation of lander positions and Mars' rotation parameters

On the basis of these improved lander positions, the least squares adjustment is now performed over 100 weeks. The NEIGE and DSN normal matrices are produced, then stacked and finally inverted to obtain both Mars' rotation parameters and lander positions. This least squares adjustment is repeated two times by introducing the adjusted values as a priori values from iteration to the next. Indeed, the transfer function for the nutations is non-linear [7, 8] and the least squares adjustment needs to be iterative to estimate the two nutations parameters. The errors on the lander position estimates are given in Fig. 2.

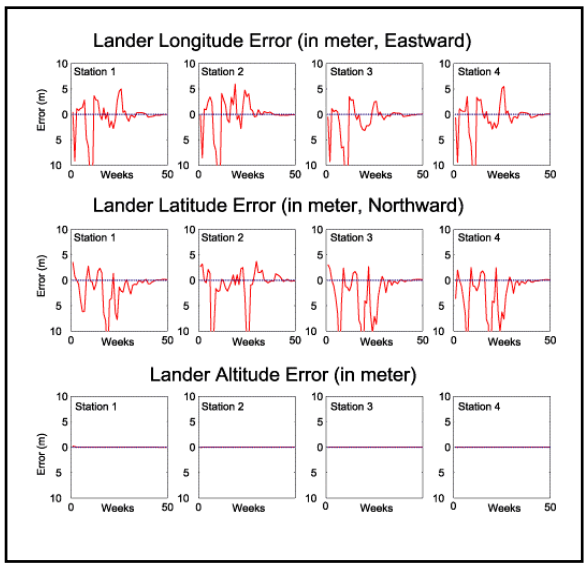

Fig. 2. Accurate estimation of the lander positions over 50 weeks (half a Martian year). The errors are about 1 cm after 40 weeks.

The errors on longitude and latitude show strong oscillations, which are damped after about 40 weeks of data. This behaviour is due to the fact that high correlation exist between lander positions estimates and rotation parameters estimates (see Fig. 3.), until about 40 weeks of data. These correlations decrease when more data are stacked, explaining why the lander positions can be accurately adjusted after 50 weeks (see fig. 4.)

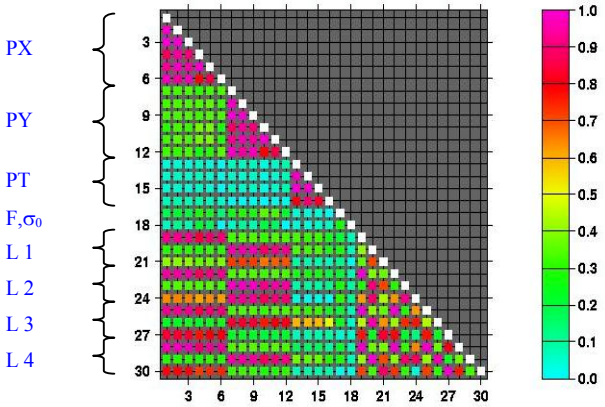

Fig. 3. Correlation between the estimates of the positions of the four landers (denoted by L 1 to L 4) and Mars' rotation parameters (polar motion denoted by PX and PY, the nutations denoted by F and σ_0 and the LOD variations denoted by PT). 25 weeks of data have been stacked.

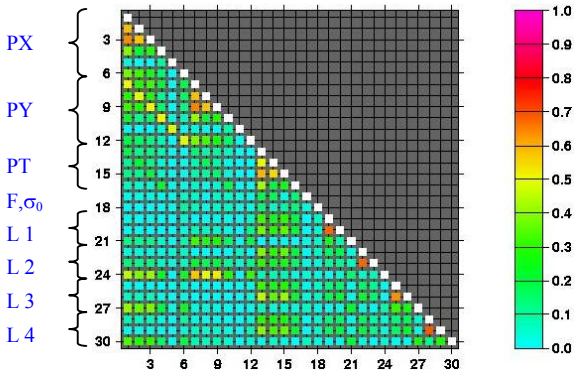

Fig. 4. Same as Fig. 3 but after 75 weeks of stacked data.

As lander positions have been accurately estimated, the Mars' rotation parameters can be now estimated with a few milli-arc-seconds (or centimetres on Mars' surface) of precision, in agreement with results from [2, 3]. Fig. 5 and Fig. 6 show the uncertainty and the error on the nutations parameters (F and σ_0) estimates. The uncertainty is the square root of the a posteriori variance resulting from the least squares adjustment and represents the formal error on the adjusted value of the parameter. The error is the difference between the adjusted and initial values.

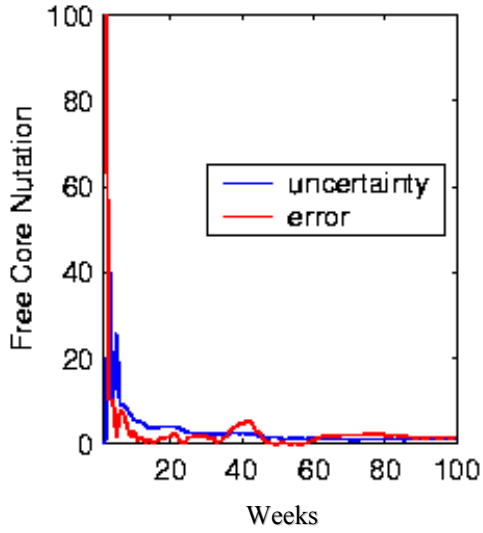

Fig. 5. Estimation of the Free Core Nutation period (in days). This nutation parameter is related to Mars' core state, size and flattening.

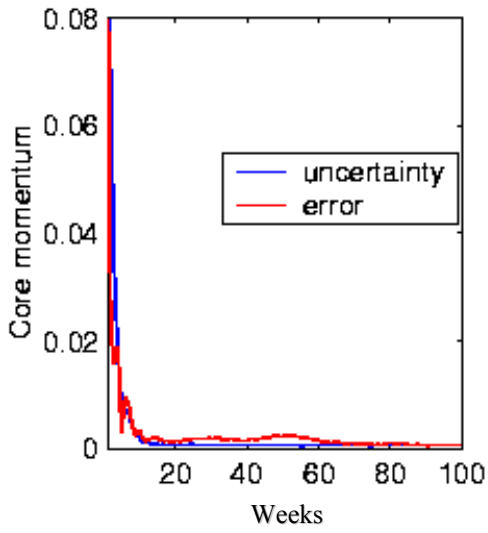

Fig. 6. Same as Fig. 5 but for the core momentum factor, which is related to the inertial momentum of the Martian core.

4. Conclusions and perspectives

A Martian geodetic network science experiment needs to have an accurate knowledge of the lander positions on Mars' surface. However, these positions are not well known upon landing, depending on the performance of the entry-descent-landing phase. In this study, we have shown that given an accurate Doppler tracking (instrumental noise of 0.1 mm/s), it is possible to recover these positions at a level of precision of 1 cm, which is needed to achieve the objectives of a geodetic network experiment such as NEIGE. The strategy consists in first improving the position with only 5 passes of the spacecraft over each lander (each pass lasting 15-20 minutes, representing about 25-30 Doppler shift measurements). This is realized by an iterative least squares adjustment of these Doppler shifts as well as Doppler tracking of the orbiter from the Earth. This latter Doppler signal is used to accurately determine the orbit before adjusting the lander positions. Second, these adjusted positions are used to estimate Mars' rotation parameters over one Martian year (the nominal lifetime of the NEIGE experiment). The precision of a few milli-arc-seconds (or a few centimetres at Mars' surface) is achieved and the lander positions are finally estimated with a precision of a few centimetres.

This study has assumed that the orbit of the spacecraft is accurately determined from Earth-based Doppler tracking. In reality, the orbit determination is perturbed because the forces acting on the orbiter are not correctly modelled. This is the case for the force generated by the inertial wheel desaturation maneuvers. These maneuvers are regularly repeated (every 3 or 6 hours), and induce an rms error on the orbiter position determination of a few tens of centimetres [12]. Moreover, an additional noise is expected on the lander-orbiter Doppler link. This is due to the drift (up to 1 ms) of the clock that is used for dating the Doppler measurements on-board the orbiter. These two sources of noise will be taken into account in future simulations.

The GINS software, used in this study, can also be used for other geodetic experiments than NEIGE. It is also possible to simulate the motion of the spacecraft during fly-bys over planets or satellites of giant planets. Missions with a lander on the surface of these satellites could be simulated and, given technical specifications about the communication-link between the orbiter and the lander, we would be able to evaluate the possibility to estimate its position and the precision on this estimation.

5. REFERENCES

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