The Sun, the Earth, the Ionosphere: What the Numbers Mean, and Propagation Predictions--a brief introduction to propagation and the major factors affecting it.

By Carl Luetzelschwab, K9LA k9la@arrl.net

The sun emits electromagnetic radiation and matter as a consequence of the nuclear fusion process. Electromagnetic radiation at wavelengths of 10 to 100 nanometers (extreme ultraviolet) ionizes the F region, radiation at 1 to 10 nanometers (soft X-rays) ionizes the E region, and radiation at 0.1 to 1 nanometers (hard X- rays) ionizes the D region. Solar matter (which includes charged particles--electrons and protons) is ejected from the sun on a regular basis, and this comprises the solar wind. On a "quiet" solar day, the speed of this solar wind heading toward Earth averages about 400 km per second.

The sun's solar wind significantly impacts Earth's magnetic field. Instead of being a simple bar magnet, Earth's magnetic field is compressed by the solar wind on the side facing the sun and is stretched out on the side away from the sun (the magnetotail, which extends tens of earth radii downwind). While the sun's electromagnetic radiation can impact the entire ionosphere that is in daylight, charged particles ejected by the sun are ultimately guided into the ionosphere along magnetic field lines and thus can only impact high latitudes where the magnetic field lines go into the Earth.

Additionally, when electromagnetic radiation from the sun strips an electron off a neutral constituent in the atmosphere, the resulting electron can spiral along a magnetic field line (it spirals around the magnetic field line at the electron gyrofrequency). Thus Earth's magnetic field plays an important and critical role in propagation.

Variations in Earth's magnetic field are measured by magnetometers. There are two measurements readily available from magnetometer data--the daily A index and the three-hour K index. The A index is an average of the eight 3-hour K indices, and uses a linear scale and goes from 0 (quiet) to 400 (severe storm). The K index uses a quasi-logarithmic scale (which essentially is a compressed version of the A index) and goes from 0 to 9 (with 0 being quiet and 9 being severe storm). Generally an A index at or below 15 or a K index at or below 3 is best for propagation.

Sunspots are areas on the sun associated with extreme ultraviolet radiation. Thus they are tied to ionization of the F region. The daily sunspot number, when plotted over a month time frame, is very spiky. Averaging the daily sunspot numbers over a month results in the monthly average (monthly mean) sunspot number, but it is also rather spiky when plotted. Thus a more averaged, or smoothed, measurement is used to measure solar cycles. This is the smoothed sunspot number (R_{12}). R_{12} is calculated using six months of

data before and six months of data after the desired month, plus the data for the desired month. Because of this amount of smoothing, the official R_{12} is one-half year behind the current month. Unfortunately this amount of smoothing may mask any short-term unusual solar activity that may enhance (or hinder) propagation.

Sunspots come and go in an approximate 11-year cycle. The rise to maximum (4 to 5 years) is usually faster than the descent to minimum (6 to 7 years). At and near the maximum of a solar cycle, the increased number of sunspots causes more extreme ultraviolet radiation to impinge on the atmosphere. This results in significantly more F region ionization, allowing the ionosphere to refract higher frequencies (15, 12, 10, and even 6 meters) back to Earth for DX contacts. At and near the minimum between solar cycles, the number of sunspots is so low that higher frequencies go through the ionosphere into space. Commensurate with solar minimum, though, is less absorption and a more stable ionosphere due to a quiet magnetic field, resulting in the best propagation on the lower frequencies (160 and 80 meters). Thus, in general, high smoothed sunspot numbers are best for high-frequency propagation, and low smoothed sunspot numbers are best for low-frequency propagation.

Most of the disturbances to propagation come from solar flares and coronal mass ejections (CMEs). The solar flares that affect propagation are called X-ray flares due to their wavelength being in the 0.1 to 0.8 nanometer range. X-ray flares are classified by magnitude as C (the smallest), M (medium size), and X (the biggest). Class C flares usually have minimal impact to propagation. Class M and X flares can have a progressively adverse impact to propagation.

The electromagnetic radiation from a class X flare in the 0.1 to 0.8 nanometer range can cause the loss of all propagation on the sunlit side of Earth due to increased D region absorption. Additionally, big class X flares can emit very energetic protons that are guided into the polar cap by Earth's magnetic field. This can result in a polar cap absorption event (PCA), with high D-region absorption on paths passing through the polar areas of Earth.

A CME is an explosive ejection of a large amount of solar matter, and can cause the average solar wind speed to take a dramatic jump upward--kind of like a shock wave heading toward Earth. If the polarity of the interplanetary magnetic field is southward when the shock wave hits Earth's magnetic field, the shock wave couples into Earth's magnetic field and can cause large variations in Earth's magnetic field. This is seen as an increase in the A and K indices (elevated geomagnetic field activity).

In addition to auroral activity, these variations to the magnetic field can cause those electrons spiraling around magnetic field lines to be lost into the magnetotail. With electrons gone, maximum usable frequencies (MUFs) decrease, and return only after the magnetic field returns to normal and the process of ionization replenishes lost electrons. Most of the time, elevated A and K indices reduce MUFs, but MUFs at low latitudes may increase (due to a complicated process) when the A and K indices are elevated.

Solar flares and CMEs are related, but they can happen together or separately. Scientists are still trying to understand the relationship between them. One thing is certain, though--the electromagnetic radiation from a big flare traveling at the speed of light can cause short-term radio blackouts on the sunlit side of Earth within about 10 minutes of eruption. Unfortunately we detect the flare visually at the same time as the radio blackout, since both the visible light from the flare and the electromagnetic radiation in the 0.1 to 1 nanometer range from the flare travel at the speed of light--in other words, we have no warning. On the other hand, the energetic particles ejected from a flare can take up to several hours to reach Earth, and the shock wave from a CME can take up to several days to reach Earth, thus giving us some warning of their impending disruptions.

Each day the Space Environment Center (a part of NOAA, the National Oceanographic and Atmospheric Administration) and the US Air Force jointly put out a Solar and Geophysical Activity Report. The current and archived reports are in the "Solar and Geophysical Activity Report and 3-day Forecast" section in the "Daily or less" section under "Alerts and Forecasts" at **http://sec.noaa.gov/Data/index.html**. Each daily report consists of six parts.

Part IA gives an analysis of solar activity, including flares and CMEs. Part IB gives a forecast of solar activity. Part IIA gives a summary of geophysical activity. Part IIB gives a forecast of geophysical activity. Part III gives probabilities of flare and CME events. These first three parts can be summarized as follows: normal propagation (no disturbances) generally occurs when no X-ray flares higher than class C are reported or forecasted, along with solar wind speeds due to CMEs near the average of 400km/sec.

Part IV gives observed and predicted 10.7-cm solar flux. A comment about the daily solar flux--it has little to do with what the ionosphere is doing on that day. This will be explained later.

Part V gives observed and predicted A indices. Part VI gives geomagnetic activity probabilities. These last two parts can be summarized as follows: good propagation generally occurs when the forecast for the daily A index is at or below 15 (this corresponds to a K index of 3 or below).

WWV at 18 minutes past the hour every hour and WWVH at 45 minutes past the hour every hour put out a shortened version of this report. A new format began March 12, 2002. The new format gives the previous day's 10.7-cm solar flux, the previous day's mid-latitude A index, and the current mid-latitude three-hour K index. A general indicator of space weather for the last 24 hours and next 24 hours is given next. This is followed by detailed information for the three disturbances that impact space weather: geomagnetic storms (caused by gusts in the solar wind speed), solar radiation storms (the numbers of energetic particles increase), and radio blackouts (caused by X-ray emissions). For detailed descriptions of the WWV/WWVH messages, visit **http://sec.noaa.gov/Data/info/WWVdoc.html** and **http://sec.noaa.gov/NOAAscales/**.

Normal propagation (no disturbances) is expected when the space weather indicator is minor. A comment is appropriate here. Both the Solar and Geophysical Activity Report and WWV/WWVH give a status of general solar activity. This is *not* a status of the 11-year sunspot cycle, but rather a status on solar disturbances (CMEs, particles, and flares). For example, if the solar activity is reported as low or minor, that doesn't mean we're at the bottom of the solar cycle; it means the sun has not produced any major space weather disturbances.

In order to predict propagation, much effort was put into finding a correlation between sunspots and the state of the ionosphere. The best correlation turned out to be between R_{12} (the smoothed sunspot number) and monthly median ionospheric parameters. This is the correlation that our propagation prediction programs are based on, which means the outputs (usually MUF and signal strength) are values with probabilities over a month time frame tied to them. They are not absolutes; they are statistical in nature. Understanding this is a key to the proper use of propagation predictions.

Sunspots are a subjective measurement. They are counted visually. It would be nice to have a more objective measurement – one that actually measures the sun's output. The 10.7-cm solar flux has become this measurement. But it is only a general measure of the activity of the sun, since a wavelength of 10.7-cm is way too low in energy to cause any ionization. Thus 10.7 cm solar flux has nothing to do with the formation of the ionosphere – it is simply a proxy for the true ionizing radiation for each region. The best correlation between 10.7-cm solar flux and sunspots is the smoothed 10.7-cm solar flux and the smoothed sunspot number--the correlation between daily values, or even monthly average values, is not very acceptable.

Since our propagation prediction programs were set up based on a correlation between the smoothed sunspot number and monthly median ionospheric parameters, the use of R_{12} or the equivalent smoothed 10.7-cm solar flux gives the best results. Using the daily 10.7-cm solar flux--or even the daily sunspot number--can introduce a sizable error into the propagation predictions outputs due to the fact that the ionosphere does not react to the small daily variations of the sun. To reiterate, for best results use the smoothed sunspot number or smoothed 10.7-cm solar flux, and understand the concept of monthly median values.

For short-term predictions, the use of the effective sunspot number (SSNe) may be helpful. In this method, an appropriate sunspot number is input to the propagation prediction software to force it to agree with daily ionosonde measurements. Details of this method can be found at **http://www.nwra-az.com/spawx/ssne24.html**.