AN ARCHITECTURE FOR A LUNAR NAVIGATION SYSTEM: ORBIT DETERMINATION AND TIME SYNCHRONIZATION

M. Di Benedetto [(1)], G. Boscagli [(1)], F. De Marchi [(1)], D. Durante [(1)], F. Santi [(1)], A. Sesta [(1)], M. K. Plumaris [(1)], A. Fienga [(2)], N. Linty [(3)], K. Sosnica [(4)], J. Belfi [(5)], and L. Iess [(1)]

[(1)] *Sapienza, Università di Roma, via Eudossiana 18, Rome, Italy, Email: mauro.dibenedetto@uniroma1.it*
[(2)] *GéoAzur, CNRS, Observatoire de la Côte d'Azur, Université Côte d'Azur 250 Av. A. Einstein, 06560 Valbonne, France*
[(3)] *Argotec s.r.l., via Cervino 52, 10155 Turin, Italy*
[(4)] *Wrocław University of Environmental and Life Sciences, Norwida 25, 50-375 Wrocław, Poland*
[(5)] *Leonardo S.p.A, Viale Europa snc, IT-20014, Nerviano (MI), Italy*

ABSTRACT

This paper shows the architecture of a Lunar Radio Navigation System (LRNS) constituted by a small constellation of satellites supported from Earth by a dedicated network of small dish antennas, capable of establishing Multiple Spacecraft Per Aperture (MSPA) tracking at K band and of implementing the novel Same Beam Interferometry (SBI) technique. SBI will complement standard Doppler and ranging measurements thanks to Code Division Multiplexing with Majority voting (CDM-M) method, where the uplink signal is sent to multiple satellites with a single carrier and onboard transponders will implement Code Division Multiple Access (CDMA), sharing the same bandwidth in downlink. Time synchronization across the constellation will be performed by measuring the desynchronization of each satellite with terrestrial time and compensating accordingly the drift of onboard clocks within the navigation message. The proposed architecture has been validated with numerical simulations showing that orbital accuracies at meter level are achievable for the positioning of lunar orbiters.

1. INTRODUCTION

In the past few years, the interest in lunar exploration and missions has grown significantly, to the level that it is absorbing most of the global effort in the robotic and manned exploration of the solar system. The number of missions to the Moon from both space agencies and private actors will likely exceed in the next decade the total number from the 60s. By this, the development of a Lunar Radio Navigation System (LRNS) would be the most cost-effective approach to cope with most of the navigation requirements of those missions.

ESA is already addressing this need with its Moonlight initiative aimed at deploying a small constellation of small/medium size satellites in highly eccentric orbits (see [1]) to provide communication and navigation services to a broad class of users in cis-lunar orbits or on the lunar surface. As for any other terrestrial GNSS, the two fundamental pillars for providing a Position Navigation & Time service (PNT) are the accuracy of the satellites' ephemerides and the time synchronization across the constellation. By this, in 2021 we have established an international consortium funded by ESA and named ATLAS, aimed at defining the architecture of an Orbit Determination and Time Synchronization (ODTS) system capable of meeting an end-to-end SISE (Signal in Space Error, according to typical terrestrial GNSS nomenclature) requirement of about 25 m, including both position errors and time synchronization accuracy within the lunar constellation (see [2]).

The aim of this paper is to show the ATLAS team's concept for the lunar ODTS system, capable of providing both good orbit determination and precise time distribution to the lunar constellation. The proposed architecture relies on a dedicated ground network of small tracking stations (~30 cm) establishing two-way coherent K band links with the lunar constellation and supporting Spread Spectrum (SS) modulation of ranging signals at 20-25 Mcps. Such small dish antennas are needed to implement Multiple Spacecraft Per Aperture (MSPA) tracking, keeping all the satellites of the constellation, separated by as much as 20000 km, in simultaneous visibility from the Earth. Remarkably, the combination of SS modulation and MSPA allows also implementing Same Beam Interferometry (SBI), a very powerful technique to enhance ODTS performances of the proposed architecture.

Section 2 describes the architecture of the proposed ODTS concept, including the main elements for both the ground and space segments. Section 3 describes the time transfer method to keep time synchronization within the constellation, while Section 4 shows the setup and results of numerical simulations. Finally, in Section 5, we provide conclusions and possible future augmentations of the LRNS.

2. ODTS architecture for a LRNS

According to the International Telecommunication Union (ITU) definitions and radio regulations (see [3]), a mission to the Moon falls within the Space Research (RS) Category A mission and the allocated bandwidths are 7190-7235 / 8450-8500 MHz for the forward and return links at X band, and 22550-23150 / 25500-27000 MHz at K band. The ODTS concept described in this work is based on two-way coherent K band links from ground, mostly for three reasons. A higher frequency allows: 1) a wider occupational bandwidth (i.e., higher chip rates at about 20-25 Mcps), providing better ranging performances and time transfer accuracy (discussed below), 2) lower interference and occupancy issues with already existing space services (together with S band, X band is currently the classical communication band used for TT&C functions), and 3) easier future system augmentations (e.g., using a mixed SS and frequency division approach for a possible future increase of the size of the constellation). Even if K band is the baselined band for the proposed architecture, we stress that the use of X band is still possible and could be seen as a backup option, although with some limitations on the achievable system performances.

The ground segment consists of a dedicated network of ~30 cm antennas (needed at K band to keep the entire constellation in the same field of view and implement the MSPA tracking), 120° separated in longitude at most (for a minimum of three distinct ground tracking sites) to ensure continuous support to TT&C operations. Any ground station shall be capable to send a single uplink frequency to the entire constellation modulating the K band carrier with different SS ranging codes using the Code Division Multiplexing technique based on the Majority voting (CDM-M). In the downlink, multiple carriers can share the same beamwidth and bandwidth by implementing Code Division Multiple Access (CDMA) within the onboard transponder (see in [4]). The capability to fully support the CDM-M method is not yet ready. However, a breadboard has been already developed for the on-board receiver (see [5] and [6]), while the ground station modem is currently under development [7]. The use of the SS technique combined with MSPA is the most efficient way to communicate with the constellation minimizing the impact on the occupied bandwidth and simplifying the ground station operational procedure for its control (i.e., simultaneous tracking and control of all the satellites).

The constellation in [1] is composed by only 3 satellites but for the link budget we have considered ~8.5 dB losses due to CDM-M (valid for 4-5 satellites, as reported in Tab. 1). Given the mass constraints imposed by using smallsats, an onboard 30 cm Medium Gain Antenna (MGA) and 5 W in the return link ensure a *SNR* always larger than 35 dB-Hz (while 100 W in the forward link provide higher margins). For contingency operations, we have conservatively considered an onboard off-pointed Low Gain Antenna (LGA), To support this scenario, the ground segment must include an additional antenna with a minimum aperture of 5 m, allowing a comfortable *SNR* above 40 dB-Hz in the uplink, while in the downlink a more marginal value around 27 dB-Hz. If deep space complexes are used to host the LRNS network, the deep space 35 m antennas can be used for contingency, improving the downlink *SNR* by about 17 dB with respect to the considered 5 m terminal. In this case, a CCSDS/ECSS Standard Modulation (residual carrier), as reported in [3] and [8], will be used.

The ground segment shall also include typical elements needed to support deep space tracking:

- An accurate Frequency and Timing Standard (FTS, typically an H-maser).
- Weather station.
- Tropospheric and ionospheric calibration system.
- K band delay calibration system (for calibration of ranging measurements).

N° sat	1	2-3	4-5	6-7	8-9	10-11
CDMM losses (dB)	0	6.0	8.5	10.1	11.3	12.2

Table 1: CDMM losses due to power sharing and sign flipping during code correlation for a different number of users (sat).

In addition to standard Doppler and range measurements, the CDM-M and the MSPA approach allow for generating on ground very precise SBI observables. The phase of the carrier signal received by each satellite of the constellation at epoch t_3 may be written as:

$$\Phi_{RX}^{GS}(t_3) = M \cdot [\omega_0 t_3 + \varphi_0 + \Psi_{RTLT}] - 2\pi N \qquad (1)$$

where ω_0 is the nominal carrier angular frequency, φ_0 is an initial phase offset, $\Psi_{RTLT} = -\omega_0(\tau_{up} + \tau_{down})$ is a phase term slowly varying with time due to the relative motion between each satellite pair ($\tau_{up} + \tau_{down}$ represents the total round trip light time), and M is the onboard turnaround ratio. The measured phase is obtained at the ground station with a phase-locked loop (PLL) and dedicated signal processing able to reconstruct the unwrapped phase (averaged over a count time) with an ambiguity corresponding to the integer number of cycles within the initial spacecraft position relative to the ground station. This is modelled by the integer N, which is different for each spacecraft. The SBI observable can be built by comparing the phase received from satellites A and B of the constellation at the same epoch t_3. Since the ground station transmits the same frequency ω_0 to all the satellites of the constellation (thanks to CDM-M) and they all use the same turnaround ratio (thanks to CDMA), the phase difference can be written as:

$$\begin{aligned}\Delta\Phi_{SBI}(t_3) = M \cdot [\Psi_{RTLT}^{B} - \Psi_{RTLT}^{A}] \\ - 2\pi(N^B - N^A) \\ = \frac{M\omega_0}{c}[\rho_{RTLT}^{A} - \rho_{RTLT}^{B}] \\ - 2\pi K\end{aligned} \qquad (2)$$

where K is simply the difference in the integer number of

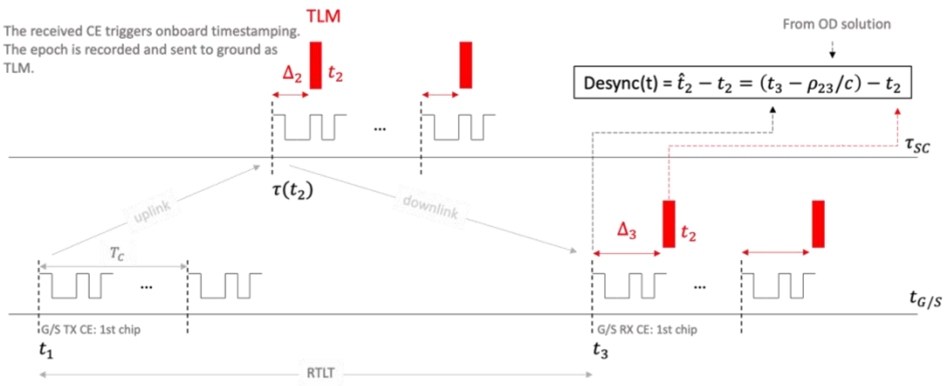

Figure 1: Scheme for time synchronization adopting the two-way coherent ranging approach. Note that the delays Δ_2 and Δ_3 introduced by data encoding/decoding in the telemetry transmission may even exceed the code repetition period, accordingly to the chosen coding method. In any case, what really matters for the system to work is that both $\delta\Delta_2$ and $\delta\Delta_3$ are $\ll T_L$.

cycles between satellites A and B. In practice, the SBI observables correspond to the difference in the two-way range $\rho_{RTLT}^{A,B}$ between the two satellites, scaled by a constant factor, and having an initial ambiguity that shall be solved within the OD process. This observable is computed on ground by post-processing of carrier phase measurements and can be generated for each pair of satellites, estimating for each pair and each tracking pass a separate phase bias.

3. TIME TRANSFER & SYNCHRONIZATION

In the proposed architecture the time synchronization across the constellation is decoupled from the satellites orbit determination because only two-way coherent observables are used on ground (or their combination for SBI). This way, radio metric observables are immune to both random noise and drift of clocks onboard the satellites, as these latter only affect the performances of the PNT service to end-users.

Two-way coherent links established from ground with each satellite of the constellation can be exploited to perform ground-to-space time transfer (TT). We have identified two potential methods to perform TT: one based on a novel concept relying on two-way coherent ranging measurements, and a second one based on two-way asynchronous links, conceptually very similar to a technique routinely used on Earth in the generation of the UTC timescale, and commonly referred to as Two-Way Satellite and Frequency Transfer (TWSTFT), see in [9].

The novel approach is schematically shown in Fig. 1 and it is compatible with both standard CCSDS PN ranging [10] and CCSDS SS signals and modulation format [11]. In two-way measurements, there are three distinct epochs involved in the measurement:

- t_1: epoch of the signal transmission from ground.
- t_2: epoch of signal reception onboard.
- t_3: reception time on ground.

Measuring the clock desynchronization between distant clocks means comparing their readings at the same coordinate time. This would involve general relativistic transformations between proper time τ (the actual time read by each clock) and a coordinate time t. Here we use a simplistic formulation, *de facto* assuming proper and coordinate times are equivalent, thus neglecting relativistic transformations that, however, only represent deterministic corrections to be applied in a real scenario. We only need to consider the finite speed of light to describe the TT methods.

The onboard clocks have only access to the time when the uplink signal is received onboard (e.g., t_2) while the OD process relies on the light-time (LT) solution, which provides an estimate of both t_1 and t_2 by solving backward from t_3, that is measured by ground clocks. We can, therefore, write the following expression for the clocks' desynchronization:

$$\text{Desync(t)} = \hat{t}_2 - t_2 = (t_3 - \rho_{23}/c) - t_2 \qquad (3)$$

where c is the speed of light, $\hat{t}_2$ is the epoch coming from the LT solution (thus from the OD and that we can write as $\hat{t}_2 = t_3 - \rho_{23}/c$, with ρ_{23}/c being the one-way return link travel time) and t_2 is the onboard clock reading. In the CDM-M modulated signal there is one chip of the ranging code that assumes a special meaning and defines a Code Epoch (CE), which repeats itself after one code period T_L, this being the ratio between the code length and the chip rate (thus $T_L = \frac{256\cdot(2^{10}-1)}{24Mcps} \approx 10$ ms in the signal structure proposed in our architecture). When the CE is received onboard, it triggers a timestamp operation through a fast strobe line, and the onboard time t_2 is recorded and encoded in the telemetry channel for transmission to ground. Data encoding and transmission may add an additional delay Δ_2. For the proposed method to work, it is crucial that the uncertainty in this delay $\delta\Delta_2 \ll T_L$, or in other words, that we are always capable of unambiguously coupling any CE event with the associated telemetry data (note the code ambiguity resolution exceeds by far the uncertainty in the satellite's position). This requirement is not difficult to be met because also in case of large delays in the TLM channel (e.g., depending on the adopted coding method that may cause Δ_2 even to exceed T_L), this delay is mostly deterministic, and its residual uncertainty is expected to be much lower than T_L. When the signal is received on ground, a similar timestamp operation is triggered by the received CE to record the epoch t_3. In parallel, the telemetry data received by the satellite (providing t_2 time information) is decoded. This may add an additional delay Δ_3 for which the same considerations as for Δ_2 apply. The final desynchronization accuracy depends on both OD performances along the line-of-sight (LOS), i.e., accuracy in ρ_{23} computation, and on the precision of timestamp operations (i.e., when measuring t_2 and t_3). These two terms are of the same order: below 20 cm (thus less than 0.6 ns) for the OD error along the LOS, as shown from our numerical simulations (see Section 4), while the timestamp precision can be kept at sub-ns level with a proper design (e.g., LRO LOLA laser altimeter has a timetag precision of 0.5 ns, see in [12]). The delays introduced by the telemetry data channel and encoding/decoding operations do not induce additional uncertainty in the time transfer accuracy, provided that, as stressed above, both t_3 and t_2 can be uniquely associated with the corresponding telemetry time data (CE time stamp). The main advantage of this novel technique is that it can be performed in parallel with nominal ground tracking operations. Thus, this means that with continuous visibility from ground and the proposed implementation of the MSPA approach, in principle it would be possible to perform almost continuously space-to-ground time transfer with each node of the constellation.

The second possible method to perform ground-to-space TT relies on asynchronous links, similarly to the TWSTFT technique daily applied on Earth for the generation of the UTC timescale through geostationary satellites (used as relays for the signals coming from/to remote terminals). The basic equation for the clock de-synchronization between clocks A and B is:

$$\tau_B - \tau_A = -\frac{1}{2}\left[[\Delta\tau_B - \Delta\tau_A] + [\Delta_T^A - \Delta_R^A] + [\Delta_R^B - \Delta_T^B] + [T_\uparrow - T_\downarrow]\right] \quad (4)$$

where $\Delta\tau_{A/B}$ are the two observables computed on ground and onboard each satellite as the difference between the received code and a local replica, Δ terms are electronic delays in the transmitter/receiver chains, while $T_\uparrow$ and $T_\downarrow$ are propagation delays in the uplink/downlink paths. This technique in principle may even provide superior performances because noise terms mostly cancel out in the differentiation procedure, and it is also virtually immune to OD errors. The major drawback is that it requires the interruption of normal tracking operations to settle the onboard Deep Space Transponders (DST) to operate in asynchronous mode.

Remarkably, even if not explicitly reported in this work, we stress that we have identified an onboard architecture capable of supporting both methods and requiring only minor adjustments to standard DST architectures, in that it shall be capable of supporting both coherent and not-coherent operations.

4. ODTS results

We have performed numerical simulations of the proposed ODTS architecture to assess the attainable positioning performances. For the lunar constellation, we have considered ELFO orbits having the orbital parameters reported in Tab. 2 and coming from [1].

Orbital parameter	ELFO constellation
Semimajor axis	9750.7 km
Eccentricity	0.7
Pericenter altitude	1187.8 km
Apocenter altitude	14838.8 km
Orbital period	24 h
Inclination	63.2 °
RAAN	0° | 120 ° | 240 °
Argument of pericenter	90 °
True anomaly	0 ° | 164 ° | 196 °

Table 2: Orbital parameters of the considered ELFO constellation, taken from [1].

The simulation is divided into two steps. In the first step, we propagated the satellite orbits for 4 days, and we generated the associated set of synthetic observables (Doppler, SS ranging, and SBI) assuming on average 6 hours of continuous MSPA tracking from each ground site per day. A realistic model has been used to simulate the expected measurement noise for each data type. At K band, the noise level is:

- $\sigma_y \approx 1.5 \times 10^{-14}$, where σ_y is the standard Allan deviation and corresponding to 4.5 μm/s at 60 s integration time for Doppler (derived from [13]).
- ~12 cm every 10 s for SS modulated ranging observables at 20-25 Mcps (derived from [13]).
- ~3.5 mm for SBI (for the differential phase, as derived from [14]).

The dynamical model of each satellite includes the gravitational attraction from all Solar System bodies, spherical harmonics coefficients of the Moon (up to degree and order 120) and quadrupole coefficients of the Earth, as well as non-gravitational perturbations due to the solar radiation pressure (SRP). For the SRP acceleration, we have represented each spacecraft as a sphere (radius of 1 m modelling the spacecraft bus) and two separate plates, one having a 11 m^2 area (modelling the solar arrays) and a smaller one (0.4 m^2) modelling an antenna dish constantly pointed toward the Earth. The area-over-mass ratio is ~0.06 m^2/kg (corresponding to a solar radiation pressure acceleration of about 3x10^{-7} m/s^2).

In the second step, we performed an OD batch estimation filter over the full data arc, estimating the following parameters:

- Satellite state vectors at the beginning of the data arc.
- Range biases (one per station).
- SBI biases (one per spacecraft pair, per tracking pass, per station).
- Solar arrays total area.
- Empirical accelerations parameters. Two separate models have been considered:
  - Piecewise-constant accelerations: $a_{X,Y,Z}$
  - RTN: Radial-Transverse-Normal accelerations modelled as functions of the true anomaly θ:

$$a_{R,T,N} = p_{R,T,N} + c_{R,T,N} \cos\theta + s_{R,T,N} \sin\theta \qquad (4)$$

The time update of the two empirical models is, respectively, 8h and 24h for the piecewise-constant and RTN, to have the same number of estimated parameters over one orbital period (see Tab. 2). The empirical accelerations have been included to compensate for unavoidable errors in the dynamical model, with the SRP being likely the main contributor. The a priori uncertainty of each acceleration model has been therefore set to ~ 7.5×10^{-9} m/s^2, roughly corresponding to 2.5% of the expected SRP total acceleration.

A Monte Carlo analysis has been carried out by recursively shifting the epoch of the constellation initial conditions by 6 hours, for a total of almost 100 cases, to cover the variation of the Earth-Moon relative geometry over 28 days, and thus a full lunar sidereal month.

Our results show that on average, for each satellite of the constellation, about 4 days of data are sufficient to reach for each satellite of the constellation a position accuracy better than 2 m (RMS, 2-σ). Fig. 2 shows an example of the position error and accuracy for the three spacecraft for a randomly selected data arc. The plot shows both 1-σ and 3-σ position accuracy (dark and light-coloured areas respectively) and the estimation error (solid line). The vertical black line indicates the last data point for each satellite and the right side of the plot shows the evolution of ephemeris aging.

For TT accuracy, the relevant component of the position error is the one along the LOS (ground-to-space). This is always lower than 20 cm, being the LOS the direction over which ranging measurements are performed, and thus determined much better in comparison to the 2 m RMS at 2-σ obtained for the RSS.

In addition, we have also assessed the temporal evolution of the SISE (ephemeris aging) considering both orbital and clock error contributions. The latter clearly depends on the accuracy and stability of the onboard clocks. Being limited by mass constraints imposed by using smallsats, the more promising solutions for the onboard clocks are high-quality Ultra Stable Oscillators (USO) and compact/miniaturized Rubidium Atomic Frequency Standard (RAFS). Considering typical spectral properties of USO and (mini)RAFS we have however verified that the SISE requirement (e.g., 25 m 2-σ at maximum aging of data) can still be met after ~ 6 hours (or more) after the last contact with ground.

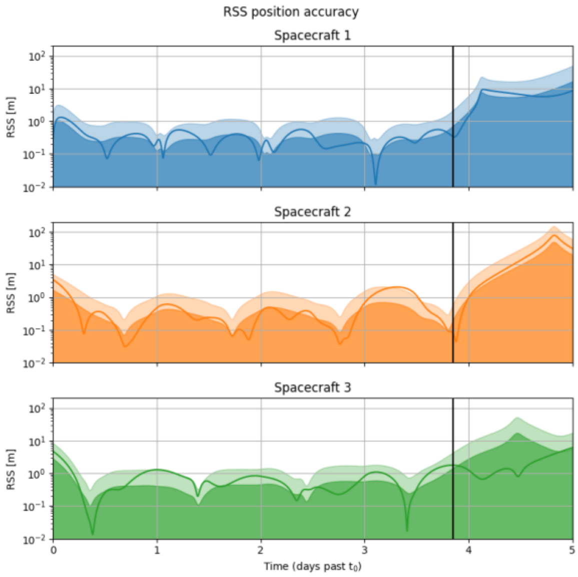

Figure 2: RSS of position accuracy for a randomly selected 4-day data arc. Dark and light shaded areas indicate, respectively, 1-σ and 3-σ estimation accuracies. The solid line shows the estimation error while the vertical black line indicates the epoch of the last data point. The right side of the solid black line shows the orbital error evolution (ephemeris aging).

5. CONCLUSIONS

In this paper we have presented the architecture proposed by the ATLAS team for implementing an ODTS system supporting a lunar constellation providing a LRNS capable of meeting an overall SISE requirement of 25 m 2-σ many hours after the last contact with ground. We have shown that the proposed architecture will rely on a dedicated network of very small tracking stations that shall establish two-way coherent K band links with each satellite of the constellation and support MSPA and SS modulation technique with CDM-M. The orbit determination of the constellation will be carried out by combining very accurate Doppler, SS ranging observables and SBI measurements.

The ground-to-space time synchronization can be performed any time a satellite is visible from ground and in parallel with tracking operations by means of a novel approach based on two-way coherent ranging measurements. Being the constellation virtually always in visibility from the Earth, ground-to-space TT could be performed almost continuously, reducing degradation of the LRNS service due to drifts of the onboard clocks. We have also identified an alternative method for TT based on asynchronous links providing even superior performances thanks to the suppression of some noise sources but requiring short temporary interruptions of tracking operations.

We have reported the results of numerical simulations showing that the satellite orbits can be estimated with an accuracy of a few meters after only 4 days of data and that time synchronization can be performed at the level of a few ns (or better).

The proposed architecture is relatively simple to be implemented and fully compatible with the timeline of the ESA moonlight initiative, aiming at an initial system deployment for the 2025-2026 timeframe. Additional system augmentations, requiring however further technological efforts and increasing costs have been already foreseen. Among the most promising solutions, one envisages the use of lunar beacons, particularly suited to magnify the effectiveness of the SBI technique to tie the constellation with a Moon-fixed reference frame.

6. ACKNOWLEDGMENTS

The authors wish to thank the rest of the ATLAS team, all giving their precious support for this work. We thank, in particular, P. Cappuccio, G. Cascioli, S. Molli, P. Racioppa, I. di Stefano, D. Pastina (Sapienza Univ. of Rome), G. Bury, R. Zajdel (Wrocław University of Life and Environmental Science), N. Rambaux (Observatoir de la Côte d'Azur) and A. Balossino (Argotec/Turin). The authors would like also to thank P. Giordano (ESA) for his continuous encouragement and supportive approach during the study. This work has been funded by ESA, under the contract No. 4000136075/21/NL/CRS.

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