THE ISIS PROJECT: INDICATIONS FOR FUTURE NEAR-EARTH PLASMA STUDIES THROUGH FUTURE GALILEO SATELLITES

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ABSTRACT

The Earth's plasmasphere variability is a consequence of the Sun's forcing, determining our planet's space weather. Plasmaspheric dynamics 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) aimed to design a system for the continuous monitoring of the Earth's plasmasphere based on the future Galileo satellites. 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) were put together in this work of assessment.

ISIS Team proposed new experimental facilities of the Galileo satellites, designed to realize inter-satellite and *in situ* measurements to monitor global and local quantities; in particular, a scalable system of Langmuir probes was suggested, while the TEC along all possible inter-satellite ray paths throughout the plasmasphere could be monitored via phase- and group-delay analysis of inter-satellite radio signals.

1. INTRODUCTION

The objective of the ISIS Project was to provide ESA with a preliminary assessment about the feasibility of a continuous and geometrically rich monitoring of the Earth's plasmasphere through future Galileo satellites.
The vision, synthesized by the acronym of the project (i.e., *Inter-Satellite* and *In Situ*) is that the assortment of locations and geometries of the Galileo satellite constellation allows for the study of the integral and local properties of the medium through the collection of time series of the inter-satellite total electron content (TEC), respectively (TEC being measured thanks to inter-satellite radio links, as Galileo-Galileo and Galileo-GEO links), and local quantities (ionization density in particular, measured by space-born Langmuir probes). This integral-local distinction corresponds to some extent to background-fluctuation decomposition [1] of the plasma quantities.
Reasonable values of the occurring inter-satellite TECs in various satellite configurations were simulated, as described in § 2, so to design the specifications for the signals to be used at best. Then, a preliminary technological study has been realized about how to perform the inter-satellite measurements with the present Galileo technology: in particular, the C band was envisaged as a reasonable compromise between the necessity of using frequency affected by the medium, and the opportunity of working with channels already available on the Galileo satellites, as presented in § 3.
Laying the Galileo orbits within the plasmasphere for a wide portion, each Galileo satellite could carry in principle instruments monitoring the local plasma. The orbit of the EGNOS satellites, instead, lays outside the plasmaspheric bulk, and it would be interesting to have measures from outside the plasmasphere simultaneous to those collected inside it; let alone that the plasmapause motion may take place across the geostationary orbit itself, giving the chance to detect directly the crossing of this limit by the external edge of the plasmasphere. *In situ* measurements theoretical review was done, with some conclusions presented in § 4, while the technological feasibility of such campaigns as concluded by ISIS is resumed in § 5.

2. MODELING OF INTER-SATELLITE BACKGROUND TEC

In order to calculate the total electron content $T_{TR}(t)$ existing between the transmitter T and the receiver R at time t, namely: the free electron distribution in its "background" component $N_e^{(0)}(\vec{x},t)$; the positions $\vec{x}_T(t)$ and $\vec{x}_R(t)$ of the transmitting and receiving satellite.

As far as the modeling of $N_e^{(0)}(\vec{x},t)$ is concerned, the use of the Gallagher plasmaspheric model described in [2] was sufficient The TEC calculated by Ciraolo's program implementing Gallagher's model produces TEC referred to as $T_{TR}\left[N_e^{GCC};t\right)$. This model is rather "rigid" and "rough", from the point of view of the Space Weather. Indeed, it is an empirical model which does include *no dependence on season*, *no dependence on solar activity* or other Space Weather parameters. More, the geomagnetic field is not conceived yet as a separate call that could optionally ingest empirical data, but is just represented as dipole field, inclined and off-set with respect to the Earth's axis. Anyway, we underline that passing from the original Gallagher model to more recent ones wouldn't give a deep change in the TEC simulation.

As far as modeling the positions $\vec{x}_T(t)$ and $\vec{x}_R(t)$ is concerned, the satellite configuration has been as assorted as possible: indeed, ISIS aimed at assessing all GNSS-GNSS inter-satellite measurements, i.e. along both the Galileo-Galileo and Galileo-EGNOS links.

In order to simulate the time series $T_{TR}(t)$ with the precision needed here the Galileo orbits $\vec{x}_{Gal}(t)$ were simulated by TAS-I according to the so called Walker Constellation for Galileo satellites, with 3 orbital planes, each containing 9 of the total 27 satellites. This is expected to be very close to the full Galileo constellation, hence to mimic very well the future European GNSS system. TAS-I provided ISC-CNR personnel with data sets of $(t,\vec{x}_{Gal}(t),\vec{v}_{Gal}(t))$ for the whole RTI.Gal selected: this had as an initial time the Julian date 2455744.00000000, while the final time is the Julian date 2455753.00000000 (the length of the RTI.Gal is 9 days). The resolution with which the satellite data $(t,\vec{x}_{Gal}(t),\vec{v}_{Gal}(t))$ are simulated is 60 seconds.

The orbit of a geostationary satellite EGNOS is mimicked by assuming that one of the positions delimiting the transmitter-receiver segment is $\vec{x}_{GEO}(t)=(R_{GEO}\cos\omega_\oplus t, R_{GEO}\sin\omega_\oplus t, 0)$ in the GSE coordinates, being R_{GEO} the radius of a geostationary orbit, at $R_{GEO}=35{,}786\text{ km}$, and $\omega_\oplus$ corresponding to the angular frequency of the Earth rotation.

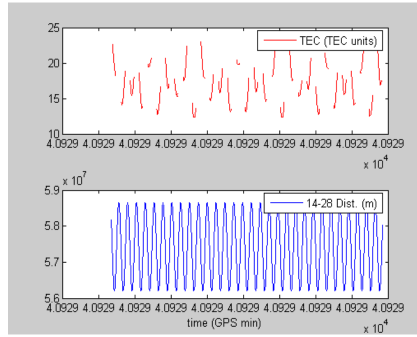

Figure 1. The simulated TEC $T_{TR}\left[N_e^{GCC};t\right)$ and distance between two Galileo satellites, namely PRN14 and PRN28. The TEC time series is very discontinuous, and the TEC has high values, meaning that the radio link came very close to the Earth, crossing the topside of the ionosphere and then being censored.

In order to illustrate two examples of the outcome of this study, we show a Galileo-Galileo simulated TEC, in Figure 1, and a Galileo-EGNOS simulated TEC, in Figure 2, both calculated assuming the plasmaspheric electron density to be N_e^{GCC} .

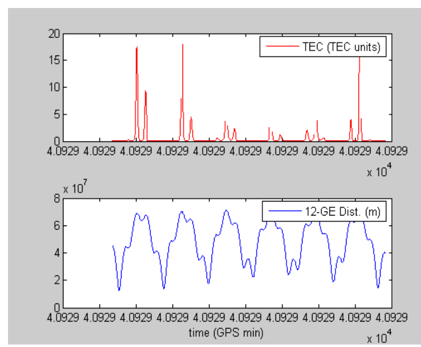

Figure 2. simulated TEC and distance between the Galileo satellite nominally indicated as PRN12 and the simulated geostationary satellite sitting at $\vec{x}_{GEO}(t)$.

3. INTER-SATELLITE MONITORING INSTRUMENTATION

The following plots in Figures 3 and 4 collect an overview of the plasmaspheric delays for an example of observation frequency chosen in the ISIS assessment (C band), obtained by simulation. The plasmaspheric delay is given in [m], i.e. scaled on the carrier frequency considered according to the previous equation. This approach provides the effect on the pseudorange observables. Effects on the carrier phase have an opposite sign.

Several geometries were investigated: "Same-plane adjacent" (SPA), "Same-plane Far" (SPF), "Cross-Plane" (X-Plane) and GEO-Galileo.

The results were organized in form of plots representing elevation, azimuth, TEC (in TECU or "metric" quantities when scaled by the frequency) and relative geometry in a "RAAN vs. anomaly" plane. Elevation and azimuth are the angles of the Tx as seen by Rx. The small plot on the top right panel shows the Rx satellite in the constellation (in red) and the Tx (in black).
In the following case the plasmaspheric TEC is represented in form of pseudorange delay in [m] for a C-band inter-satellite link (ISL) over one day of continuous observation.

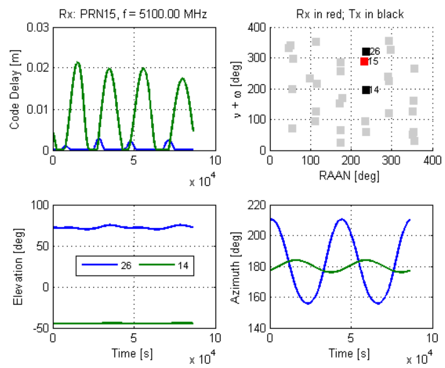

Figure 3: C band - Same Plane Adjacent Geometry – GPS case

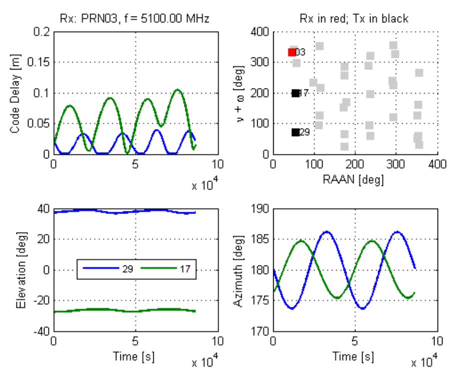

Figure 4: C band case - Same Plane Far – GPS case

It was noted that the "SPA" geometries are very poor in terms of TEC (from fraction of TECU to few TECU). A slightly better situation was found on "SPF" geometry: a range up to 8-9 TECU was observed. For the X-Plane geometries, it has been found that the better observations are seen by looking to couples of satellites with large anomaly difference, while satellites with small anomaly difference behave like SPA observation geometries. GEO-GPS is a promising case. In fact, large (up to 20) TEC excursions are found in some cases.
Concerning the choice of the ISL frequency it is immediate to note that, as expected, the lowest the frequency, the better the plasmaspheric signal observability. As a rule of thumb, we recall here that 1 TECU at L1 is ~ 16 cm. Any ISL case considered in UHF frequency give high observability (SPA, SPF, X-Plane) of plasma TEC compared to the expected ranging accuracy derived by high C/N0 conditions[1]. Rising the frequency, the delay on Rx observable is more difficult to detect: in L band ISL, TEC delays larger than 1 m are barely observed. In S band it is even worst, with the peaks of the delay at the level of ~ 0.2-0.5 meters.
The last case considered is the most important one, since it depicts the case in which the frequency selected is the C band, which was the technological baseline for ISR-ISL by the studies of RD 14-16. On the other hand, the latest technological choices by ESA shifts the ISL frequency upward, outside the sensitivity range of a standard ISL instrumentation as studied here. In this case, peaks of plasmapsheric delays are not very different from receiver thermal noise (expected to be ~ 2 cm 1-sigma in C band). Detection of a signal with the plasmaspheric signatures could be very difficult and should devise additional investigations. This is particularly true in the case of envisioning a Dual-Frequency system, in which the noise terms are amplified by the linear combination as shown in the next paragraph.
Therefore, as a first conclusion, a combination of optimal geometry and, more important, choice of the ISR frequency are crucial for exploiting the ISR plasmaspheric science.

4. PLASMASPHERIC DYNAMICS THROUGH LOCAL FLUCTUATIONS

Coordinated observations from different Galileo satellites operating in different parts of the magnetosphere could be ideal for the study of the 3-D structure of this region, its dynamical deformations and its role in the dynamics of the ionosphere-magnetosphere system. Although data coming from single satellite are capable of measuring the densities directly and can sample wide and continuous latitudinal and longitudinal ranges, they suffer from a number of inherent weaknesses. Data availability is also very often limited in space and time. Coordinated observations from different Galileo satellites operating in different parts could solve this problem opening the way to new global studies.
One of the aim of this project has been to characterize the fluctuations of the plasma parameters and magnetic field in the plasmaspheric region by investigating both the spectral and scaling features of in-situ observations to see if there was evidence of turbulent features inside the plasmasphere.
ISIS results were obtained using CLUSTER electron density profile measured during plasmasphere crossing on 11st April 2002 and reconstructed according to [3]

[1] It has to be noted anyway that the range accuracy is a function of frequency as well , not only C/N0.

and [4]. It is a quiet period characterized by a value of the geomagnetic index Kp = 3 (the plasmasphere is observable at Galileo constellation altitude only during quiet geomagnetic activity periods when the plasmapause will be at a distance from the Earth greater than 4.5 Re). In this period, the mean value of the electron density is of about 40 electron/cm^3 while the fluctuations are of the order of 20% in terms of standard deviation.

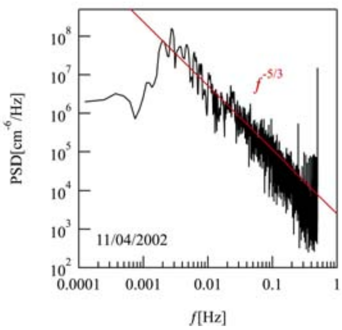

Figure 5. Power Spectral Density (PDS) for the electron density measured during plasmasphere crossing on 11st April 2002.

Figure 5 shows the obtained Power Spectral Density (PSD) for the analyzed electron density fluctuation time series. The main feature of the PSD is a nearly power-law behaviour f^{α} with a spectral exponent close to $\alpha \cong -5/3$. This power-law behaviour is well in agreement with the analysis reported in [5], where a power spectral analysis on sweep frequency receiver data from the CRRES satellite was presented. The authors found that on some orbits plasma density irregularities in the outer plasmasphere had power spectral slopes near -5/3, thus suggesting the presence of well-developed two-dimensional turbulence equal to that expected for Kolmogorov fluid turbulence. This means that according to Kolmogorov's theory (K41) the dynamics of this physical quantity is similar to that of a turbulent flow where there is a cascade of energy toward small scale where dissipation is due to molecular friction. The energy cascade is hierarchical, i.e. a disturbance on a certain scale receives its energy from a larger-scale disturbance and transfers it to smaller-scale disturbances. However, the distribution of energy at smaller scales is not homogeneous. Indeed, we have found that while the Probability Distribution Functions (PDFs) tend to a standard normal distribution for time delays t>80 s conversely, the PDFs associated with low time delay (t<20-40 s) are characterized by heavy tails (data are not shown). This result suggests the possible occurrence of a certain degree of intermittency in the analysed physical quantity, which means that the fluctuations are not uniformly distributed in space and/or time. To better analyse this point, we have studied the scaling features of the p-order of the structure functions, the results obtained are consistent with a multifractal nature of the fluctuations and therefore with the occurrence of intermittency. Thus, the emerging picture is that of an ensemble of evolving and interacting multiscale fluctuations/structures, which are responsible for the observed fluctuations field.

5. IN SITU MONITORING INSTRUMENTATION

During the ISIS *in situ* study, a certain set of instruments has been surveyed. The candidate technologies have been restricted to the "flight-able" ones inside a reasonable mass budget, telemetry and risk free toward the main mission. This approach has been based on the cooperation of the engineering team with the science team, so to trade-off a solution technically optimized with the scientific return.

More schematically, the choice has been driven by: whatever the instrument selected for in situ measurement, it has to be scalable, i.e. it has to ensure unique science return while flying on board all the constellation as well as flying on board a small satellites subset; the demand of spacecraft resources has to be minimized; synergy with present missions data collection is expected (e.g. SWARM constellation in the ionosphere); no meaningful constraint should be posed to the spacecraft; the risk added to the main mission by embarking the in-situ package has to be minimized or nulled (e.g. no moving mechanism); the installation of the detector on the external surfaces of the spacecraft should be flexible (e.g.: no preferred orientation); the selected instrument should better be a well consolidated one. The choice landed on the Langmuir Probe.
In fact this is a basic instrument for plasma characterization. Langmuir Probes fly on board many science mission, from ionosphere orbit (as today SWARM constellation) to space exploration as Cassini. Some of the flying Langmuir Probes have been designed and manufactured by Thales Alenia Sace Italia.
One example is reported in Figures 7 and 8.

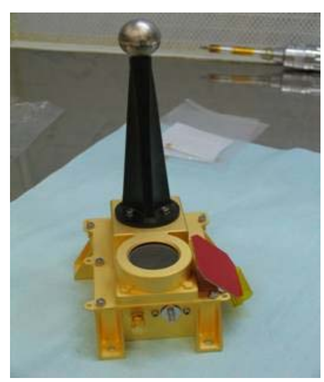

Figure 7. A detector unit with a Langmuir Probe from Thales Alenia Space.

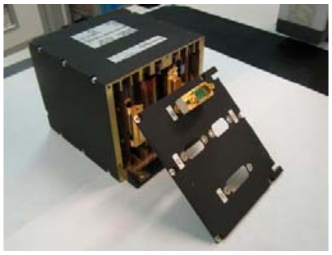

Figure 8. The electronic unit of the Langmuir Probe. (Thales Alenia Space).

A critical aspect highlighted by ISIS study has been the telemetry budget. To circumvent this feared limitation, some solutions has been suggested, including the use of unfilled data frames in the L band channels. If this critical aspect should be confirmed, a “design must” is the on-board data processing, so to mitigate the telemetry by data compression Diagnostic modes and indicators of compression quality will be defined so to quantitatively rely on the received data.
A second point is related to the sensibility. The table below compares for example the measurements ranges requested to a Langmuir Probe devoted to the on board diagnostic of electrical propulsion with the ISIS specifications. To cope with these, more stringent requirements, design parameters such as the sensor dimension, the integration time, the voltage ranges and the processing will be optimized.

Application	Min plasma density [electrons/m^3]	Max plasma density [electrons/m^3]
On board Diagnostic	2*10^11	8*10^13
Galileo Orbit	1*10^7	1*10^9

6. CONCLUSIONS

The ISIS Project started on October 2011 and its results were finally presented on October 2012, during an ESA conference in Paris. The scientific community have had the opportunity to know about it during the 3rd Galileo Colloquium in Copenhagen [6].
The main aim of this project was to show how it was possible to monitor the Earth’s plasmasphere by equipping the future EGEP satellites with instruments capable of making TEC monitoring via inter-satellite links and *in situ* measurements of some fundamental plasma quantities. We have found the our knowledge of the Earth’s plasmasphere dynamics could be greatly improved using global and local measurements performed via the Galileo (and EGNOS) satellites. For this reason, we have decided to propose a new study focalised on the C band for the inter-satellite TEC monitoring, and a scalable assortment of Langmuir probes to measure the electron density in the plasmasphere region.
This realization will take the long period program of making quantitative Space Weather, as illustrated in [7], very close to being realized.

7. REFERENCES

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