MOURA magnetometer for Mars MetNet Precursor Mission. Its potential for an in situ magnetic environment and surface characterization

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Abstract

MOURA magnetometer and gradiometer is part of the scientific instrumentation for Mars MetNet Precursor mission. This work describes the objective of the investigation, summarizes the work done in the design and development of the sensor as well as its calibration, and shows the demonstration campaigns to show the potential of such instrument for planetary landers and rovers.

Key words: Space and planetary magnetometer; gradiometer; magnetic cleanliness; Mars magnetic anomalies; terrestrial analogues of Mars; geomagnetic field.

El Magnetómetro MOURA para la Misión Mars MetNet Precursor y su potencial para la caracterización magnética de la superficie del Planeta

Resumen

El magnetómetro y gradiómetro MOURA forma parte de la instrumentación científica de la misión precursora de MetNet a Marte. En este trabajo se describen los objetivos de esta investigación, se recopilan las tareas de diseño y desarrollo del mismo así como su posterior calibración y se muestran las principales acciones de demostración emprendidas con el instrumento que muestran su capacidad para medidas magnéticas a bordo de aterrizadores y rovers.

Palabras clave: Magnetómetro espacial y planetario; gradiómetro; limpieza magnética; anomalías magnéticas de Marte; análogos terrestres; campo geomagnético.

Summary: Introduction 1. Magnetic Cleanliness in the Design 2. Instrument scientific objective 3. Demonstration of MOURA capability for MetNet goal 4. Demonstration of MOURA capability for planetary rovers 5. Conclusions. Acknowledgements, References.

Introduction

MOURA instrument is one of the payloads of Mars MetNet Precursor Mission (MMPM). It consists of a vector magnetometer and gradiometer to measure the surface magnetic field and its temporal variations in this static precursory mission.

To cover the largest amount of scientific needs and because of the necessity of complementary measurements, planetary surface platforms normally try to reach an optimized suite of instruments, which measure many magnitudes at the expense to have payloads with limited physical and energy envelopes. This makes that in general payloads of planetary missions have constraints on their dimensions, masses and power. In the case of MOURA instrument, the physical envelope is a mass of 72 g and a volume of 150 x 30 x 15 mm^3. This is a real challenge that affects many aspects of the design of the magnetometer. For instance in our instrument the proper transducer has been chosen of Anisotropic MagnetoResistive (AMR) technology because of its very good trade-off between performances, and dimensions and weight (commercial HMC1043 three axes sensor is 25.6 mg and 3.5 x 3.0 x 1.2 mm^3 typically). However this implies other difficult technological constrains to deal with as the relatively important swings of AMR technology magnetic response with temperature together with the large temperature range expected daily during the mission. Also some radiation tests were performed to guarantee a proper behavior of the sensors with the radiation (Sanz et al., 2012).

Another challenge with respect to the implementation of magnetic payloads is to avoid magnetic noise from the platform (e.g. Connerney et al., 2015). A boom to deploy the magnetic head could partly solve this problem but due to the additional mechanical problems it is not foreseen in general. In MMPM the magnetometer is a compact instrument and therefore the magnetic signature of the electronic components needs to be minimized below the expected resolution of the sensor. This is a difficult task with restrictions on the kind of selected components, making sometimes necessary the use of Plastic Encapsulated Microcircuits – PEMs; and in the layout, which needs to be carefully studied to minimize the magnetic signature of the components and routes carrying currents.

Besides, in the particular case of MMPM lander the roughness of the touching down, based on an intense impact against the martian surface, leaves an extra degree of uncertainty in the orientation of the instrument respect to the surface. Due to the necessity to know not only the intensity of the magnetic field but also its orientation

and the varying components during the effects of solar events, MOURA comprises a tilt angle detector of moderate precision (Diaz Michelena et al., 2015).

The calibration of the magnetic response has to cope with the magnetic field but also with the temperature and all aspects related to the orientation of the sensing axes. Such calibration of the instrument in terms of the response under the influence of a magnetic field and different temperatures as well as in the different orientations of the magnetometer respect to the surface has been described in Diaz Michelena et al. (2015). In this work some new aspects related to the magnetic cleanliness issues of the design will be described.

Regarding the scientific objectives, so far, magnetic signatures of Martian surface and its crustal rocks have only been measured between 100 and 440 km altitude by Mars Global Surveyor with a very sparse resolution of thousands of square kilometres (Acuña et al., 1998; Connerney et al., 2005). These remote sensing data indicate up to 20 times higher magnetic anomalies than those of the Earth (Scott and Fuller, 2004). However, they are restricted to areas with old Noachian (>3.8 Ga) crustal rocks exposed at low and southern latitudes of the planet. They acquired their remanent signature during its early geological history with an active core dynamo like that on Earth (e.g. Sandu and Kieferl, 2012).

Since no magnetic measurements have been performed directly on the Mars surface, the novelty of on ground measurements and the importance of the first analysis is clear. However, it is undoubtedly that much more information could be extracted in the case to have a roving instrument capable because of the increased surface area of study, which can be used together with the satellite data to construct better models of local and regional anomalies of the crust and its relationship to the ionosphere (Lillis and Fang, 2015; Matta et al., 2015). On ground magnetometry with landers and rovers seems to be the most immediate feasible technology to complement the satellite measurements and to explore the mystery of the martian strong remanent signature.

In this context the scientific objective of MOURA instrument is the measurement of the surface magnetic field and its variation along the time (internal and external fields; e.g. Lillis and Fang, 2015). Since Mars lacks an internally generated active global magnetic field, the internal field is sourced by the poles of the rocks remanence (e.g. Acuña et al., 1998) and the external field by the ionosphere (Brain et al., 2015). The time variations of the field comprise two effects: on the one hand the variations due to the changes in the remanence with the temperature swing along a sol (martian day), and on the other hand, the influence on the magnetic field of the different solar events whose effects reach the martian surface. Thus, the first demonstration of the instrument has been a comparative study of the measurements of MOURA with the reference instrumentation at a geomagnetic observatory.

A second demonstration regarding the capability of the instrument to measure the anomalies contrast on the surface has been done in terrestrial analogues of Mars. These represent also high intensity range scenarios of the red planet (Diaz Michelena and Kilian, 2015 and Diaz Michelena et al., 2016). For the selection of appropriate terrestrial analogues mineralogical and chemical implications from remote sensing

data, meteorites derived from Mars and fallen on Earth as well as rover explorations on the Mars surface during last 10 years have been considered. They indicate volcanic, plutonic and sedimentary rocks which are in general comparable to our selected rock suites on Earth.

This work intends to summary the eight years effort devoted to the design, calibration, and static and surveying measurements performed to demonstrate the potential of MOURA instrument for planetary surveys.

1. 1. Magnetic Cleanliness in the Design

It is a general rule for magnetometers to have the electronics box separated from the sensor head in order to minimise the magnetic contamination of the parts of the electronics box and the currents, which may generate non-desirable magnetic fields in the proximity of the sensor. In the same sense, the magnetometers are commonly deployed from the platform. But MMPM has a very limited mass and volume budgets and thus it is not possible to separate the electronics and the sensor in two boxes but it consists of a boom-shaped instrument which comprises sensor head and electronics (Fig. 1). Furthermore the deployment of the instrument is made through the inflatable structure achieving a distance > 0.5 m.

This scenario has some implications in the vector measurements due to the fact that the proper instrument needs to provide the angles respect to the vertical and an optical system for the orientation. However, this also implies important needs concerning the design of the magnetometer (part list, layout and routing)
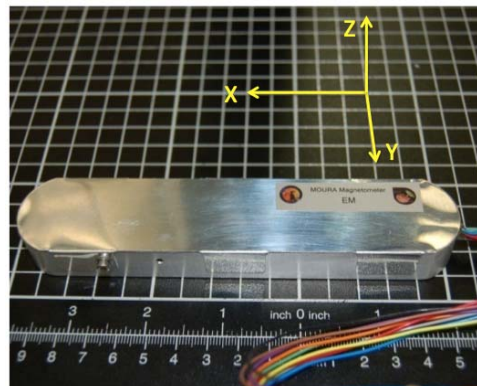

Figure 1. Engineering Model of MOURA Magnetometer. Dimensions are: 150 x 30 x 15 mm.

Table 1. Scheme of the table elaborated for the magnetic field of every kind of component. This table, together with the equivalent displaying the magnetic moment (not included in this article), allows a categorization in three levels: Not Permitted, Critical and Permitted components.

The methodology developed to overcome this problem has been the following: Firstly we have measured the magnetic moment and stray magnetic field of all the components of the part list in the two perpendicular directions of the printed circuit board (X and Y axes). For all the components (including the passive components) and for every axes, we have elaborated a table (Table 1) with 1) non permitted, 2) permitted and 3) critical components regarding their magnetic moments m_x and m_y and the field created at different distances along the two directions. The values of this table 1 (in which not all the information can be shown because it is considered confidential) strongly depend on the manufacturer and therefore it has to be used carefully and always applied to the same batch of components

In many cases one of the main barriers that prevented the use of the components is the packaging material. Many integrated circuits (ICs) have kovar packages because of the flexible thermal expansion of this material, which can be made to match other elements in the ICs. The problem is that kovar is an alloy with a high contents of Iron, Nickel and Cobalt, which are three transition elements with considerable magnetic moments (5.0-5.6, 4.3-5.2 and 2.9-3.9 Bohr magnetons respectively), and often a non-negligible magnetic signature. Due to this drawback, some of the ICs have been substituted by Plastic Encapsulated Microcircuits (PEMs), with the consequent screening and qualification of these components, which has been done with procedures based on NASA Jet Propulsion Laboratory (JPL) PEMs screening and qualification flow rev. K 2008.

The table equivalent to table 1 for the magnetic moments has been the input to perform a magnetic model of punctual dipoles (Fig. 2) of the Printed Circuit Board (PCB). The layout therefore responds to an electronic basis formerly affected by a criterion to minimise the magnetic signature of the components in the position of the sensor head.
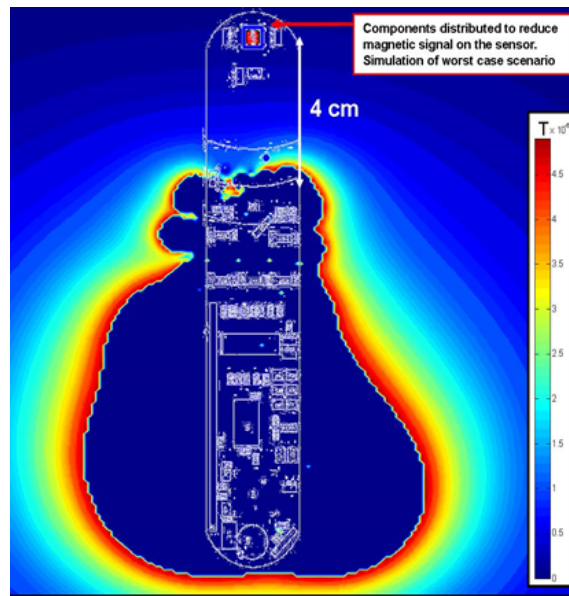
Figure 2. Punctual dipole models of the instrument layout. The components have been placed at a minimum distance of 40 mm of the sensor head.

2. Instrument scientific objective

The main goal of MOURA magnetometer on board MMPM is the measurement of the magnetic field at a single point of the surface of Mars.

The different features of this field for the Earth and Mars are shown in table 2. As it has been outlined before, Mars does not have a global field dynamo generated as it is the case of the Earth. Mars Global Surveyor measurements lead to an estimated value of the martian magnetic moment lower than $2 \cdot 10^{18}$ Am^2 (Table 1), which is less than four orders of magnitude lower than the paleodipole of our planet. However, at its initial stages, Mars had a global field whose intensity at the surface was calculated to be similar to that of the terrestrial field i.e. in the order of tens of µT (Stevenson, 2001). The crust formed in the period before the field was extinguished acquired a magnetization (remanent + induced) and nowadays the magnetic field measured in orbit responds to the remanent magnetization of the crust. The variations are due to the volume, the location and the different characteristics of magnetized rocks (local magnetic anomalies). Therefore, the local and static magnetic field (of internal origin) at the landing site of MMPM is expected to be produced by the poles of the nearby

magnetized rocks which appear in the boundary of rocks with different magnetisations or at the surface in contact with the atmosphere.

The gradient of this field will be very influenced by the poles distribution. If the rocks are uniformly magnetized, the gradient of the field will be negligible whilst if the rocks are non-uniformly magnetized, the poles distribution will lead to a non-negligible gradient. Furthermore the field and its gradient will change with the daily and seasonal temperature swing of the planet (-120° to +20° C) reaching temperatures where some minerals present magnetic transitions, like the Morin transition of hematite.

Regarding the external origin, the surface field is expected to change with the solar exposure and its activity. At this point, the field variations on the red planet are expected to have lower amplitudes than those of the Earth with an active global field and a well-defined area of influence of this field inside the magnetosphere.

The demonstration of the capabilities of the instrument has been done on Earth in two lines: on the one hand, static measurements registering the absolute value of the field and its orientation as well as the daily variations to show the ability of the instrument to measure these features on Mars (MetNet goal), and on the other hand, mobile measurements to show the extra capability of such device for rovers (future scenarios). In the next sections the methodology and results of these demonstrations are explained.

3. Demonstration of MOURA capability for METNET goal

This part of MOURA ability has been done in cooperation with the personnel of the Geophysics Observatory of San Pablo de los Montes – Toledo (SPT) which belongs to the Instituto Geográfico Nacional. SPT is located in Spain, at 39.547ºN, 4.349ºW, where the large distance to the populations guarantees a low magnetic noise. The observatory belongs to the INTERMAGNET (www.intermagnet.org) global network and to the International Association of Geomagnetism and Aeronomy (IAGA) (www.iugg.org/IAGA), and counts with proper instrumentation to the measurement of the surface magnetic field and its variations along the time. In particular, the instrumentation comprises a fluxgate magnetometer FGE – Danish Meteorological Institute and a fluxgate vector magnetometer Geomag M390 as well as an Overhauser effect magnetometers GSM90. The instrumentation set up is completed by a dIdD Gemsystem equipment, two declinometers-inclinometers Zeiss 010B with a fluxgate Bartington probe for absolute weekly observations.

Table 2. Main field intensities of the magnetic sources on Earth and Mars (Data compilation in Diaz Michelena et al., (2015) after Acuña et al., 1999, Connerny et al., 2015; Plattner and Simons, 2015).

Source	Feature	Earth	Mars (estimated)	Main temporal and spatial characteristics
Interior	Paleodipole	10^{22} - 10^{23} Am^2	< $2 \cdot 10^{18}$ Am^2	Inversions
Crust	Strong, stable, remanent magnetization	0.1 - 1 Am^{-1}	12 – 20 (up to >54) Am^{-1}	Tens of km thick magnetized layer
Surface	Surface rocks	100 nT	10^5 nT	
	Local Strong Magnetic fields	10 - 10^4 nT	2,200 nT	Earth: In many cases related with geological structures (volcanoes, magnetite out-crops…) Mars: mainly in the highlands in the Southern Hemisphere
Ionosphere and Magneto-sphere	Daily variation	20 nT (200 nT at the Equator)	0.5 - 5 nT at the Equator	
	Magnetic Storms / Substorms	100 – 1,000 nT	Few nT	Earth aurora: High latitude Auroral oval, 80 - 500 km height Mars aurora: High and low latitudes. 30 km long – 8 km height
	Elongate-shape density bulges near the surface	---	Few nT	Local Magnetospheres
	Pulses	0.1 - 100 nT	---	
	Flux ropes	20 nT	< 5 nT	
	Interplanetary - planetary transition	30 nT	< 5 nT	Earth: Solar wind-magnetosphere Mars: Solar wind-ionosphere
	Several ionos-pheric layers	≈ 2,500 nT	Few nT	Earth: From 60 to 2000 km height Mars: From 80 to 200 km height
	Plasma current	10 - 20 nT	< 5 nT	

The raw data provided by the magnetometers are further analyzed and treated by the personnel in the observatory, who publishes final data within a year compiling worldwide measurements of the other observatories (Diaz Michelena et al., 2015). In this work, partially compensated data (provided by the observatory in a month from the moment of the measurements) will be used as reference.

Due to the moderate intensity of the magnetic anomalies in the Iberian peninsula (Martínez Catalán, 2012), MOURA magnetometer was placed at the observatory and aligned according to the SPT reference magnetometers and the data collected by the instrument were correlated with those of the reference magnetometers in intensity and orientation. During the campaigns MOURA magnetometer was operated remotely by INTA personnel.

Two campaigns were carried out with MOURA instrument in SPT. The former one was used to fine adjust the offset i.e. the response at zero field of the sensors. It is described in Díaz Michelena et al., 2015. The latter had the purpose to register a geomagnetic storm in June 2013 28th and 29th.

The occurrence of a magnetic storm is determined by the low values of the Equatorial Geomagnetic Index Dst. This index is a measure of geomagnetic activity derived from the horizontal component of the geomagnetic field $H = (X^2+Y^2)^{1/2}$ of four low-medium latitude observatories (between $\pm$ 40º). During quite periods its value is zero but Dst values in the order or < -50 nT indicate a geomagnetic storm as it is observed in the upper graph of Fig. 3.

Fig. 3 (second to fourth graphs) shows the three components of the magnetic field of MOURA sensors 1 and 2 as well as the reference data provided by the magnetometers of SPT. In the figure it can be seen how the values registered by MOURA magnetometers reproduce those of the reference instruments along the monitored period. In addition to the high amplitude variations, the components show non-periodic fluctuations with amplitudes ranging between units and tens of nT, which are accurately registered by MOURA, whose data match very well with SPT ones.

4. Demonstration of MOURA capability for planetary rovers

As it has been introduced, it is an important objective to demonstrate the capability of the miniaturized MOURA instrument in a real context of terrestrial analogues. This has been done by means of the intercomparison with the data of a scalar caesium reference magnetometer commonly used for magnetic prospections (Geometrics 858; Diaz Michelena and Kilian 2015; Diaz Michelena et al., 2016).
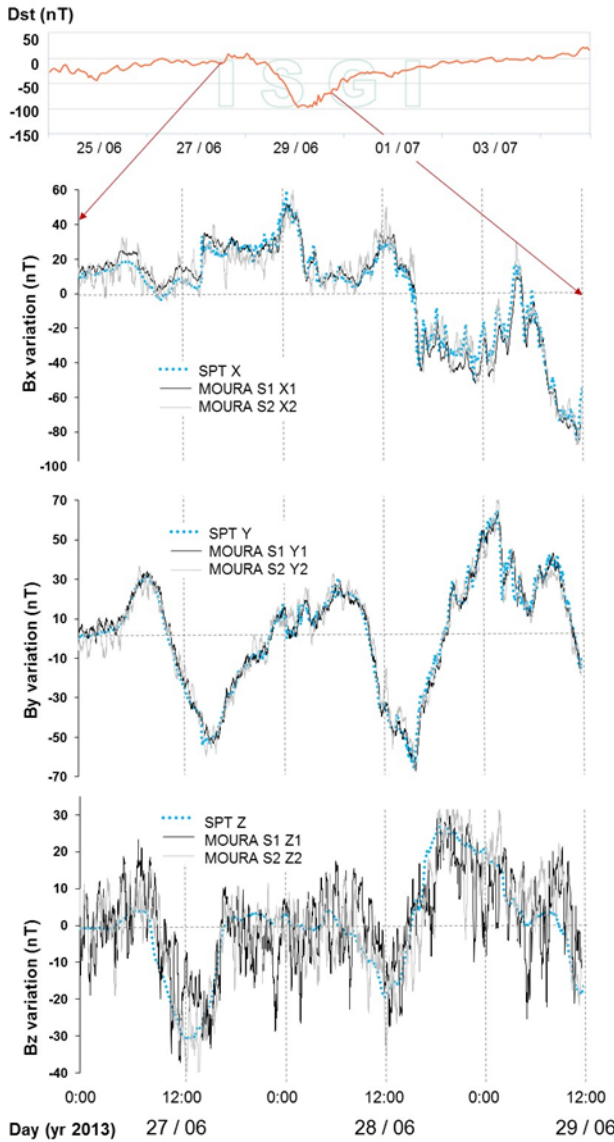
Figure 3. Plot of Dst by the International Service of Geomagnetic Indices (ISGI) and variations of the three orthogonal components of the magnetic field (X – North, Y – East and Z – Vertical downwards) registered by MOURA magnetometers (Black S1 and grey S2) and SPT reference magnetometers (blue and dotted) in the period of the magnetic storm.

The sites for the surveys have been selected with the following criterion: a) relatively unaltered exposed rocks that are not covered by soils or perturbed by anthropogenic interferences; b) the existence of well-defined rock transitions where high resolution grids, with spacing of metres to centimetres, can be performed, and c) exposed rocks that are representative for a large number of martian surface rocks with most distinct magnetic signatures and amount of magnetic carriers.

Based on these criteria three test sites have been selected in unpopulated areas in or near the Southern Andes between latitudes 20S to 52S (Fig. 4). Besides, the different sites present a high variability in the climatic factors as strong wind (up to 120 km/h), extreme temperature (- 10º C to 35º C), pressure (100 to 50 kPa) and humidity (from 90 to 15 %) ranges including some dust storm events. The characteristics and mapping results are described in the following, itemized from extremely high to low anomaly sites, and with an increasing spatial resolution of the anomaly detection:
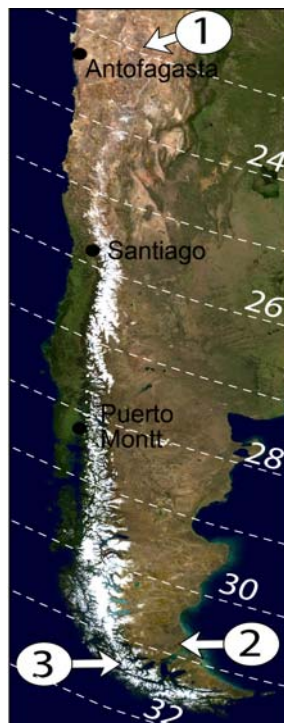

Figure 4. Selected test sites 1 to 3 in South America between 20 to 52°S and areas with different intensities of the International Geomagnetic Reference field ranging from 23,000 to 32,000 nT at the different sites.

SITE 1 "El Laco" is characterized by large magnetite bodies which crop out around El Laco volcano in the Central Andes and have been formed by either volcanic and/or hydrothermal processes (Alva-Valdivia et al., 2003; Naranjo et al., 2010). Together with the iron ore deposits of Kiruna (e.g. Jonnsson et al., 2013) they represent world-wide unique examples for very strong local magnetic anomalies like that of the southern Noachian highlands of Mars (Connerney et al., 2005). Our surveys of magnetite-bearing outcrops exhibit very high positive magnetic anomalies from 30,000 to > 110,000 nT (Fig. 5A; Diaz Michelena et al., 2016) which are of extreme intensity compared to other magnetic mappings on Earth (e.g. Hinze et al., 2013). The high variability of the magnetic signature on this ore deposits within a small scale of decimetres to meters is probably related to multiple magnetite orientations and a large grain size variability with multi and single domain status reflecting a complex ore formation history between 2.2 to < 2.0 Ma including Earth magnetic reversals. Surrounding andesitic lavas and pyroclastic material have much lower positive anomalies (+ 100 to + 2,000 nT; Fig. 5A) and the surface transition between andesitic rocks and magnetite-bearing ores is very sharp within less than a metre distance.

The surveys with the reference magnetometer G-858 yield similar results but a lower spatial resolution and reduced definition of the surface rock transitions since this magnetometer became often saturated when high local magnetic anomalies were reached (> 80,000 nT). MOURA surveys were not affected by such saturation since our magnetometer has an extended range mode that doubles the nominal range to ± 130,000 nT per axis, and thus, allows measurements up to higher field intensities as it has been partly suggested for the martian surface.

MOURA magnetometer also provides vector magnetic data. On Mars such data can indicate the orientation of the paleodynamo, since there was no plate tectonic reorientation. On Earth such vector data shows paleo-orientations of the rocks if the magnetic signature is sourced mainly by their remanence and only little by an induced signature (high Köningsberger ratios: Q ratios). At El Laco, MOURA measurements show a clear northward declination between 350° to 10° N (Fig. 5A), similar to the present orientation of the IGRF at this site (3° N). This can be explained by a very strong induced magnetization of magnetites, which have very high susceptibilities and thus low Q ratios (0.01) as have been also measured in samples from El Laco Sur by Alva-Valdivia et al. (2003).

SITE 2 "Pali Aike" is represented by an agglutinated spatter cone of 170 m diameter and surrounding Quaternary lava sheets of the Pali Aike Volcanic Field in southernmost Patagonia (Fig. 5C-E; Diaz Michelena et al., 2016). Such volcanic formations represent common features in many martian areas (Kereszturi and Németh, 2012; Robbins et al., 2013). On Earth such volcanic rocks often exhibit distinct magnetic anomalies (e.g. Bolos et al., 2012) depending on the composition of volcanic rocks, its cooling history and the single versus multi domain status of their magnetites (Clark, 1997).
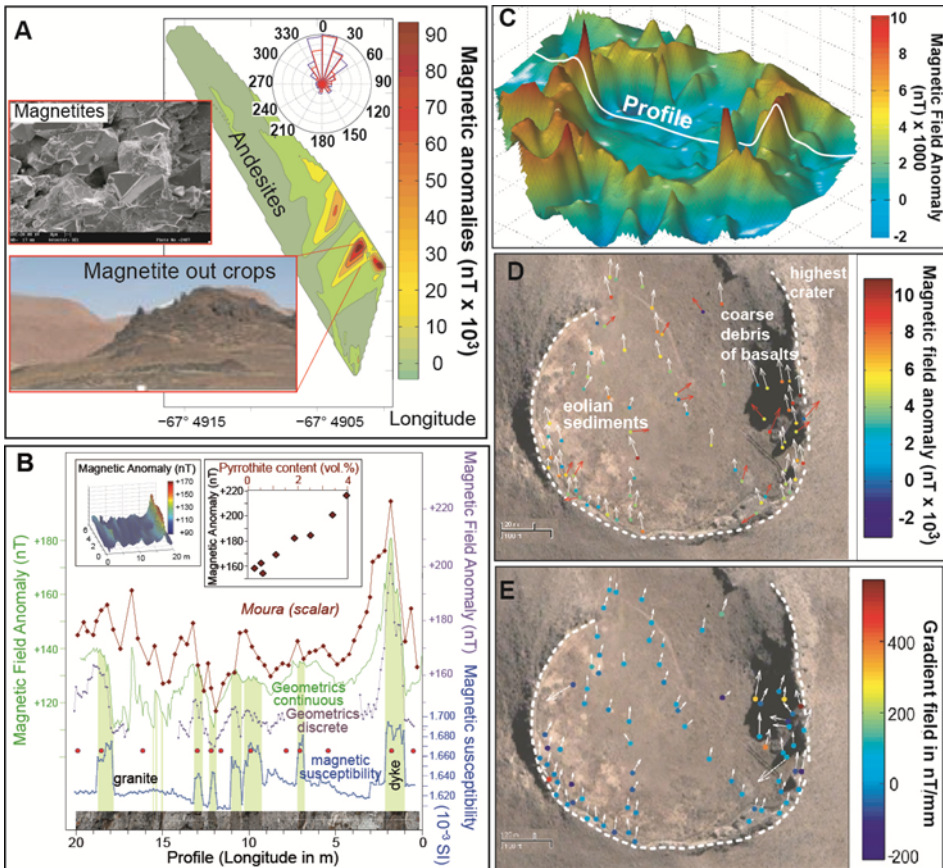
Figure 5. Examples of MOURA magnetic surveys: A) "Highly" magnetic El Laco magnetite outcrops surrounded by "low" magnetic andesites in the Central Andes (Diaz-Michelena et al. 2016). B) Transect across a granite of the Patagonian Batholith cross-cut by various mafic dykes with comparison between MOURA and a Geometrics reference magnetometer. Insets show the 3-D anomalies of the dykes and the relationship between the magnetic anomaly and the pyrrhotite contents (modified after Diaz-Michelena & Kilian 2015). C) 3-D visualisation of the magnetic anomalies of a volcanic crater in the Pali Aike (PA) volcanic field in south-ernmost Chile measured with G-858 reference magnetometer. D) MOURA magnetic vector orientations in the same crater on primary consolidated blocks (white arrows) and re-oriented collapsed blocks (red arrows). And E) MOURA gradient field within the PA crater indicating stronger gradients towards the higher magnetic crater rim.

A continuously measured grid was performed in an area of 400 x 400 m with G-858 reference magnetometer while MOURA measurements were done with a discrete mode to also obtain well-referenced vector data. Both scalar data sets match very well. Fig. 5C shows a 3-D view of the interpolated magnetic map with high positive anomalies along the crater rim (up to + 12,000 nT) where the agglutinated spatter have been mainly deposited as metre sized pillow-like blocks. Their strong magnetic signature can be explained by frequent tiny magnetite crystals with single domain characteristics in the glassy matrix of the lava. High amounts of pyroclastic deposits inside and outside of the crater have reduced the integrated magnetic anomaly due to reorientations during the re-deposition processes on the steeper slopes. Vector orientations of MOURA magnetometer at the individual points on consolidated lava blocks range from 352° to 360° N (white arrows in Fig. 5D). Due to high Q ratios and the strong remanent signature of the these basalts, the measured orientations have been interpreted to reflect paleoorientations and this differs from the induced interpretation of the EL Laco vector data (Diaz Michelena et al., 2016). The paleofield orientations are consistent with known paleo-orientation during the formation of the crater at approximately 1.0 Ma and differ clearly from the IGRF at this site with a declination of 12°N). Our measurements which have been performed directly on detached lava and scoria blocks, clearly collapsed from the inner crater wall, show multiple orientations (red arrows in Fig. 5D).The gradient field shown in Fig. 5E also highlights the MOURA potential as gradiometer.

SITE 3 "Bahia Glaciares" is an example for very low magnetic anomalies. The selected mapping area is located within the Patagonian Batholith of the southernmost Andes at latitude 53°S and provides a good example of continental crust formation on Earth and other planets (Behrmann and Kilian, 2003). Such plutonic rocks and layered intrusions form significant parts of the martian crust (e.g. Francis, 2011) and provide analogues on Earth (McEnroe et al., 2009). The site represents also a window to magnetic signatures of the deeper planetary crust since the exposed rocks have been previously equilibrated at amphibolite facies conditions. During this process all primary magmatic magnetites have been transformed to iron-bearing silicates and in particular the mafic dykes lost their initial magnetic signature and a later hydrothermal mineralization produced pyrrhotite as only magnetic carrier (Diaz-Michelena and Kilian, 2015).

The small survey area of 20 x 6 m was defined on a Cretaceous granite which is cross-cut by several mafic dykes. The freshly exposed transitions between granites and mafic dykes have been mapped on a decimetre-scale (Fig. 5B). Despite the remaining very low magnetic contrast from 20 to 80 nT between both rock types they could have been clearly distinguished in the surveys. MOURA and G-856 magnetometers gave similar results. In addition, the amount of pyrrhotite, ranging from 1 to 4 vol. %, is well correlated with the positive magnetic anomalies of the dykes. The site documents the potential for mapping of hydrothermal mineralization processes which also occurred on Mars (Osinski and Pierazzo, 2013) as well as associated gold and copper enrichments, even if the magnetic contrast is very low (Direen et al., 2008).

5. Discussion and conclusions

It can be concluded that MOURA instrument is a robust device which presents a good performance both in punctual and prospective measurements. Moreover, it is feasible to have a compact instrument when the magnetic signature of the integrated circuits is controlled and minimized.

Regarding the extrapolation of the performance for the exploration of Mars, the capability is very different in the two analysed cases.

On the one hand, regarding the daily variations, the temporal variations will be due to the ionospheric interaction with the surface fields (by the anomalies and not a global field). Also, the trajectories of the electrified dust can be influenced on these interacting fields generating new superimposed magnetic fields. With this respect, the ideal site for external field magnetometry on Mars would be the Northern hemisphere where the crustal anomalies have lowest intensities and the internal field contribution does not mask other effects.

On the other hand, probably the scenario of very magnetic crustal rocks of the Southern hemisphere of Mars can enhance the magnetic contrast along the surface and therefore, the magnetometer could provide very useful information with the benefit of vector and gradient measurements. Vector measurements allow a better evaluation of the sources, and gradient ones permit their interpretation in depth as well as to discern between the platform magnetic signature and that of the rocks.

In old terrains without implication of past tectonic activity, it would be even possible to derive information on the intensity and orientation of the ancient magnetizing field.

However, the precision of the oriented data are highly dependent on the attitude determination of the vehicle and this may vary along the planet surface due to the reduced satellite coverage.

More information on the rock magnetism (susceptibility, Köningsberger ratios, etc) and the mineralogical characteristics of rocks could be achieved with more sophisticated instruments, which also determine the susceptibility or permeability, when a higher physical envelope (mass, volume and power) is available.

To summarise, this kind of robust compact and miniaturized magnetometer is a very good instrument for on ground magnetometry on Mars and other planets and its design has been adapted to accomplish the restrictions of the exploration vehicles as well as the extreme conditions of Mars.

Acknowledgements

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