ISIS - INTER-SATELLITE & IN SITU PLASMASPHERIC MONITORING AND MODELLING: A UNIQUE OPPORTUNITY OF STUDYING THE EARTH'S PLASMASPHERE VIA THE EUROPEAN GNSS SATELLITE SYSTEM

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ABSTRACT

The extension and the local plasma properties of the Earth's plasmasphere are governed by the interaction with the magnetosphere above (in turn forced by the solar wind) and by the matter exchange and electromagnetic coupling with the underlying ionosphere. The variability of the plasmasphere, as a consequence of the Sun's forcing, defines our planet's space weather, and could be entirely caught only by studying together global and local proxies of the state of this extended system.

The ISIS project (Inter-Satellite & *In Situ* plasmaspheric monitoring and modelling) aims to imagine a system for the continuous monitoring of the Earth's plasmasphere, and its boundary, the plasmapause, based on the future European GNSS satellites. It puts together the efforts and expertise of ISC-CNR (Institute for Complex Systems of the National Research Council of Italy), INGV (Istituto Nazionale di Geofisica e Vulcanologia) and TAS-I (Thales Alenia Space - Italy).

New experimental facilities of the Galileo satellites, designed to realize inter-satellite and *in situ* measurements to monitor global and local quantities, are proposed as a tool for comprehensive monitoring of the Earth's plasmasphere. The total electron content variability along all possible inter-satellite ray paths throughout the plasmasphere could be monitored via phase- and group-delay analysis of inter-satellite radio signals; *in situ* data of local plasma and magnetic field proxies, collected by instrumentation on board of the satellites, instead, are expected to give information about small scale structures and short time variability of the medium, as dependent on the helio-geophysical conditions.

1. INTRODUCTION

The plasmasphere is the widest part of the near-Earth plasma co-rotating with the planet, shaped by the geomagnetic field, re-filled by the ionosphere beneath and forced by the solar wind pressure. It has been studied since decades as a very important element of the Earth's space weather, both in its "quiet" or "average" configuration, as well as in its behaviour in response to stormy helio-geomagnetic activity. It is basically an extension of the Earth's ionosphere, from where the plasma flows up and is captured and shaped by the geomagnetic lines of force. The plasmasphere shrinks when forced during geomagnetic storm events, refilling gradually during the recovery phase [1], so its configuration is very sensitive to space weather events.

In its largely major part, the plasmasphere of our planet is composed of low energy free electrons and protons (in this context, when with "low energy" particles are we refer to spoken about, one means chemical species at the local thermal equilibrium, usually described as fluids). Other ion species, as He^{++}, He^{+} and O^{+}, refill this environment when the geomagnetic lines of force are pushed into the lower ionosphere and let them flow upward. Quasi-neutrality holds everywhere.

The Earth's plasmasphere would be completely described giving both its global characteristics (its extension and "shape") and its local characteristics (the behaviorbehaviour of the local medium point by point). The opportunity to make this twofold monitoring, possibly offered by the EGEP (European GNSS Evolution Programme), is the pivot of ISIS.

In Figure 1, the geometrical relationship between the orbits of the future GNSS satellites and the "average" configuration of the Earth's plasmasphere is visually presented. The pictures is freely elaborated from [2].

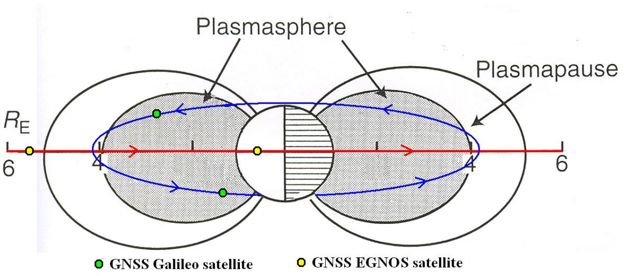

Figure 1. The Earth's plasmasphere "average" configuration. Possible orbits of the GNSS are superimposed: Galileo (green, with blue inclined orbit) and EGNOS (yellow, with red equatorial orbit). Credits: freely elaborated from [2].

The ISIS concept is to assess the possibility of studying the global plasmaspheric configuration by measuring time series of the TEC between two GNSS satellites (Galileo or EGNOS): due to the rich geometry of the future European GNSS constellation, the collection of such inter-satellite TEC data could give an unprecedentedly complete information about the "shape" of the plasmasphere varying with time. Equally unprecedented would be the possible time continuity and length of campaigns done via EGEP facilities.

In order to design at best the signals to be used, ISIS will simulate reasonable values of inter-satellite TECs in various GNSS configurations and under different helio-geospace conditions. An empirical model of the plasmaspheric ionization density was presented in [3], and this will be the first approximation adopted in ISIS to mimic the plasmasphere. In this model, an analytical expression of the density profiles for moderate geomagnetic activity is given, well reproducing the density fall off in the ionosphere as well as the sharp density decrease at the plasmaspause. We will refer to the model as Gallagher Plasmaspheric Model (GPM). Figure 2 shows an example of the model as will be used in ISIS.

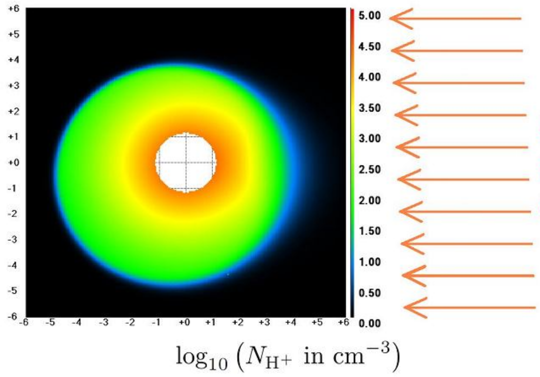

Figure 2. Equatorial section of the GPM used in the TEC simulations presented in § 2.

The investigation on local plasmaspheric dynamics will be studied too. ISIS suggests that this could be done by collecting *in situ* measurements with instrumentation space-borne by the future Galileo and EGNOS satellites. The orbits of the Galileo satellites will lay within the plasmasphere for a wide portion: each Galileo satellite could be used as a spacecraft monitoring the local proxies along its trajectory. The orbit of the EGNOS, instead, lays "right outside" the plasmaspheric bulk. It is definitely interesting to have measures from "right outside the plasmasphere" simultaneous to those collected inside it; let alone that the plasmapause motion may be monitored, as taking place across the geostationary orbit.

ISIS project will develop two research lines. On the one hand, a line pertaining the possible plasmaspheric inter-satellite TEC monitoring; on the other hand, the line concerning the study of probing the local plasma dynamics via the GNSS satellites.

The research groups involved in the ISIS Project, ISC-CNR and INGV, and the engineering team of TAS-I, will interact with a continuous exchange of ideas, suggestions, inputs and feedbacks aiming at assessing what plasmaspheric science will be desirable to do via GNSS, at understanding what real conditions will be more likely for the future European GNSS satellites. Then, they will indicate the possible best measurements and suggest technological solutions able to make the desired research possible. The product of such activity will be a series of documents about the feasibility of inter-satellite and *in situ* monitoring of the plasmasphere via the missions planned in the EGEP, hopefully to be part of the future state-of-the-art of plasmapsheric science.

2. INTER-SATELLITE MONITORING

Since a large amount of GPS data were made available for the scientific community, it has been possible to study the TEC of the plasmasphere by comparing the GPS-to-ground TEC data with the NNSS-to-ground TEC data. That gross evaluation of the plasmaspheric TEC presented in [4] still remains a benchmark for plasmaspheric global monitoring, and represents a starting point of ISIS.

In the prospective of having the full future European GNSS, measuring multi-geometry TEC of the plasmasphere becomes a much more concrete and attractive possibility. Hence, ISIS hence is intended to provide the community with a feasibility study of inter-satellite TEC monitoring. For this purpose, good models of the medium and of the satellite kinematics will be needed.

In [5], the density of the H^+ ions modelled via GPM was shown to have produced inter-satellite TEC equivalent to what obtained from the real data collected via the TOPEX/POSEIDON mission: those results suggest to adopt GPM as the starting point to model the Earth's plasmaspheric density. An example of the agreement between GPM and real data of inter-satellite GPS-to-TOPEX TEC is given in Figure 3, where both the general agreement between the two time series, and the disagreement in correspondence of an impredictableunpredictable "bump" of ionization in the real data, may be observed.

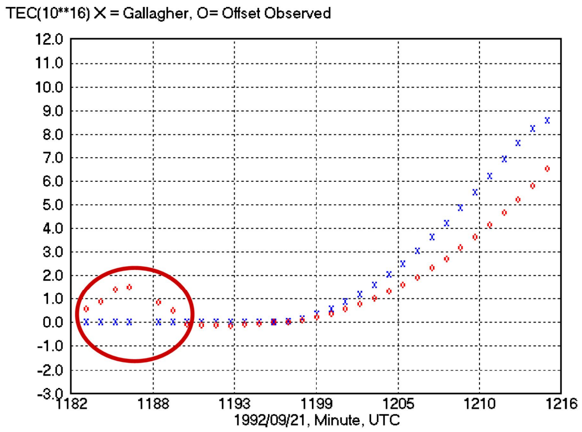

Figure 3. Inter-satellite TEC predicted by GPM (blue crosses) and observed in the TOPEX/POSEIDON campaign (red circles).
Note the general agreement between the two curves, and the disagreement in the "bump" in real data around minute 1186 UTC (models can't predict Nature's improvisations) [5].

As far as the GNSS geometry-kinematics modelling is concerned, the model SEGRE (Simulation Environment for GNSS REceivers) will be adopted: it is a navigation software and constellation simulator, elaborated by TAS-I between 1998 and 2008.

Here we report just some preliminary results about using GPM for inter-satellite TEC simulation: in Figure 4, a time series of the TEC between a GPS and a geostationary satellite is reported in black, while the red curve indicates the minimum height of the GPS-GEO link in Earth radii. TEC units of the total electron content included are few, because the plasmaspheric density is expected to be rather small, but still might be measureable. The use of GPS instead of Galileo is due to the fact that we still have to implement Galileo orbits in the software, while GPS ones were already available: actually, no important difference is expected in the results.

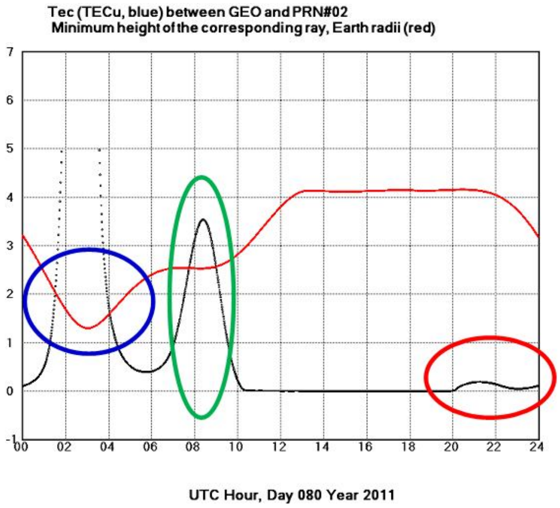

Figure 4. Simulated GPS-GEO TEC time series assuming the plasmasphere to be GPM. Note that an occultation like event (blue circle), a low-altitude high-density event (green circle) and a local bumpy structure (red circle) may be recognized.

Some interesting features of the inter-satellite TEC are highlighted in Figure 4, encircled in colours. The blue circle indicated an apparently divergent TEC peak, corresponding to a minimum in the impact parameter of the radio-link: this is an *occultation-like situation.*

The greenish circle, in the same picture, indicates a peak of the inter-satellite TEC due to the intersection of the radio-link with *lower and denser strata of the plasma.*

Last but not least, the red circle highlights a *local bump* not corresponding to a particular variation of the ray geometry, likely to pertain to *a real structure* of the plasmasphere (even if barely distinguishable from zero).

ISIS aims at assessing how it is possible to detect structures as those in Figure 4 by EGEP-based inter-satellite measurements. This requires to enter more technical details about how the inter-satellite TEC is measured, thanks to the differential phase Doppler effect (DPDE).

Two plane electromagnetic waves, of frequencies f_1 and $f_2 = qf_1$, are transmitted through two points crossing a plasma of ionization density N_e. Let φ_1 and φ_2 be the respective transmitter-receiver phases of the first and second wave; then, the differential phase, defined as

$$\Delta\varphi = q\varphi_1 - \varphi_2, \qquad (1)$$

may be related to the integral of N_e along the radio link:

$$\Delta\varphi = \Delta\varphi_0 + \frac{e^2}{4\pi\varepsilon_0 mc}\left(\frac{q}{f_1} - \frac{1}{f_2}\right)T_\gamma, \qquad (2)$$

where the total electron content along the link γ

$$T_\gamma = \int_\gamma N_e d\ell \qquad (3)$$

has been defined, and $\Delta\varphi_0$ in Eq. 2 is an offset equal to the would-be-phase if pure vacuum were crossed by the waves. The relationship between $\Delta\varphi$ and T_γ as expressed in Eq. (2) is to be exploited: clearly, very small values of T_γ, or of variations of it revealing weak plasmaspheric local structures, could give still measureable $\Delta\varphi$s, provided the pre-factor $\frac{e^2}{4\pi\varepsilon_0 mc}\left(\frac{q}{f_1} - \frac{1}{f_2}\right)$ is suitable. This is why the right frequency band must be designed: an assessment on this is exactly the purpose of ISIS.

The unbiased DPDE $\Phi = \Delta\varphi - \Delta\varphi_0$ is dependent on the frequencies and on the TEC (remarkably, getting rid of this $\Delta\varphi_0$ is one of the most difficult task in ionospheric observation science! The techniques used by Ciraolo in [5] proved to be of some value). In the assessment of the inter-satellite TEC monitoring, the signal-to-noise ratio

$$Q(f_1, f_2, T_\gamma) = \frac{\Phi(f_1, f_2, T_\gamma)}{N} \qquad (4)$$

between the unbiased DPDE and the noise of the GNSS-GNSS transmission will be constructed. The optimization of Q in Eq. (4) with respect to the frequency choice for different possible plasmaspheric T_γ is the research tool to assess the inter-satellite TEC study feasibility. In § 4 the technological issues involved in this are shortly exposed.

Before closing this section, let's consider again Eq. 3: in general, the ionization density N_e may be expressed as the sum of a background density N_0 and a fluctuation component δN. Models as GPM aim to represent satisfactorily the component N_0, while the characterization of the fluctuations δN would be among the objects of the *in situ* monitoring discussed in § 3. These fluctuations are expected to be so irregular and "stochastic" that their integral along a finite optical path γ vanishes, so that the quantity T_γ is thought of as being directly the integral of N_0: this renders it possible to simulate it via models.

3. IN SITU MONITORING

The TEC between two points of the plasmasphere may give information about global features, and contributes to characterizing "background" properties, as the density N_0 mentioned in § 2.

As far as the "more irregular" aspects of the plasmaspheric dynamics are concerned, one should expect local proxies to play a great role. Local proxies describing the plasmasphere are the ionization density N_e (quasi-neutrality and the absence of negative ions), the magnetic field **B** and the electric field **E**, plus all the proxies of the local ion populations, as the velocity $\mathbf{V}_I$, the temperature T_I, the numeric density N_I of the I-th ion species (i.e., $I = \mathrm{O}^+, \mathrm{He}^+, \mathrm{He}^{++}, \ldots$). The fluctuations of N_e, **B**, **E**, $\mathbf{V}_I$, T_I, N_I, … will be the object of the studies of local dynamics.

In the last two decades it has been clearly shown that *local turbulent behaviours of the local quantities* play a relevant role in triggering short-range as well as global phenomena in several regions of the Geospace. In many dynamically relevant situations (e.g., the onset or the evolution of storms, in the formation of plasmoids in the magneto-tail giving rise to particle precipitation and auroræ, …), the observed fluctuations rise to the same order of magnitude of the average quantities, which is exactly the most relevant sign of "turbulence" [6].

One of ISIS aim is to assess how to study the character of local fluctuations in the plasmasphere via EGEP satellites. Two points naturally arise: how those satellites could really make in situ measurements, and which data analysis techniques should be applied to the data collected. The authors claim that the best data analysis techniques to be used are Turbulence Oriented Statistical Analysis (TOSA) methods, "imported" from a great number of fields: fluid, space plasma and magnetospheric science, but also geomagnetism and complexity science in general.

In TOSA methods we include traditional techniques, like Fourier spectral analysis, and ones much less traditional in the field of geo-science, as multi-scale statistical analysis, wavelet analysis, Lyapunov exponent analysis.

Some of the TOSA methods have already been applied, by some of the ISIS people, to time series of different physical quantities to study different physical systems.

For instance, the magnetospheric response to the solar wind changes has been studied through the investigation of the probability distribution functions of the AE-index fluctuations at different scales and of the statistical features of the waiting times among successive activity bursts in AE-index ([7], [8]).

Another example is the investigation of the physical dynamical regimes that are at the origin of the dynamical complexity of the solar cycle by means of a method of decomposition applied to the time series of the sunspot area butterfly diagram and by means of the estimation of the corresponding Lyapunov exponents [9].

The main geomagnetic field fluctuations have been analysed to investigate the nontraditional turbulent dynamics of the fluid motions in the outer layers of the Earth's liquid core ([10], [11]).

Finally, some of these methods have been applied also to the study of the so-called geomagnetic secular variation: in one case to analyze the nonlinear properties of the physical system responsible of this variation [12], in another case to detect intermittent phenomena within the behaviour of geomagnetic secular variation. This has been achieved through a method, i.e. local intermittency measure (LIM), based on wavelet analysis [13].

An example of the application of LIM is displayed in Figure 46 5 that shows how this method is able to extract six large singularities (in 1901, 1913, 1925, 1969, 1978 and 1991) starting from the time series of the Y component of the geomagnetic field measured at the French magnetic observatory of Chambon La Foret (upper panel of Figure 5) without any *a priori* assumptions.

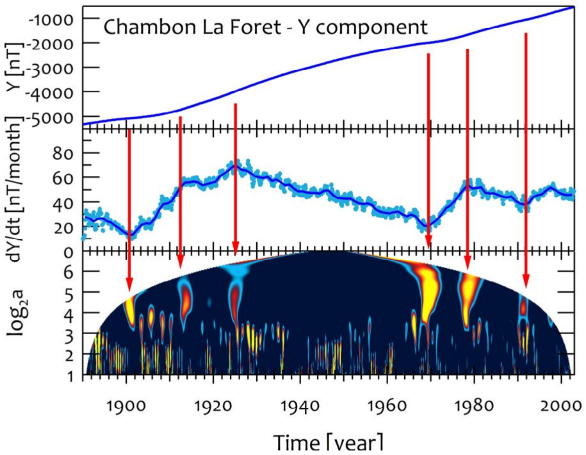

Figure 5. Wavelet analysis and secular variation. Upper panel: Y component of the geomagnetic field measured at the magnetic observatory of Chambon La Foret (France). Central panel: secular variation estimated as first differences of the Y component. Lower Panel: scalogram obtained applying LIM technique.

It can be demonstrated that LIM approach has several advantages with respect to traditional wavelet analysis. For instance it is able to extract straightforwardly only those singularities characterised by intermittency, it displays slighter boundary effects and it allows obtaining satisfying results also from time series whose analysis would result more difficult with traditional wavelet analysis.

Coming to the application of TOSA methods to the local analysis of data from the space environment, consider the references [23] and [24]. In [23] the usefulness of a spectral analysis of turbulent data is discussed: different slopes of the spectrum indicate different statistical (turbulent) regimes along the presumed energy cascade.

Fourier analysis is however a rather old techniques, and there are modern approaches more suitable to characterise the complex nature of fluctuations, as multi-scale statistics.

In Figure 3 of [24] the probability distribution functions of the fluctuations of the interplanetary magnetic field are plotted for different scales. The field $\mathbf{B}_{\mathrm{IMF}}$ was measured on board of ACE, as reported in the plot. It is remarkable how for smaller and smaller scales the PDF shapes departs from a Gaussian one, denoting the presence of intermittency in the local dynamics [6].

Due to the continuousness and long duration of the monitoring possible via future GNSS satellites, it would be interesting to use this facility to study the changes of the local statistical features of plasmaspheric fluctuations under different helio-geomagnetic conditions, so to stress how the space environment triggers the plasmasphere local dynamics. To assess this kind of campaign, ISIS will construct a database using the available free access data coming from the more recent space missions (e.g. CLUSTER), in which data are organized for different geomagnetic activity level.

4. THE ISIS PROJECT OUTLOOK

A visual expressive way of tracing the outlook of the ISIS project is just reporting the scientific part of its work breakdown structures, as done in Figure 8.

The essential idea is that scientists of ISC-CNR and INGV will design the desirable measurement campaigns that could be realized by suitably equipped future GNSS satellites, while the engineers of TAS-I will trace the technological perimeter and constraints within which those campaigns could be realized employing the satellites presently understood in EGEP.

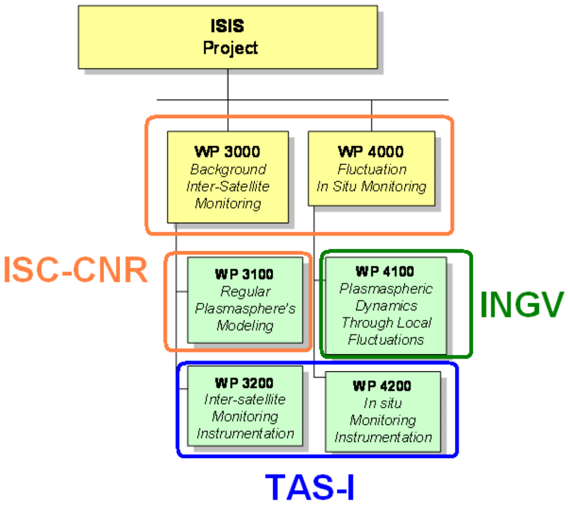

Figure 8. Scientific part of the work breakdown structure of the ISIS project. The WPs in the orange frames are responsibility of ISC-CNR, while WP4100 is under INGV direction, and TAS-I leads the WPs within the blue frame.

As described in § 2, the possible inter-satellite TEC measurements will be studied by simulating data with sensible models of the plasmaspheric N_0 and satellite geometries. Once this is done under ISC-CNR responsibility, the TAS-I engineers will study the technological needs to render it possible. About this, consider that inter-satellite ranging is a promising technology that has been recently investigated in the framework the ESA GNSS evolution study on “Future

Satellite Navigation System Architecture" (FSNSA) [14], [15] (the study on FSNSA was conducted by Astrium GmbH and subcontractors). The objective of that study was the analysis of the necessary system level activities in preparation of the evolution of the European GNSS infrastructure beyond the current Galileo. The next generation of Galileo satellites is planned in the time frame of 2020, and the inclusion of inter-satellite communications is expected. The major motivation for this is the enhancement of the orbit and clock prediction accuracy and the reduction of the dependency from ground infrastructure.

Among the problems studied in [16], the following aspects are of interest for ISIS: characteristics of the inter-satellite ranging and inter-satellite communication signals, and link power budget; inter-satellite ranging and inter-satellite communication payload mass and power; characteristics of the on-board transmitting and receiving chains, including antenna subsystems, for both ranging and communication signals. An analysis of similar issues will provide a valuable "engineering perimeter" on which to compare the scientific aspects that will be analyzed in detail within the framework of ISIS (where more emphasis will be given to the scientific aspects of the plasmaspheric monitoring).

Some important and concerning aspects came out from the GNSS evolution study. For example due to on-board antenna aperture constraints, inter-satellite measurements cannot be performed simultaneously. To this aim, couples of satellites pairs must be identified and a Time Division Multiple Access (TDMA) scheme envisioned. Moreover, from the FSNSA study it turned out that the frequency preference for the inter-satellite range (ISR) is on the C band (~5 GHz), while the impact of the plasmasphere (and ionosphere) on a signal is much more evident in lower frequencies. The dispersive nature of the medium is naturally exploited by means of a dual-frequency ranging system (providing both f_1 and f_2 in Eq. (2)), while the ISR studied in the mentioned work was a single frequency link.

The GPS system has already implemented a similar concept in the past and the cross-link functionality was already present in the Block IIR satellites, for "self navigation" (such an Autonomous Navigation (AUTONAV) permits the system to autonomously operate within specifications for ~ 180 days in the presence of a worldwide nuclear event). Block IIR satellites maintain accurate clock and ephemeris data by employing a UHF crosslink ranging and data communication with other GPS satellites of the same kind. Unfortunately, being this a security system, detailed information about the specification and implementation of this capability for GPS are lacking, and cannot be used for ISIS. Available information are collected on [17] and [18]. According to [19], referring to Block IIF GPS, the transmission frequency seems at 250-290 MHz well below the usual L or C navigation frequency bands.

In addition to MEO-MEO satellite links, the capability of the future EGNOS payload to include a ranging system allow the exploitation of MEO-GEO links. In fact, the EGNOS system uses geostationary satellites to broadcast the augmentation to the Earth user over a certain areas (mainly Europe). Ranging signals of opportunity between Galileo and EGNOS satellites will allow the sounding of the plasmasphere in the altitude ranging between 26000-29000 km and 42000 km.

The feasibility study of GNSS-based *in situ* monitoring will instead involve WP4100, directed by INGV people, in which the TOSA techniques will be applied to the local data of existing geospatial campaigns: once the scientifically desirable measurements are assessed, TAS-I people will lead WP4200, in which the possibility of using future Galileo and EGNOS satellites to carry the needed instrumentation on board is dressed with technological quantitative contents.

ISIS images that the next generation GNSS satellites shall embark a dedicated payload for the monitoring of the local plasmaspheric structures and their fluctuations: clearly, it is mandatory that such secondary payload employs the most advanced technology granting the performance with very low mass and power demand.

Starting from the model output and a preliminary definition of the user requirements, both in terms of measurements and quality defined in the theoretical study, the activities carried out by TAS-I personnel will encompass the engineering assessment of the required payload. Available literature and relevant information on existing instrument developments in Europe will be collected and reviewed. Then, a preliminary evaluation of the necessary on-board instruments, their gross requirement specifications, the definition of the associated engineering budgets (mass, power, data, etc.) and the environmental compatibility with the primary navigation payload will all be performed.

Among the instruments that will be evaluated as candidates for those scientific payloads, triaxial fluxgate magnetometers (TFR), Languimir probes (LP) and energetic ion composition spectrometers (EICS) must be considered. A TFR may permit to obtain vector magnetic field data needed to study the magnetosphere-ionosphere coupling through the Earth's Plasmasphere (EPS). LPs provide with the local free electron density, which is far the most important parameter for the EPS-effects on radio links. Finally, EICS is good for monitoring the fields N_I and $\mathbf{V}_I$ for ions (large fluxes of energetic O^+ from the ionosphere during magnetic storms; minor species as He^+ and He^{++}, as a hint to study the various mass-or charge-dependent energization, transport, and loss processes).

The findings resulting from the above activities will support the analysis of the potential benefit for the mission together with the impacts that the accommodation of this scientific payload will have on the future generation European GNSS satellites.

5. CONCLUSIONS

Some conclusions are to be drawn at the end of our presentation of the ISIS Project.

This is a project in which theoretical physics, experimental physics and engineering experiences and skills come together to devise a science opportunity of the future European GNSS network (with a particular reference to the use of Galileo satellites).

It is important to underline how both traditional analysis methods [20] and more newer ones [21] will be employed, and how avant-garde ideas about space weather science [22] will be involved. Still, its science opportunity must be quantified in terms of general feasibility and cost to realize it in the EGEP framework, which is the proper scope for which ESA agreed to place a contract on ISIS.

Scientists' "desires" and physical obstacles will be expressed and analysed by people from ISC-CNR and INGV, on the basis of reasonable models and pre-existing plasmaspheric data. Engineers from TAS-I will then study the scenario from a technological cost-benefit point of view, formulating technical suggestions for the implementation of the campaigns envisaged.

At the end of the project, ESA will be given documentation where scientific suggestions and technological advices are carefully considered for the EGEP, as far as the plasmaspheric science is concerned.

As a final remark, may we underline that, even if the Authors strongly hope the EGEP to include the scientific applications that will be described and evaluated in ISIS, we are aware of the technological, physical and political pressure existing on the future European GNSS satellites. Nevertheless, we hope at least that the ISIS outcomes will be of use in designing future plasmaspheric science-oriented missions.

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