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UNDERSTANDING THE NEAR-EARTH SPACE ENVIRONMENT: A CHALLENGE FOR BOTH SOLAR-TERRESTRIAL RELATIONS AND COUPLING WITH THE LOWER ATMOSPHERE

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Abstract. The near-Earth environment, namely the upper atmosphere (in the range 100-1000 km altitude) and the ionosphere, is increasingly regarded as a critical region of the Sun-Earth system. Indeed, this region is essential for understanding the impact on Earth of intense solar events (e.g. solar flares), since it is where most of the energy dissipation takes place. Recently, it has also become increasingly important for understanding couplings with the mid and low atmosphere and with the signatures of hazardous geological events such as earthquakes and volcanic eruptions that propagate through the ionosphere. In this paper, we will review the state of the art of existing problems in this region and the tools needed to understand the processes that occur there and improve its description (especially ground-based data, numerical modelling).

Keywords: ionosphere, thermosphere, upper atmosphere, magnetic storms, numerical modelling, ground-based instrument

1 Introduction - Formation and dynamics of the ionosphere

In the solar system, the upper atmosphere of planets is heated and photoionized by X-rays and Extreme ultraviolet (EUV) radiation from the Sun. This region is made up of the underlying neutral atmosphere, called the thermosphere, and its ionized counterpart, called the ionosphere. The ionosphere is in equilibrium between chemical processes and plasma transport which are highly dependent on thermospheric properties (density, temperature, winds). On Earth, the ionosphere is stratified in altitude and is structured into 3 main regions: D-Region (60-90 km), with a low degree of ionization and the creation of complex ions, E-Region (90-120 km), where ions and electrons decouple, generating horizontal ionospheric currents (see below for details) and F-Region (120-500 km), where the maximum ionospheric density is generally observed, and which is highly dynamic due to its coupling with the solar wind, ejected from the Sun's surface, and the magnetosphere, created by the Earth's magnetic field around the Earth. Due to the density of the atmosphere below 120 km, D- and E- Regions at mid- and low-latitudes disappear at night due to sustained recombination, while F-Region, as well as E-Region at high-latitudes, shrink but are nevertheless maintained, due to the horizontal transport of plasma and particle precipitation along the magnetic field also responsible for ionization. E- and F-Regions are composed of electrons and ions O^+, O_2^+, NO^+, N_2^+, originating from the main constituents of the atmosphere: O, O_2 and N_2. The dynamics of the ionosphere is strongly influenced by daily, seasonal and solar cycle variations of the Sun (see Blelly 2007 for a complete review).

The ionosphere is also strongly structured by the magnetic field. In the dense E-Region, ions are decoupled from the magnetic field because of collisions on neutrals, while electrons are bound to the magnetic field because of a gyrofrequency much higher than collisions on neutrals. At higher altitude, in the F-Region, gyrofrequencies of ions and electrons are higher than the collision frequencies and all the ionospheric plasma species are bound to the magnetic field (frozen-in condition), with plasma diffusion aligned to the field and drift velocity transverse to the magnetic field identical for ions and electrons. As a result, a differential motion between ions and electrons is possible, which peaks around 110-120 km. It is responsible for intense horizontal currents, particularly at high latitudes and in the equatorial region, which strongly contribute to the global electrodynamics of the Magnetosphere-Ionosphere-Thermosphere system.

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At the equator, the main driver of electrodynamics is the neutral thermospheric wind caused by solar heating and the almost horizontal geometry of the magnetic field, which creates an intense equatorial current and a positive ionization anomaly on either side of the equator. At high latitudes, electrodynamics is created by strong electric fields and currents arising from the coupling with the solar wind and the magnetosphere, as well as by particle precipitation. This gives rise to strong ionospheric plasma motion and to polar auroras (see Figure 1) encircling the magnetic poles in both hemispheres, known as 'auroral ovals'. This high-latitude electrodynamics is strongly influenced by the Sun, and can affect the ionosphere as a whole during solar storms, for example.

In this paper, we first present in Section 2 the French strengths in terms of ground-based instrumentation and modelling to monitor the ionosphere. In section 3, we briefly describe three of the main challenges facing the ionosphere community in the coming years, and how the French community is taking its place in these different challenges. Finally, Section 4 will be devoted to a brief conclusion and some ideas for the future.

Fig. 1. Image of austral aurora taken above the Kerguelen SuperDARN radar. Photo Credit: Grégory Tran - AWIPEV / Institut Polaire Français (IPEV) / Alfred Wegener Institute (AWI).

2 Diagnostic tools – ground instrumentation and physical models

While the ionosphere can be observed thanks to space missions, ground-based instrumentation is also extremely valuable, notably thanks to networks of instruments used to monitor density (ionosonde, in High Frequency range, HF, receiver in Very Low Frequency range, VLF), currents (magnetometers, such as those in the INTERMAGNET network, `https://intermagnet.org/`), convection (coherent HF radars, such as the international SuperDARN consortium, `https://www.irap.omp.eu/sno/superdarn/`) or light emissions (all-sky visible light cameras). Several CNRS/INSU institutes (see acknowledgment section for a detailed list) are strongly involved in the study of the Near-Earth Environment through international scientific partnerships: either by contribution to the type of instrumentation mentioned above or by collaborations and/or networking. Several magnetometers are operated in France (Chambon-La Forêt), Africa, Asia, the sub-Antarctic islands and Antarctica by the Bureau Central de Magnétisme Terrestre (BCMT, `http://www.bcmt.fr/`), maintained by IPGP and ITES/EOST. A VLF receiver is installed at the Nançay Observatory and operated by LESIA/OP. An ionosonde and airglow cameras have also been installed and will soon be operated by IRAP at the Atmospheric Research Centre (CRA) and the Pic du Midi Observatory respectively (both part of the Midi-Pyrénées Observatory). At high latitudes in the southern hemisphere, thanks to ongoing support from the French Polar Institute (IPEV, `https://institut-polaire.fr/en/scientific-research/supported-projects/`), a SuperDARN radar on the island of Kerguelen operated by IRAP/OMP and all-sky cameras in Antarctica, to be installed and operated jointly by IPAG/OSUG and IRAP/OMP, enable us to monitor electrodynamic coupling with the magnetosphere and solar wind.

These instruments are very useful for continuous monitoring of the ionosphere, but modelling this environment is also essential to cover global scales, even in regions where no instruments are installed, and to provide access to unobservable physical parameters. Since the 1990s, France has held a leading position in Europe for physical modelling of the ionosphere, thanks to the former TRANSCAR model (Blelly et al. 2005), which more recently gave rise to the Transsolo (IPAG) and IPIM (IRAP Plasmasphere-Ionosphere Model) models. The Transsolo model is a static kinetic model that reconstructs 1D profiles aligned with the magnetic field of ionospheric densities, temperatures and light emissions from particle precipitation (Robert et al. 2023). The IPIM model (Marchaudon & Blelly 2015, Blelly et al. 2019, Marchaudon & Blelly 2020) solves the time-evolving transport equations along the magnetic field line, combining a kinetic module for suprathermal electrons and a fluid module for thermal species to reconstruct the complete dynamics of the ionosphere (density, temperature, velocity, heat flux), taking into account exchanges between thermal and suprathermal populations (e.g. particle precipitation), plasma diffusion and horizontal convection. An online version of the model is available at: `https://http://transplanet.irap.omp.eu/`. For both models, by simulating a multitude of flux tubes, a global 3D reconstruction of the ionosphere can be obtained. At the equator, a new module describing electrodynamics and coupled to IPIM, is currently under development at IRAP and will be extended to mid-latitudes. The IPIM model is very well suited for reproducing ionospheric dynamics, even during solar storms, as long as the external inputs from the Sun (irradiance), the magnetosphere (electrodynamics due to electric field and particle precipitation) and the thermosphere (density, temperature, winds) are accurate. These three regions present inaccuracies or gaps in their description, and represent the main challenge for IPIM in the future to correctly reproduce the variability of the ionosphere.

3 Main scientific challenges linked to the ionosphere

3.1 Coupling with the Sun and the solar wind during magnetic storms

During intense solar events, such as Coronal Mass Ejections (CMEs) or solar flares, the ionosphere can be strongly impacted (Astafyeva et al. 2017, Briand et al. 2022). Coupling begins at high latitudes, where the Earth's magnetic field is in direct contact with the interplanetary medium. In this region, the electrodynamics is generally strongly reinforced, with intensified plasma convection, electric currents and particle precipitation responsible for energy deposition within the ionosphere-thermosphere system. The disturbance can then spread to mid-latitudes and even low latitudes, possibly modifying the electrical circuit at the equator. The main impact is sharp variations in ionospheric density, which can be reduced or increased depending on the thermodynamics of the system and its history (for example, the potential impact of previous storms) on a global scale, but also on more local scales in the form of small-scale structures such as patches or bubbles. Warming and expansion of the thermosphere are also observed. The impacts on human infrastructures, which we monitor in the context of space weather, are manifold, the most important being: increased drag and orbit disturbances for satellites orbiting at low altitude around the Earth; modification of waves propagation, or even their absorption through the ionosphere, leading to possible disturbances in HF communications or GNSS positioning; and overheating of electrical transformers on the ground due to induced currents circulating in power lines and caused by their ionospheric counterpart.

Intensive research is therefore being carried out: to effectively monitor the impact of solar events on the ionosphere-thermosphere system, to model them in order to access physical parameters that are not directly observable (Pitout et al. 2015,Marchaudon et al. 2018), and finally, in the future, to predict them for space weather applications. To achieve this, a major improvement in the description of high-latitude electrodynamics will be required, in particular by building a fully self-consistent module coupled to the solar wind on the one hand and to the ionosphere on the other, via IPIM. The assimilation of available data, such as ionospheric convection measured by SuperDARN radars, will also be a major asset in guaranteeing a more accurate description. IPIM is developed with the main constrain that it is able to reproduce structure and dynamics of the ionosphere in a quantitative way. As a consequence, through a comparison between measured electron density altitude profiles from ionosondes or Total Electron Content (TEC) recovered from satellite-ground station GNSS links and IPIM-modelled ones, it is possible to infer some key parameters of the atmosphere, by mitigating the differences between measurement and simulation. This is the way we can assimilate data in the model. Adding a feedback loop, we then get a powerful data analysis tool, allowing for inferring global neutral atmosphere characteristics.

Such a feedback is time consuming if we need to explore a large domain and so, it is not well suited for 'near real-time' analysis, though IPIM model offers such capabilities. To overcome this difficulty, we will take advantage of Machine Learning techniques to explore the domain and accelerate the way the optimization process could run to find the best solution for the atmosphere (see Figure 2 for a summary of the proposed development).

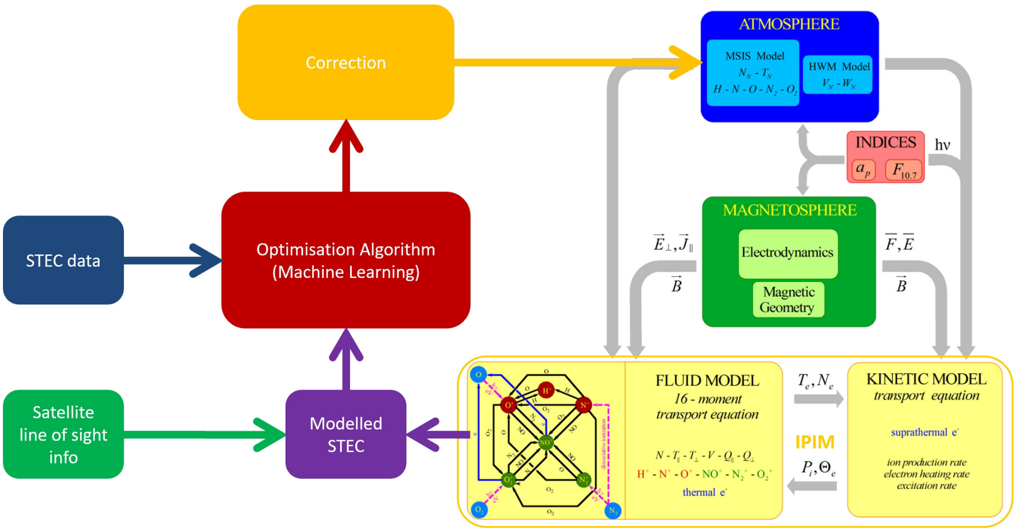

Fig. 2. Synospsis presenting IPIM and a possible optimisation algorithm. On the right is displayed the IPIM model (yellow boxes), the different inputs: atmosphere (blue box), Sun (red box), magnetic field and electrodynamics (green box). On the left is displayed the optimisation algorithm based on Machine Learning to adapt atmospheric inputs from Slant Total Electron Content (STEC) data obtained from GNSS satellites) and their satellite-ground station links (line of sight).

Finally, another avenue to follow will be to develop proxies to better constrain energy deposition in the ionosphere-thermosphere system in an integrated way. These proxies can be built from a network of ground-based magnetometers, are called magnetic indices, and are part of the research being carried out by ITES/EOST, in charge of the International Service of Geomagnetic Indices, `https://isgi.unistra.fr/` and IRAP/OMP, for example, to improve their spatio-temporal resolution (Chambodut et al. 2013, Chambodut et al. 2015).

3.2 Coupling with the thermosphere and the other layers of the atmosphere

As mentioned above, understanding the response of the thermosphere is essential during magnetic storms (Loutfi et al. 2020), but also during calm periods, as uncertainties about its behaviour remain significant. This is mainly due to the fact that it is often poorly observed with current instruments, and inaccurately described by models which, while correctly reproducing variations on climatological timescales, are far less suited to shorter timescales. What's more, even with realistic global variations, the background level of specific parameters such as density or temperature is not always accurate. Thus, it is not uncommon for empirical models of the thermosphere to give results far from the thermosphere actually observed, which may explain why the ionosphere is also poorly reproduced. In such cases, it is necessary to manually adjust various parameters in the thermosphere model, such as the density ratio between the O and N_2 constituents of the thermosphere, or the thermospheric temperature at key altitudes. Winds are even less well described, even though they can have a considerable impact at the equator or during solar storms.

At the same time, it is now well established that, even during calm periods, ionospheric and thermospheric parameters often exhibit day-to-day variability of up to 20% (Haberle et al. 2022), due to tides and gravity waves generated in the lower layers of the atmosphere and propagating into the thermosphere-ionosphere system. Their origin is linked, for example, to the Sun or the stratospheric polar vortex, but these waves often mix and the different modes become difficult to disentangle. Finally, the constant modification of the lower layers of the atmosphere by human also has significant effects on the thermosphere. For example, the injection of CO_2 into the troposphere also affects all other atmospheric layers, and is responsible for a long-term trend towards cooling and contraction of the thermosphere through enhanced infrared (IR) radiation emission.

To meet these challenges, it is crucial to improve thermospheric monitoring and observation. IPAG/OSUG is currently developing a new generation of miniaturized interferometer capable of measuring density, temperature and even winds from ionospheric emissions on board small spacecraft. At the same time at IRAP/OMP, a new strategy will be to use the day-to-day variability contained in the ionospheric signal (observed with ionosondes or magnetometers) to control the critical parameters of the empirical thermospheric models used as input to ionospheric models such as IPIM. As already presented in Section 3.1, with a machine learning algorithm, these critical parameters can be identified and their modification accelerated to reproduce the ionosphere. This will also provide important information on how the thermosphere is impacted by this day-to-day variability from the lower atmosphere.

Finally, in the longer term, better physical modelling of the thermosphere itself and its coupling with the lower layers of the atmosphere will be essential.

3.3 Coupling with the Earth's surface during hazardous geological events

The ionosphere is an interesting medium in which processes occurring on the Earth's surface can be detected. Indeed, hazardous geological events such as volcanic eruptions, earthquakes or tsunamis are sources of atmospheric waves, which propagate horizontally and vertically. Due to the rarefaction of the atmosphere as a function of altitude, the waves have a higher speed when they reach the ionosphere. Thanks to ionospheric measurements, it is in principle possible to monitor and even predict the impact of these waves on the Earth's surface, the most obvious example being the front wave of a tsunami hitting a coastline. For such monitoring to become relevant, better spatial coverage of the ionosphere must be achieved, especially over the seas, through the deployment of ground and space instruments capable of measuring the electron density or the nightglow (nocturnal de-excitation of ionospheric atoms and molecules causing faint light emissions), in which wave trains can be detected. In addition, modelling of wave propagation in all layers of the atmosphere, from the ground to the ionosphere, as well as their interaction with other wave types (e.g. travelling ionospheric disturbances) that can cause destructive interference, is also required. This promising work is currently underway at IPGP and Géoazur/OCA (Coïsson et al. 2015, Rakoto et al. 2018, Astafyeva & Shults 2019).

4 Conclusion and perspectives

A complete understanding of the ionosphere, through its characterization and modelling in all circumstances, remains a major challenge today. All the more so, as the ionosphere can be subject to strong modifications caused either from below (Earth's surface and lower atmosphere) or from above (Sun and solar wind). The latter is particularly important during violent solar events, and is behind the development of space weather applications. France, with its dual expertise in physical modelling and ground-based instrumentation of the ionosphere, is perfectly positioned to help resolve these issues at European level, despite the limited size of the French scientific community. In the future, it will be essential to continue developing models to improve the description of high-latitude electrodynamics and the thermosphere. This must be accompanied by the development of new algorithms based on data assimilation and machine learning. At the same time, a strong federation at European level to maintain the ground infrastructure network will be essential. Finally, collaboration with industry and national agencies (Centre National d'Etudes Spatiales, CNES, Direction Générale de l'Aviation Civile, DGAC, etc.) must be pursued to develop the operational aspects of space weather more effectively. To conclude, even if the ionosphere has been known for a long time, it can still make us dream! Take, for example, the spectacular auroras seen as far away as South of France during the last magnetic storms in May and October 2024. The emergence of participatory science (Grandin et al. 2024) has also shown that great discoveries can still be made, such as the STEVE (Strong Thermal Emission Velocity Enhancement) observed at subauroral latitudes and discovered less than 10 years ago by amateur photographers (MacDonald et al. 2018).

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