The erroneous GPS signal

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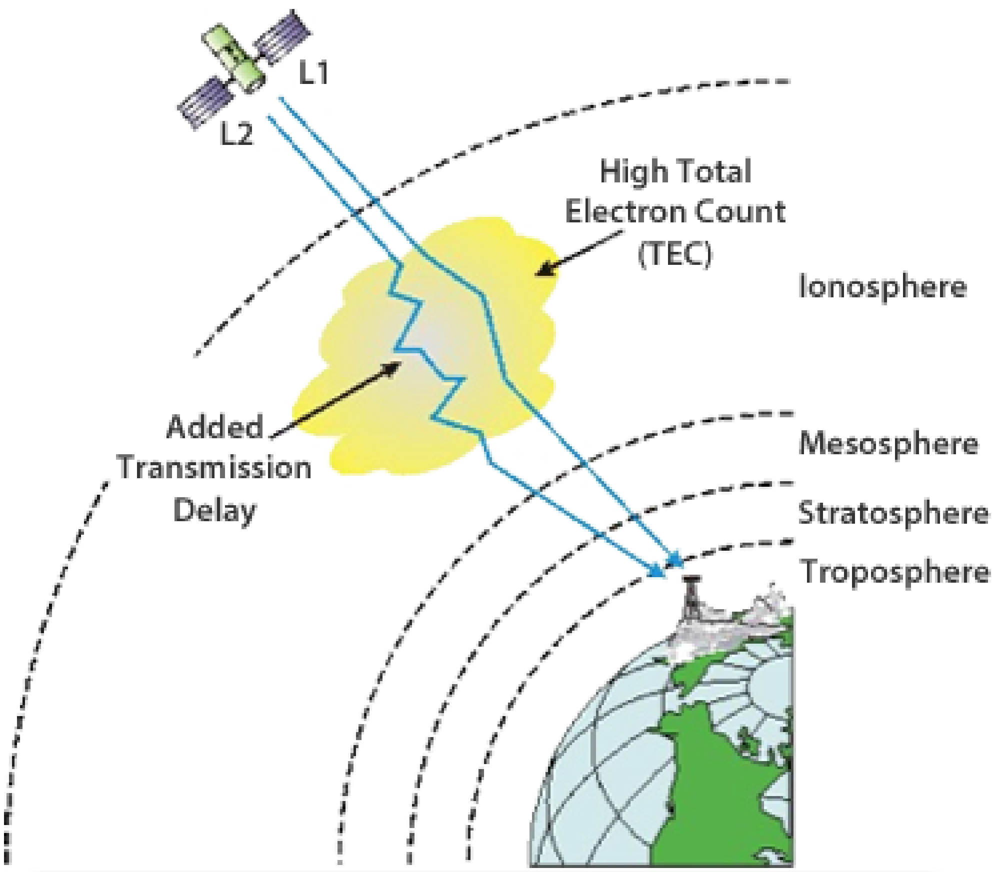
Two researchers from the University of Liège have developed a real-time monitoring system allowing GPS users to assess the level of precision of their measurements. High precision positioning is indeed affected by large and small scale ionospheric variability. These ionospheric irregularities have been characterised and it is now possible to predict their occurrence in mid-latitude regions. The researchers in Liège have even developed an e-mail alert system: you simply have to register on their site and as soon as irregularities reach a certain level, an e-mail is automatically sent to all users (surveyors, for instance) registered on the site. The latter are therefore warned of the possible unreliability of their measurements.
When we talk about **GPS**, we immediately think of the system integrated in our car or in our smartphone, which we use to find our way. But this isn't its only use. Indeed, this positioning system (or rather **GNSS**) is a valuable tool in areas requiring the highly precise measurement of distances such as geophysics (volcanology, seismology, etc.), civil engineering and even agriculture.

Small mistakes… big consequences

Within the framework of the above-mentioned applications, the movements to be detected are in the order of centimetres, corresponding to the level of precision that sophisticated GPS' can currently achieve, thanks to observation networks and properly adapted mathematical processing. However, in some cases the precision of the measurements is out of tolerance, with values that can exceed a metre. The problem is that professional users are only rarely informed of the inaccuracies associated with their devices. The research carried out by **Gilles Wautelet** and **René Warnant**, assistant and professor respectively at the University of Liège's **Unit of Geomatics-Geodesy and GNSS**, should provide them with a better understanding. And should prevent certain inconveniences, as the main author of this research, Gilles Wautelet, underlines: *"If bridges or civil structures are being monitored and the measurements are out by several decimetres when the work is being done in centimetres, there will indeed be a big problem. Also, in the case of surveyors, if they are supposed to* *guarantee centrimetric precision and the final measurement is 15-20 cm off, then they are no longer meeting the specifications"*. In addition to the study's theoretical framework, the two researchers therefore wished to take into account the practical importance of the problem by seeing things from the users' point of view.

When the codes no longer in line



Effect of ionospheric refraction. The GPS signal are affected in different ways, depending on whether it is a question of codes or phases.

The measurements based on the GPS signal are affected by errors from various sources, which can be classified according to whether they are linked to satellites, receivers or the propagation of the signal in the Earth's atmosphere. It was this last source of error that the two researchers decided to examine.

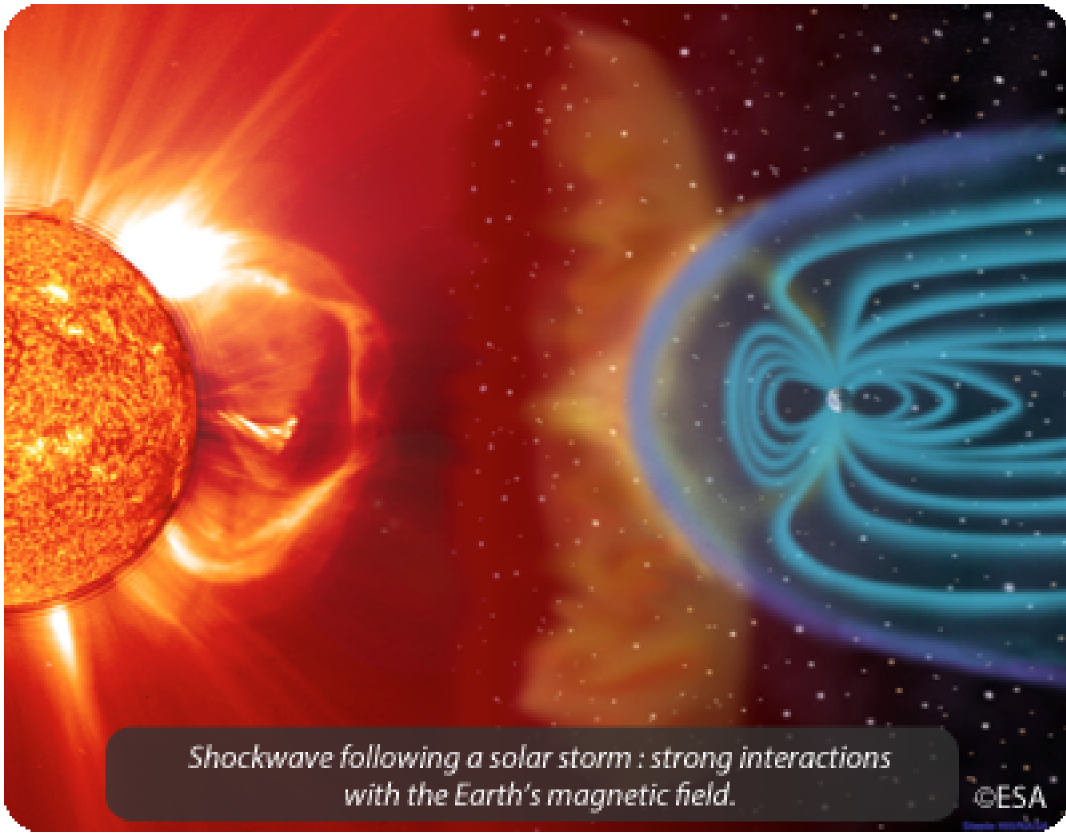
The GPS signals can be described as messages transported by **electromagnetic waves**, like radio waves. In a vacuum, a radio signal travels at the speed of light (300,000 km/s). This is not the case in the Earth's atmosphere which disrupts the propagation of the signal. The latter is affected by atmospheric **refraction** on two levels: in the **troposphere** (tropospheric refraction) and in the **ionosphere** (ionospheric refraction) (Fig 2). In other words, explains Gilles Wautelet, *"the wave that carries the signal travels the distance between the satellite and the station on the Earth's surface. By crossing the Earth's atmosphere, the speed of the wave is slightly less or slightly more than the speed of light (1). All in all, the delay (or advance) suffered by the GPS signal is in the order of several tens of nanoseconds, which, translated into units of length, is equal to several metres"*. This delay or advance actually depends on the type of message (**code or phase**) and

the atmospheric layer crossed (troposphere or ionosphere). Hence, the tropospheric refraction results in a delay, both in the codes and the phases, that is relatively small and stable: 2.4 metres. On the other hand, the ionospheric refraction has the contrary effect on the codes and phases. The codes are slowed down and the phases speeded up. As for the extent of the delay, this is conveyed by a far more variable an error in distance: between 1 and 50 metres. This ionospheric variability is the main source of error in GPS accuracy.
One of the ways of overcoming these errors is modelling. *"While tropospheric models allows us to overcome a great deal of the tropospheric refraction, the ionospheric models are far more difficult to implement and only represent part of the actual situation"*, says Gilles Wautelet. According to René Warnant, *"the study of these irregularities in the ionosphere is absolutely vital because they are at the origin of major errors in the measurements of positions made using GPS".*

The ionosphere: a battleground between waves and electrons

To understand how a GPS signal might interact with the ionosphere, we must remember that the composition of the latter results from two complex processes. First of all, there is an ionisation process which is initiated by **radiation** from space, mainly the sun's **ultraviolet** rays and **x-rays**. The **photons** (luminous particles) in these rays contain enough energy to strip the **electrons** (negative charge) from the neutral **atoms** and atmospheric gases. Some free electrons are then captured by positive **ions** according to a second process known as recombination. The result is a continuous competition between the ionisation and recombination processes, thus determining the overall electronic density of the ionosphere. The concentration of electrons can therefore vary at any time and depends on two main factors: on the one hand, the density of neutral atoms and molecules (the recombination process is less pronounced at high altitudes because there is very little pressure there) and, on the other hand, the amount of sunlight received from space. While the pressure gradient (which is governed by a physical law dependent on altitude) remains stable and regular, this is far from the case for sunlight. Indeed, daytime (day/night) and seasonal (summer/winter) variations as well as solar activity (solar eruptions, 11-year cycles, etc.) will considerably modify the concentration of electrons, and consequently the propagation of the electromagnetic waves, including the GPS signals.

Gilles Wautelet based his research on this premise: "the objective of my work is to model the irregularities of what is known as the Total Electron Content (TEC), which is the total number of electrons between the satellite and the station, or more precisely, to identify the recurring behaviours as well as the amplitude of these irregularities according to the season, local time or solar activity". It is also necessary to precisely define what we mean by "irregularity". Various types of irregularities exist depending where we are on Earth, as the young researcher reveals: *"we're quite lucky in Europe, in our mid-latitude sector. In fact, there are very few extreme irregularities compared with the magnetic equator or the poles. And the situation is different depending on whether you're in the northern or southern hemisphere, or even in Japan or the United States even though these are also mid-latitude sectors. In Europe, there is an average variability which mainly manifests itself as Travelling Ionospheric Disturbances (**TID's**), itinerant waves that spread throughout the ionosphere"*. The geomagnetic storms (solar storms) are another major type of irregularity. In this case, coronal mass ejections, directed towards the Earth, interact with the geomagnetic field, thus creating a variability in the ionosphere. Although greater than the variability due to TID's, this nevertheless occurs far less frequently.



Shockwave following a solar storm : strong interactions with the Earth's magnetic field.

While it is possible to predict the effects of a solar storm several hours in advance thanks to imaging satellites capable of detecting ionised clouds, it is far more complicated with regard to TID's: *"these are observations made over several years. We know that TID's are generally observed in autumn and winter, and around midday. We can therefore only predict TID's on a climatological basis, thanks to a certain recurring characteristic. Of course, this isn't checked every day. For the time being, it's possible to predict their occurrence fairly accurately, but not their source"*, Gilles Wautelet explains.

As for René Warnant, he is very satisfied with the study carried out at the GPS stations installed in Belgium and whose raw data was processed by software developed at ULg: *"this is the first complete statistical study of the different types of ionospheric irregularities affecting GPS in mid-latitudes in Europe. The study covers a period of 10 years* (editor's note: from 2002 to 2011), *representing practically the duration of a solar cycle (approximately 11 years). This point is important because the "behaviour" of ionospheric irregularities depends on solar activity".*

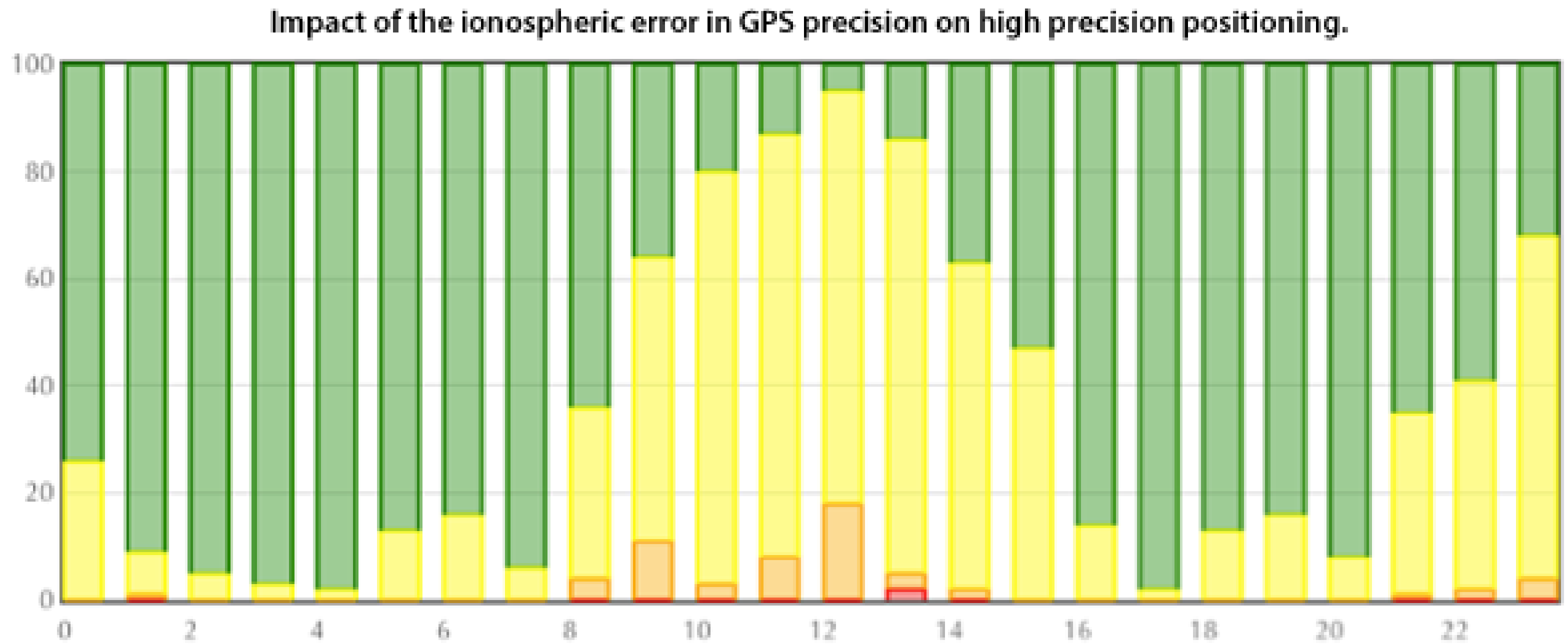
Study results

This research has revealed a number of points (2). First of all, irregularities are observed maximum 9% of the time, which means that they aren't frequently observed, even during periods of high solar activity. Secondly, ionospheric irregularities can be divided into two major categories: those associated with spatial events (Space Weather - SW) and those occurring during "quiet-time". Even if SW irregularities are responsible for the largest TEC fluctuations, their contribution oscillates between 0 (solar minimum) and 25% (solar maximum) of the total annual amount. Consequently, the study of occurrence rates and the amplitude analysis were focused on "quiet-time" irregularities, which form the majority of irregularities detected in mid-latitudes. The latter are classified into two groups, i.e. Winter Daytime (WD) and Summer Night time (SN). While WD is responsible for almost 75% of annual irregularities in "quiet-time", this is quite rare in SN (less than 10%). The analysis also revealed the amplitude of WD irregularities is proportional to the TEC. On the other hand, the amplitude of SN irregularities seems to be negatively correlated with the TEC, with the largest values generally observed during periods of low solar activity. Considering these occurrence rates and amplitude characteristics, it would seem that the WD irregularities correspond to daytime TID's, sometimes referred to as "classical" TID's. However, the physical origins of SN irregularities are more difficult to establish.

And on a practical level?

Currently, the model we can derive from this study isn't implemented either in the receivers or in the GNSS processing software. This will only be possible when the causes of the irregularities can be definitely established.

In the meantime, ULg's geomatics unit offers free real-time monitoring (available on the website: **www.gnss-ulg.be**) of the state of the ionosphere, measuring its impact on high precision positioning within the entire network of GPS stations in Belgium, i.e. some sixty reference stations. This monitoring is accompanied by a proactive approach: *"We know that surveyors receive training to make sure they are always up to date. The idea is therefore to come to these gatherings and to offer them this aid that can be used for planning or, in any case, the verification of their GPS measurements. They can therefore check all their measurements by observing the ionospheric conditions when readings are taken in the field"*, explains Gilles Wautelet. And in order not to miss any disturbance, an e-mail alert system has been set up: "you simply have to register on our website. As soon as the irregularities reach a certain level, an e-mail is automatically sent to all the users registered on our website. Obviously, there is a slight latency as we have to process the data first", the geodesy specialist points out.



In green, nominal centrimetric precision is reached. In orange/red, the ionospheric error is very high; it is better to take the measurements again. For instance, on 9 December between 13:00 and 14:00, 2 to 3% of measurements in Belgium were significantly altered. Only 16-17% of the measurements benefited from absolute precision.
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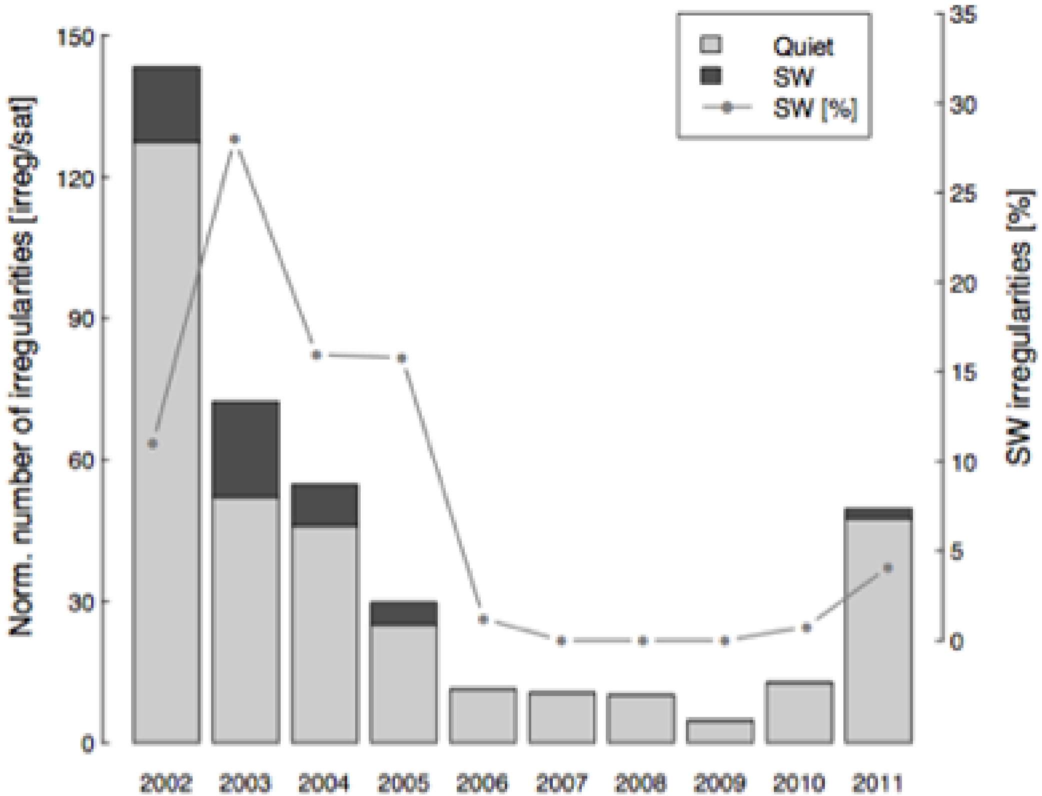
If there is a degradation in the ionospheric conditions visible on the website, the user can thus take the appropriate decision: return to the field to take another reading if the ionospheric error is too great or keep the measurements, knowing approximately the level of inaccuracy attributed to ionospheric variability. *"However, it wouldn't be wise to "correct" the measurements on the basis of our diagnostic since this only reflects the ionospheric conditions found by the stations that we have processed, and not that of the user in the field"*, Gilles Wautelet specifies. Indeed, the position errors available on the website can't simply be applied such as they are to all users in the field; every measurement environment is unique, with its own configuration of satellites in the user's sky and its own errors due to the close environment. The ULg researcher compares this problem with a more explicit case: "*It's a bit like wanting to know the precise wind speed at the bottom of a valley when you only know the wind speed in a place outside the valley. While we can indeed obtain a good estimation of this speed, we won't ever be able to obtain the exact value in our valley: we know that local influences such as topography or plant cover have a significant effect on wind speed. What we observe at point A is therefore not applicable to point B, whether we're talking about wind speed or the ionosphere."*

Less uncertainties, more accuracy

This study can't directly correct the inaccuracies of each device, so its aim is to warn GPS users of the occurrence and the amplitude of the ionospheric irregularities, as well as their impact on high precision positioning. It is now possible to measure and quantify this variability although it is still difficult to predict. Nevertheless, future research should be directed at a better understanding of the physical phenomena behind these irregularities, allowing a better forecast to be established.



Occurrence of ionospheric irregularities. On the one hand, we observe the existence of solar minimums and maximums (11-year cycle) and on the other, the greater occurrence of "quiet-time" irregularities compared with irregularities originating from space (SW). © Wautelet&Warnant

Gilles Wautelet is confident: *"the next objective is to adapt current methodology, which is well defined at 30-second intervals, to data at 1-second intervals. Therefore, we will have 30 times more data, allowing us to obtain a far more precise range of irregularities, especially with regard to low and high latitudes, where ionospheric variations are extremely high and very fast*".

To obtain such data, the researchers can count on the arrival of other GNSS on the market. *"New positioning systems are being developed such as the European Galileo system* (Read : **Galileo, a European "GPS"**)*, which will offer a higher degree of precision than GPS. Galileo emits an extra signal (editor's note: three signals instead of two for GPS) and, what's more, these signals are more precise. At the moment, we are studying the influence of ionospheric irregularities on all these new signals*", René Warnant concludes.

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(1) Remember that in a given environment, a particle or a signal can travel faster than light in this environment. Therefore, it isn't a question of exceeding the speed of light in a vacuum!

(2) « Climatological study of ionospheric irregularities over the European mid-latitude sector with GPS ». Journal of Geodesy. DOI : 10.1007/s00190-013-0678-4