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Study the simultaneous variation of the Ionosphere, GNSS derived position accuracy, and magnetic fluctuations during storm and substorms

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14. ABSTRACT
This project was quite successful despite serious impacts of COVID on the Chilean educational system. Prof Alejandro has developed an excellent computational model for predicting total electron count (TEC) that match well with other proprietary models, but is being made freely available. This model should be able to test both small and large scale solar storm effects on TEC when such an event occurs. They have further studied the TEC from the 2020 solar eclipse over Chile and found that it had a profound effect on TEC. The project produced 5 journal papers and the PI presented at 13 international conferences.

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Study the variations of Ionospheric state during storms and substorms

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Table of Contents

Summary

In this project, we have taken advantage of an active and internationally recognized group of researchers and laboratories at Universidad de Chile and Universidad de Santiago to study the sun – solar wind -magnetospheric – ionospheric (SSWMI) system. In particular, we are studying total electron content (TEC) and magnetic fluctuations (MF), taken as global indexes or high-resolution spatial patterns. We have already developed our own code to construct high resolution spatial TEC maps from a very dense Chilean network in combination with other South American dual frequency GPS receivers and its precision was compared with 2 other standard TEC reconstruction techniques to study the behavior of the ionosphere during the 2020 eclipse. The results are quite interesting, as we show how the Eclipse can affect the ionosphere away from its umbra and penumbra. To have a picture of the state of the ionosphere, we complemented these measures with an analysis of the complexity of the MF around the Earth, the magnetotail, and the solar wind during reconnection events. Of course, the final driver of all of these dynamics is the sun and the solar wind, so constructed solar wind driven nonlinear dynamic models, particularly of MF at the surface of Eath, that are based on new robust artificial intelligence techniques that we developed in the paper. We started a collaboration with the visit of PhD student Nicolas Dunkler to Dr. Jesper Gjerloev laboratory at The Johns Hopkins University Applied Physics Laboratory in Maryland, USA, during the summer of 2022. in this collaboration we started the characterization of the spatial patterns of MF over the surface of the Earth, as measured by a network of magnetometers that are provided by the supermag site (https://supermag.jhuapl.edu/) at APL, and the effect of solar wind parameters on these spatial patterns. This work has been fundamental to conduct part of the PhD thesis of Nicolas Dunkler that is in progress. These spatio-temporal studies are relevant to the understanding of the SSWMI system and the constructed models are expected to eventually evolve into more precise space weather applications, with particular emphasis on local effects on the ionosphere and surface of the Earth. Many of these issues can have profound implications for telecommunications, positioning, geophysically induced currents in power grids, precision farming, etc.; topics that may be of interest to the US Air Force.

Products 1st year:

- **Accepted Manuscript 1: S. Blunier, B. Toledo, J. Rogan, J. A. Valdivia,** A Nonlinear System Science Approach to Find the Robust Solar Wind Drivers of the Multivariate Magnetosphere, *Space Weather*, 19, e2020SW002634, 2021, (https://doi.org/10.1029/2020SW002634).
- **Accepted Manuscript 2: B. Toledo, P. Medina, S. Blunier, M. Stepanova, J. Rogan, J. A. Valdivia,** Multifractal features for the northern hemisphere geomagnetic field fluctuations at Swarm altitude, *Entropy*, 23, 558, 2021, (https://doi.org/10.3390/e23050558).
- **Invited Seminar:** October 30 2020, Talk titled "Space Weather and Machine Learning", presented at the "Seminario de Heliofisica y Clima Espacial Sciesmex - LANCE Laboratorio Nacional de Clima Espacial UNAM Mexico" presented by Dr. J. A. Valdivia. https://www.facebook.com/sciesmex/videos/364200611566839/?vh=e&d=n
- **International Conference Presentation:** November 24 2020, Talk titled "Thermally induced Electromagnetic Fluctuations Theory and Simulations", presented by Dr. B. Toledo at "XXII Simposio Chileno de Física", held in Antofagasta, Chile
- **International Conference Presentation:** January 11-15 January 2021, Talk titled "A Nonlinear System Science Approach to Find the Robust Solar Wind Drivers of the Multivariate Magnetosphere" presented by Dr. S. Blunier at the "American Meteorological Society's 18th Conference (101st Annual Meeting) on Space Weather", held Online.
- **International Conference Presentation:** May 17-22 2021, Invited talk titled "Neural network-based method to characterize the robust interactions between geomagnetic storms and substorms" presented by Dr. J. A. Valdivia at the Virtual Conference on "Applications of Statistical Methods and Machine Learning in the Space Sciences", held online

(http://spacescience.org/workshops/mlconference2021.php).

- **International Conference Presentation:** May 17-22 2021, Invited talk titled “Sylvain Blunier - Neural network-based methods to determine the robust SMI couplings” presented by Dr. S. Blunier at the Virtual Conference on "Applications of Statistical Methods and Machine Learning in the Space Sciences”, held online (http://spacescience.org/workshops/mlconference2021.php)
- **International Conference Presentation:** Aug 30-Sep 3 and Sep 13-16, 2021, Invited talk title “Storm-Substorms modeling in one step and iterated fashion” presented by Dr. J. A. Valdivia at the “Solar wind–Magnetosphere Interaction Workshop”, held online (https://secwww.jhuapl.edu/EventLink/Event/32).
- **International Conference Presentation:** Aug 30-Sep 3 and Sep 13-16, 2021, Invited talk title “Storm-Substorms modeling in one step and iterated fashion” presented by Dr. S. Blunier at the “Temporal resolution impacts in iterated forecasts of Geomagnetic indices”, held online (https://secwww.jhuapl.edu/EventLink/Event/32).

Products 2nd year:

- **Accepted Manuscript 3:** Bravo MA, Molina MG, Martínez-Ledesma M, de Haro Barbás B, Urra B, Elías A, Souza J, Villalobos C, Namour JH, Ovalle E, Venchiarutti JV, Blunier S, Valdés-Abreu JC, Guillermo E, Rojo E, de Pasquale L, Carrasco E, Leiva R, Castillo Rivera C, Foppiano A, Milla M, Muñoz PR, Stepanova M, Valdivia JA and Cabrera M (2022), Ionospheric response modeling under eclipse conditions: Evaluation of 14 December 2020, total solar eclipse prediction over the South American sector, Front. Astron. Space Sci. 9:1021910, (https://doi.org/10.3389/fspas.2022.1021910).
- **Accepted Manuscript 4: C. M. Espinoza, P. S. Moya, M. Stepanova, J. A. Valdivia, R. E. Navarro**, Spontaneous Magnetic Fluctuations and Collisionless Regulation of Turbulence in the Earth's Magnetotail, The Astrophysical Journal, 914, 8, 2022, (https://doi.org/10.3847/1538-4357/ac33a2).
- **Accepted Manuscript 5: R. A. Miranda, J. A. Valdivia, A. C.-L. Chian, P. R. Muñoz**, Complexity of magnetic-field turbulence at reconnection exhausts in the solar wind at 1 AU, The Astrophysical Journal, 923, 132, 2021, (https://doi.org/10.3847/1538-4357/ac2dfe).
- **International Conference Presentation:** DIc 13-17, 2021, Oral Presentation “Total Electron Content above South-America during the recent Total Solar Eclipse” presented by Dr. S. Blunier at the “American Geophysicsl Union Fall Meeting”, held in New Orleans and online (https://www.agu.org/Fall-Meeting).
- **International Conference Presentation:** DIc 13-17, 2021, Oral Presentation “Robust Machine Learning modeling of the solar wind-magnetosphere interaction optimized in iterated fashion” presented by Dr. J. A. Valdivia at the “American Geophysicsl Union Fall Meeting”, held in New Orleans and online (https://www.agu.org/Fall-Meeting).
- **International Conference Presentation:** Jul 16-22, 2022, Oral Presentation “The universality of the kinetic regulation of plasma turbulence and thermally induced electromagnetic fluctuations ” presented by Dr. J. A. Valdivia at the “Cospar 22th Scientific Assembly”, held in Athens, Greece, (https://www.cosparathens2022.org/).
- **International Conference Presentation:** Jul 16-22, 2022, Invited plenary Presentation “The complexity approaches in Space plasmas” presented by Dr. J. A. Valdivia at the “6th Asia-Pacific Conference on Plasma Physics (AAPPS-DPP)”, held in Japan, and online (https://aappsdpp.org/DPP2022/index.html)
- **International Conference Presentation:** Nov 27- Dic 3, 2022, Oral Presentation “The universality of the

kinetic regulation of plasma turbulence and thermally induced electromagnetic fluctuations" presented by Dr. J. A. Valdivia at the "Conference of Latin American Space Geophysics (COLAGE 2022)", held in Sao Jose Dos Campos, Brazil (https://www.gov.br/inpe/en/events/colage/2022/).

- **International Conference Presentation:** Nov 27- Dic 3, 2022, Oral Presentation "Ensemble Forecasts Of Geomagnetic Indexes" presented by G. Yupanqui at the "Conference of Latin American Space Geophysics (COLAGE 2022)", held in Sao Jose Dos Campos, Brazil (https://www.gov.br/inpe/en/events/colage/2022/).

Some of the conference presentations and publications were financed by other complementary sources. We are also strengthening a close collaboration with Dr. Clezio De Nardin and Dr. Joaquim E.R. Costa at the "Instituto de Pesquisas Espaciales" (INPE) of Brazil; Dr. Americo Gonzalez at the Universidad Nacional Autonoma (UNAM) of Mexico; and Dr. Sergio Dasso at the Universidad de Buenos Aires (UBA) of Argentina on topics related to Space Weather.

Participants

- **Principal Investigador:** Dr. Juan Alejandro Valdivia Hepp (Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: alejo@macul.ciencias.uchile.cl) is an expert in plasma theory, non-linear dynamics, machine learning, solar wind-magnetosphere-ionosphere coupling, magnetospheric dynamics, and particle simulations in plasmas. Participated in all aspects of the project, namely, conducted part of the research through analytical descriptions, simulations, data analysis, and research presentations. He also took part in paper writing, administrative work related to the development of the project, student and postdoc guidance, coordinated research meetings, etc. Orcid: 0000-0003-3381-9904

- **Co-Investigator:** Dr. Marina Stepanova (Departamento de Física, Universidad de Santiago de Chile, e-mail: marina.stepanova@usach.cl) is an expect in the solar wind-magnetosphere-ionosphere coupling, and magnetospheric dynamics. Participated in part of the research through data analysis, and research presentations. She also took part in paper writing, student and postdoc guidance, research meetings, etc. Orcid: 0000-0002-1070-3602

- ***Co-Investigator:*** Dr. Marcos Díaz Quezada (Department of Electrical Engineering, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, e-mail: mdiazq@ing.uchile.cl) is an expert in satellite and instrumentation design. He is a head of the Space and Planetary Exploration Laboratory at the Faculty of Mathematical and Physical Sciences, University of Chile. Participated in part of the research through data analysis, and research presentations. He also took part in paper writing, student and postdoc guidance, research meetings, etc. Orcid: 0000-0002-7701-5839

- **Co-Investigator:** Dr. Benjamin Toledo (Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: btoledo@macul.ciencias.uchile.cl) is an expect in the solar wind-magnetosphere-ionosphere coupling, and artificial intelligence. Participated in part of the research through data analysis, and research presentations. He also took part in paper writing, student and postdoc guidance, research meetings, etc. Orcid; 0000-0001-5928-2290

- **Postdoctorial Researcher:** Dr. Sylvain Blunier (Postodc at the Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: sylvain.blunier@gmail.com) has a strong background in Space Physics, nonlinear dynamics, and machine learning. Participated in part of the research through analytical descriptions, simulations, data analysis, and research presentations. He also took part in paper writing, research meetings, etc. Orcid: 0000-0002-9456-2332

- **Postdoctorial Researcher:** Dr. Pablo Medina (Postodc at the Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: pab-medi@uniandes.edu.co) has a strong background in nonlinear dynamics, and machine learning. Participated in part of the research through analytical descriptions, simulations, data analysis, and research presentations. He also took part in paper writing, research meetings, etc. Orcid: 0000-0003-3139-042X

- **PhD student**: Sebastian Carrasco (former PhD student, Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: sebastian.carrasco@ug.uchile.cl) has a strong background in nonlinear dynamics and machine learning. Now as a postdoc at Army Research Lab in Maryland, USA. Participated in part of the research through analytical descriptions, simulations, data analysis, and research presentations. He also took part in paper writing, research meetings, etc.
- **PhD student**: Nicolas Dunkler (Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: nicolas.dunkler@ug.uchile.cl) has a strong background in space physics, nonlinear dynamics, and machine learning. Visited Dr. Jesper Gjerloev (jesper.gjerloev@jhuapl.edu), a Principal Scientist at The Johns Hopkins University Applied Physics Laboratory in Maryland, USA, during the summer of 2022. Participated in part of the research through data analysis. He also took part in research meetings, etc.
- **MS student**: Gabriela Yupanqui (Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: yupanqui.g@gmail.com) has background in space physics. Participated in part of the research through data analysis. She also took part in research meetings, etc.
- **Technical staff**: Cristina Sanhueza (B.S. Engineer, Departamento de Física, Facultad de Ciencias, Universidad de Chile, e-mail: ccc.fisica.ciencias@uchile.cl) has a strong background in technical, scientific, outreach, data analysis, and programming support. Participated as technical, scientific, outreach, data analysis, and programming support.

Spending during the 2 years in US Dollars:

Cost Category	**1st year Person paid**	**2nd year Person paid**
Graduate student support		
PostDoc support	Dr. Sylvain Blunier US$ 23.699 Dr. Pablo Medina US$ 11.918	Dr. Sylvain Blunier US$ 9.367 Dr. Pablo Medina US$ 23.554
Technical Staff	Cristina Sanhueza US$ 4.764	Cristina Sanhueza US$ 7.422
International trips to US		
PhD student trip to US (Nicolas Dunkler to APL)		Nicolas Dunkler US$11.000
Overhead (5%)	US$ 2.019	2.056
Total US$ 95.798	**US$ 42.399**	**US$ 53.399**

During the 1st year, we supported Dr. Sylvain Blunier (PostDoctoral fellow) for the full year and Dr. Pablo Medina (PostDoctoral fellow) for 6 months to help conduct the research. We also partially financed Cristina Sanhueza (Technical Staff) as a technical, scientific, outreach, data analysis, and programming support.

During the 2nd year, we supported Dr. Sylvain Blunier (PostDoctoral fellow) for about 5 months and Dr. Pablo Medina (PostDoctoral fellow) for the full year to help conduct the research. We also partially financed Cristina Sanhueza (Technical Staff) as a technical, scientific, outreach, data analysis, and programming support.

Because of the difficulty to travel during this time, the fact that most of the conferences and now online, and other restrictions; we adapted the spending in each Category to the current budget after sending a request and receiving permission from the program manager.

During the 2nd year we received additional funding to support the trip of the PhD student Nicolas Dunkler to Visit Dr. Jesper Gjerloev (jesper.gjerloev@jhuapl.edu), a Principal Scientist at The Johns Hopkins University Applied Physics Laboratory (APL) in Maryland, USA, during the summer of 2022. During that time Nicolas worked in close collaboration with Dr. Jesper Gjerloev on the characterization of the spatial patterns of magnetic fluctuations over the surface of the Earth, as measured by a network of magnetometers that are provided by the supermag site (https://supermag.jhuapl.edu/) at APL, and the effect of solar wind parameters on these spatial patterns. This work has been fundamental to conduct part of the PhD thesis of Nicolas Dunkler that is in progress.

Note: Some of the conference presentations and publications were financed by other complementary sources.

Technical Report

In the past few years, the study of the sun-solar wind-magnetosphere-ionosphere (SSWMI) system and the dynamics of space weather have become some of the most relevant endeavors that our civilization has had to pursuit. This is important not only because dynamic processes in the SSWMI can affect our daily life, but also because such system is a nearby accessible natural laboratory to make precise studies of the interaction of a star with a planet. Such knowledge becomes essential as human beings embark on the colonization of other planets of the solar system, and eventually make the big jump to become an interstellar civilization. There have been great advances in understanding this SSWMI system and space weather dynamics [Borovsky and Funsten 2003; Consolini and De Michelis 1998; El-Alaoui et al., 2013; Klimas et al., 2000; Sitnov et al., 2000; Valdivia et al., 2013; and many others]; primarily due to the combination of theory, simulations, and satellite and ground-based measurements. However, there are a number of fundamental open science questions [*Denton et al.,* 2016] that remain to be solved. For example, our modern society relies strongly on precise positioning and communication. As new technologies are developed, the demands and reliability requirements of these services are constantly increasing. Farming, defense, smartphone apps, telecoms, electricity networks, financial markets are some of the many areas in which normal operation depends on precise timing and positioning. A failure of the positioning and communication system would cause an inestimable loss in the world economy and would affect military and scientific operations. Many of these issues can be of interest to the US Air Force. Hence, understanding the dynamics of the ionosphere, for example as represented by total electron content (TEC), and the magnetic fluctuations (MF), for example as a monitor of induced current systems, become a relevant endeavor.

At the same time, we have consolidated a group of researchers and laboratories at Universidad de Chile and Universidad de Santiago that has been working actively on understanding the SSWMI system, with emphasis on the dynamics of Space Weather. This project has been taking advantage of such a consolidated group of researchers to study the of total electron content (TEC) and magnetic fluctuations (MF), taken as global indexes or high-resolution spatial patterns, for example during interesting events such ellipses, magnetic storms, and substorms.

Substorms l*ast for about 1-3 hours, while storms last for about 1 to 4 days. Both geomagnetic disturbances deposit significant amounts of energy in the thermosphere-ionosphere system in the form of large high-latitude and equatorial ionospheric currents and precipitation, producing large changes in TEC/EGDP. Storms and substorms can also dramatically increase the energetic particle population in the near Earth's radiation belts causing multiple satellite anomalies and destruction in man-made* satellites*. Eclipses provide a natural situation in which we can study the response of the ionosphere when one of the forcings, namely solar radiation and ionization, are drastically reduced.*

Methods, Assumptions, and Procedures

The proposed measures (TEC and MF) give useful information about the state of the ionosphere and magnetosphere as part of the SSWMI system, and as such, they provide emergent and relevant space weather-related themes that aim to provide valuable knowledge for future technologies (mining, natural disaster management, remote communications, precise farming, power grid management, etc.). As part of the project, we analyzed the possibility of constructing robust system science models, based on machine learning, to nowcast/forecast indexes and spatial patterns of TEC and MF.

Hence, the understanding of ionospheric disturbances, as characterized by TEC and MF, particularly through high time and space resolution maps, provide invaluable information about the behavior of the ionosphere and its effect on radio blackouts, communication, positioning, electric networks, etc. Furthermore, it has also been shown that the dynamics of the ionosphere can influence the energy deposition in the troposphere and vice-versa [Pedatella et al., 2019], therefore, TEC can bring relevant information to improve climatological models of the lower layers of the atmosphere.

For the estimation of the error in positioning, it is possible to use GNSS which can provide the position on the ground when the signal is caught from at least 4 satellites, however, many factors can alter its accuracy

[Arasavali et al., 2018; Kos et al., 2010; Sathyamoorthy et al., 2016]. Similarly, the atmospheric refraction due to ionospheric total electron content (TEC) is one of the most important source of error in positioning. The ionosphere has an electron density perturbation that can vary several orders of magnitudes depending on the hour of the day, the seasons, solar and space weather activity, among others. The varying ionospheric electron density changes the phase and group velocities of the waves, affecting the effective estimated distance between the satellite and the receiver. Therefore, the accuracy of positioning relies on the state of the ionosphere and the errors can also be of the order of several meters.

GNSS satellites are constantly emitting signals in two radio-frequencies that are captured by antennas (receivers) on the ground. Using the measurement of the distance traveled by the two waves and the value of the frequencies, the number of electrons along their trajectory can be calculated as

$$STEC = \frac{f_1^2 f_2^2}{40.31\left(f_2^2 - f_1^2\right)}\left(P_2 - P_1\right).$$

This quantity is called Slant Total Electron Content (STEC), it is measured in TECU (TEC units) with the correspondence of 1 TECU = 10^{16} electrons. f_1 and f_2 correspond to the emitted frequencies, P_1 and P_2 are the distances traveled by the respective signals, and the value 40.31 is a physical constant calculated from the charge and mass of the electron. STEC depends on the position of the satellites and it would be more practical to use a quantity that does not. To achieve that, STEC is rescaled with the elevation angle of the satellite α, such that we obtain the Vertical Total Electron Content (VTEC). The actual calculation is a little more involved and is corrected by the bias at the satellite and at the receiver, error estimation of the phases, among other things [Håkansson et al., 2017].

The state of the ionosphere must also be characterized and understood in terms the magnetic fluctuations that the different current systems in the magnetosphere and solar wind produce on and around the Earth, serving as a monitor of the dynamics of these current systems. Hence, in terms of the geophysical induced magnetic fluctuations on and around the Earth, we have used data analysis, for example based on multifractal techniques; and system science model construction, or example on artificial intelligence techniques.

The multifractal techniques, are based on the fractal dimension of the different sets of points in the time series that behave

$$(x(t) - x(t-\tau)) \sim \tau^{\alpha}$$

and have the same singularity exponent α, and as such, serve to describe the complexity of these magnetic fluctuations. In a monofractal system al points have a unique value of α, while in a multifractal time series we have distribution of such values, so that the width and asymmetry of the acceptable range of α values define the complexity of the system. Knowing the multifractality properties, for example the range of values of α, of the systems, and in this case of the magnetic fluctuations, provide insight into the type of models that need to be constructed to study such systems. See Fig. 1 for two examples.

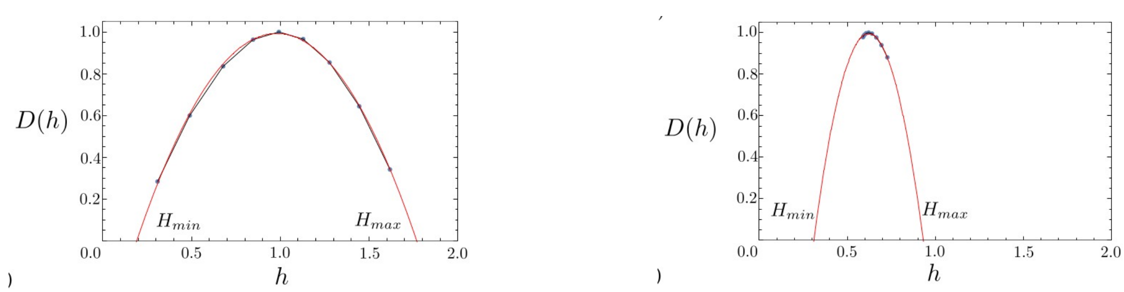

Fig 1: 2 different multifractal spectra of the magnetic fluctuations, measured at two positions close to the Earth (taken from **paper 2**)

There are other techniques to help characterize the magnetic fluctuations that appear in these turbulent systems, such as beta-anisotropy diagrams, or complexity-entropy planes, that help organize and characterize these fluctuations in terms of different type of behavior, namely, fully stochastic, chaotic, presence of coherent structures, etc.

Similarly, it is important to realize that to construct system science model of magnetic fluctuations, particularly in view of the previous paragraph, we must always keep in mind that the SSWMI system is a high dimensional system that is driven by the high dimensional solar wind, so that we observe a large amount of fluctuations, and as such, it requires special techniques to handle such inherent property of the system. For example, we have designed a way to determine the most relevant variables that enter a neural net model for 3 geophysical indexes based on magnetic fluctuations measured at the surface of the Earth driven by solar wind parameters, by adding noise to each of the variables and look for the solar wind variables that produce the largest error on the geophysical indexes. The technique (paper 1) was able to determine that only few of the variables are geophysical relevant as shown in Fig. 2

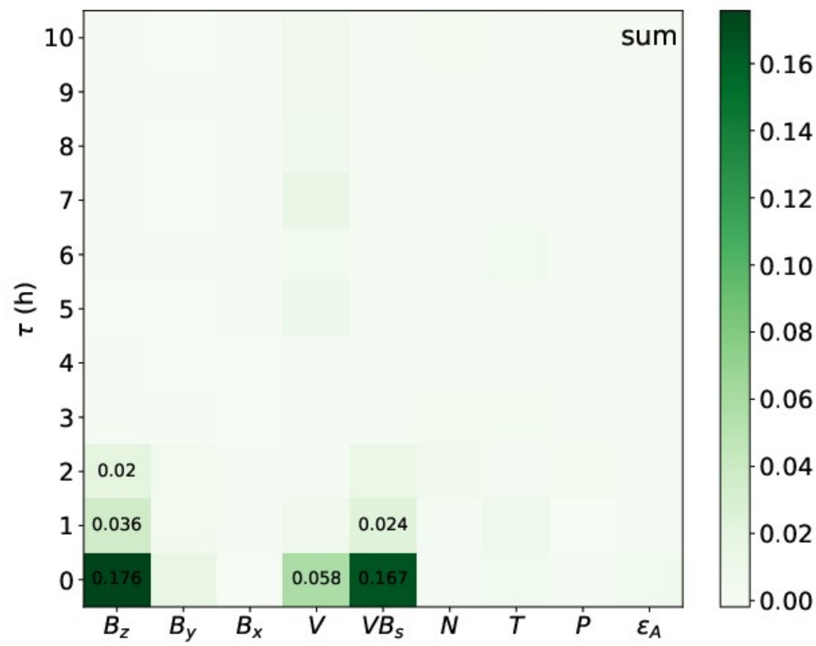

Fig. 2, diagram of relevant and robust solar wind variables that are need to construct the neural net model with different time delays. Other variables are not included in the final model (from ***paper 1****)*

It is then possible to construct a robust model that only considers these robust and relevant solar wind drivers at particular time delays. As a bonus, the strategy tell us what are the relevant variables, so that we can understand the physics of the system.

Accomplishments

We have constructed our own open source code to calculate TEC from the Rinex files and the satellite trajectories, as shown in Fig.3a-b using the high-resolution Chilean data with some additional South American stations. We use a non-homogeneous linear interpolation with a 5 minutes time resolution. In the figures we compute the latitudinal dependence along the magnetic meridian of Chillán (36.6 ° S, 72.0 ° W) as a function of UT time, before and during the eclipse. We also show the ΔTEC between the two patterns to isolate the effect of the eclipse in the ionosphere due to the trajectory of the Eclipse shadow. These are then compared with the INPE-supin model (see paper 3 for details), and we note that the effects are quite similar..

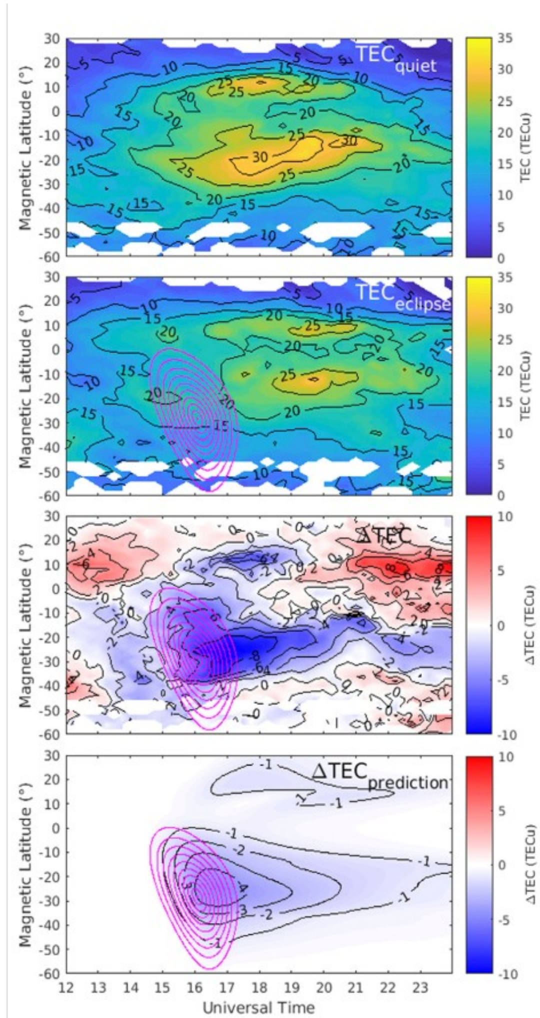

Fig 3: Total electron content response time evolution obtained with our TEC code for reference day (top), the 14 December 2020, solar eclipse (middle), and eclipse-modified differences of TEC (ΔTEC, third row) along the magnetic meridian of Chillán (36.6 ° S, 72.0 ° W) and the SUPIM-INPE predicted differences (ΔN prediction , bottom). Evolution of the eclipse obscuration mask at 300 km height each 10% obscuration (magenta lines).

The comparison of our open source code (red) with other commonly used codes (Seemala (blue) and Ciraolo (red), which are not open source) is shown in Fig. 4 at four different locations during the time of the 2020 Eclipse. We observe that the results are quite similar. In fact, using a ΔTEC technique, it is possible to observe the effect of the Eclipse on the ionosphere with a excellent spatial resolution.

Our idea is to make the code accessible for people to use it, and we have started to have workshops in which it is shown how can be used or changed. These figures were taken from one of our publications (**Paper 3**: Bravo et al., 2022) and the results were presented in a couple of conferences. The results are quite interesting, as the effect of the Eclipse can be seen beyond the umbra and penumbra of the Eclipse.

As future work, we are waiting for a relevant magnetic storm to study using this technique, as there have been very few such events during the past years where the network has been active. We also hope to study the ionospheric dynamics during strong substorms. The TEC maps can be nonlinearly correlated with solar wind parameters and magnetospheric indexes (based on MF). Such work can then be translated into static and dynamical evolution models, based on neural nets (artificial intelligence), to nowcast/forecast the state of the ionosphere, as described by maps of TEC, that are driven by solar wind parameters and magnetospheric indexes. Similar work for magnetospheric indexes and magnetic field spatial patterns on the surface of the Earth, driven by solar wind parameters, has been done in the past as shown in Refs. [Valdivia et al., 1996; Valdivia et al 1999a; Valdivia et al., 1999b; Vassiliadis et al., 1999; and many others].

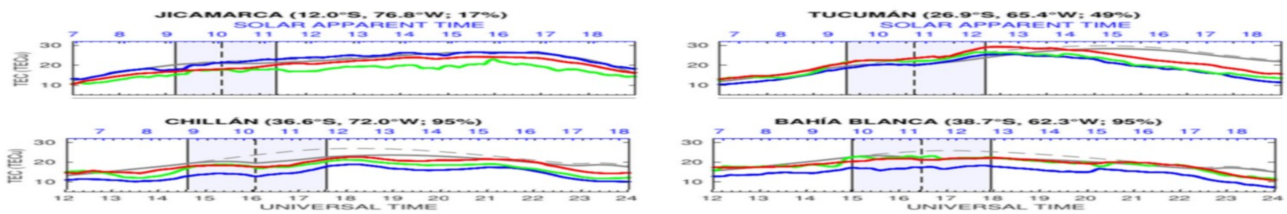

Fig 4: Comparison of our open source TEC code (red) with other commonly used codes (Seemala in blue)and Ciraolo in red), which are not open source. The similarity is quite good.

In order to understand the ionospheric state, it is also necessary to also study the magnetic fluctuations on and around the Earth, as a monitor of the dynamics of a number of current structures that in are part of the SSWMI system. For example, we constructed robust models of magnetospheric indexes representing MFs at or near Earth, based on robust artificial intelligence techniques that we are developing, particularly neural nets (NN), that are driven by the solar wind parameters (**see paper 2**). Using the strategy to get obtain the relevant and robust solar wind variables described above, we were able to run this robust model to forecast these 3 geophysical indexes from solar wind parameters in an iterated fashion (see fig. 5)

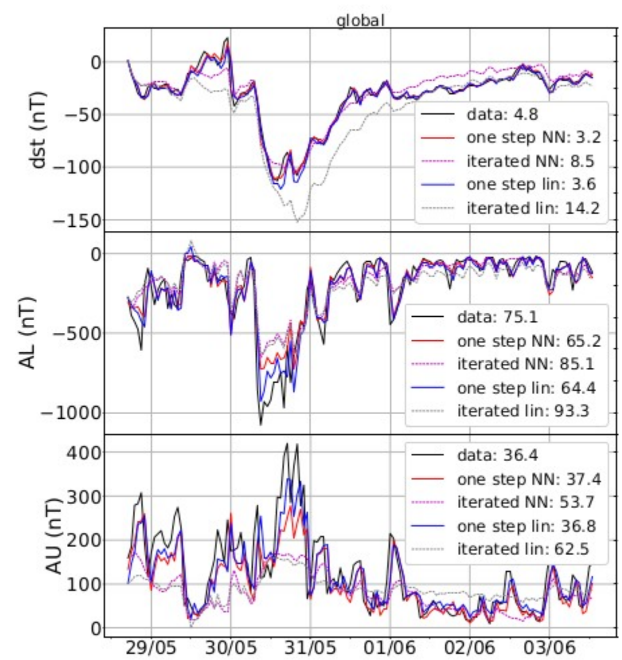

Fig 5: Forecasts of the geomagnetic indices Dst, AL, and AU during the storm of May2013 for the Globally robust models. The solid black line shows the data, the solid red (blue) corresponds to the one step prediction of NN (linear models). Similarly, the red (blue) dashed curves are the iterated nonlinear (lineal) models based on NN.

It is important to mention that magnetic fluctuations are an inherent part of the dynamics of the SSWMI system, being a high dimensional driven system, and as such it is important to learn to characterize these magnetic fluctuations to test the validity and complement these reduced AI techniques. In this respect, we have been working on analyzing the complexities, particularly the range of values of α (ΔH) shown in Fig. 6 for active ajd quiet times, of the spatial patterns of MFs at the surface and around the southern and northern hemispheres of

Earth (**see paper 1**). These results have consequences for the accuracy and type of spatial model that can be constructed for the MF around the Earth.

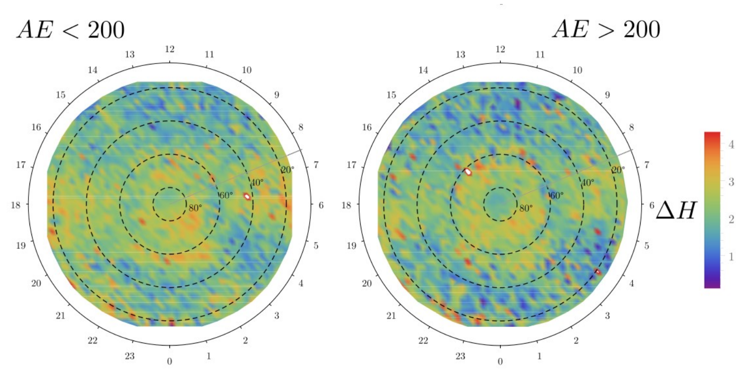

Fig 6: calculation of DH, for example as obtained from Fig. 2 at a particular position in space, as the satellites move around the Earth.

We have also conducted additional studies of the complexity of the magnetospheric fluctuations in reconnection exhausts in the solar wind through the complexity-entropy, to characterize the anisotropy of the different components of these fluctuations, showing that in general are quite stochastic but with different levels of coherent structures (see **paper 5 and Fig. 7**).

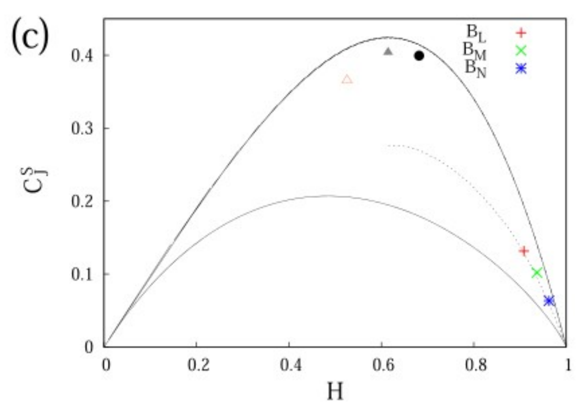

Fig 7: The d = 5 C-H plane for the B L (red plus symbol), the B M (green cross), and the B N (blue asterisk) components of the magnetic field during the reconnection exhaust. The full black circle, open red triangle, and full gray triangle represent the chaotic time series of the logistic map, the skew tent map, and the Hénon map, respectively The crescent-shaped curves indicate the maximum and minimum values of Complexity (C) for a given value of Entropy (H), and the dotted line represents stochastic fractional Brownian motion.

Similarly, we used these type of techniques to try to characterize or organize the magnetic fluctuations and the turbulence in the magnetotail using \beta-anisotropy diagrams, which is relevant for our understanding of how magnetic fluctuations, and the turbulence in general, get organized in these space plasma systems (see **paper 4**).

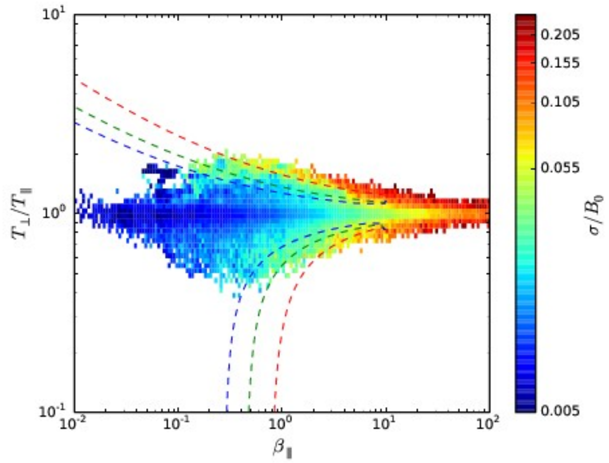

*Fig 8: fluctuation level in the magnetotail in the beta-anisotropy that hows that the fluctuations can be organized (**paper 4**)*

Finally, Nicolas Dunkler, the PhD student that visited Dr. Jesper Gjerloev at The Johns Hopkins University Applied Physics Laboratory during the summer of 2022, whom was financed by this project, is working on characterizing the spatial patters, the complexity, and the nonlinear interaction with solar wind parameters of the magnetic fluctuations observed by the Supermag magnetometer network, an endeavor that is fundamental to contrast and improve our physical understanding of the physical process and current systems that produce these fluctuations. They provide a natural monitoring systems of the current structures that are induced by the SSWMI system.

Impacts and Conclusions

There studies are extremely relevant for our understanding of space weather and possible applications. It is expected that with these data derived system science models we can improve our understanding of the underlying processes that drive ionospheric variations at the relevant spatial and time scales. That would ultimately help improve space weather nowcasts and forecasts. We know that TEC correlates with solar wind parameters and magnetospheric indexes. The data was obtained directly from OMNI, Supermagnet, CDAWeb, among others resources.

It would be quite useful to have reliable nowcasts/forecasts of the spatial profile of TEC and MF during storms and substorms, so that in a future work it could be important to apply machine learning techniques to construct them from solar wind parameters and magnetospheric indexes. Such maps would provide a way to monitor the solar wind-magnetosphere-ionosphere coupling that is finally responsible for the energy that is deposited in the ionosphere affecting communication between ground, satellites, airplanes, and ships; producing position errors; inducing drag on satellites; etc. This is especially true in view of the high density of dual frequency antennas Chile and its quite unique latitudinal coverage in the southern hemisphere.

Hence, the present project contributed to strengthen the space science activities in Chile with a special focus on Space Weather. The support also strengthen the existing cooperation between Chilean and American scientists, and enhance the research/training infrastructure of Chilean universities, which will also strongly energize and benefit regional universities. Furthermore, the proposed researched is done in close collaboration with Dr. Clezio De Nardin and Dr. Joaquim E.R. Costa at the “Instituto de Pesquisas Espaciales” (INPE) of Brazil; Dr. Americo Gonzalez at the Universidad Nacional Autonoma (UNAM) of Mexico; and Dr. Sergio Dasso at the Universidad de Buenos Aires (UBA) of Argentina.

Maps of TEC will eventually be displayed on our space weather website, which already provides the SYMH index (average of the horizontal magnetic field at the equator) with one-hour forecasts, solar winds indices, and images of the Sun in different wave-lengths (https://cefei.ciencias.uchile.cl/climaespacial/). If time permits, with such a high density of TEC data we could test the possibility of building a three-dimensional map of electron density by including the height variations using a tomography reconstruction technique from multiple paths. In the middle term, we hope to be able to have a simultaneous spatial view of the state of the ionosphere through TEC, MF maps.

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List of Symbols, Abbreviations and Acronyms

SSWMI	sun-solar wind-magnetosphere-ionosphere
TEC	total electron content
STEC	Slant Total Electron Content
VTEC	Vertical Total Electron Content
MF	Magnetic Fluctuations
GNSS	global navigation satellite system