REVIEW OF SOME IONOSPHERIC AND THERMOSPHERIC PROCESSES RELATING TO SPACE WEATHER

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ABSTRACT/RESUME

The ionosphere and the thermosphere are two keys in the space weather context. There are the location of spacecraft flight and of most of the communication paths. Their composition, temperature, density are very sensitive to the solar activity through magnetic, electromagnetic, and collisionnal phenomena. At high latitude, they are subject to strong electric fields and particle precipitation.
In this paper, we will review some geophysical effect and their implication in the frame of space weather : satellite drag, telecommunication, positioning … We show how they are estimated, through modelling and experiment corrections.

1. INTRODUCTION

The main domains of space weather involved in this paper are :

- Satellite drag (LEO), re-entry and debris, which depend on the thermosphere
- Telecommunication / Positioning, which depend on the ionosphere
- Public outreach and tourism industry, which are linked to the aurora, auroral oval …
- Relation to classical meteorology, which are linked to the cosmic ray screening, sprites ...

We will focus on the reasons the thermosphere and the ionosphere are influencing these domains, not on quantifying the geophysical perturbations.

2. THE DRAG : A THERMOSPHERIC PROCESS

When an object (spacecraft, debris …) travels through an atmosphere it experiences a drag force in a direction opposite to the direction of its motion. In a first simple approach, this drag force is given by :

$$D = \frac{1}{2} \rho v^2 A\, Cd \qquad (1)$$

where r is the thermospheric density, v the satellite speed, A the satellite cross-sectional area and Cd is a drag coefficient of the order of 2.
The reduction in the period P due to atmospheric drag is given by:

$$\frac{dP}{dt} = -3\,\pi\, a\, \rho \frac{A\ Cd}{m} \qquad (2)$$

where a is the semimajor axis and m the mass of the satellite.

The evaluation of the drag force is conditioned by the knowledge of the thermosphere density. This usually comes from a model. There exist several. MSIS (Hedin, 1991) is the most commonly used in the research thermospheric community. The Drag Temperature Model (DTM, Barlier, 1978; Berger et al., 1998) is used and developed by the French space agency CNES. They are both based on a large set of data, physics and statistics. However, no statistical model can reproduce exactly the true ionosphere at a given time because several sources of variations are very variable. These sources of variations of the thermosphere are mainly X rays and EUV fluxes, particle precipitation and E fields. The physical processes involved are photo-absorption, particle collisions, Joule heating and frictional heating. For space weather, the main consequences (amongst other phenomena) is a dilatation of the thermosphere : density may increase by a factor of 10 at the altitude of the International Space Station.

It is of prime importance to realise that most of the perturbation sources are badly known, monitored, predicted, modelled. It is the case for X rays and EUV fluxes (Torr and Torr, 1985; Richard et al., 1994; Tobiska, and Eparvier, 1998; Warren et al., 1998) and for particle precipitation (Hardy, 1985). Thanks to the Superdarn facility, the knowledge of the electric field has been improved in the recent years
(http://superdarn.jhuapl.edu/map/index.html).
However, this measurement depends on the presence of irregularities in the ionosphere. When there is no irregularities, a model is used to fill the gaps. A second limitation is that the Superdarn facility covers 18 MLT,

and there is a need for global coverage. Finally, Superdarn is in several aspects a research tool, and for being used in Space Weather, data accessibility must still be improved.

It is therefore not surprising that the models fail in reproducing the real time atmosphere, especially at high latitude and during magnetic perturbations. This implies a large uncertainty on the position of the spacecraft, summarized in tab. 1

Tab 1 : uncertainties (in km) on the position of a LEO after x days of initial time for uncertainties on the thermosphere density of 5%, 10%, 15% and 20% (Nicholas et al., 2000)

Days since epoch	*± 5%*	*± 10%*	*± 15%*	*± 20%*
1	5	22	33	43
2	46	91	137	182
5	280	559	839	1120
10	1261	2516	3750	5000

Since the actual goal is to reach a precision of 20 km after 24 hours, there is a necessity of a permanent monitoring and adjustment of the drag equation through neutral atmosphere models. Several methods are used.

2.1 A "proxy" approach

Use of indices : Do remain basic data in Space Weather. Several exists to monitor the solar activity and the EUV flux variation (Ri, $f_{10.7}$, Hg…) or the geomagnetic activity at different scales (Ap, Kp, Dst, Ae, …). They are still impossible to bypass for long term studies. Better indices with better space and time coverage are needed in several applications. In order to keep long records (past and future) of geophysical evolution, any Space Weather program should continue the monitoring of the main indices.

2.1 A "technological" approach

An example is given in figure 1 (from Marcos et al., reported in Nicholas et al., 2000). Here, a reference object is used to estimate the thermospheric drag, which then feed the drag equation for the other spacecrafts.

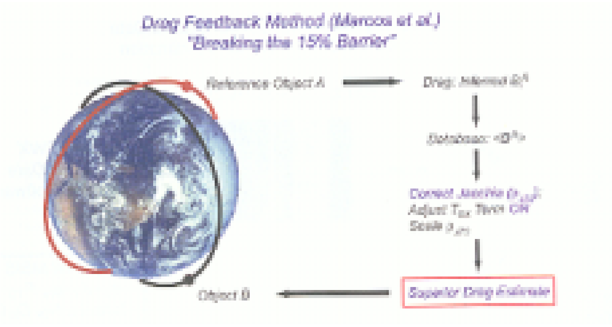

Figure 1 : technological approach to estimate the thermospheric drag (Nicholas et al., 2000)

2.1 "Physical" approaches

The physical approaches consist in feeding the models with observations. The observations are of different kinds
UV airglow monitoring (Nicholas, 2000) : a spacecraft observes the airglow over a large scale. The thermosphere is adjusted in glow model until computation fits the observations. This is a ground operation, made in the US in the 55^{th} squadron for Space Weather .

Temperature monitoring : Here, the neutral exospheric temperature is measured and compared to the exospheric temperature given by empirical models.

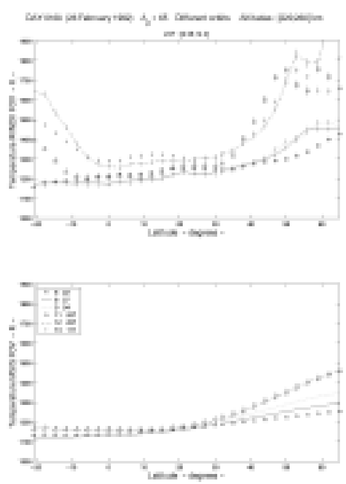

fig. 2 : Latitude/local time variations of the temperature measured by the WINDII interferometer onboard the UARS spacecraft, averaged between 220 and 260 km altitude, for 6 orbits on 26 February 1992. The upper panel shows WINDII temperatures, while the bottom panel shows the MSIS-90 ones.

The adjustment is made directly on the models, without the necessity of an additional modelling (like the airglow in the example above). The total density is then extracted from the model to calculate the drag force.Since the end of 1991, the Earth' s upper atmosphere winds and temperatures are observed by the Wind Imaging Interferometer (WINDII) onboard the Upper Atmosphere Research Satellite (UARS) (Reber et al., 1993, Shepherd et al., 1993). Figure 2 is extracted from Lathuillère, 2001. It displays temperature measurements along successive orbits for a very active day of the WINDII data base (26 February 1992, Ap =65). The 3 hours ap values corresponding to each orbit are indicated on the figure with the orbit number: they range from 22 for orbit 6 to 207 for orbits 11 and 12. A corresponding dramatic increase of the northern auroral latitude temperatures is observed. This increase is also present at lower latitudes, but it starts only for orbit 12. This corresponds to a time delay greater than 3 hours with the auroral latitude increase. At 20° south latitude, the observed increase in temperature is already very large.
The bottom panel shows the corresponding MSIS-90 temperatures. What is important to note is that the variations of the model temperatures agree qualitatively with the observations but not at all quantitatively. Such a behavior is common for each magnetic active day of the data base. The temperature variations associated to magnetic activity are always underestimated, while the temperature variations associated to solar activity are much better estimated as shown in Lathuillère et al., 2002.

This approach is still very promising, but necessitates an improvement of the empirical models in order to better reproduce the atmospheric variations due to magnetic activity. The use of the 2 proxys f10.7 and kp (or ap) is not sufficient to reach this goal (Lathuillère, personnal communication).

Use of the ionosphere as a tracer of the thermosphere : In this case, one may use ionospheric profiles measured by incoherent scatter radars (Blelly et al., 1996), or integrated parameters such as the Total Electron Content (Lilensten and Blelly, 2002). In figure 3, one shows such an example where the Total Electron Content has been fitted by an ionospheric model where the oxygen density is multiplied by a factor f. The advantage of this method is that it requires routinely measurements (TEC are obtained in real time and at a planetary scale through GPS constellation spacecraft). The disadvantage is that it requires an ionospheric model which also depends on other parameters (solar EUV and particle precipitation). Finally, the fit of a single integrated parameter such as the TEC does not give a unique solution, and the method must be improved with the use of a second type of observation.

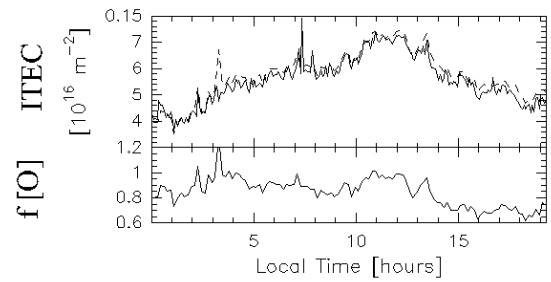

Fig. 3 : the upper panel shows the ITEC (i.e. total electron content integrated up an altitude lower than the upper boundary of the ionosphere, here up to 500 km) by the EISCAT incoherent scatter radar in Tromso (full line). The dashed line is the fit obtained when a correction factor f[O] is used in the neutral atmosphere model (Lilensten and Blelly, 2002)

Combined method are of course possible, such as incoherent scatter + visible airglow (red and green lines of the atomic oxygen) (Witasse et al., 1999)

3. TELECOMMUNICATION AND POSITIONNING : IONOSPHERIC PROCESSES

When a wave crosses through the ionosphere, it experiences several phenomena : scattering, absorption, faraday rotation (J.L. Leroy, 1998)... Its wave number is related to the pulsation of the wave through the optical index. The optical index is a complex number which is a function of the plasma pulsation, the collision frequency and the pulsation of the wave. Therefore, it is strongly dependant of the electron density and also depends on the thermospheric composition.
The Sources of variation of the ionosphere are the same than for the thermosphere, i.e. X rays and EUV fluxes, particle precipitation, and E fields. An additional source is the physical link with the exosphere, in particular with the protonosphere. The physical processes involved are slightly different. They are photo-ionisation, particle collision ionisation, currents and frictional heating. They result (amongst other phenomena) in rapid variations and creations of small scale disturbances (blobs, patches, scintillations …). Then, the models (physical, profilers, TEC derived from GPS …) fail in reproducing the real time ionosphere, especially at high latitude and during solar events (Jakowsky, 1999; Lunt 1999; Lilensten et al., 2002). Like for the thermosphere, there is a necessity of a permanent monitoring and adjustment of the equations. The strategies are the same : Proxy, physical (topside sounders …). However, the ionosphere is

somehow more accessible from ground than the thermosphere, which offer some additional opportunity to calibrate the models. As an example, we show thereafter a comparison between the EISCAT incoherent radar electron density profiles, and the results of a model. Developed under the auspices of the European action COST 251, the European profiler COSTprof (Hochegger et al., 2000) has been fed here with NmF2 and hmF2 deduced from EISCAT measurements (figure 4).
In a large scale, this approach would necessitate a network of ionosondes

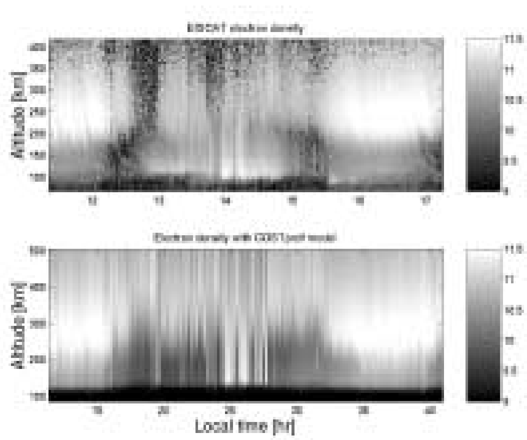

Figure 4 : Comparison between the electron density profiles obtained by the EISCAT incoherent radar (top panel) and the profiler COSTprof (bottom panel) (Lilensten and Cander, 2002)

4. PUBLIC EDUCATION AND TOURISM INDUSTRY

These domains are the subjects of other papers of these proceedings. However, it is worth to recall that most of the impacts of space weather in the industry of tourism (at least as long as space journeys are not easily available for tourists) is linked to the Thermosphere – Ionosphere coupled system. As far as public education is concerned, this system is still one of the major actor, since it is directly part of our atmosphere. The term public education is certainly more suitable than public outreach, or vulgarisation. Indeed, we are exploring a new field of the solar-terrestrial relationships of which most of the public is not aware, while most of the public could be very interested in. SOHO has shown the way to follow, and there is no doubt that its amazing success is largely due to the incredibly beautiful pictures and movie taken by EIT and LASCO. Franck (1990) has shown pictures of the auroral oval that have certainly been very helpful in advertising the Sun – Earth connections. It is not only a necessity of advertisement. It is a necessity of education.
Behind this, the whole tourism industry is of course interested, since the “polar light” travels may become a source of incomes.

5. SPACE WEATHER VERSUS CLASSICAL WEATHER

These domains too are the subjects of specific papers in these proceedings, and are only cited here to recall that the Earth atmosphere can hardly be spitted in independent layers.
Geophysical and historical records show that mankind already experienced several climatic or meteorological changes. Several phenomena contribute to these changes. Some may be related to space weather :
• Impact of the solar constant and solar energy (Friis-Cristensen and Lassen, 1991, Lassen and Friis-Cristensen,1995)
• Impact of the cosmic rays : condensation nucleus (Svensmark and Friis-Christensen, 1997, 1999, Svensmark 2000)
• Impact of the greenhouse gazes : falling sky theory (Roble and Dickinson, 1989)
• Impact of upper lightning : red sprites, blue jets, elves (Sentman et al., 1995)

The two last at least may be directly related to the thermospheric and ionospheric processes.

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