Dual Frequency DGPS Service for Combating Ionospheric Interference

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The 11-year solar sunspot cycle is approaching a maximum in 2000. The sunspot activity causes an increase in the solar flux, charged particles and electromagnetic rays emitted from the Sun. This solar flux affects the ionosphere, thus influencing the transmission of radio waves through the ionosphere. The GPS satellite navigation system is affected in that the transit time of the signals varies, introducing position errors. Also GPS equipment may experience degraded performance in tracking of the GPS satellites due to scintillations, rapidly varying amplitude and phase of the GPS signal. The equatorial and high latitude regions are most severely affected by this increased ionospheric activity. Experience has shown that, in equatorial regions, errors of 10–20 m may be introduced in Differential GPS services, even on distances down to a few hundred kilometres from the reference station. During the peak of the solar cycle, for the next 3–4 years, this situation will rather be the rule than the exception in the affected areas. Fugro has introduced an enhanced real-time DGPS service utilising dual frequency GPS called Starfix-Plus in selected areas. This service removes ionospheric delay errors by calculating the delay using dual frequency GPS receivers on the reference stations and the mobiles. The resulting accuracy is down to a few metres, even using reference stations up to 2000 km away. This increases the availability and redundancy of usable reference stations in a region, increasing the probability that the required accuracy is available, even if individual stations are not available due to scintillations or for other reasons.

1. INTRODUCTION. In the past 18 months there have been increased incidents of navigation and positioning problems using the NAVSTAR GPS system. Seismic exploration contractors and other users of Differential GPS have reported errors of 10–20 metres for extended periods. At other times, the L Band Differential GPS communications equipment has lost 'lock' on the satellite signals and consequently stopped receiving differential correction data or even the GPS signals, resulting in complete loss of Differential GPS. These problems have been regional and seasonal, appearing primarily in Africa, South America and South East Asia, occasionally in Europe and rarely in North America. These positioning errors are consequences of increased solar activity. This increased solar activity was expected to peak in mid-2000, at the predicted maximum of the current 11-year solar sunspot cycle.

2. THE SOLAR CYCLE. Even before the 1600s when Galileo started viewing the Sun with his telescope, astronomers noted that the Sun went through cycles where

greater and lesser numbers of visible black spots would develop on its surface. This sunspot cycle has an average of 11 years, peak to peak. The current cycle is referred to as number 23 and was expected to peak during mid-2000. Figure 1 is the historical data for the last four cycles. The progress of the current cycle is displayed in Figure 2.

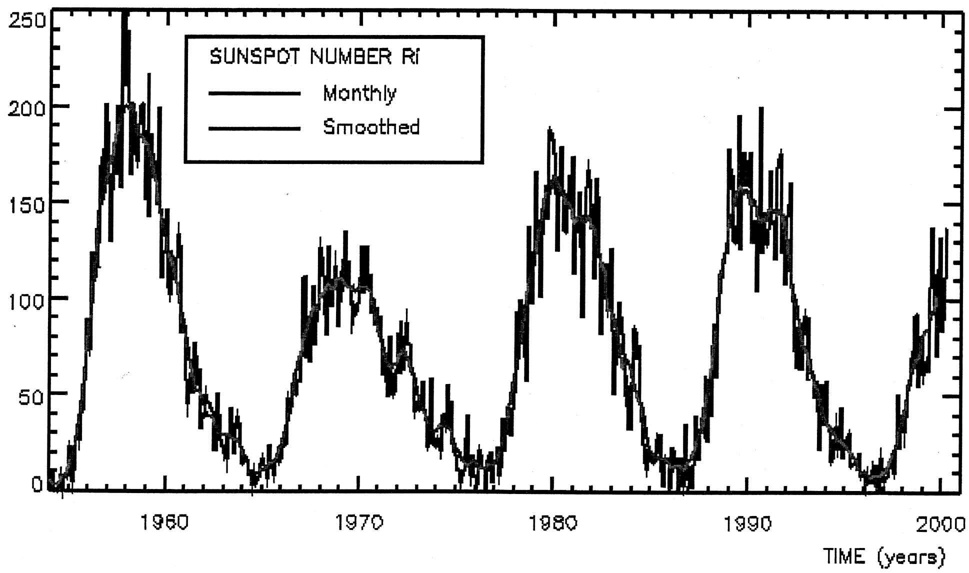

Figure 1. Sunspot numbers for the last four cycles (Royal Observatory of Belgium).

Sunspots are relatively cool areas that appear as dark blemishes on the face of the Sun. They appear and dissipate for periods lasting days or weeks, rotating over the surface of the Sun with an average 27-day period. The sunspot number is basically the sum of the visible dark areas on the surface of the Sun, with adjustments for the instrumentation used. Sunspots are formed when extremely strong magnetic field lines just below the Sun's surface are twisted and poke through the solar photosphere. The twisted magnetic fields above the sunspots are sites where solar flares and Coronal Mass Ejections (CME) are observed to occur. These and other types of solar events add energetic particles, solar materials and gravity waves to the solar wind, which, over a period of minutes to days, impacts the Earth's magnetosphere, disrupting the ionosphere.

This disrupted ionosphere is what causes the positioning errors seen by navigators. The signal from the GPS satellites passes through the ionosphere and is changed, causing the GPS user equipment to compute an incorrect position. The term 'Space Weather' is used to refer to the general condition of the Sun – Earth connection and the level of disruption in the ionosphere.

3. THE IONOSPHERE. The ionosphere is created by the solar x-rays and extreme ultraviolet rays, which pass into the magnetosphere, causing photo ionisation of the upper atmosphere, creating free electrons. The measure of the number of free

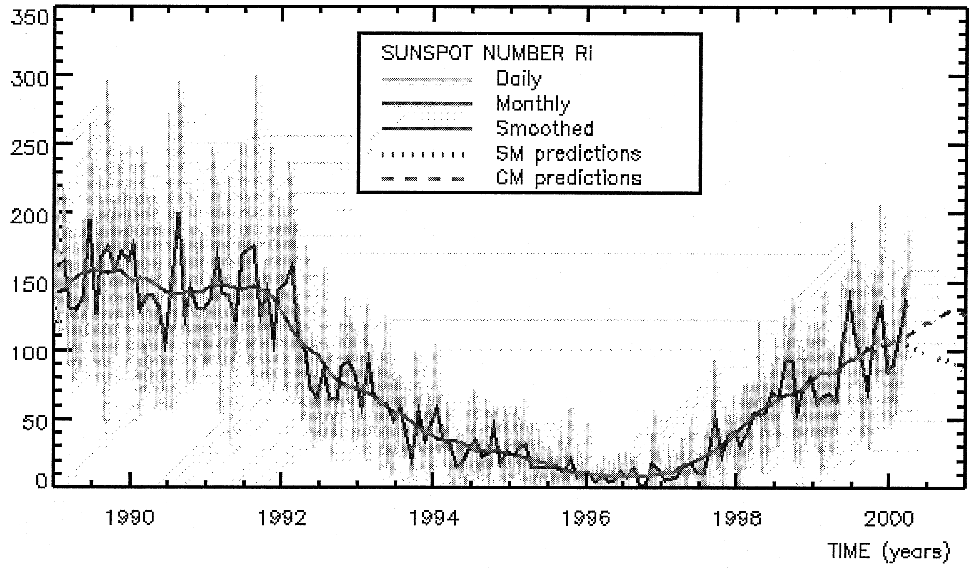

Figure 2. Sunspot numbers since 1990 (Royal Observatory of Belgium).

electrons in the ionosphere, the electron density, is called the Total Electron Content (TEC). The ionosphere ranges from 50–1000 km above the surface of the Earth, averaging about 450 km. 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. Particles from the Sun form the solar wind that tends to enter the Earth‘s atmosphere along the magnetic field lines close to the poles. This disturbs the ionosphere and creates the Auroras.

4. EFFECTS ON GPS.

The GPS satellite navigation system is affected in two ways:

(a) *Ionospheric Delay Errors* (*Proportional to Total Electron Content*). These are unmodelled delays in the ionosphere affecting the range measurements to GPS satellites. They are most severe in equatorial regions, affecting baselines from a few hundred km. They occur almost daily and persist for a large part of the day.

(b) *Scintillations*. These are rapid phase and amplitude variations on the GPS signal, causing GPS receivers to lose lock. The effect is most severe in equatorial regions, affecting individual satellites at individual stations for short periods, 1–2 hours a day with irregular intervals.

During the peak of the solar cycle for the next 3–4 years, these effects on GPS will be the rule rather than the exception in the affected areas. High latitude regions are affected by this increased ionospheric activity, but the effects are smaller when compared with the equatorial regions.

The delay of the GPS signal through the ionosphere can be expressed by:

$$\Delta t = 40{\cdot}3 \times TEC \div (c \times f^2),$$

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where:

Δt = Ionospheric delay (sec),
TEC = the Total Electron Content (electrons/m^2),
c = Speed of light (m/s),
f = Frequency of the transmitted signal (Hz).

5. COMBATING ERRORS CAUSED BY IONOSPHERIC DISTURBANCES. Methods of combating problems due to ionospheric interference include:

(a) *Combating Ionospheric Delay Errors*. These errors can be reduced by improved ionospheric modelling and dual frequency GPS measurements.
(b) *Combating Scintillations*. There is no guaranteed solution for scintillation as the GPS signals themselves are affected. However, some GPS receivers and antennae perform better than others and using the GLONASS system in addition to GPS provides additional satellites to chose from. The problem is indirectly dealt with by using reference stations further afield that are unaffected, thus increasing availability as all sites are not affected at the same time. Experience in West Africa shows that vessels tend to be less affected than reference stations, due to the higher noise level and lower margins on land than at sea.

Figure 3 shows how the standard ionospheric model in GPS (the Klobuchar model) compares to a more accurate model of the ionosphere. It can be seen that, especially around the equator on the sunlit side of the Earth, the agreement between the two is not very good. The more accurate model has two peaks, while the Klobuchar model has only one peak. Better global modelling of the ionosphere does not solve all of the problems caused by the ionospheric delay errors. Global models tend not to be accurate enough, especially in equatorial regions where the errors are largest. Regional models would improve the situation; however, it would require a denser network of reference stations and the result could never be guaranteed.

Using the two frequencies in the GPS system, L1 at 1575·42 MHz and L2 at 1227·60 MHz, it is possible to calculate the delay of the GPS signal through the ionosphere:

$$c\Delta t = f_2^2/(f_1^2 - f_2^2) \times (PR_2 - PR_1)$$

where:

Δt = Delay on L1,
c = Speed of light,
f_1, f_2 = Frequency of L1 and L2,
PR_1, PR_2 = Pseudo-range measurement on L1 and L2.

In the GPS system, the civil C/A code is only available on the L1 frequency. This means that the L2 frequency must be tracked with special techniques resulting in lower tracking margins than on L1. The result of this is that the tracking on L2 tends to lose lock more readily than tracking on L1 due to scintillations etc.

6. FUGRO DUAL FREQUENCY SERVICE. Fugro has introduced an enhanced real-time DGPS service utilising dual frequency GPS called Starfix-Plus in selected areas. The Starfix-Plus service is an addition to the regular Starfix service and

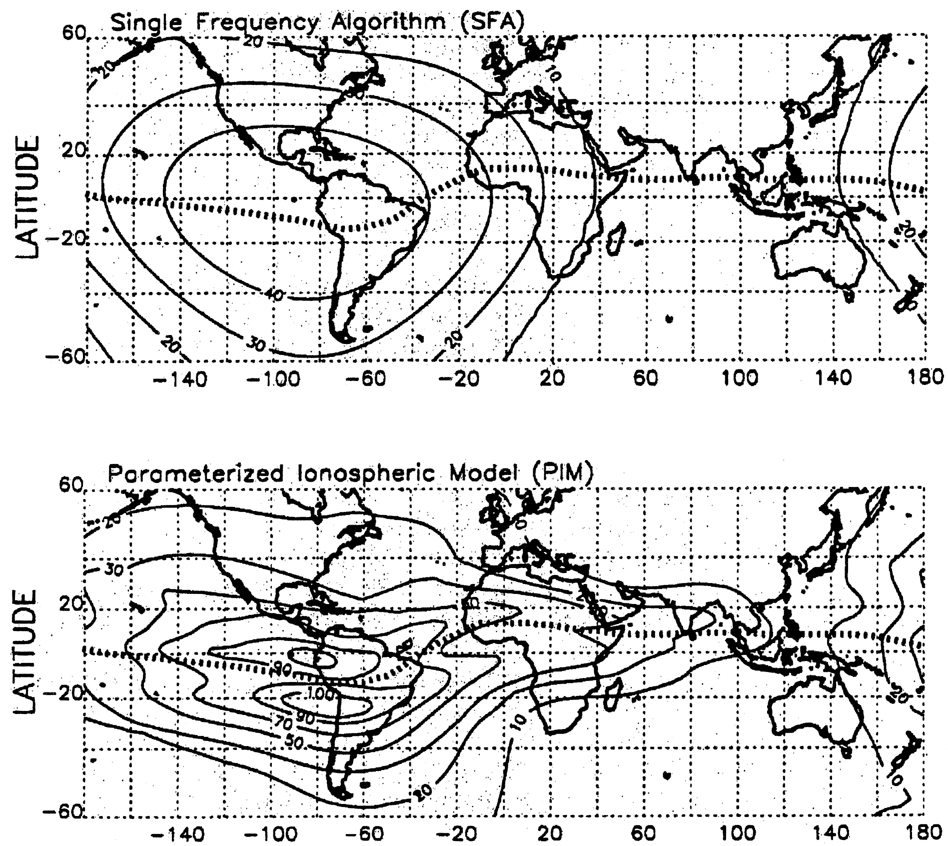

Figure 3. (a) Contours of ionospheric TEC using the standard GPS model (Klobuchar model), (b) a more accurate model (Parametrised Ionospheric Model, PIM) (1 TEC Unit is 0·316 m delay on L1) (Smitham *et al.*, 1999).

uses data broadcasts by geostationary satellites for distribution. The ionospheric delay is calculated at the DGPS reference station as indicated above. In order to reduce the noise on the ionospheric measurements, carrier phase smoothing of the delay is applied. An RTCM (Radio Technical Commission for Maritime Services, 1998) Type 15 message is generated and broadcast with the standard RTCM Type 1 message. The Type 15 message contains the ionospheric delay to each satellite at the reference station, while the Type 1 contains the pseudo-range correction to each satellite.

At the mobile (see Figure 4), a dual frequency GPS receiver is also used to calculate the ionospheric delay. Instead of correcting the pseudo-range corrections for the difference in ionospheric delay at the reference and the mobile using a model, the dual frequency measurements at the reference station and the mobile are used. The mobile can then output ionospheric-free, RTCM Type 1 corrections to an external navigation package. This navigation package can use these corrections without any changes. Also, the RTCM Type 15 message (ionospheric delay at the reference stations) can be output to an external system equipped to handle it.

The Starfix-Plus mobile can also calculate a set of (iono-free) RTCM corrections optimised for the user position based on corrections from several physical reference

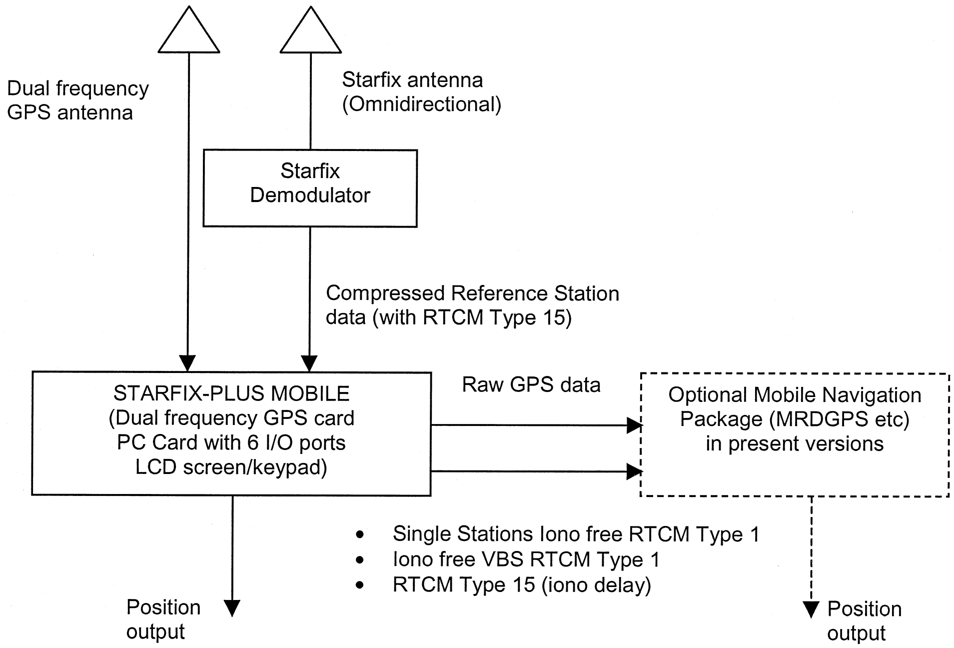

Figure 4. Mobile setup in Starfix-Plus.

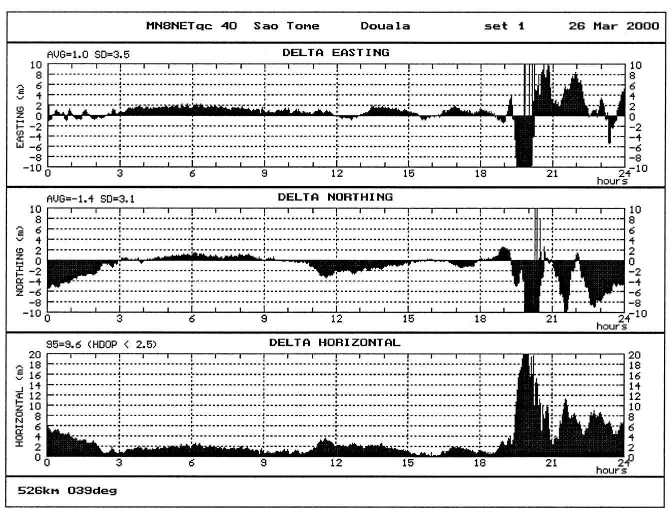

Figure 5. Baseline Sao Tome – Douala (526 km) using single frequency corrections on 26 March 2000. The plots are east error (top), north error (middle) and horizontal error when HDOP < 2·35 (bottom). The 95 % Horizontal error is 9·36 metres during the 24 hour period with peak error over 20 metres.

stations. This will increase the availability of a position output if corrections are missing from individual reference stations, for example due to scintillations. This is called a VBS (Virtual Base Station) solution and can also be output to an external system as a RTCM Type 1 correction message. The most common configuration,

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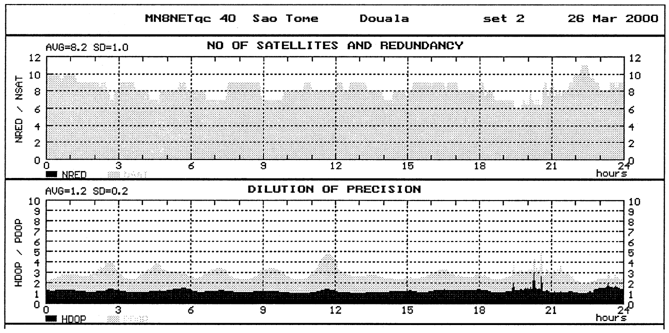

Figure 6. Baseline Sao Tome – Douala (526 km) using dual frequency corrections on 26 March 2000. These plots show the number of satellites used (top) and HDOP, PDOP (bottom).

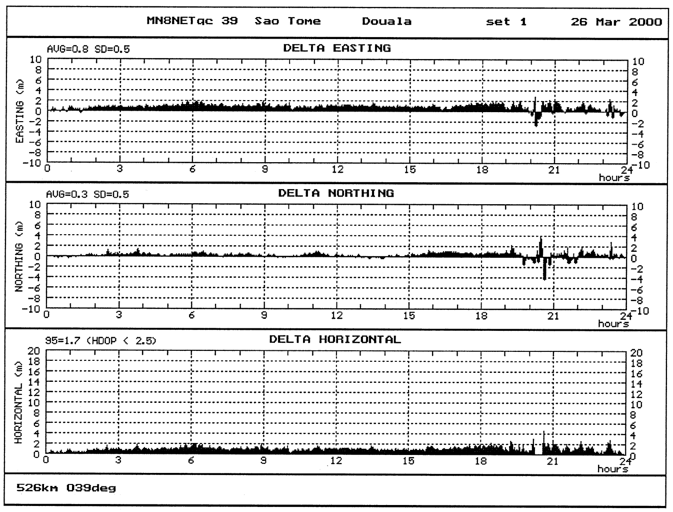

Figure 7. Baseline Sao Tome – Douala (526 km) using dual frequency corrections on 26 March 2000. The plots are east error (top), north error (middle) and horizontal error when HDOP $<2{\cdot}35$ (bottom). The 95% Horizontal error is 1·37 metres during the 24 hour period with peak errors about 4 m.

however, is to use the GPS raw data and the VBS within the Starfix-Plus mobile and calculate a position which is then output to an external system.

Figures 5 through 8 show the navigation errors using single frequency and dual frequency DGPS on a 526 km baseline between Sao Tome (0°19′N, 6°44′E) and Douala in Cameroon (4°01′N, 9°43′E). The plots show that single frequency errors of 9·36 m (95% horizontal) during the 24-hour period is reduced to 1·37 m (95% horizontal).

The plots also show the effect of scintillations around 19–21 hours UTC. During this period some satellites lost lock, making the HDOP (Horizontal Dilution of Precision) increase and the errors increase. Comparing the single frequency case (Figure 6) and the dual frequency case (Figure 8), it can be seen that more satellites lose track in the latter case, resulting in higher HDOP. This is due to the fact that the tracking of the L2 frequency in GPS has lower signal-to-noise margins, making it more susceptible to amplitude and phase fluctuations during scintillations. In Figure 8,

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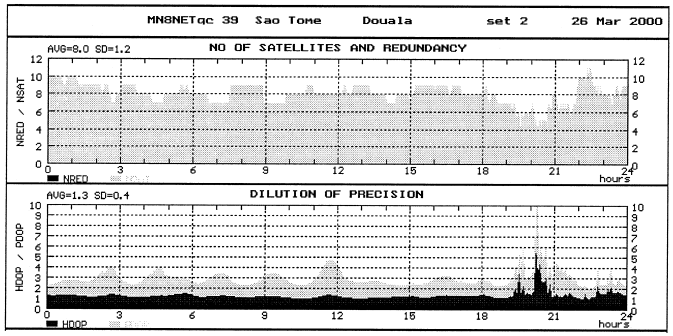

Figure 8. Baseline Sao Tome – Douala (526 km) using dual frequency corrections on 26 March 2000. These plots show number of satellites used (top) and HDOP, PDOP (bottom).

the increased errors in east and north in the top two plots during this period are due to increased HDOP. In the horizontal error (root sum square of the east and north error) plot at the bottom, values are only shown when HDOP is less than 2·35.

Other data collected on baselines of 1500–2000 km in the equatorial region shows errors in the 10–20 m range, typically 12 hours a day. Even on such baselines, errors are reduced to around 3 m 95 % horizontal using dual frequency systems.

Fugro now has this dual frequency service available in South America, West Africa, The Mediterranean, Middle East, and the Far East.

7. CONCLUSIONS.

The peak of the solar sunspot cycle was expected to be reached in 2000. Rays and particles from the Sun result in a more disturbed ionosphere. This affects the GPS system in that the errors are increased due to un-modelled delay errors. GPS receivers can also lose track of the signal due to scintillations, rapid variations in the phase and amplitude of the GPS signal. The errors in differential GPS systems can be removed by using dual frequency GPS receivers both at the reference station and the mobile. Errors of 10–20 m can be reduced to about 3 metres or less even on baselines up to 2000 km. The effect of scintillations will also be reduced, as reference stations at longer distances, that may not be affected, can be used.

Fugro has introduced a dual frequency service called Starfix-Plus with about 15 dual frequency reference stations in the equatorial region around the world.

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RTCM. (1998). RTCM Recommended Standards for Differential GNSS Service. *Radio Technical Commission for Maritime Services*. Version 2.2, January 15 1998, Alexandria,Virginia, USA.

RECOMMENDED WEB SITES

http://www.sec.noaa.gov/nav/nav.html: Navigation Systems Alerts.
http://www.sec.noaa.gov/today.html: Today's Space Weather.
http://www.astro.oma.be/SIDC/sidc-graphics.html: Royal Observatory of Belgium.
http://www.sunspotcycle.com: Sunspot Cycle Progress.
http://www.nwra-az.com/ionoscint/sp-main.html: NorthWest Research Scintillation Predictions.
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