Mem. S.A.It. Suppl. Vol. 16, 50

Memorie della
Supplementi

Contributions of Italian Spring Accelerometer to lunar exploration: gravimetry and seismology

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Abstract. The opening of the XXI century sees a new wave in lunar exploration, with a significant number of missions, both ongoing and in preparation. The exploration of our natural satellite is indeed important to gain understanding on the formation of Solar System and to create the basis for a future human colonization. On this respect, the study of the Moon gravity field is an important tool: indeed, the fine knowledge of selenopotential will put strong constraints on Moon internal structure and composition, and therefore on its formation and evolution towards current state. This is one of the main objectives of the proposed mission MAGIA (Missione Altimetrica Gravimetrica geochImica lunAre). Its GRACE–like two–spacecraft configuration, with a microwave link between the main satellite and a subsatellite, will enable a uniform coverage with high resolution. Due to the selected very low orbit (necessary for high resolution), the contribution of non–gravitational perturbations to the spacecraft dynamics will not be negligible. An effective way of accounting for them in the orbit determination and parameter estimation procedure is to measure their effect directly by means of an on–board accelerometer like ISA (Italian Spring Accelerometer). Its role in the mission scenario is discussed.

ISA instrument works also on ground, as seismometer and gravimeter, as it does in fact on Earth in a number of sites. It therefore can be used on lunar ground, as part of a selenodetic station permanently monitoring a selected location. This further capability of ISA accelerometer fits well with two current projects, the ILN (International Lunar Network) by NASA and the First Lunar Lander by ESA. Both aim to put on the Moon surface selenodetic stations which include instrumentation to investigate on its interior structure and composition, and on fundamental physics. Seismic measurements to constrain the Moon interior structure are a primary objective in both projects, and ISA is a candidate for this; its use in the context of ILN and of First Lunar Lander is discussed.

Key words. Solar system – Moon – Accelerometers – Gravimetry – Seismometry

1. Introduction

In recent times there has been a renewed interest in Earth's natural satellite, the Moon. This is due of course to several reasons, largely connected to the "renaissance" of space missions around

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Earth and in the Solar System in the 1990s. Scientific reasons are still present, though, and an overall list can be compiled:

- Nearest body outside Earth
- Solar System history
- Outpost for Solar System settlement
- Quiet place
- Fundamental physics.

The development of a space mission is not an easy task, and requires a considerable amount of funds. It is therefore important to integrate the right number of motivations in a coherent design, in order to obtain a feasible proposal and try to maximize the scientific return. In this framework, a quick view shows that a primary role is played by gravitational phenomena. Indeed, the gravitational interaction is responsible for the existence of Solar System bodies, but in particular it relates to the following issues of direct interest for our present objectives:

- Lunar probe precise navigation
- Selenodesy (lunar road map)
- Gravity field reconstruction
- Constraints on lunar interior
- Fundamental physics tests in the lunar environment.

It is important to underline that — at the present state of our knowledge — any improvement in the aforementioned points could require an equivalent improvement in instrumentation, modelization and analysis techniques.

In this context, we discuss here the role of **Italian Spring Accelerometer** (**ISA**) measurements in two lunar exploration scenarios: a global lunar gravitational field determination by a couple of orbiting probes (Section 3) and seismometric measurements on selected lunar ground sites (Section 4). ISA is a high–sensitivity three–axis accelerometer suitable for both space and ground use. Its working principle and characteristics are described in Iafolla et al. (2011) and are not repeated here.

2. The lunar gravitational field: its determination, features and current knowledge

As for the other bodies in the Solar System, the gravitational field produced by the Moon mass distribution is an important source in order to obtain information on its internal structure and composition. Indeed, the gravitational field produced by a body depends on its internal density distribution and can be used to put constraints on, e.g., the existence of a core or mantle or crust features.

It is customary in geophysics to expand the gravitational potential in spherical harmonics (see for example Bertotti et al. 2003; Hofmann-Wellenhof & Moritz 2006):

$$U(\boldsymbol{r}) = -\frac{GM}{r}\left[1 + \sum_{l=1}^{\infty}\left(\frac{R}{r}\right)^{l}\sum_{m=0}^{l}(\bar{C}_{lm}Y^{C}_{lm}(\theta,\phi) + \bar{S}_{lm}Y^{S}_{lm}(\theta,\phi))\right], \quad (1)$$

where M and R are mass and equatorial radius of the primary, $\boldsymbol{r}$ the vector from its center, Y^{C}_{lm} and Y^{S}_{lm} the spherical harmonics (real basis) of **degree** m and **order** l respectively. The normalized coefficients $\bar{C}_{lm}$ and $\bar{S}_{lm}$ characterize the specific gravitational potential and are the quantities to be measured. In practice the series has to be truncatd at some l_{max}: the model has therefore a resolution $\sim 5458/l_{max}$ km for the Moon. It has to be noticed the behaviour $\sim 1/r^{l+1}$ of the harmonic components of degree l. The acceleration contribution of these components scales as $\sim 1/r^{l+2}$, therefore the higher degree terms are effective only for objects close to the primary.

Given a spacecraft in orbit around its primary (in our case the Moon), its orbit is sensitive to the various harmonics, being perturbed with respect to the Keplerian (monopole) case. The orbit therefore contains information about the gravitational field producing these perturbations, and this information is contained in the spacecraft tracking data[1]. The extraction of this information is performed in the so–called orbit determination and parameter estimation procedure, in which a model for spacecraft dynamics is fitted to the experimental data, estimating a number of parameters the model depends upon; among them, the $\bar{C}_{lm}$ and $\bar{S}_{lm}$ coefficients (Milani & Gronchi 2010; Montenbruck & Gill 2000).

Tracking data of lunar missions have been used along the years to obtain increasingly precise models of the selenopotential. A number of them is listed in Table 1, together with data type employed and maximum degree of the expansion. A useful means to compare them is to consider the so–called **degree variance** C_l, which is given by

$$C_l^2 = \frac{1}{2l+1} \sum_m (\bar{C}_{lm}^2 + \bar{S}_{lm}^2). \tag{2}$$

This quantity gives the average contribution of the harmonics for a given degree l. For terrestrial planets it follows the following empirical rule (**Kaula's rule**):

$$C_l^2 = A_K \frac{10^{-10}}{l^4} \tag{3}$$

with A_K depending on the body (Kaula 1966; Bertotti et al. 2003). In Figure 1 the degree variance for the models listed in Table 1 is shown, together with the related error (declared standard deviation σ). The improvement over the various missions and techniques is apparent. The curves plotted in Figure 1 show also that extending l_{max} (and therefore the resolution of the model) for a given data set could not result in effective improvement of the model. The models LP100K, LP150Q and LP165P are based on the same data set: the data do not contain useful information for the higher harmonics, resulting in a signal–to–noise ratio of about 1 (or worst); see the discussion in Konopliv et al. (2001).

A somewhat surprising result of the first selenopotential models has been the discovery of local anomalies in the gravitational field. These are mainly correlated with the positions of the lunar maria and have been explained as caused by anomalous mass concentrations (**mascons**) in the crust and upper mantle (Muller & Sjogren 1968). Apart from their important geophysical value, these anomalies must be taken into account for the navigation of spacecraft around the Moon. They make its orbit more and more eccentric, eventually leading the spacecraft to crash on Moon surface.

The procedure for tracking the Lunar Orbiters, the Apollo subsatellites, Clementine and Lunar Prospector was the "standard" one: Doppler tracking of spacecraft from Earth stations. This has a main brawback: since the Moon is in a 1:1 resonance between revolution and rotation, the spacecraft passes over the farside when it is not in view from Earth stations. This causes a severe loss in information for the harmonics related to farside gravitation. A way to overcome this problem, recently implemented by the Japanese mission SELENE (Kaguya), is a four–way link employing an additional — relay — satellite (Rstar) which enables a coherent signal to be transmitted, thereby recovering the farside information (Namiki et al. 2009). The strong improvement over the previous models is apparent in Figure 1.

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[1] Spacecraft tracking is done routinely for navigation purposes. Currently, the most used technique employed for interplanetary probes involves radiometric tracking providing range and range–rate data (Montenbruck & Gill 2000).

Table 1. A selection of selenopotential models, with data type employed and maximum degree of related spherical harmonics expansion.

Model	Data type	Max degree	Reference
GLGM-2	Doppler tracking of Lunar Orbiters 1 to 5, the Apollo-15 and Apollo-16 subsatellites, and the Clementine spacecraft	70	Lemoine et al. (1997)
LP75G	Radio tracking of the Lunar Orbiter 1 to 5, Apollo 15 and 16 subsatellites, Clementine, and the first three months (to April 12, 1998) of Lunar Prospector spacecraft	75	Konopliv et al. (1998, 2001)
LP100K	Radio tracking of the Lunar Orbiter 1 to 5, Apollo 15 and 16 subsatellites, Clementine, and all the data (Jan 11, 1998 to July 30, 1999) of the Lunar Prospector spacecraft	100	Konopliv et al. (2001)
LP150Q	Same as LP100K	150	Konopliv et al. (2001)
LP165P	Same as LP100K	165	Konopliv et al. (2001)
SGM100h	Four–way Doppler tracking of SELENE (Kaguya) Main and Rstar spacecraft	100	Namiki et al. (2009)

3. The MAGIA mission proposal

As discussed in Section 2, the precise knowledge of lunar gravitational field is hindered by the poor coverage of farside, and only recently — with SELENE (Kaguya) mission — there has been a dramatic improvement in this direction. A further step is the italian mission proposal **MAGIA** (**Missione Altimetrica Gravimetrica geochImica lunAre**). MAGIA, whose Phase A has been funded by Agenzia Spaziale Italiana, has several scientific objectives (MAGIA Team 2008):

- Detailed study of the internal structure of the Moon through its gravity and figure
- Study of the polar and subpolar regions in terms of their morphology and mineralogy
- Study of the lunar exosphere and radioactive environment
- Improved measurement of the gravitational redshift
- Precursor test for 2nd generation Lunar Laser Ranging
- Determination of the position of the seleno–center.

The study of the Moon gravitational field is therefore an important objective for this mission. In particular, accurate knowledge of mantle and crust structure and composition requires a rather low orbit and the overcoming of the farside problem which has been solved by SELENE (Kaguya) with the relay satellite.

The proposed strategy for MAGIA implies the use of a GRACE–like (see for example Tapley et al. 2004) configuration in which two satellites (the main spacecraft and a subsatellite) are on the same orbit — a distance between 40 and 70 km apart — and are connected by an S–band link. This link will provide further data in addition to the standard X–band tracking of main spacecraft, thereby improving the knowledge of the mid–wavelength part of selenopotential ($l \leq 80$). This technique is known as **Satellite–to–Satellite Tracking** (**SST**): also the forthcoming lunar mission GRAIL (Zuber et al. 2008) is based on it.

The need for high resolution implies a rather low orbit for the satellites (see Eq. 1), thereby enhancing the strength of non–gravitational perturbations like albedo and infrared radiation pressure (and related thermal effects). These perturbations (for an account of them see Milani et al.

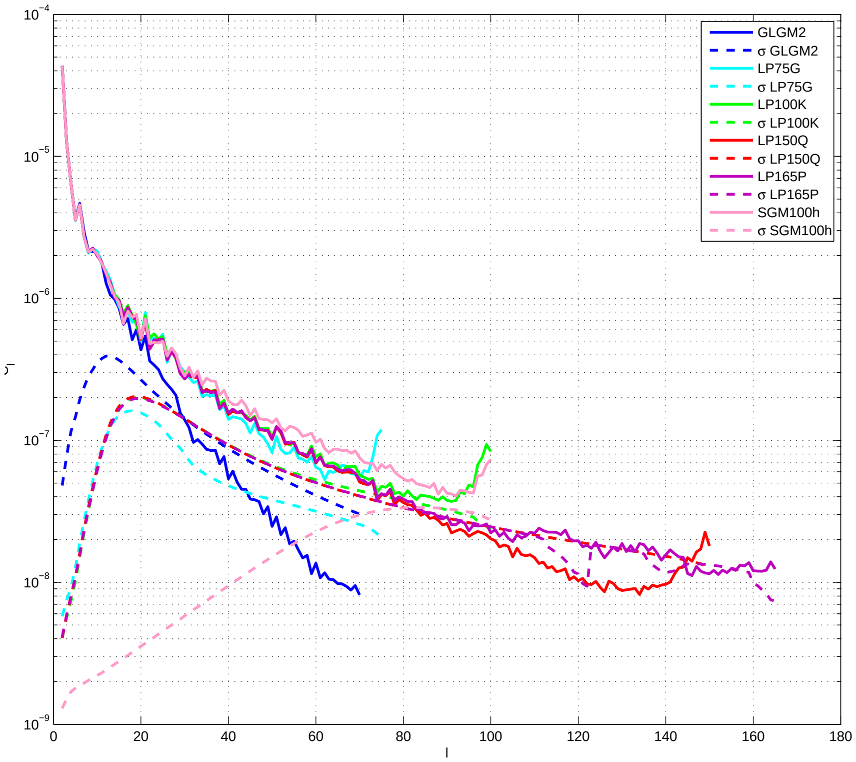

Fig. 1. Degree variance and related error for the selenopotential models listed in Table 1.

1987), if not properly taken into account in the modelization of the spacecraft dynamics, can bias the estimate of the sought–for parameters, e.g. the geophysical ones. In MAGIA, it is proposed to measure them directly by the ISA accelerometer, in a way similar to that employed for BepiColombo mission (Iafolla et al. 2011). This could at least in principle improve the fit and the parameters estimate.

4. Lunar seismology

Seismology is one of the few means at our disposal to gather information on the internal structure of a body. This of course requires a seismometer to be put and operated on the surface of that body and, while it is routine activity for Earth–based instruments, it is not so for the other bodies in the Solar System. The Moon does not have global scale tectonic activity: the expected signals are related the most to its internal vibration modes, possibly excited by tides, thermal behaviour of the crust, asteroid impacts.

In order to characterize the lunar seismic environment, two current projects, the ILN (International Lunar Network) by NASA (Science Def. Team for the ILN Anchor Nodes 2009; ILN Communications Working Group 2009) and the First Lunar Lander by ESA, aim to put on

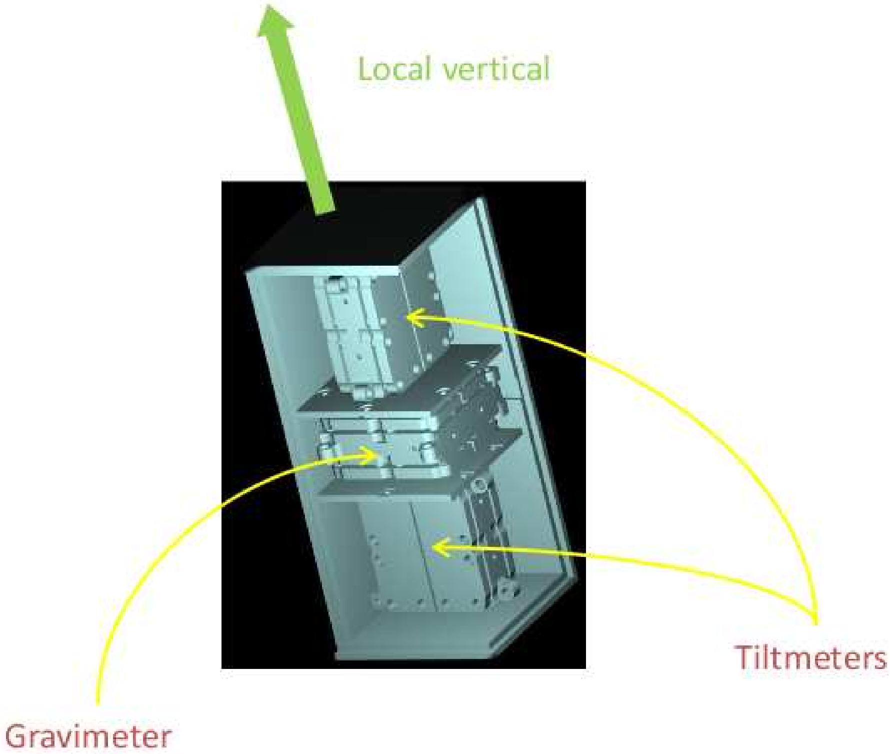

Fig. 2. Proposed arrangement of the sensing elements for ISA-S.

the Moon surface selenodetic stations to permanently monitor a selected location. These stations should include instrumentation to investigate on its interior structure and composition, as well as to perform fundamental physics tests.

ISA accelerometer, its sensing elements being composed of three one–dimensional harmonic oscillators, works equally well on the ground and can be used in fact as a high–sensitivity seismometer (Iafolla et al. 2001, 2002). The three sensing elements are arranged orthogonally with respect to each other and measure the three different components of the seismic signal. The seismometer must be hard–mounted on the surface of the Moon so that the displacements of the Moon surface are equal to that of the ISA-S external structure.

The implementation of the three–axis seismometer is made by arranging the three sensing elements with their centers of mass along a common axis that will be placed along the local vertical. With this choice two of these elements behave like tiltmeters, while the last one behaves like a gravimeter under the direct action of the Moon gravity. In Figure 2 the three elements with sensitive axis aligned along the local vertical are shown, while in Table 2 the main parameters of the ISA-S seismometer are indicated.

One of the main issues to be considered about the proposed seismometer is its thermal stability. Due to the high temperature variations on the surface of the Moon, especially at very

Table 2. ISA-S characteristics.

Parameter	**Value**	**Remarks**
Measurement accuracy A_0	10^{-9} m/s^2	Accuracy required for the acceleration measurements
ISA-S intrinsic random noise S_0	10^{-9} m/s^2/ $\sqrt{Hz}$	Level of the total random noise in the ISA-S measurements process
Frequency range	10^{-5} — 1 Hz	The maximum resolution is obtained inside the frequency band, but ISA-S can work quite well also at frequencies out of the indicated band, increasing the bit rate and taking into account the mechanical transfer function
Dynamic range	10^6	Set by acquisition system and converter
Frequency readout interval	1 s	The required data rate is 1 sample/s for the three acceleration components and the three sensing temperatures
Resonance frequency	3.5 Hz	Frequency of the mechanical oscillator
Quality factor Q	10	Quality factor of the oscillator
Thermal stability x, y	$5 \cdot 10^{-7}$ m/s^2/°C	ISA-S thermal stability for the two tiltmetric components
Thermal stability z	$1.6 \cdot 10^{-5}$ m/s^2/°C	ISA-S thermal stability for the gravimetric component (using Ni-Span C)
Total mass	5.5 Kg	
Dimensions	300 × 300 × 300 mm	
Power dissipation	6 W	
Data rate (nominal)	15 kbit/s	
Capability of ISA-S	—	Capability to recover the local vertical autonomously, in order to operate with two of its elements like tiltmeters and one like gravimeter

low frequency (period corresponding to the Moon day), the immunity of the seismometer to the thermal variations must be very high. A recent configuration for the instrument had a thermal stability equal to $5 \cdot 10^{-7}$ m/s^2/°C for the mechanical part and one order of magnitude better for the electronic part.

The above stated value for the thermal stability of the mechanical parts is meant for the two elements that work as tiltmeters, i.e. they are arranged with their sensitive axes perpendicular to the local gravity. For the element that will be arranged with its sensitive axis along the local gravity the condition is different and the effects of the temperature arise directly on the mechanical spring, changing its elastic constant. Using the appropriate material as e.g. Ni-Span C, it is possible to have an intrinsic thermal stability of 10^{-4} m/s^2/°C under the action of the gravity field of the Earth and a factor 6 better in the gravity field of the Moon.

As baseline for the proposed seismometer, in order to keep the power consumption at a low level, a passive thermal arrangement has been chosen. The internal power dissipation, of the order of 5 W, necessary for the seismometer functionality, will be also used, by means of an appropriate choice of the thermal conductivity vs the external environment, to bring the temperature of the electronics at a value higher than -55°C, insuring its functionality during the moon night, when the external temperature is lower than the indicated value, below which the electronics components don't work. A second condition is imposed to the maximum operative temperature of the electronics, usually equal to 125°C. Under almost every temperature condition present on the Moon landing site, we can choose an appropriate thermal insulation allowing the electronics to work properly. It is clear that the passive thermal system cannot attenuate the values of the total thermal variation, but it can only translate them. The worst working condition for the seismometer is between -80 and +125°C. It is clear that in this passive case at the output of the seismometer there is a quite high spurious noise signal; in the worst case it varies in the range (-80 to +125) $\cdot 5 \cdot 10^{-7}$ m/s^2, with an amplitude equal to $\approx 10^{-4}$ m/s^2. To follow this signal, if the required resolution is 10^{-9} m/s^2/°C, it is necessary to have a dynamics equal to 10^5 for the two tiltmeters. For the gravimetric component, having a thermal stability a factor 30 worst, the required dynamics is $3 \cdot 10^6$, quite difficult to obtain. A second advantage of the passive thermal system is that it ensures a quite high level of thermal attenuation at frequencies above the thermal cut frequency of the system; this is helpful in order to attenuate the possible thermal effects inside the measure frequency band.

A critical point that is necessary to verify is the aging that acts especially on the gravimetric component, changing the equilibrium position of the test mass during a very long time; this causes a signal that can bring the elements out of their dynamics. Our experience matured in the implementation and operation of the GEOSTAR gravimeter (Iafolla et al. 2002) suggests that the problem can be reduced if the mechanical spring will be used to hold the mass under the gravity effects for long time before the instrument operation in order to extinguish the transient. The mechanical stops, used to protect the apparatus against the strain at launch, avoid the mechanical spring to restart another transient. The better values obtained in one of the GEOSTAR missions after several months is $2.1 \cdot 10^{-6}$ g/day.

ISA-S will be a totally autonomous and self standing instrument, it will only sends the data to the central control system of the station that provides the communication to Earth. The most delicate parts are the mechanical springs that hold the proof masses. A passive system of stops keeps the mass close to the equilibrium position also during the strain occurring at the launch. This passive system has been well tested. Electrically controlled micrometric screws provide the capability to bring the seismometer in its operational position, with the tiltmetric elements with sensitive axes perpendicular to the local gravity and the gravimetric element with sensitive axis in the direction of the local vertical.

5. Conclusions

The exploration of the Moon has become again an important issue in space science. In particular, improved models of its gravitational field will add significant constraints to its internal structure and composition. Seismic measurements will be also important. The Italian Spring Accelerometer is a candidate for both types of measurements, by supporting gravimetric space measurements (MAGIA) and by performing on–ground direct seismic measurements (ILN and First Lunar Lander).

Acknowledgements. The authors wish to thank the MAGIA Team, in particular Angioletta Coradini, Alessio Di Salvo, Cesare Dionisio, Giorgio Perrotta and Marco Fermi. This research has made use of NASA's Astrophysics Data System.

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