Solar cycle 24
and its impact on GNSS positioning

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Executive summary

In the coming years it is expected that a periodic disturbance in the Earth's ionosphere will affect the radio signals that are transmitted by GNSS (Global Navigation Satellite System, i.e., GPS, GLONASS and future Galileo and Compass) satellites. This phenomenon is caused by a period of increased solar activity that repeats itself every 11 years, a period during which the Sun's surface shows an increased number of dark areas, the so-called sun spots.

In March 2008 we reached the end of a quiet period and it is expected that we will see the effects of an increase in ionospheric activity on GPS signals from 2009 onwards. The highest levels of these ionospheric disturbances are expected to be reached around 2011-2012 and the next minimum around 2018. The effects of these disturbances will be most prominent in equatorial (essentially following the geomagnetic equator) and Polar Regions. Mid-latitude areas are less affected.

In anticipation of the above effects, all high precision GNSS services provided by Fugro are prepared to mitigate the adverse effects that can result from this phenomenon. This is done by a variety of methods, the most important being the utilization of dual frequency GNSS receivers that provide data that can be used to virtually eliminate ionospheric effects.

As the correction signals that are transmitted from reference to mobile receivers can also be affected by increased solar activity, Fugro provides an option to deliver corrections via multiple independent satellite links in order to reduce the risk of failing communication in these adverse conditions. For the areas most affected by ionospheric disturbances, Fugro also uses terrestrial radio links.

Further, the DGNSS services that Fugro provide use a network of reference stations, many of which contain a combined GPS/GLONASS dual frequency receiver. The GPS/GLONASS stations are located in regions that are affected most by solar activity. The additional GLONASS data can be used to reduce the effects of ionospheric disturbances in those regions even further. In the coming year, Fugro will expand its GLONASS capabilities and should Galileo become available, then also this system will be fully incorporated to provide the highest quality services possible to support our client base.

Within the framework of GPS modernization more satellites will become operational that transmit an additional, new civil signal on L2, called L2C, allowing for much improved signal tracking. The L2C signal will help to mitigate the scintillation effects that cause GPS signals to vary very rapidly and may make GPS receivers lose lock on the existing L2 frequency. Fugro's hardware and services are fully prepared to take advantage of the new L2C signal. Currently six out of 31 GPS satellites are transmitting this additional signal, a number that will increase in the years to come.

All Fugro's high end DGNSS hardware systems and services are prepared for dual frequency GPS, including L2C, GLONASS and Galileo to provide a solid foundation for further expansion of performance and services.

Introduction

There are several space weather phenomena which, when strong enough, create disturbances in the Earth's ionosphere and magnetosphere that are reflected in GNSS positioning performance and satellite tracking ability. Ionospheric storms stem from various space weather phenomena that include Coronal Mass Ejections, coronal holes and the background solar wind speed; they are usually (but not always) related to the 11 year solar cycle. In March 2008 solar cycle 24 started. It will reach its maximum in 2011 or 2012. This document gives a brief explanation of space weather phenomena related to the solar cycle, their impact on GNSS positioning and the actions taken by Fugro to mitigate their effects.

Background

Solar wind

The solar wind is a stream of charged particles, or plasma, ejected from the upper atmosphere of the Sun, see Figure 1. The source of the solar wind is the Sun's corona, which is so hot that the Sun's gravity cannot hold it. Solar wind mainly consists of electrons and protons, with energies of about 1 keV. A number of phenomena are related to the solar wind, such as geomagnetic storms, auroras and the plasma tails of comets. The solar wind streams off the Sun in all directions with an average velocity of about 400 km/s.

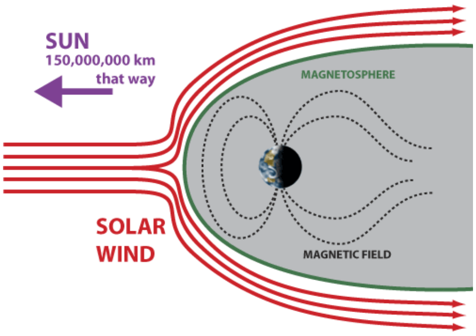

Figure 1 – Solar wind (from http://www.-space.gc.ca).

Sunspots

Sunspots are relatively cool areas that appear as dark blemishes on the face of the Sun. They appear and dissipate lasting days or weeks. As seen from the Earth, they rotate over the surface of the Sun, with the Sun's rotation period of about 27 days. A sunspot may have a diameter as large as 80,000 km, see Figure 2. Sunspots are formed when extremely strong magnetic field lines just below the Sun's surface are twisted and poke through the solar photosphere. Sunspot populations quickly rise and more slowly fall on an irregular cycle about every 11 years. Significant variations of the 11 year period are known over longer spans of time. For example, from 1900 to the 1960s the solar maxima trend of sunspot count has been upward; from the 1960s to the present, it has diminished somewhat. The sunspot number is basically the sum of the visible dark areas on the surface of the Sun with adjustments for the instrumentation used. Figure 3 shows the sunspot number since 1755. As can be seen from this figure, we are currently (2008) at the end of solar cycle 23 or the beginning of solar cycle 24.

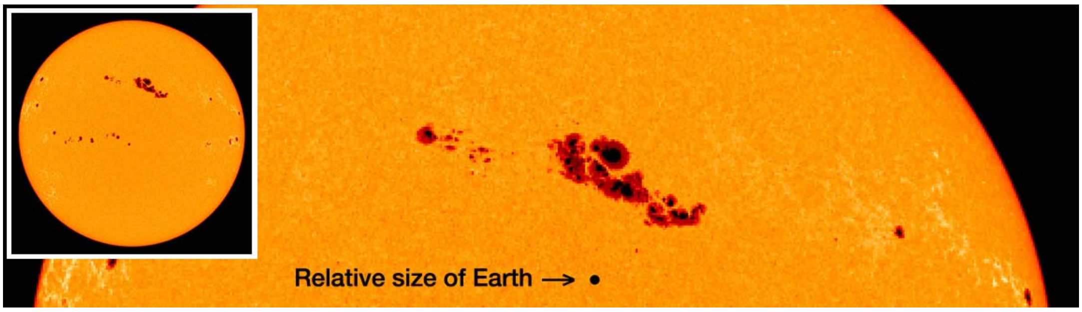

Figure 2 – Sunspots (from http://en.wikipedia.org).

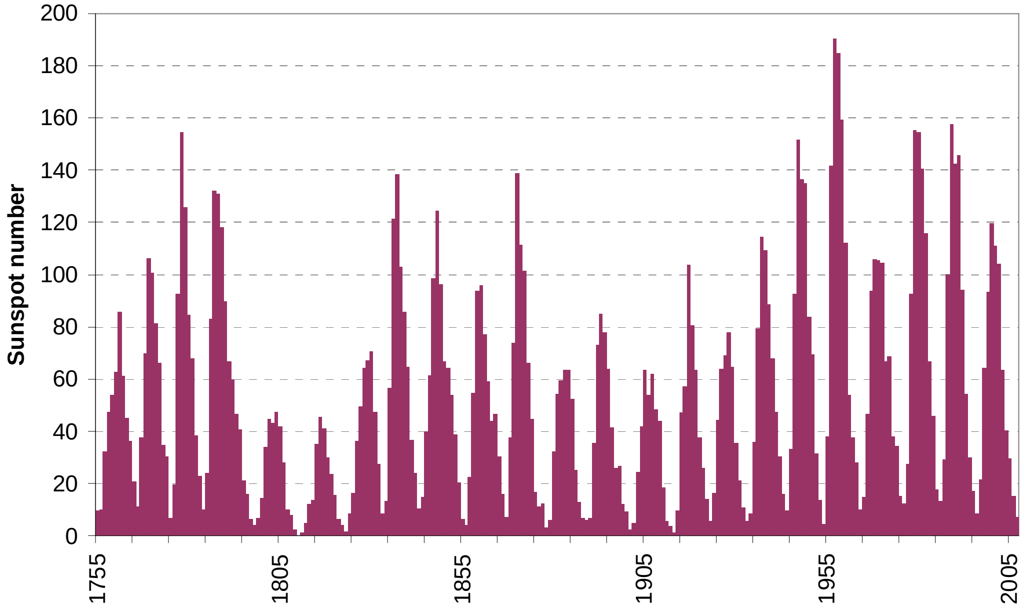

Figure 3 – Sunspot numbers since 1755 (based on data from http://www.ngdc.noaa.gov/stp/SOLAR/ftpsunspotnumber.html).

Coronal Mass Ejection

A Coronal Mass Ejection (CME) is the eruption of a huge bubble of plasma (charged particles) emitted from the Sun's outer atmosphere, or corona, see Figure 4. The corona is the gaseous region above the surface that extends millions of miles into space. CME's have velocities from 400 km/sec up to 2000 km/sec. A typical CME can carry more than 1 trillion tons (10^{15} kilograms) of plasma into the solar system. As the material from the CME merges with the solar wind, it can create a shock wave that accelerates particles to high energies and speeds. Behind this shock wave, the CME cloud is filled with plasma threaded with magnetic field lines. Halo events are produced by CME's that are directed toward (or away from) the Earth. CME's from just east of central meridian have the strongest impact on the magnetosphere.

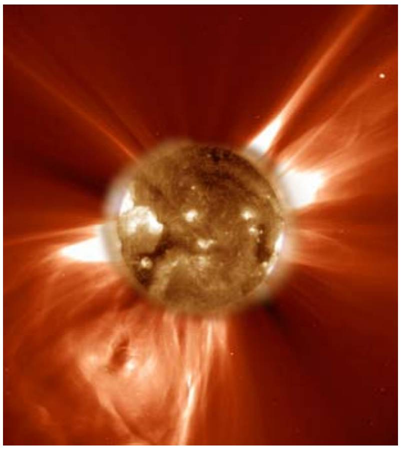

Figure 4 – Coronal Mass Ejection (from http://en.wikipedia.org).

Coronal hole

A coronal hole is a magnetic void in the corona from which solar wind continually streams out into space. This is due to the nature of the magnetic field opening the hole, which has an open magnetic field topology. The solar wind, due to the lack of constraint from an overlying closed magnetic field, can be as fast as 800 km/s over coronal holes. Long-lived coronal holes return periodically as the Sun rotates on its axis. The Sun has an approximate surface rotation period of 27 days, called the Carrington Rotation. Sunspot groups, on the other hand, have a magnetic structure that rises out and then reconnects nearby, thus inhibiting its contribution to the solar wind. Solar flares are usually associated with the strong magnetic fields seen in sunspots. Solar flares produce a rapid increase in extreme ultraviolet and X-ray emissions. These photons impact low frequency navigation, i.e., Loran–C, and HF radio communications in the sunlit hemisphere.

The Earth’s magnetosphere

The Earth’s magnetosphere, see Figure 5, defined by the region of space influenced by the Earth’ s magnetic field, shields us from most of the charged particles in the solar wind. The solar wind carries with it a magnetic field of its own which defines the Interplanetary Magnetic Field (IMF). The orientation of the IMF is important in defining the shape of the Earth’s magnetosphere. Southward IMF conditions enable a very efficient transfer of the energy in the solar wind to the magnetosphere. If the IMF turns suddenly north, a sharp expansion can occur with associated ionospheric and magnetospheric perturbation. For average conditions, when the IMF is oriented northward, we can take a strong solar wind shock from a CME and see only a small change in the level of disturbance of the Earth’s magnetic field.

Charged particles and electromagnetic energy from the solar wind can enter into the magnetosphere. High energy charged particles enter, in particular, near the North and South Pole where the magnetic field is weaker and the magnetosphere is partially open to space. Low energy particles are captured by the magnetosphere and eventually some precipitate into the Polar Regions. These low energy particles are responsible for the aurora. Depending on the severity of the geomagnetic activity, the auroral footprints can extend into lower latitudes.

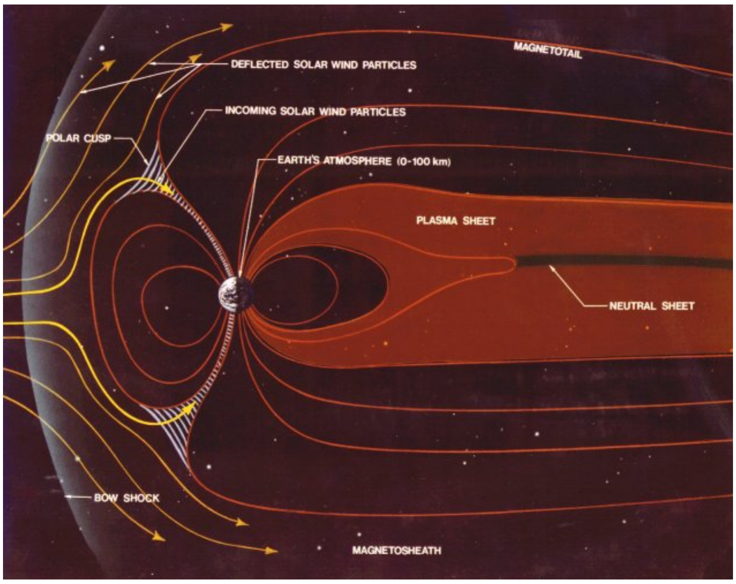

Figure 5 – The Earth's magnetosphere (from http://science.-nasa.gov).

Solar flux

The Sun emits radio energy with slowly varying intensity. This radio flux or solar flux changes gradually from day to day in response to the number of sunspots on the surface of the Sun. Solar flux density at 2800 MHz (corresponding to a wavelength of 10.7 cm) is monitored by several observatories around the world and is used as a proxy for overall solar activity levels by many modelers and theorists. When the 10.7 cm solar flux is 160 we start to see a correlation between high Kp index values and Differential GNSS (DGNSS) positioning problems. The Kp index is a quasi-logarithmic index, computed on a three-hour basis, which represents the overall level of planetary geomagnetic field disturbance. It is derived from ground based magnetic field measurements and ranges from 0-9, with each scale step being ten times more disturbed than the previous step at the higher end of the scale. A typical quiet day will have Kp values of 0-2. Kp values of three or greater are considered moderately disturbed, while Kp values of six or greater occur during a major magnetic storm. The Ap index, another method of estimating planetary geomagnetic activity, is a 24-hour average of overall disturbance levels on a linear scale. For quiet days, the Ap is generally below eight, while values greater than 20 indicate significant disturbances in high latitude auroral areas and along the geomagnetic equator. The Ap index ranges are as follows: 16-29, Active, 30-49 Minor Storm, 50-99, Major Storm, 100-400 Severe Storm. The highest value the Ap index has been in the last few years is 204 (2003), during the so-called “Halloween storm” at the peak of the 11-year solar cycle, see Figure 6.

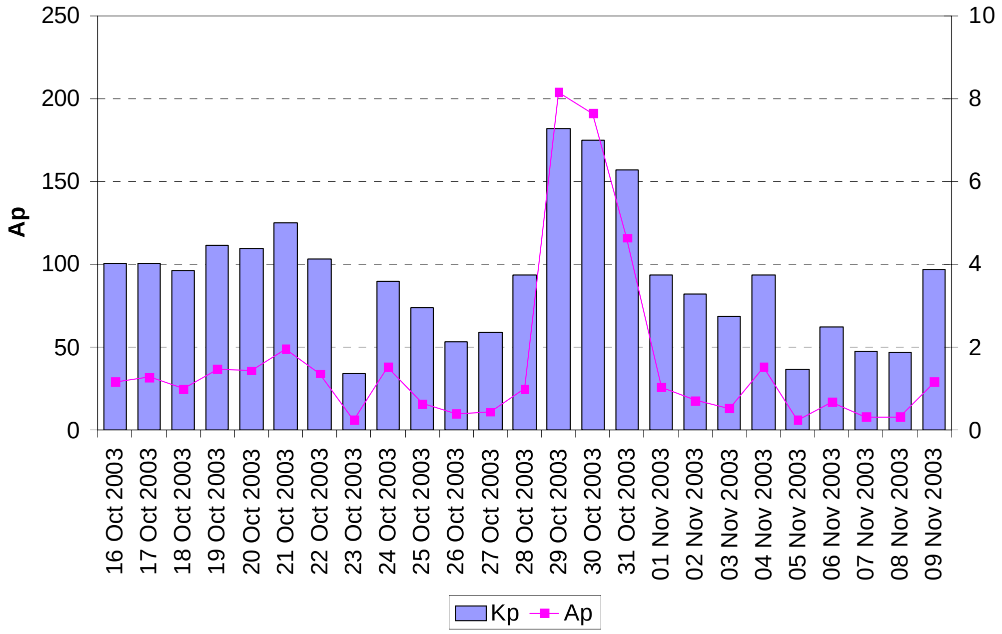

Figure 6 – Kp and Ap indices for October and November 2003; around 29 October, the "Halloween storm" occurred (based on data from ftp://ftp.ngdc.noaa.gov).

The ionosphere

The ionosphere is the ionized uppermost part of the atmosphere. The ionization depends primarily on the Sun and its activity, as reflected by the 11-year solar cycle. The ionosphere ranges from 50-1000 km above the surface of the Earth. During the evening hours the lower bound of the ionosphere rises to 200 km above the surface as the magnetosphere turns away from the Sun and fewer solar particles interact with the atmosphere. Radio signals from satellites pass through the ionosphere and experience a propagation delay or a travel time that is different than would occur in a vacuum, due to the presence of free electrons. Most of the electrons are concentrated in the F-layer, at a height of about 400 km, see Figure 7. The ionospheric delay is a function of the Total Electron Content (TEC) of the ionosphere along the signal path and the frequency of the radio signal: the lower the frequency the longer the delay. One TEC Unit (TECU) corresponds to 10^{16} electrons/m^2. At night, as the lower extreme of the ionosphere rises, low frequency signals will bounce off this lower limit, causing the 'skywave' or 'skip' effect well known to users of terrestrial systems such as LORAN. For radio operators the skip enables them to transmit and receive over much longer distances (depending on the frequency of operation) while for the navigator attempting to position his vessel the skip can cause incorrect range measurements inducing errors in his position.

As an example, for the GPS L1 frequency (1575.42 MHz) the ionospheric delays corresponding to one TECU is equal to 16.2 cm. The total slant range delay caused by the ionosphere is in the range of 1-50 m over the course of a day. Generally, during relatively stable ionospheric periods the TEC and its gradient is predictable over a period of several days. For GPS, the US Air Force

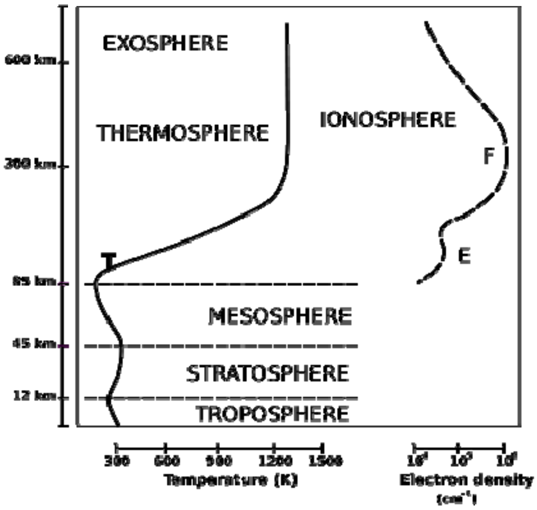

Figure 7 – The Earth's atmosphere (from http://en.wikipedia.org).

GPS control center predicts the ionosphere, based on sunspot number related indexes, and uploads it into the satellite network. A GPS receiver then downloads this information and uses it as part of its position computation. This predicted model of the ionosphere is called the Klobuchar model after its developer.

When observations at different frequencies are available, for example, GPS L1 and L2 (1227.60 MHz) first order ionospheric effects can be eliminated. The remaining higher order effects are usually small for quiet periods, but may be as large as 2-4 cm during active periods.

Ionospheric disturbances

When a GNSS signal encounters large gradients in TEC, the error in the range measurement is difficult to model. These gradients can be caused by bubbles, plumes, streams, or even sharp borders of enhanced or depleted regions in TEC. Frequently associated with these large gradient regions are smaller structures within the ionosphere that can be associated with scintillation effects. Scintillation can cause both amplitude and phase fluctuations that in turn can cause a GNSS receiver to lose lock. Scintillation is typically seen during auroral periods but can occur at other times depending on the level of ionospheric disruption. Large gradients in TEC are primarily associated with equatorial and polar regions, and are more frequently observed during conditions of high geomagnetic activity. However, large gradients in TEC can also appear in mid-latitudes during moderate to severe geomagnetic disturbances and can significantly impact GNSS users.

During the course of the year, the equinoxes (September-October, March-April) are statistically more likely to see geomagnetic disturbances and ionospheric structuring than other months. During these seasons it is not uncommon to have periods of degraded GNSS performance in the late afternoon and especially at dusk and after sundown. These periods typically occur at the same time each day and last for several days or a few weeks.

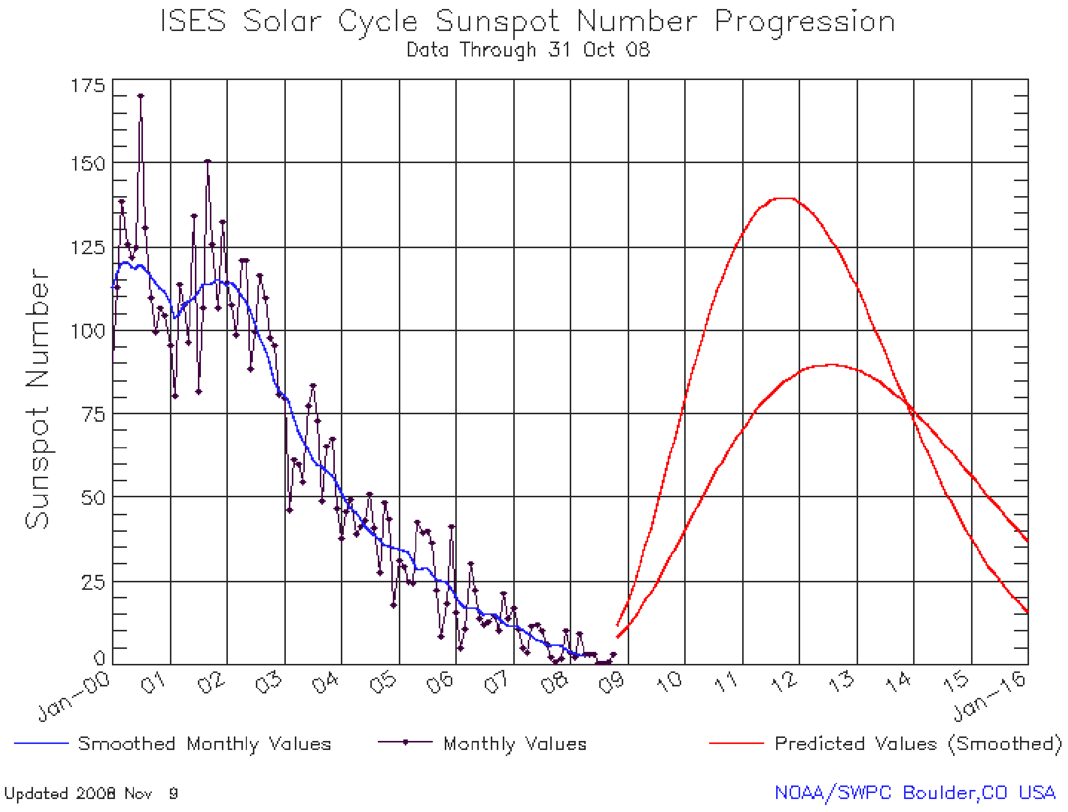

Figure 8 – Solar cycle 24 prediction (from http://www.swpc.noaa.gov/SolarCycle/index.html).

Solar cycle 24

In 2008 we are at a solar minimum, which marks the beginning of solar cycle 24. The Solar Cycle 24 Prediction Panel provides two predictions, based on different models, which are shown in Figure 8. One model expects the solar cycle to reach a peak sunspot number of 140 by the end of 2011; the other predicts a peak of 90 by mid 2012. The actual maximum could be much higher; in fact, it could be the highest ever.

Effects of increased solar activity

As the solar cycle progresses, the average daily sunspot number rises, creating conditions favorable to solar flares and CMEs. This adds energetic particles, solar materials and gravity waves to the solar wind. Disruption of the ionosphere occurs due to the additional energy striking the magnetosphere and entering the upper atmosphere. The changes are rapid and significant. The ionospheric model used in GNSS receivers to compute their position no longer matches reality, resulting in biased position estimates.

Other solar cycle effects are damage to satellite electronics and increased drag on spacecraft, altering their orbits. This energetic wind also affects the Earth's magnetic field and can cause significant DC ground currents, potentially disrupting local power grids. During the solar maximum of solar cycle 22 (1989), the Hydro-Quebec electric power system failed, resulting in 6 million people in the US and Canada being without power for 9 hours.

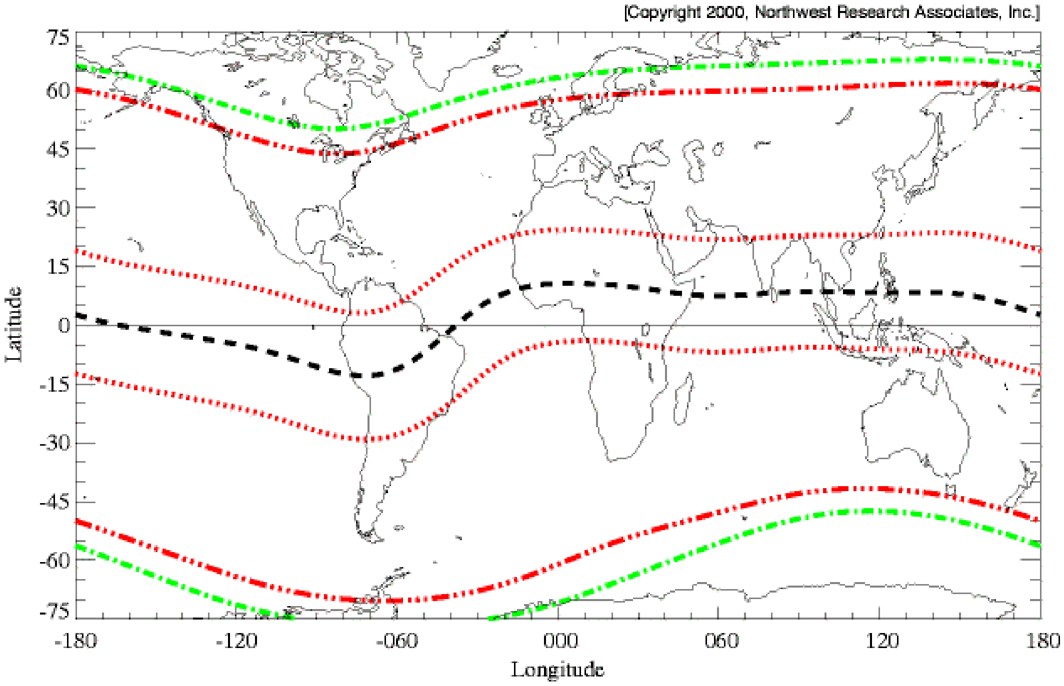

Figure 9 – Geomagnetic equator and auroral regions (©Northwest Research Associates).

With increased solar activity, the Polar Regions and a band extending to about 15° north and south of the geomagnetic equator are the areas most susceptible to ionospheric disturbances, see Figure 9. In equatorial regions the effect is on the TEC gradient, which will change quickly. These regions include Brazil, Central Africa and parts of Southeast Asia where oil exploration is ongoing and where significant GNSS position errors have been reported. There are a number of different types of ionospheric events that occur in these regions which are lumped into the broad category referred to as equatorial anomalies. Canada, Alaska and other high-latitude regions are affected as well, due to auroral activity. Ionospheric disturbances have the smallest impact on standard DGNSS positioning performance in mid-latitude areas like the Gulf of Mexico or the North Sea, although they may be affected during moderate to large geomagnetic storms. Typically, a greater number of users are affected by ionospheric disturbances as Kp and Ap indices increase. In areas where ionospheric prediction models, like the Klobuchar model for GPS, are inaccurate, the actual TEC values needs to be measured to allow users to correct their position with a more realistic estimate of the ionospheric delay.

Figure 10 shows position errors for a 1700 km baseline between Belem and Recife in Brazil, computed using standard (L1 only) differential GPS corrections and the broadcast ionospheric model parameters. This data was collected during the Halloween storm of October 2003. The horizontal position error (95%) is 12.8 m.

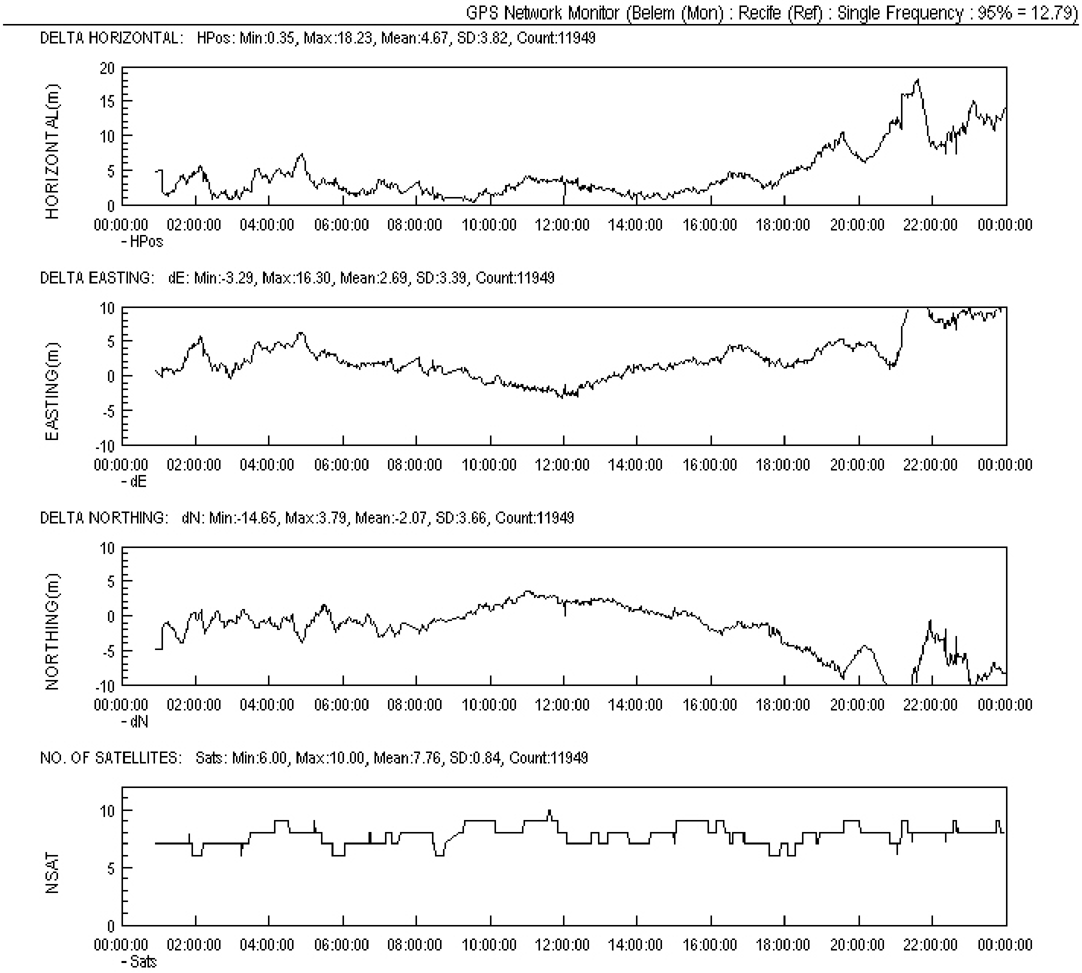

Figure 10 – Horizontal position errors for a baseline of 1700 km in Brazil. Position was computed using GPS L1 corrections and Klobuchar ionospheric model.

Figure 11 shows the effect of a severe ionospheric storm on the number of tracked satellites for a receiver in the northwestern United States. For comparison, the number of tracked satellites for the corresponding period by the same receiver is also shown when the ionosphere was quiet again (30 days later, the period was shifted by 120 minutes).

Possible solutions

Improved ionospheric models

Introducing better models than e.g. the GPS Klobuchar model, can compensate for the ionospheric delays in GNSS range measurements. This might be more detailed models that are updated with additional ionospheric delay data and they could be regional or global. For DGNSS systems this means that additional information has to be transmitted to the user over the data link together with the standard GNSS range corrections. Drawback is that the models

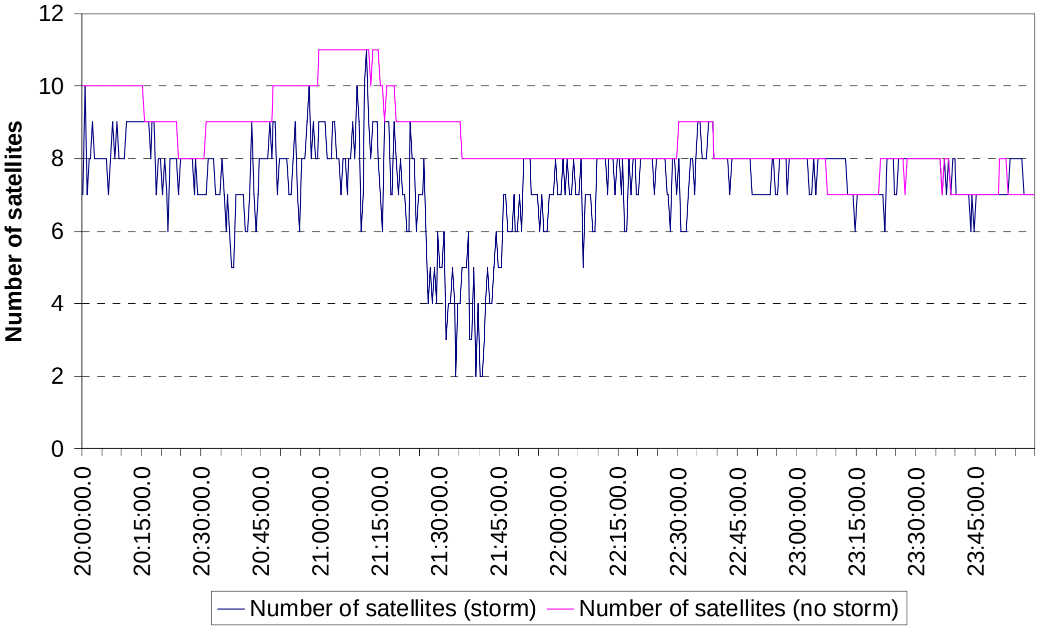

Figure 11 – Effect of a severe ionospheric storm on the number of tracked satellites.

may not accurately represent the actual ionospheric delays, especially in case of severe disturbances, and may have a different performance in different areas for a variety of reasons.

Dual-frequency data

The alternative to modeling is using dual-frequency GNSS data. Since the ionosphere is a dispersive medium, the delays depend on the frequency of the signals and can be significantly reduced or even eliminated by forming a linear combination of range observations at two frequencies. Alternatively, the delay can be estimated from dual-frequency data. In Fugro's DGNSS services, this method of using actual observation data to compensate for the difference in ionospheric delay at reference station and mobile has proven to be very effective. In this case the ionospheric information from the reference site needs to be transmitted over the DGNSS data link along with the standard single frequency range errors. Both the reference station and the mobile have to equiped with dual frequency receivers in order to compute the ionospheric delay.

Figure 12 shows horizontal position errors for the same baseline as Figure 10, but this time the results were obtained using dual frequency data. It is clear from this figure that the errors have been significantly reduced (1.2 m (95%)) and that using dual frequency data is very effective. Fugro has been providing dual frequency GPS services for more than a decade and will introduce a dual frequency GLONASS service soon.

New GNSS signals and systems

Using dual-frequency data provides an effective means to deal with ionospheric errors. However, it may be possible that the ionospheric disturbances are such that the receiver loses lock on a number of satellites and the number of remaining satellites is too small to estimate a precise position. For GPS, this could in particular occur for the L2 signal, which originally was never intended for civil use, although most receiver manufacturers have found ways around this and are able to provide L2 observations, albeit with a lower signal to noise ratio. However, as part of the GPS modernization, a new and stronger civil L2 signal (L2C) has been defined. This signal is currently (2008) available on six satellites. It is expected that by 2014 24 GPS satellites will be transmitting this new signal. To benefit from these new signals, upgraded or new receivers are required.

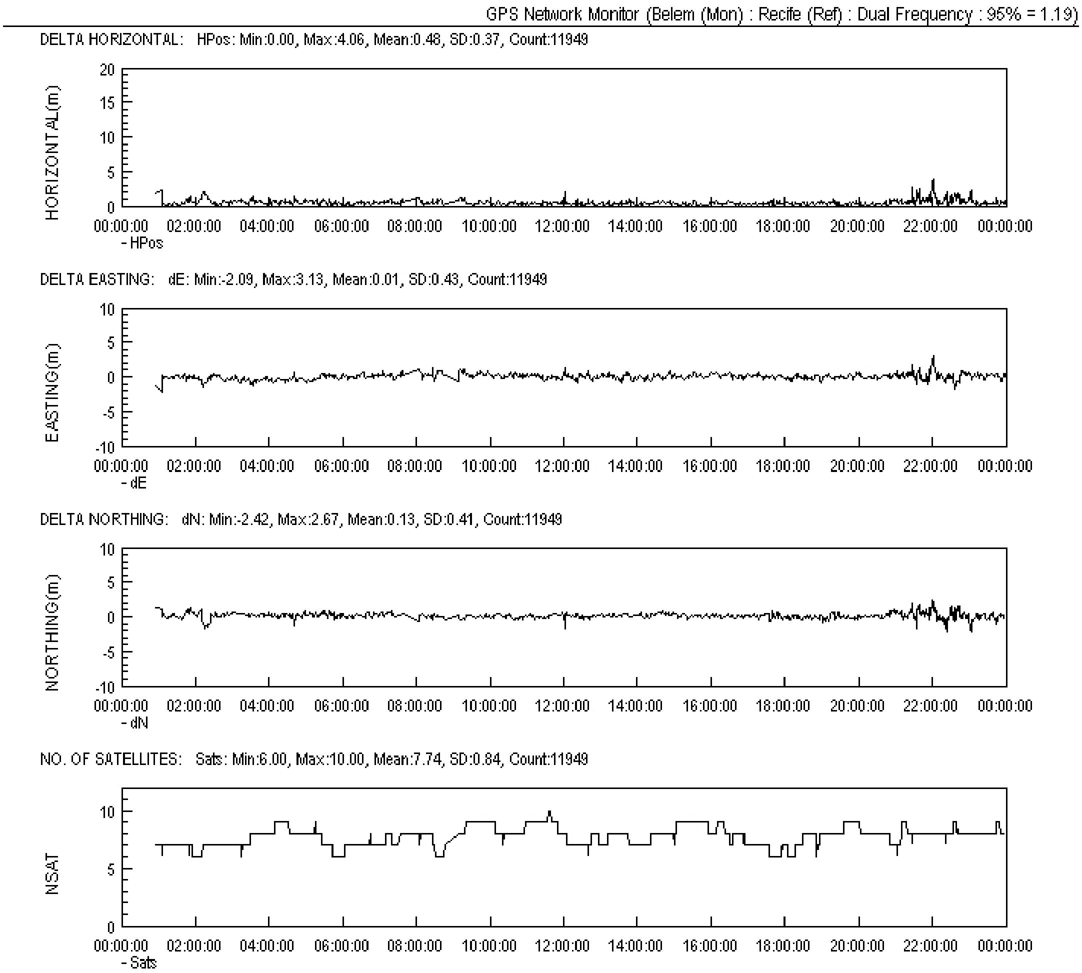

Figure 12 – Horizontal position errors for the same 1700 km baseline as in Figure 10. Position was computed using dual frequency GPS observations.

Shown in Figure 13 are the signal to noise ratios of the traditional L2 and new L2C signals for the same GPS satellite, observed by a receiver which initially was tracking L2 for one hour, followed by one hour of L2C tracking. Also shown are the L1 signal to noise ratios. The signal to noise ratio of L2C and L1 are virtually the same.

GLONASS is currently being revitalized. Plans are to have a constellation of 30 satellites in 2010, well before the solar maximum. The impact of additional GLONASS satellites is already significant. Figure 14 shows the total number of GPS and GLONASS satellites for an equatorial receiver in early July 2008. At that time, the number of satellites increased by 40-50% compared to GPS only. The Fugro GNSS positioning service is ready for GLONASS; in fact, integrated single-frequency GPS and GLONASS services have been provided since the mid 1990's.

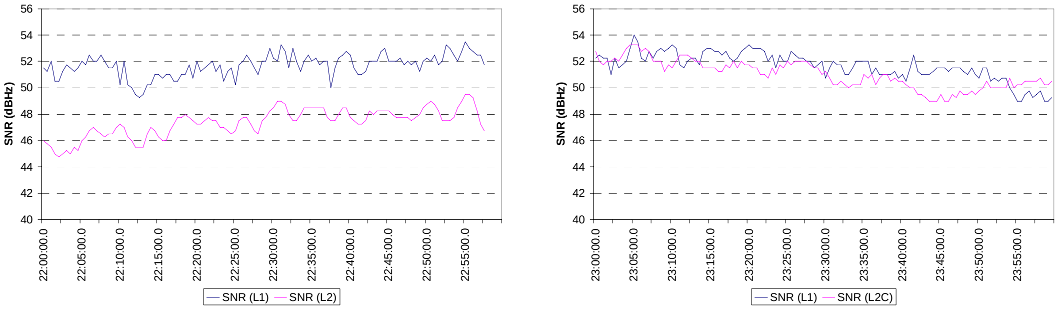

Figure 13 – L1 and L2 (left) and L1 and L2C signal strengths for the same satellite and receiver.

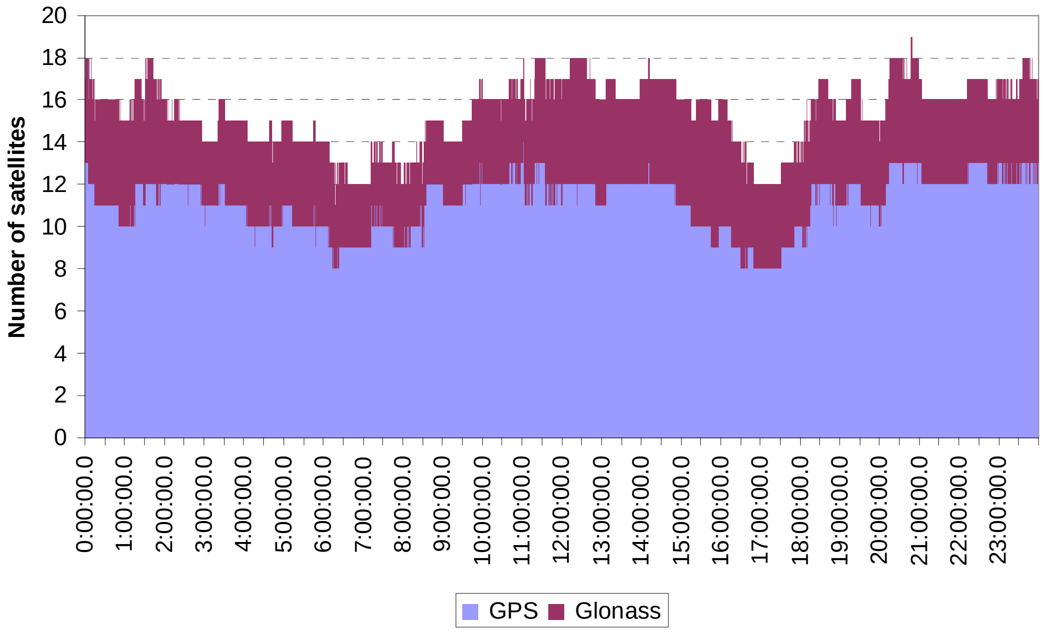

Figure 14 – Number of visible GPS and GLONASS satellites for a receiver located near the equator in July 2008.

Data links

GNSS correction data is usually broadcast over satellite or terrestrial radio links. These links can be affected by ionospheric disturbances as well. To reduce the risk of failed delivery, Fugro uses multiple and redundant data links and satellites. These satellites are in different orbit positions, to reduce the risk of failure in case of ionospheric scintillations. Fugro also sends correction at twice the rate that is actually needed by the users of its services. This allows for missed messages on the data link without impairing the performance. In addition to using redundant satellites, Fugro also has redundant Network Control Centers (NCCs) each generating every Fugro beam. Primary and backup beams are not uplinked by the same NCC, unless one NCC fails. Each NCC also has a physical backup location. Further, in the case of an uplink failure, Fugro has alternate uplink locations to all the Fugro beams, reachable by either NCC. Figure 15 gives an example of the way Fugro guarantees independence and robustness of their GNSS positioning services, Figure 16 shows the coverage area of the Fugro satellite beams, used to provide GNSS correction data to users worldwide. As is clear from this figure, there is significant separation between the satellite positions and at the same time sufficient overlap between coverage areas. In the unlikely event that one link fails, another can take over. In addition to satellite links, Fugro also uses terrestrial radio links in Central Africa and Brazil.

Conclusions

The upcoming solar cycle 24 will reach its maximum in 2011 or 2012. Using state of the art GNSS receivers, capable of tracking all available signals, satellites and systems and using independent and redundant data links, Fugro is confident it will be able to continue providing reliable and robust GNSS services to its global user base.

Table 1 lists the effects due to unpredictable ionospheric delay errors on Fugro's GNSS services. These errors are seen almost all of the time all over the world. Table 2 summarizes the effects of ionospheric scintillations. Scintillations are more sporadic and more likely to occur near the geomagnetic equator, especially in Brazil.

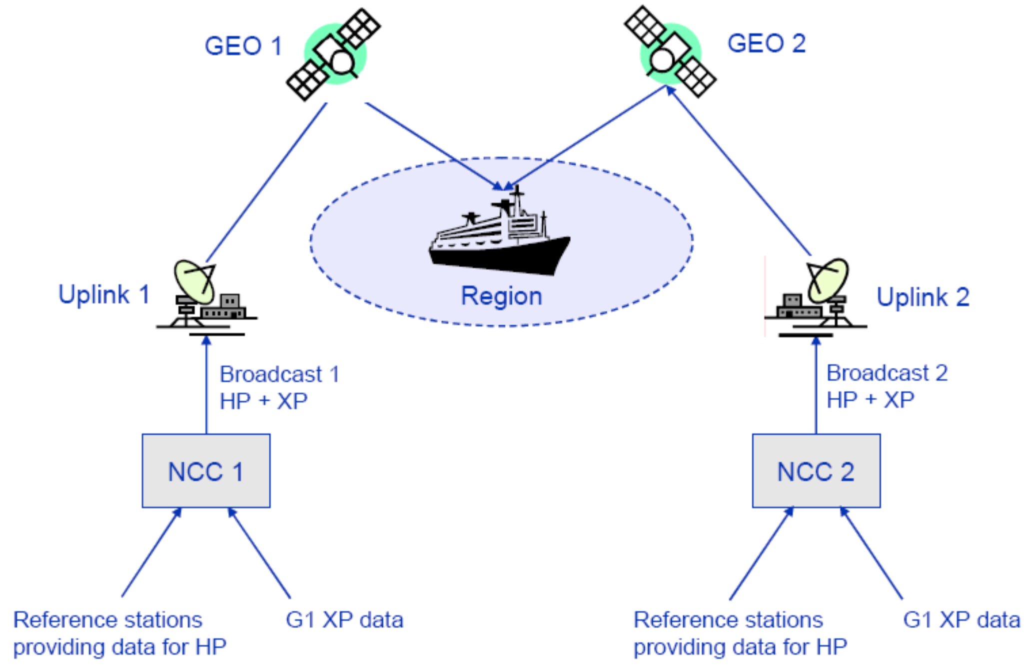

Figure 15 – Example of independence and robustness of Fugro’s high-precision GNSS positioning services.

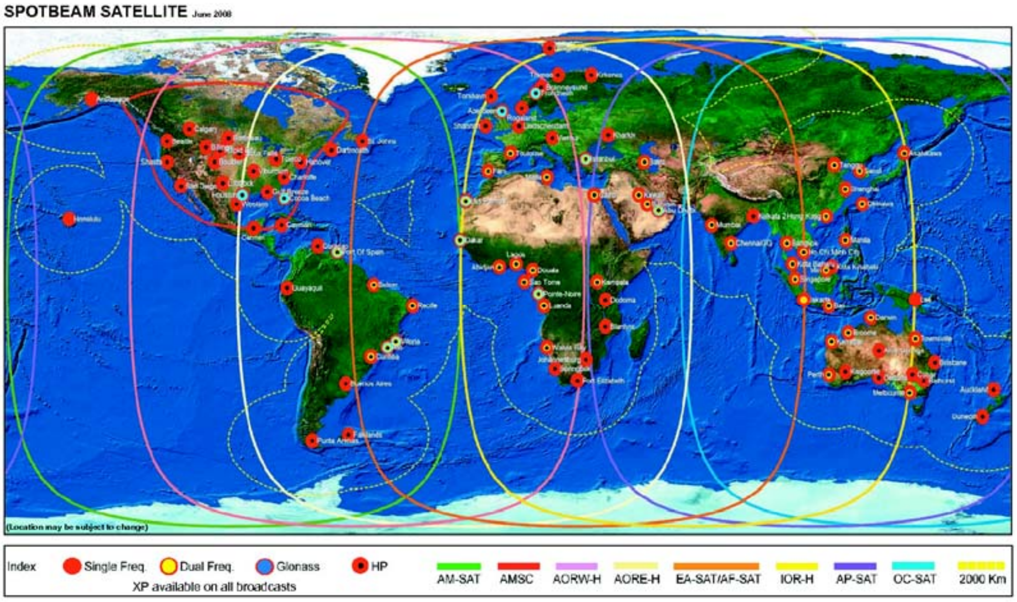

Figure 16 – Coverage areas of Fugro’s satellite beams, used to provide GNSS correction data to users all over the world.

Table 1 – Impact of ionospheric delay errors on Fugro's GNSS services.

Service	**Exposure**	**Remedy**	**Notes**
Seastar VBS	High	Upgrade to dual frequency receivers.	Some single frequency receivers can be upgraded to dual frequency.
Seastar Plus	None		
Seastar HP	None		
Seastar XP	None		

Table 2 – Impact of ionospheric scintillations on Fugro's GNSS services.

Service	**Exposure**	**Remedy**	**Notes**
Seastar VBS	Medium	Upgrade receivers to track GLONASS.	
Seastar Plus	Medium	Upgrade receivers to track GLONASS.	Transition to HP/XP is encouraged.
Seastar HP	Medium/low	Upgrade receivers to track GLONASS.	
Seastar XP	Medium/low	Upgrade receivers to track GLONASS.	