# EXECUTIVE SUMMARY REPORT

## RC-SIM. RADIOCOMM SIGNALS: A "NEW" WAY OF PROBING THE SURFACE OF PLANETS

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**ESA STUDY CONTRACT REPORT - SPECIMEN**

| ESA Contract No: | SUBJECT: | CONTRACTOR: |
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| **C22396/09/NL/AF** | **RC-SIM. Radiocomm Signals: A "new" way of probing the surface of planets** | **GMV**<br>**University of Roma, La Sapienza**<br>**University of Bologna** |
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ABSTRACT:

The RC-SIM project is enclosed in the initiative of using more extensively the capability of the radio communication signals (telemetry and datalinks) of interplanetary probes for remote sensing the structure of planets and moons. In more detail, the objectives of this study are:

-Investigate the physical parameters that can be obtained from the use, as a remote sensing instrument, of the radio communication systems on-board interplanetary probes.

-Recommend new approaches to the optimum operation of the radio links of these vehicles, both for communication and remote sensing purposes.

-Analyze the added value that can be provided with this approach with respect to other types of instruments that also supply surface parameters.

-Develop a prototype simulator that will give quantitative results and sensitivity analysis of the different aspects involved in the radio communication link.

-Design a test plan that allows the demonstration of the concept in a controlled environment on Earth and also using signals from real spacecraft.

Three scenarios were considered during the activity:

-**Titan scenario**. Defining an orbiter around Titan and a balloon overflying its surface, different configurations for the realization of radar bi-static experiments have been defined: orbiter-Earth; balloon-orbiter; Earth-orbiter; Earth balloon. The objective of this scenario is to retrieve physical properties of the Titan's surface like the dielectric constant or the rms surface slope, analyzing the precision that can be reached in each configuration.

-**Martian lander**. The objective of this scenario would be the determination of the Martian rotational state by using the radio communications signal coming from a lander on the surface of Mars to an Earth station. The analysis will show the level at which rotational state parameters can be retrieved using state-of-the-art instrumentation and Ka-band radio links. For the rotational state determination both Doppler and range may contribute equally to the determination of the parameters. The study will determine their relative value through a covariance analysis and simulation.

-**Moon interferometric mission**. This scenario involves a network of 3-4 widely spaced landers on the Moon. This proposed scenario aims to perform an accurate determination (to 0.2 mm) of lunar tides and librations. In this network of landers, the radio-communication signals are combined in an interferometric mode, effectively cancelling the orbital motion of the Moon and the effect of propagation media used to measure tidal deformations and/or rotational state of the planetary body (Moon, Mars, or Mercury).



The work described in this report was done under ESA Contract. Responsibility for the contents resides in the author or organisation that prepared it.



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| 1.0 | 11/11/2010 | 28 | |
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# LIST OF TABLES AND FIGURES

# 1 INTRODUCTION

## 1.1 PURPOSE AND SCOPE OF THE DOCUMENT

This document is the executive summary report of the activity "RC-SIM. Radiocomm Signals: a "new" way of probing the surface of planets". It provides the description of the tasks that have been carried out and the analysis of the most important results and conclusions that have been extracted.

The present document constitutes an output of WP-7100: "Management", in the frame of ESTEC contract Nº 2396/09/NL/AF, [AD. 3]. The description of the simulation scenarios, the scientific requirements and models associated to those scenarios, the description of the simulation tool and the analysis of the obtained results have been collected in this document, with the purpose to be self-contained. In addition, the findings of the contract have been summarised in a more detailed way in the Final Report.

## 1.2 STRUCTURE OF THE DOCUMENT

This document contains the following sections:

Section 1 is this introductory chapter.

Section 2 includes the list of applicable and reference documents.

Section 3 describes the background of the activity.

Section 4 contains the review of previous experiments of the use of radiocomm signals for probing the surface of planets.

Section 5 presents the scenarios that have been selected for their implementation in the simulator.

Section 6 describes the scientific requirements and associated models to each scenario

Section 7 includes the summary of the simulator design.

Section 8 analyses the results extracted from the simulator in the 3 scenarios.

Finally, section 9 contains the list of future improvement that might be considered.

## 1.3 DEFINITIONS AND ACRONYMS

### 1.3.1 DEFINITIONS

| Concept / Term | Definition |
|---|---|
| | |

### 1.3.2 ACRONYMS

- **CM** Carrier Module
- **DM** Descent Module
- **DSN** Deep Space Network
- **DTE** Direct To Earth
- **DTTL** Data Transition Tracking Loop
- **EDL** Entry, Descend and Landing
- **EIRP** Equivalent Isotropically Radiated Power
- **ESA** European Space Agency
- **GNSS** Global Navigation Satellite System
- **GPS** Global Positioning System
- **GSP** General Studies Programme
- **HF** High Frequency
- **HW** Hardware
- **ICRF** International Celestial Reference Frame

- **IFT** Inverse Fourier Transform
- **LAN** Local Area Network
- **LCP** Left Circularly Polarization
- **LGA** Low Gain Antenna
- **LOD** Length Of Day
- **LOS** Line Of Sight
- **LRO** Lunar Reconnaissance Orbiter
- **LSE** Least square Estimator
- **MBRF** Mars body-fixed reference frame
- **MER** Mars Exploration Rover
- **MEE2000** Mean Earth equator 2000
- **MGS** Mars Global Surveyor
- **MSL** Mars Science Laboratory
- **MSR** Mars Sample Return
- **MTR** Mid-Term Review
- **NASA** National Aeronautics and Space Administration
- **NIR** Near InfraRed
- **NRCB** Non-rotational central body
- **ODT** Orbiter Delay Time
- **PAA** Probe Aspect Angle
- **PSD** Power Spectral Density
- **PSE** Probe-Sun-Earth angle
- **RCBF** Rotational Central Body Frame
- **RCP** Right Circularly Polarization
- **RC-SIM** Radio Communications Signal Simulator
- **RF** Radio Frequency
- **RFP** Request for Proposal
- **RFQ** Request for Quotation
- **SBI** Same Beam Interferometry
- **SBRF** Selenocentric body fixed reference frame
- **SEP** Sun-Earth-Probe angle
- **SNR** Signal to Noise Ratio
- **SoW** Statement of Work
- **SRIF** Square Root Information Filter
- **SW** Software
- **SWIR** Short Wave InfraRed
- **TBC** To Be Confirmed (by the Agency)
- **TBD** To Be Determined (by the contractor)
- **TEC** Total Electron Content
- **TID** Travelling Ionospheric Disturbances
- **TIR** Thermal InfraRed
- **TSSM** Titan and Saturn System Mission
- **TT&C** Telemetry, Telecommand & Control
- **UHF** Ultra High Frequency
- **US** United States
- **VIS** Visible

- **VLBI** Very Long Baseline Interferometry
- **VLA** Very Large Array
- **WBS** Work Breakdown Structure
- **WVR** Water Vapour Radiometer

# 2 REFERENCES

## 2.1 APPLICABLE DOCUMENTS

| Ref. | Title / Code / Version / Date |
|---|---|
| [AD. 1] | Statement of Work for the "Radiocomm Signals: a new way of probing the surface of planets", ITT AO/1-5915/08/NL/AF, issue 3 rev 2, 23/08/2008. |
| [AD. 2] | GMV proposal to "Radiocomm Signals: a new way of probing the surface of planets", GMVSA 1439/08, 24/11/2008 |
| [AD. 3] | ESTEC Contract Nº 2396/09/NL/AF: "Radiocomm Signals: a new way of probing the surface of planets" |
| [AD. 4] | Previous experiments and analysis of radiolink for planetary probes, version 1.1 06/07/2009 |
| [AD. 5] | Simulation Scenarios Report, GMV-RC-SIM-D2, version 1.2 23/06/2009 |
| [AD. 6] | Scientific Requirements, GMV-RC-SIM-D3, Version 2.0, 17/12/09 |
| [AD. 7] | Selection of Surface Wave Interaction Models, GMV-RC-SIM-D4, Version 2.0, 03/12/09 |
| [AD. 8] | Functional Verification Plan, GMV-RC-SIM-D5, Version 1.0, 16/12/09 |
| [AD. 9] | Test Cases for Simulation Scenarios Plan, GMV-RC-SIM-D6, Version 1.1, 21/05/2010 |
| [AD. 10] | Technical and User Manual of the Model Simulator, GMV-RC-SIM-D7, version 1.4, 11/11/2010 |
| [AD. 11] | Simulation Scenarios Test Results, GMV-RC-SIM-D9, version 1.1, 09/08/2010 |
| [AD. 12] | Simulation Scenarios Test Results Report, GMV-RC-SIM-D10, version 1.1, 09/08/2010 |
| [AD. 13] | Analysis of Results, GMV-RC-SIM-D11, version 1.1, 11/11/2010 |
| [AD. 14] | Test Plan, GMV-RC-SIM-D12, version 1.0, 11/11/2010 |

**Table 2-1- Applicable Documents**

## 2.2 REFERENCE DOCUMENTS

| Ref. | Title / Code / Version / Date |
|---|---|
| [RD. 1] | Williams, J. G., Dickey, J. O. *"Lunar Geophysics, Geodesy, and Dynamics"*, 13th International Workshop on Laser Ranging, October 7-11, 2002, Washington, D. C. |
| [RD. 2] | Williams, J. G., Boggs, D. H., Ratcliff, J. T., *"Lunar Interior: Results and Possibilities"*, Lunar and Planetary Science Conference XXXVII, paper 1229 (2006) |

**Table 2-2- Reference Documents**

# 3 BACKGROUND

The carrier frequencies of radio communication systems have often been used for planetary science purposes, using several techniques like radio occultation (for atmospheric and ionospheric characteristics) or bistatic radar experiments (for surface properties).

The performances of past experiments using radio communication links for surface parameter retrieval are improvable as those systems were only designed for communication purposes. Optimising the configuration of both the receiver and transmitter systems, the quality of the information extracted from the planetary body surface will increase. Therefore, the radio communications between rovers, ballons, landers and orbiters of future missions could be reviewed to allow better remote sensing experiments.

This activity is enclosed in the initiative of using more extensively the **capability of the radio communication signals (telemetry and datalinks) of interplanetary probes for remote sensing the structure of planets and moons**. In more detail, the objectives of this study are:

- Investigate the physical parameters that can be obtained from the use, as a remote sensing instrument, of the radio communication systems on-board interplanetary probes.
- Recommend new approaches to the optimum operation of the radio links of these vehicles, both for communication and remote sensing purposes.
- Analyse the added value that can be provided with this approach with respect to other types of instruments that also supply surface parameters.
- Develop a prototype simulator that will give quantitative results and sensitivity analysis of the different aspects involved in the radio communication link.
- Design a test plan that allows the demonstration of the concept in a controlled environment on Earth and also using signals from real spacecraft.

In order to cover all these objectives, the following **main tasks** have been accomplished during this study:

- First of all, a detailed review of missions involving planetary probes (current and future) was performed. In that review, it will be important to analyse the experiments using radiolinks for remote sensing, as well as the different radiolink concepts.
- With the information from the mission review, it was possible to select the mission scenarios analysed and included in the prototype simulator.
- High-level scientific requirements for the simulation scenarios were derived, and later the models for planetary surfaces characteristics, wave interaction models with those surfaces and the inversion algorithms to retrieve geophysical data were detailed for their later implementation in the simulator.
- Development of the prototype simulator with all the inputs coming from previous tasks.
- Definition of test cases for functional verification and for the scenario simulation.
- Accomplishment of the functional verification and execution of the scenario simulations previously defined.
- Analysis of the results of the scenario simulations, deriving recommendations for the design of the radio link systems and for the surface parameters and retrieval algorithms that may be used. The performances of these solutions were addressed.
- Definition of a test plan allowing concept demonstration of the recommended approach, including a prototype for testing on Earth and an experiment using signals from real probes and ground elements.

# 4 REVIEW OF EXPERIMENTS AND RADIO-LINK ARCHITECTURES

The first task performed during the project was the review of previous and planned radio-science experiments and the state-of-the-art of the radio-link architectures. As a summary of this review, the following points can be remarked:

- Although bistatic radar experiments cannot compete with synthetic aperture radar mapping or precision altimetric radar system of monostatic radar techniques, they constitute a powerful tool in the goal of overcoming the major limitations intrinsic in Earth-based monostatic observations.
- Other advantages of bistatic radar are the requirement of far less power due to proximity to the surface and the possibility to realize special geometries such as near-backscatter, really helps in investigating the possibility of clean-water ice existence, or the probing of a wide variety of latitudes and longitudes.
- Bistatic radar are useful not only to characterize landing sites for future landers/rover missions but also to model planet interiors adding to the knowledge of the average body density (computed by independently estimating its mass and volume) the estimation of surface density. With proper interpretation, the results of radar scattering data collection can provide significant information on three main surface parameters: the root-mean-square value of the surface slope ($\xi/\gamma$), the near surface dielectric constant ($\varepsilon$) and the surface density ($\rho$).
- New scenarios possibilities arose for bistatic techniques thanks to the advances in technology applicable to both spacecraft and ground elements. Technology evolution had already been noticed since more recent missions were equipped with high-precision on-board frequency references (ultrastable oscillators), quite an enhancement considering the first observations performed.
- In view of the negligible additional resources required both onboard and on the ground (with respect to standard radio science instrumentation) by bistatic radar experiments, it seems natural to envisage that such technique will be routinely used in future missions to probe planet/satellite surfaces in a fashion (and with observational goals) not feasible by any other remote sensing instrumentation.
- On the other hand, owing to the operational complications required to carry out bistatic radar experiments (the spacecraft inertial pointing must be continuously changed in order to point toward the time-varying specular point on the planet surface to allow the echoed signals to reach the Earth), these experiments have been historically performed as experiments of opportunity, i.e. combined with other atmosphere/ionosphere radio sounding experiments, which usually require a geometry (an occultation) favorable for bistatic experiments to be performed in two legs (in the Ingress and in the Egress). Depending on future mission constraints, this limitation can be removed by dedicating to bistatic radar experiments more on-board resources and dedicated observation time.
- Based on the experiments and instruments review, our recommendation in the context of the RC-SIM study is to further investigate on one side the bistatic radar technique, which seems to be an excellent tool to provide, with proper interpretation of radar scattering data, significant information on three main surface parameters: the root-mean-square value of the surface slope, the near surface dielectric constant and the surface density.
- On the other side, the use of radio links (as envisaged by the Exomars LaRa experiment) seems recommendable to constrain the rotational state of a planet/satellite, by means of two-way Doppler tracking to/from a lander and an Earth-based Ground Antenna, and thus to infer its interior structure, at depths well below those reachable by surface sounding instruments.
- The effectiveness of VLBI over Doppler and range methods in both such application has been so far limited by the attainable accuracies. When translated into position errors in the plane of the sky (orthogonal to the line of sight), an angular error of 6 nrad corresponds to a displacement of 900 m at a distance of 1 AU (4.5 km at the distance of Jupiter). Even if this accuracy corresponds to best case assumptions, it is generally not comparable with positioning errors using Doppler observables.
- Angular measurements from VLBI may be useful under special circumstances (such as pre-flyby orbital phases) or to remove degeneracy, but in general are of little value in gravity field or rotational state determination.

# 5 SELECTED SCENARIOS

After careful analysis of possible scenarios, it was decided to concentrate the efforts on scenarios where a space mission is the only available option to carry out a measurement. This does not mean that a scenario for NEO bistatic experiment is not interesting, and that getting surface roughness and dielectric constant of an asteroid is not valuable scientific objective. On the contrary, it surely is, but there are also other ways to obtain the same information, and with a broader statistical basis.

Based on the above considerations, the Study Team proposes to ESA that the final scenarios to be analysed in depth in Task 2 of the present study are:

1. **Titan Scenario (bistatic radar experiments), including:**
    a. **Orbiter-to-Earth configuration (Scenario 1a)**
    b. **Balloon-to-orbiter configuration (Scenario 1b)**
    c. **Earth-to-orbiter bistatic radar experiments (Scenario 1c)**
    d. **Earth-to-balloon bistatic radar experiments (Scenario 1c)**
2. **Martian Lander Scenario (determination of Mars rotational state)**
3. **Moon Interferometric Mission (accurate determination of lunar tides and librations)**

# 6 SCIENTIFIC REQUIREMENTS AND MODELS

This section summarises the scientific requirements that are assigned to each scenario, as well as the models that will be used for the implementation in the simulator.

## 6.1 TITAN BISTATIC RADAR SCENARIO

The Titan surface properties will be inferred by means of bistatic radar measurements where the transmitter can be on board a Titan orbiter or a Titan balloon or on the ground, and the receiver will be alternately on-board the orbiter, the balloon and the Earth. The simulated RF signals will be at S-, X and Ka-band in a Cassini-like configuration.

The precise determination of the surface dielectric constant, obtained through differential reflection of orthogonal polarizations, provides information about the surface constituents, liquid or ice, and their stratification.

Spectral broadening of the received signals may be used to derive information about surface roughness (rms slope) at scales of the incident wavelength.

The goals in the measurement accuracy are set to be in the same order of magnitude of those obtained through the Cassini Titan bistatic radar observations, namely:

- Dielectric constant to a 5-10% error
- Rms slope to a 10% error

The above objectives are required to be fulfilled for a large part of Titan's surface, in order to obtain a systematic coverage and a good statistical sampling of its surface.

The achievable accuracy of the experiment may be assessed assuming instantaneous propagation of signals. The following physical models and parameters will be included in the simulation:

| Simulation models characteristics | | | |
|---|---|---|---|
| **Simulation parameter** | **Value** | **Type** | **Notes** |
| Earth position | JPL ephemerides | Earth position will be computed by using JPL ephemeredes. | |
| Earth rotation | JPL ephemerides + EOP | Precession-nutation series included in the JPL ephemerides. EOP based upon predictions from IERS | |
| Titan position | JPL ephemerides | Titan position will be computed by using JPL ephemeredes. | |
| Titan Rotation | JPL ephemerides | Titan rotation from JPL ephemerides. | |
| Titan Surface properties | Model described in [AD. 7] | Geometric Optics (GO) approximation | |

**Table 6-1- Simulation models characteristics in Titan bistatic radar scenario**

For all media interaction models the S/W models are implemented as fixed models with configurable parameters. This is true for:

- planetary tropospheres (which can be modeled using the same model for both the Earth and Titan, but with different values of the characterizing parameters - surface pressure and temperature and partial pressure of the water vapour)
- ionospheres (where the key parameter is the zenith total electron content - TEC)
- solar and interplanetary plasma ( where the key parameter, neglecting the magnetic correction term, is the electron density - ne)

None of the above parameters needs to be estimated as part of the simulation runs, but are just "given" (with realistic values extracted from the relevant literature on the subject).

Also, for bistatic radar experiments, it is not deemed important to include errors (either statistical or deterministic) in the media models, as they do not affect the capacity to retrieve the surface properties.

## 6.2 MARTIAN LANDER SCENARIO

Two main scientific goals in Martian geophysics can be achieved with a measurement of the planet's rotational state, namely:

- physical state and size of the core, from normal rotational modes such as Free Core Nutation (FCN), which depend on the rheology and the interior structure through resonances with the planet's normal modes of the planet
- seasonal redistribution of CO2 on the surface of the planet, from changes in LOD and polar motion.

Both goals are attained together using a theoretical model of the planet rotation under the influence of mass redistribution (due to seasonal effects) and exchange of angular momentum between the atmosphere and the solid planet.

The outline of recent literature on Mars rotation allows drawing some important conclusions about the scientific requirements. We set here as a goal an improvement by at least an order of magnitude the existing determinations of pole location and LOD variations to:

- constrain the core size
- assess the core physical state
- determine the seasonal mass transfer among the hemispheres
- determine the inelastic properties of the mantle and its quality factor

To this end, at least three crucial aspects need to be addressed, namely:

- Range and Doppler measurement accuracy and stability
- Temporal basis for the estimation
- Optimal location of the lander
- Dynamical model

A crucial goal of phase 3 was to determine under which experiment configuration the following scientific goals can be attained. On the basis of the project discussions, the measurement goals were summarized as follows:

1) precession rate to 5 mas/yr
2) pole location to 1 mas (or 1.5 cm)
3) LOD to 0.1 ms

Two-way Doppler and range measurements are the primary observables of the experiment. Measurements are assumed to be generated using state-of-art Ka-band instrumentation, with capabilities derived from the Cassini and Bepi-Colombo radio system.

| Observable characteristics | | | |
|---|---|---|---|
| **Simulation parameter** | **Value** | **Type** | **Notes** |
| Doppler accuracy | 1.8 μm/s one-way | Constant value | The corresponding Allan deviation is1.2e-14 at 1000 s integration time, two-way. Doppler accuracy scales as the inverse square root of the integration time if this is < 1000 s, and is roughly constant at time scales > 1000 s |
| Ranging accuracy | 11 cm one-way | Constant value | Accuracy for time scales equal to the duration of a tracking pass (i.e. about 10 hrs). Drifts at long time scales are assumed to be < 15 cm. |
| Doppler Time Resolution | integration time from 1 to 1000 s | Configurable parameter | TBD |
| Ranging Time Resolution | integration time from 2 to 1000 s | Configurable parameter | 2 seconds is the minimum integration time in order to neglect the thermal noise error with a received $P_{mg}/N_0$ = 31.77 dBHz |

| Observable characteristics | | | |
|---|---|---|---|
| Tracking Scheduling | 1 pass/day with a duty cycle of 75%, each pass lasting about 10hrs. (TBC) | Constant value | TBD |
| Length of the simulation | 1 year | Configurable parameter | TBC |

**Table 6-2- Observable characteristics in Mars Lander scenario**

The error budget analysis singles out two major error sources for Doppler observables, and three for ranging:

| Doppler: | Ranging: |
|---|---|
| • Tropospheric noise<br>• Ground antenna mechanical noise | • Uncalibrated Ground Station delay<br>• Plasma delay<br>• Station location uncertainty |

Other error sources are negligible and do not need to be modelled provided that Ka-band is used. In particular plasma noise can be safely neglected for Doppler observables if measurements are carried out at SEP angles greater than 30 degrees. Tropospheric noise is generally negligible for the range measurements for ground antennas located in dry sites. Water vapour radiometers can be used for calibration of the wet path delay effects in Doppler and range measurements.

Error models are built in the form of power spectral densities and combined to compute a single time series encompassing all relevant error sources.

| Error model characteristics | | | |
|---|---|---|---|
| **Simulation parameter** | **Value** | **Type** | **Notes** |
| Residual zenith path delay | 4 cm | constant value | Doppler noise due to the troposphere is proportional to the residual zenith path delay mapped to the line-of-sight elevation. |
| Ground Antenna mechanical noise | Allan deviation of 5.5e-15 at 1000 s | stochastic or empirical model | (TBC) |
| Uncalibrated ground station delay | 10 cm | stochastic or empirical model | residual delay after calibration at time scale of a tracking pass (TBC) |
| TEC | TBD | stochastic or empirical model | The residual plasma delay for the ranging observable is 2.2 cm, one-way |
| Station location uncertainty | 3 cm | constant value | It includes EOP and Earth solid tides contributions (one-way) |

**Table 6-3- Error model characteristics in Mars Lander scenario**

Light time solution for the computed and (simulated) observed observables is not needed. (It is a computational burden that does not bring any change to the covariance matrix.) The achievable accuracy of the experiment may be assessed assuming instantaneous propagation of signals. The following physical models and parameters will be included in the simulation:

| Simulation geometry characteristics | | | |
|---|---|---|---|
| **Simulation parameter** | **Value** | **Type** | **Notes** |
| Earth position | JPL ephemerides | Earth position will be computed by using JPL ephemeredes. | Earth position |
| Earth rotation | JPL ephemerides + EOP | Precession-nutation series included in the JPL ephemerides. EOP based upon predictions from IERS | Earth rotation |

| Simulation geometry characteristics | | | |
|---|---|---|---|
| Mars position | JPL ephemerides | Mars position will be computed by using JPL ephemeredes. | Mars position |
| Mars Rotation and Librations | JPL ephemerides + ad-hoc simulation model | Mars rotation and precession from JPL ephemerides. Small rotations due to FCN, CW and LOD variations will be provided by an ad hoc model. | Mars Rotation and Librations |
| Lander position | goal | Optimal Lander position on the Mars Surface is a product of the simulation results. | Lander position |
| Ground antenna position | constant value | Location of the ground station is assumed fixed at some point on the Earth surface | Ground antenna position |

**Table 6-4- Simulation geometry characteristics in Mars Lander scenario**

## 6.3 MOON INTERFEROMETRIC MISSION SCENARIO

Lunar Laser Ranging (LLR) has been one of the most successful outcome of the Apollo program. Today, the current accuracy in absolute distance is less than a cm, with a large improvement with respect to the initial phases of the program (Williams and Dickey, 2002) [RD. 1]. The concept of the lunar interferometer, proposed in 1994 by P. Bender, exploits differential measurements of distances from a ground station to three or four points on the lunar surface.

In a differential (interferometric) configuration, the main sources of measurement errors affecting single links (mostly propagation noises and clock drifts) are effectively removed thanks to a common mode rejection. This configuration can provide an excellent determination of the lunar librations and tides. The configuration envisaged in this study aims to measure differential distances to 0.1-0.2 mm. The concept of a lunar microwave interferometer entails three or four transponders on the lunar face, simultaneously illuminated by a single radio antenna on the ground. Each transponder coherently retransmits a unique signal to ground, where the phase is measured and the phase differences are formed.

An essential point of this configuration is the use of a single antenna on the ground for transmission and reception of the signals to all landers. An antenna with a diameter of 3 m will cover all the transponders and will allow elimination of most common mode noise, in particular dispersion in the ionosphere and troposphere. The lunar network and the ground antenna are a realization of the concept known as Same Beam Interferometry (SBI).

Analysis of differential phase data will yield lunar orientation (physical librations) described by three Euler angles. For optimum science, data spans of years are desirable. Many lunar properties affect the orientation vs time: moment of inertia differences, gravity field, tidal distortion and dissipation, moment of inertia of the fluid core, dissipation and flattening of the fluid-core/solid-mantle boundary (Williams et al, 2006) [RD. 2]. Some of these properties slightly speed up or slow down the rotation while others affect the direction of the pole of rotation. Important time scales run from months, to years and to decades, and the separation of these effects requires long time spans of accurate data. The influence of tidal distortion on orientation gives sensitivity to the Love number k2. Tidal dissipation depends on frequency and the tidal Q can be recovered from the orientation at several frequencies. There is a few cm/sec flow of the fluid with respect to the mantle at the core/mantle boundary and the resulting dissipation gave the first detection of a fluid core. LLR detection of flattening of the CMB and core moment also indicates the core's fluid state. The moment of inertia of the core is a very important property.

The scientific goals of the lunar interferometer are:

- determine the free precession of the lunar core
- determine the core size and confirm its physical state
- determine the tidal distortion and dissipation of the core

- determine the dissipation and flattening of the fluid-core/solid-mantle boundary
- determine the k2 Love number
- determine the frequency dependence of the tidal quality factor

To this end, at least three crucial aspects need to be addressed, namely:

- accuracy and stability of differential phase measurements
- temporal basis for the estimation
- optimal location of the landers
- dynamical model in the fit

A crucial goal of phase 3 is to determine under which experiment configuration the following scientific goals can be attained. The measurement goals are summarized as follows:

1) physical librations to 0.02 mas
2) solid tides 0.02 cm
3) tidal $k_2$ Love number to $2.5 \cdot 10^{-3}$

The requirements on the radio link and the transponders will be determined in order to meet the end-to-end measurement goals. Detection of the free precession of the lunar core is optimally carried out with a differential radial motion of the two landers of 0.2 mm over time scales up to several years. For tidal deformations, the same accuracy is required over a period of six months.

The observable is a time-varying differential phase between a pair of transponders. It will be obtained by carrier phase tracking by a digital PLL in a given Integration time.

| **Observable characteristics** | | | |
|---|---|---|---|
| **Simulation parameter** | **Value** | **Type** | **Notes** |
| Differential range accuracy | 0.1 mm | Constant value | corresponding time delay is 0.334 ps |
| Time resolution | integration time from 1 to 300 s | Configurable parameter | TBC |
| Tracking schedule | 1 pass/day with a duty cycle of 75%, each pass lasting about 30 min (TBC) | Constant value | TBC |
| Length of the simulation | 3 year | Configurable parameter | TBC |

**Table 6-5- Observable characteristics in Moon interferometric mission**

The error budget analysis showed three major error sources:

- Differential tropospheric delay
- Station location uncertainty
- Differential aging of transponder electronics

Other error sources are negligible and do not need to be modelled provided that Ka-band is used.

Error models are built in the form of power spectral densities and combined to compute a single time series encompassing all relevant error sources.

| **Error model characteristics** | | | |
|---|---|---|---|
| **Simulation parameter** | **Value** | **Type** | **Notes** |
| Angular separation between a pair of transponders | max 0.14° | Configurable parameter | corresponding to a maximum separation of 1000 km on the Moon surface |
| Residual zenith delay | 4 cm | constant value | troposphere differential delay is proportional to the residual zenith path delay and the angular separation between a pair of transponder, mapped to the line-of-sight elevation. |
| Station location uncertainty | 3 cm | constant value | It includes EOP and Earth solid tides contributions. |

| Error model characteristics | | | |
|---|---|---|---|
| Model for transponder Aging | TBD | stochastic or empirical model | The model will account for differential aging between the transponders. |

**Table 6-6- Error model characteristics in Moon interferometric mission**

Light time solution for the computed and (simulated) observed observables is not needed. (It is a computational burden that does not bring any change to the covariance matrix.) The achievable accuracy of the experiment may be assessed assuming instantaneous propagation of signals. The following physical models and parameters will be included in the simulation:

| Simulation geometry characteristics | | |
|---|---|---|
| **Simulation parameter** | **Type** | **Notes** |
| Earth position | JPL ephemerides | Earth position will be computed by using JPL ephemeredes. |
| Earth rotation | JPL ephemerides + EOP | Precession-nutation series included in the JPL ephemerides. EOP based upon predictions from IERS |
| Moon position | JPL ephemerides | Mars position will be computed by using JPL ephemeredes. |
| Moon Rotation and Librations | JPL ephemerides + ad-hoc simulation model | Mars rotation and precession from JPL ephemerides. Small rotations due to FCN, CW and LOD variations will be provided by an ad hoc model. |
| Lander positions | goal | Optimal lander positions on the Moon surface is a product of the simulation results. |
| Ground antenna position | constant value | Location of the ground station is assumed fixed at some point on the Earth surface |

**Table 6-7- Simulation geometry characteristics in Moon interferometric mission**

# 7 SIMULATOR ARCHITECTURE

RC-SIM is an end-to-end simulator of radio science experiments in different scenarios enclosed in the initiative of using more extensively the capability of the radio communication signals (telemetry and datalinks) of interplanetary probes for remote sensing the structure of planets and moons.

The aim of the simulator is to give qualitative results and sensitivity analysis of the different aspects involved in the radio communication link.

The simulator high-level architecture can be studied following two alternative approaches: the functionality-based approach or the scenario-based approach. Both approaches coherently describe the whole simulator architecture.

High-level RC-SIM architecture from a functionality-based point of view is shown in Figure 7-1.

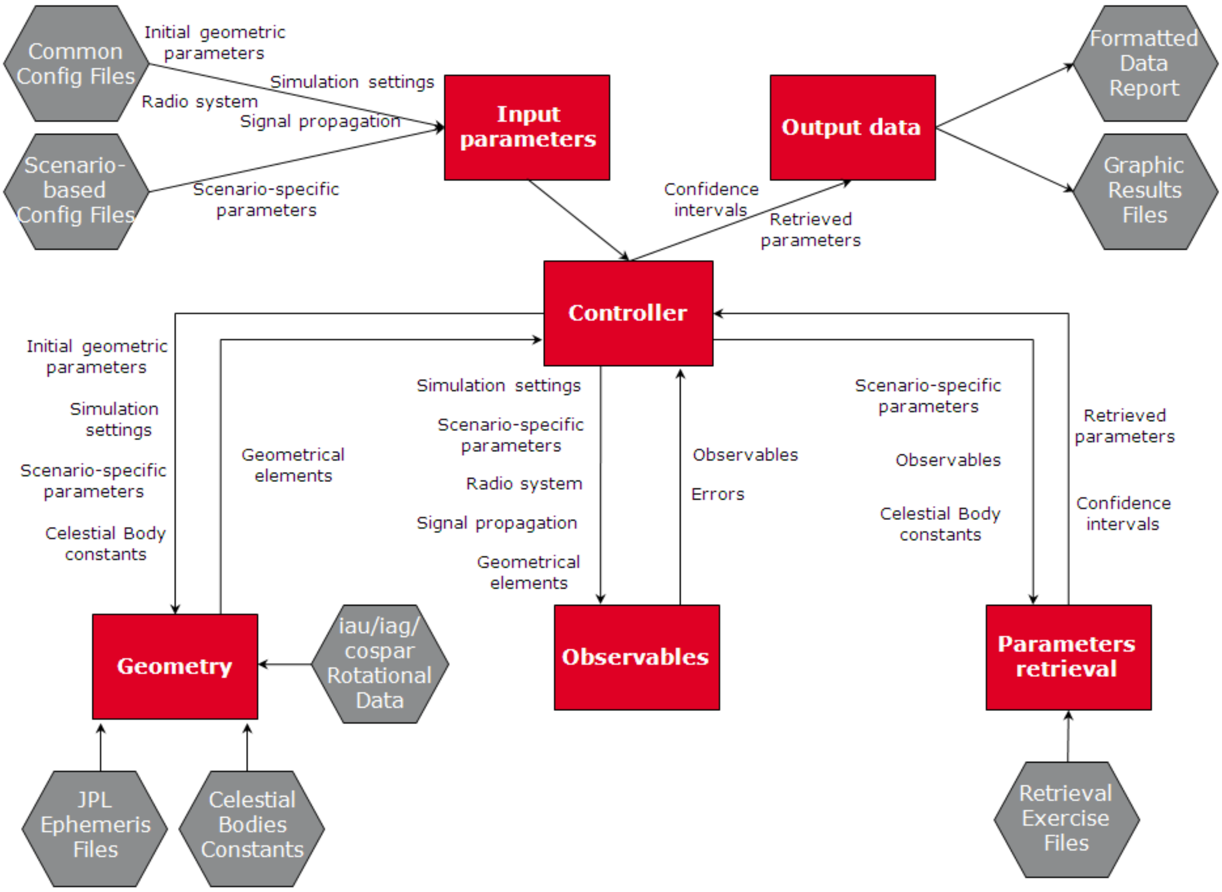


**Figure 7-1: Context diagram of the complete RC-SIM simulator (functionality-based approach)**

Different functionalities are specified in this approach by means of functional modules, in red. External data sources as well as input and output data are shown as grey hexagons.

A brief description of each functional module is given below:

- Controller: the controller is the module in charge of managing the data flow and calling all the other modules involved in the simulation. First of all it calls an initialisation module that opens the necessary data files and that adds the necessary directories to the current Matlab path; after that it reads all the data contained in the input files and it finally calls the execution of the different functional modules managing the required input/output data during the calls.
- Input parameters: the present module refers to all the information contained in the configuration files, which involves user-configurable data and settings for the simulation to be run.

- Geometry: geometry module is in charge of the computation of the relative geometry between transmitter(s) and receiver(s) in the three scenarios. It receives input user data and it computes, through models expressing planets position and rotational state, the RC-SIM geometrical elements.
- Observables: The aim of this functional module is twofold; firstly, it computes the ideal observables of the radio science experiment according to the scenario under study. Then, it calculates the errors associated to the previously computed observables adding the result in order to obtain the actual observables of the experiment. Besides, the observables module is in charge of simulating the signal interactions with the surface if needed.
- Parameters retrieval: the module which applies the inversion algorithms on the observables in order to retrieve the information we are looking for in the scenario under study.
- Output data: the results management module in charge of formatting data resulting from the simulation and showing these results through both binary files and plots.

There is also the possibility of studying the high-level architecture from a scenario-based approach as shown in Figure 7-2.

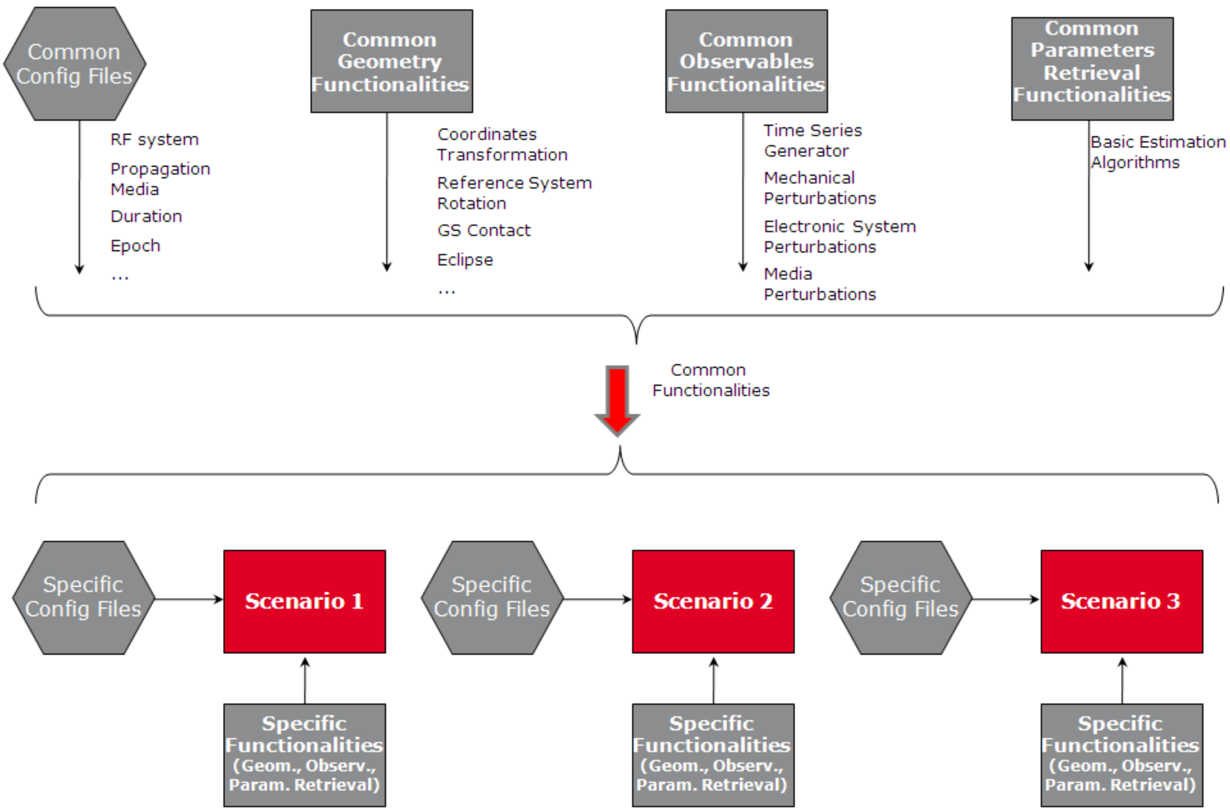


**Figure 7-2: Context diagram of the complete RC-SIM simulator (scenario-based approach)**

If the scenario-based approach is followed when describing the simulator, the elementary unit that gathers the different functionalities involving one simulation together is the scenario itself (scenarios are shown in red in Figure 7-2). Given a concrete scenario to be simulated, different functionalities (the ones previously described) must be called in order to run the simulation. Functionalities feeding each scenario are shown in grey. These functionalities can be either common to all scenarios or specific of the scenario under study. The different nature of common and specific functionalities will be thoroughly described through the following sections.

# 8 ANALYSIS OF RESULTS AND CONCLUSIONS

## 8.1 TITAN BISTATIC RADAR SCENARIO

With respect to the retrieval of the surface dielectric constant, the following conclusions have been extracted:

- the relative error between the "true" (simulated) value and the retrieved one is most of the time below 5% (in particular when all error levels are set to their default values)
- the relative error between the "true" (simulated) value and the retrieved one is only in some cases below 10% (when error levels are increased, the most critical one being the additional 1dB loss due to the polarization mismatch)
- the relative error does not depend significantly on the probed Titan's region (although the scenario geometry plays an important role in the experiment)
- the increase in the received power level does not always imply better retrieval of the surface properties. Given the low power levels registered, a numerical effect might have an important role in this result
- the retrieval algorithm works properly as long as the illuminated surface can be considered homogeneous within the antenna's footprint from the point of view of the surface's parameters to be retrieved, that is, the statistical distribution of the dielectric constant on the illuminated surface is sufficiently narrow.

And with respect to the retrieval of the rms slope:

- the aimed accuracy can be reached only under certain conditions and sometimes during long periods of time
- the relative error between the "true" (simulated) value and the retrieved one tends to be smaller as the antenna's beamwidth increases
- the retrieval algorithm works properly as long as the illuminated surface can be considered homogeneous within the antenna's footprint from the point of view of the surface's parameters to be retrieved, that is, the distribution of the rms slope on the illuminated surface is sufficiently narrow
- the periods of time satisfying the aimed accuracy (relative error less than 10%) are relatively short compared to the ones corresponding to the dielectric constant
- large 3dB antennas' beamwidths (low gain antennas) have been proved to be needed in order to achieve the aimed accuracy through the different test even in the case of a fictitious homogeneous rms slope Titan surface
- Scenario 1d, Earth to Balloon, proved to be the most favourable for the rms slope retrieval: not only time windows with relative error less than 10% are present but also this error remained low and almost constant during the tests

These investigations are particularly relevant in the context of future planetary missions currently being considered by ESA and NASA. For example, Ganymede and Europa bistatic radar observations are being considered for the Europa Jupiter System Mission (EJSM), with the aim of complementing other surface remote sensing observations, as they allow more nearly complete characterization of target scattering properties, sometimes not apparent from monostatic observations. EJSM/Laplace is an international mission to be developed in collaboration between ESA and NASA. The mission will aim at the comprehensive study of the Jupiter system with specific emphasis on Europa and Ganymede as potential habitat. The reference mission architecture consists of two flight elements: i) the Jupiter Ganymede Orbiter (JGO), assumed to be developed and launched by ESA; ii) the Jupiter Europa Orbiter (JEO), assumed to be developed and launched by NASA. The two spacecraft could operate independently in the Jovian system but the mission is designed to execute an extended choreographed exploration of the Jupiter System before the spacecraft settle into orbits around Ganymede and Europa. In this context Ganymede and Europa bistatic radar observations could be carried out (1) in a "classical" downlink configuration JGO --> Ganymede --> GS and JEO--> Europa --> GS, (2) in an uplink configuration GS --> Ganymede --> JGO and GS --> Europa --> JEO (provided both S/C are equipped with a full RF receiver) and (3) using a S/C-to-S/C communication link offering the opportunity of JGO --> Europa --> JEO and JEO --> Ganymede --> JGO (and other similar combinations) observations.

The S/W simulation capabilities for Scenario 1 which were setup in the context of the RC-SIM study are thus particularly relevant to assess the potential performance of bistatic radar experiments with EJSM, taking into account the current knowledge of Ganymede and Europa surface properties, in order to drive the optimization of some of the S/C design parameters involved in these observations.

## 8.2 MARTIAN LANDER SCENARIO

The results obtained for this scenario indicate that the measurement goals can be attained in almost every configuration if Doppler observables accurate to 4.5 micron/s over 1000 s integration are available. This conclusion is true even for short mission duration. With a long mission (5 years) the determination of the parameters pertaining to long period effects (especially the precession and nutation terms at annual frequency) can be improved, but a 1 year temporal basis appears to be sufficient. We recall here the measurement goals: an improvement by at least an order of magnitude over the existing determinations of pole location and LOD variations, summarized as:

1) precession rate to 5 mas/yr
2) pole location to 1 mas (or 1.5 cm)
3) LOD to 0.1 ms

For the Martian lander scenario, the simulations show that the measurement goals can be met for a mission duration of only one (terrestrial) year and a radio system entailing only Doppler observables at Ka-band, with stabilities of $1.5\ 10^{-14}$ at integration times of 1000 s. Given the broad interest of space agencies in the in situ exploration of Mars, the adoption of a Ka-band transponder as a joint telecom/geodesy instrument seems to be attractive and feasible. We recall here the measurement goals: an improvement by at least an order of magnitude over the existing determinations of pole location and LOD variations, summarized as:

1) precession rate to 5 mas/yr
2) pole location to 1 mas (or 1.5 cm)
3) LOD to 0.1 ms

In detail, the conclusions about the Martian lander scenario would be:

- The error in the precession rate can be inferred from the plots "Precession and nutations error signal", contained in section 4.3 of [AD. 13] (one example is included in Figure 8-1). It can be inferred by dividing the largest error (truth-estimate) by the temporal basis (1 y). We note that for this case the formal uncertainty (represented by the vertical bars to the right in the plots) is smaller than the error (truth minus estimate), so that it is appropriate to choose the largest of the two for the interpretation of the results. As 1 mas is equivalent to 1.6 cm on the Mars surface, it is apparent that the measurement goal is met. In the best case (Doppler + range, equatorial lander) the error in the rate amounts to a maximum of about 1 mas/y, a factor of 5 below the target. Even for a polar lander (82 deg latitude), the error is about 4 mas/y. By comparing the results for the three different combinations of observable quantities (Doppler+range, Doppler and range) we note that Doppler observables bear most of the information content. The results for the range only cases are systematically worse than the one including Doppler. It appears also that the measurement objective can be met also with a radio link configuration without the high accuracy ranging system.

- The error in the pole location (controlling the accuracy in the polar motion and the Chandler wobble) is read directly from the plots "Polar motion and Chandler wobbel error signal", contained in section 4.3 of [AD. 13] (one example is included in Figure 8-2), recalling the equivalence (for Mars) 1 mas → 1.6 cm. The measurement goal of 1 mas is met and exceeded in all cases involving Doppler observables. Little benefit is gained from the use of range data. The range-only solution leads to unacceptably high errors. Again, we can conclude that the information matrix of the problem is built only out of Doppler observables. We note also that for the case of an equatorial lander (Doppler+range) the estimation error (truth minus estimate) exceeds the formal error.

- The error in the LOD (related to the mass redistribution in the martian atmosphere) is read from the plots "Error signal: rotation rate", contained in section 4.3 of [AD. 13] (one example is included in Figure 8-3). The curves represent the error in the displacement of a point at the equator (the lander) as a consequence of errors in the estimation of the rotation frequency and its components. (We recall here that rotation rate variations are expected at the annual frequency and its harmonics.) By recalling the equivalence (for Mars) 1 mas → 1.6 cm, and the relationship $\sigma_{LOD} = T\delta\theta / 2\pi$ between the angular error $\delta\theta$ and the error

$\sigma_{LOD}$ in the period T, it is apparent that the measurement goal of 0.1 ms is met and exceeded in all cases involving Doppler observables. Indeed, an error of 1 ms corresponds to 24 cm displacement at the equator, a value 10 times larger than the uncertainty (over 1 year) even for the case of a polar lander. The errors in the case of an equatorial lander decrease by another factor of 2, at least. The results show again that little benefit is gained from the use of range data.

- The parameter errors is always under the 3-σ formal uncertainty (and in many cases under the 1- σ level).
- All scientific goals can be met with only 1 year temporal basis for the experiment, assuming range-rate observables accurate to 4.5 μm/s (two way).
- Range-rate observables bear most of the information content and only little benefit is gained by using high accuracy ranging channel.
- The best configuration entails an equatorial lander, even if also a mid-latitude location is sufficient to meet scientific requirements.
- The parameters uncertainty nearly halved with 5 year temporal basis, as expected for the assumed white gaussian noise.

In summary, the simulations show that the measurement goals can be met for a mission duration of only one (terrestrial) year and a radio system entailing only Doppler observables at Ka-band, with stabilities of 1.5 $10^{-14}$ at integration times of 1000 s. Given the broad interest of space agencies in the in situ exploration of Mars, the adoption of a Ka-band transponder as a joint telecom/geodesy instrument seems to be attractive and feasible.

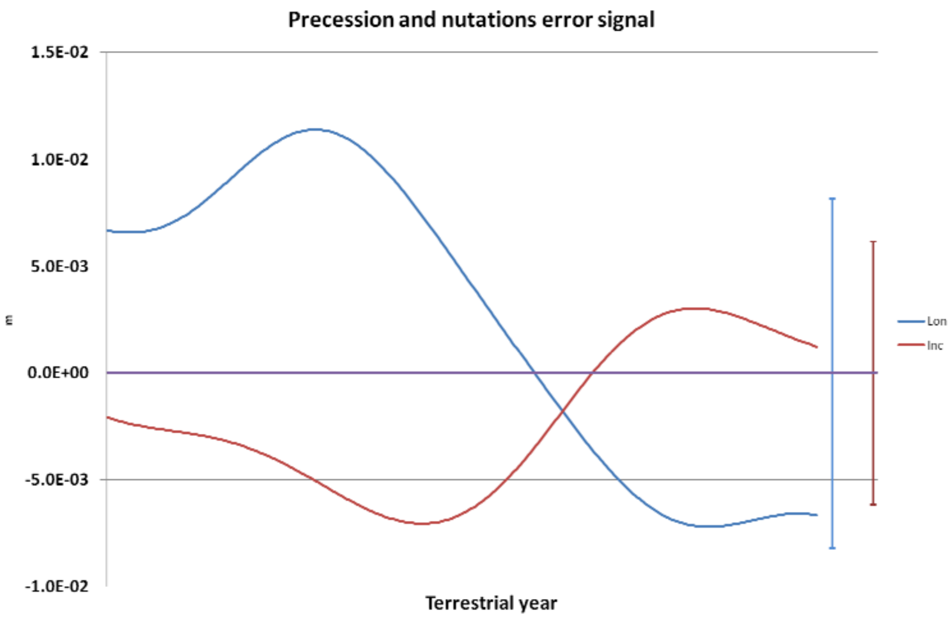


**Figure 8-1: Scenario with equatorial lander, using Doppler and range measurements. Error signals (truth minus estimate) for precession and nutation. Plotted is the displacement error for the pole (inclination) and the node (precession).**

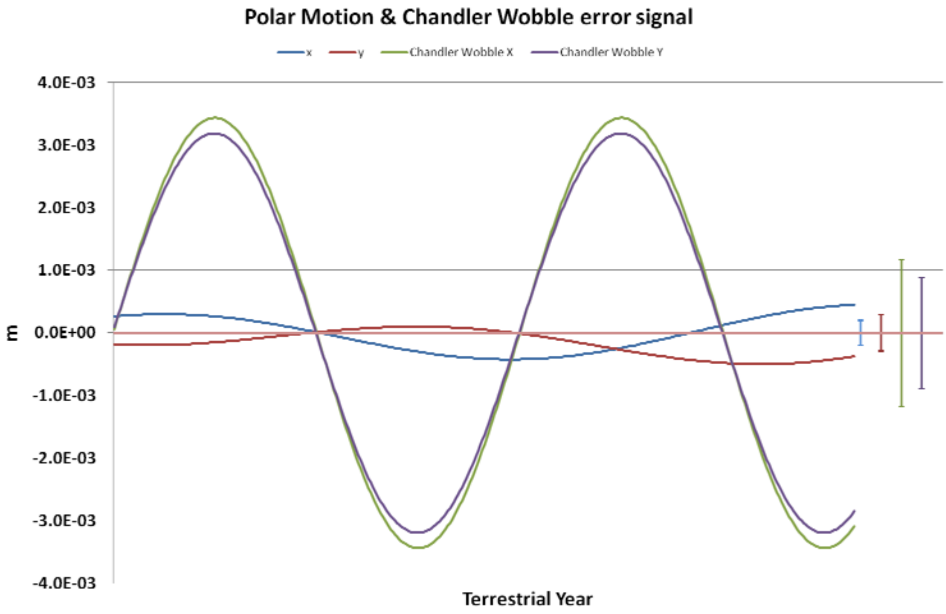


**Figure 8-2: Scenario with equatorial lander, using both Doppler and range measurements. Error signals (truth minus estimate) for polar motion and Chandler wobble. Plotted is the displacement error for the pole. Equatorial lander, 1 y observation, Doppler and range data.**

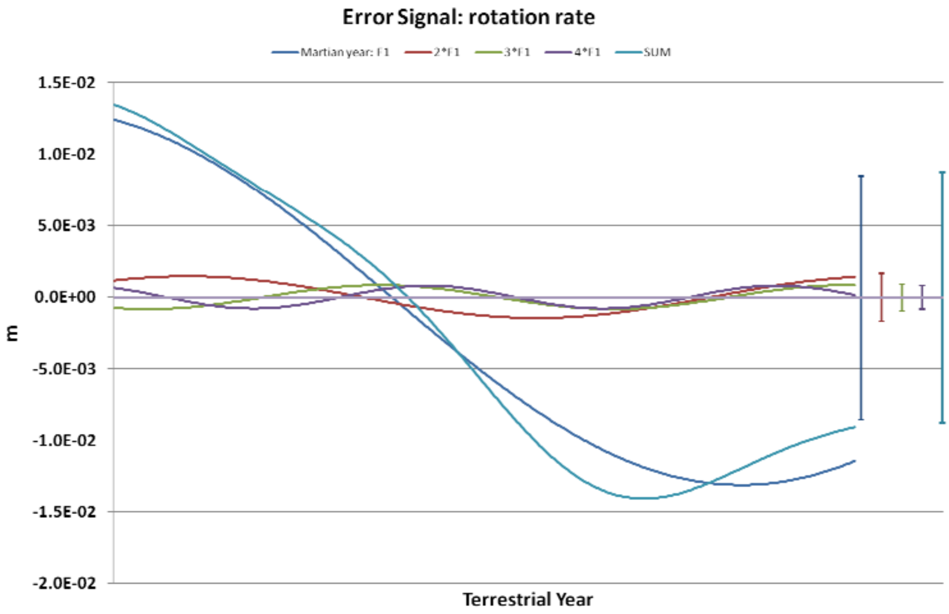


**Figure 8-3: Scenario with equatorial lander, using both Doppler and range measurements. Error signals (truth minus estimate) for LOD. Plotted is the displacement error for a point at the equator. Equatorial lander, 1 y observation, Doppler and range data.**

## 8.3 MOON INTERFEROMETRIC MISSION SCENARIO

The prospects of radio interferometry for planetary geophysics seem favourable. The concept of a lunar interferometer has been proved. With the proposed configuration librations can be measured with accuracy up to 0.02 mas provided that drift do to aging of electronics components are kept under control at the level of 1mm/year.

The next phase of planetary exploration will certainly rely more and more on in situ exploration with landers and rovers. It is therefore conceivable that some opportunities will exist in the near future for the geophysical use of telecomm links. The concept is certainly not new, and in the past even a network of landers (e.q. on Mars) has been proposed to ESA. The concept of the interferometer presented here for the moon can straightforwardly be extended to all tidally locked bodies, such as Titan and the Galileian satellites of Jupiter. However it would be of the utmost scientific interest to exploit its capabilities for fast rotators such as Mars.

# 9 FUTUTRE IMPROVEMENTS

Finally, in terms of future recommendations and possible enhancements of the tool, the following points are proposed:

- Reproduce simulated Titan maps where, at latitudes and longitudes probed by Cassini's bistatic radar experiments, the surface properties are identical to those retrieved by using real data;
- Reproduce the real experiments geometry, in terms of epoch, ground station involved and Cassini's trajectory and pointing data
- Use radio system parameters identical to those of Cassini and the GS involved
- Use propagation noises reasonably close to those experienced by Cassini's radio link during the real experiments
- Run the simulator and iterate the various settings (or debug the S/W routine) until fully consistent results are obtained, with respect to real rms slope and dielectric constant profiles obtained by Cassini
- Estimate of Lunar Martian tides and their respective h2 Love number
- Capability to iterate solutions. The current status of the simulator is more related to a covariance analysis.