Radio Blackouts!

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Absorption in Earth's ionosphere affects both terrestrial and celestial radio waves by impeding or blocking radio propagation in all or parts of the high frequency radio band. A complete blockage is called an *HF radio blackout* or simply *radio blackout*; the synonymous phrases *shortwave fade* and *shortwave fadeout* also are often used. Another phrase that may be encountered is *sudden ionospheric disturbance* (SID), but it usually is used to refer to the effect of a solar flare on VLF radio propagation and not HF propagation. Unfortunately, there is a lot of jargon and no *standard* terminology in radio science.

The causes of absorption that lead to a radio blackout are different at lower latitudes than at higher latitudes and are the subject of this article. The first section below discusses the basic mechanisms that cause radio blackouts followed by sections on how solar phenomena controls these mechanisms at different latitudes. Included are three examples in terms of worldwide absorption plots for specific solar events in March and May 2023. The explanations that follow are simplifications, and many technical details are left out to make this article more accessible. Readers wishing to further explore ionospheric radio propagation and the physics involved are referred to [Davies] and references therein.

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1. Earth's Ionosphere

The ionosphere consists of free electrons and positive ions in equal numbers – a plasma – that coexist with neutral particles consisting of atoms and molecules, mostly nitrogen and oxygen. The plasma, by definition, is electrically neutral overall. As a radio wave in the high frequency band propagates through the ionosphere, the radio wave's oscillating electric field causes the free electrons along its path to oscillate at the same frequency. The positive ions in the ionosphere are too massive to be affected by the electric field and as a practical matter are immobile. The electric field does not affect the neutral particles.

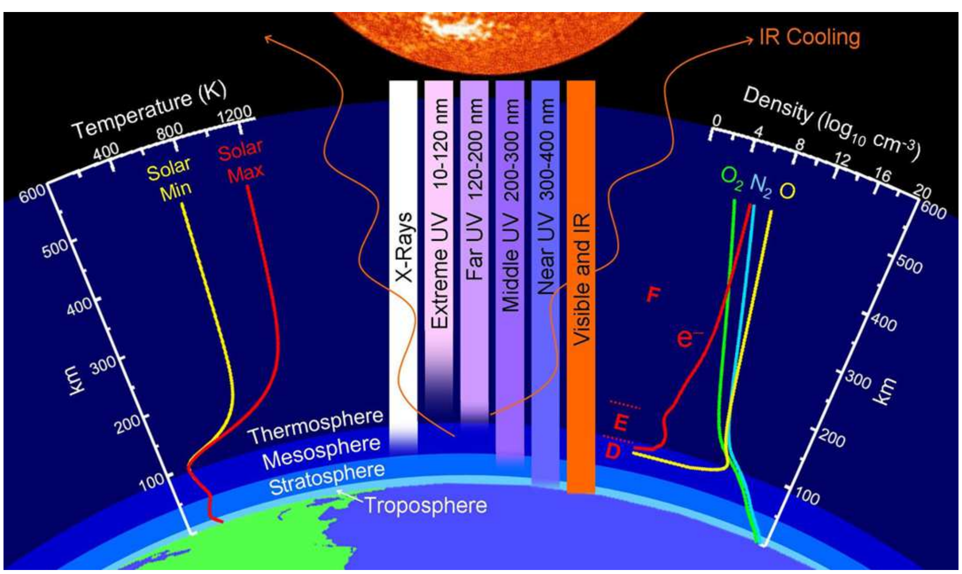

Figure 1 ~ Characteristics of Earth's atmosphere up to 600 km altitude. The chart on the right side shows particle densities. Also shown are the ionosphere regions D, E and F. The red line represents the free electron density (e). Below about 500 km, the densities of the neutral particles, molecular nitrogen N_2 and atomic oxygen O, dominate and in the D-region they, along with molecular oxygen O_2, dominate by a large margin. Image source: NASA

Although the neutral particles in the ionosphere outnumber the charged particles (figure 1), the charged particles determine the medium's electrical properties. Earth's magnetic field also influences these properties by affecting the movement of the free electrons. The electrons are *trapped* by the forces exerted on them as they move in the magnetic field.

If the oscillating electrons do not collide with ions or neutral particles, they reradiate the energy from the radio wave. The only effect on the propagating radio wave (in this simplified discussion) is refraction and reflection due to the differing electron densities along the radio propagation path. However, where the density of neutral particles is high enough, the electrons can collide with them. The collisions cause the oscillating electrons to lose energy as heat and electromagnetic noise, thereby reducing the energy available for reradiation. Thus, the radio wave experiences *absorption* and is attenuated.

The atmosphere's density and collision rate vary with altitude, so absorption and the efficiency of radio wave propagation also varies with altitude. Most of the absorption occurs in the lower ionosphere where the collision rate of the electrons with neutral particles is highest. This is the ionosphere's D-region at approximately 50 to 90 km altitude. A skywave from a terrestrial transmitter passes through the D-region at least twice, once on its way up from the transmitter to the higher reflective and refractive regions of the ionosphere and once again on its way back down to a receiver (figure 2). If the propagation involves multiple hops, then each hop passes through the D-region twice and experiences absorption on each pass. On the other hand, celestial radio waves pass through the D-region only once on their way down to a terrestrial receiver, so absorption is on the order of one-half of that experienced by a 1-hop skywave.

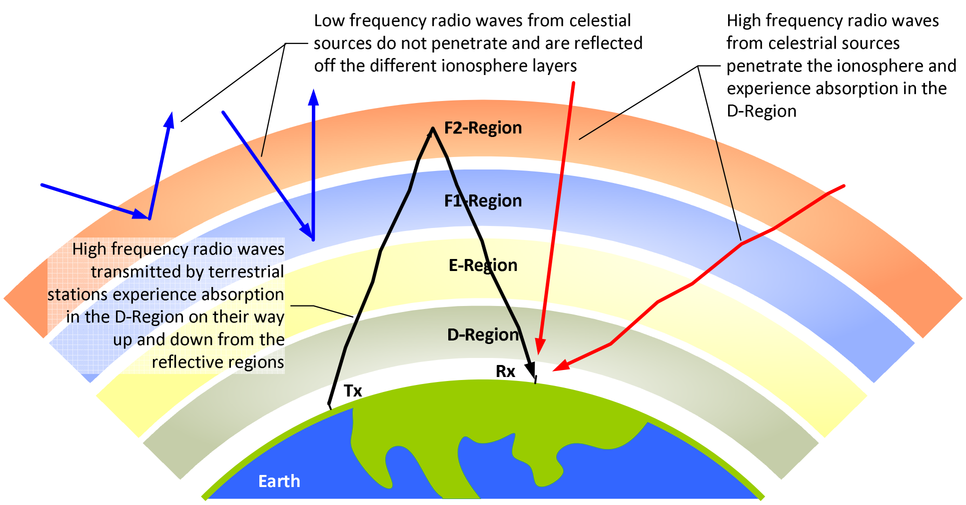

Figure 2 ~ Reflection and refraction take place in the upper regions of the ionosphere, E and F, from approximately 90 to 500 km altitude, while absorption primarily is in the lower region, D, from approximately 50 to 90 km. The ionosphere's properties are highly dependent on the frequency and level of solar activity. Drawing not to scale. Image © 2023 W. Reeve

2. Solar Effects

When the Sun is quiet, the density of the neutral particles in the ionosphere's D-region is relatively constant over time, so local variations in the electron density determine the amount of absorption. The electron density is a function of many parameters and normally varies with the position of the Sun in the sky, latitude, season, and progress of the solar cycle. The broad characteristics of these variations are predictable when the Sun is quiet. The lower HF frequencies are only moderately affected, and higher frequencies are affected very little.

When the Sun is active and a solar x-ray flare occurs on the side of the Sun facing Earth (figure 3), the flare radiation travels at light speed toward Earth, arriving in a little more than 8 min. Some of the radiation penetrates the upper ionosphere and is able to reach the D-region, causing a sudden increase in electron density and leading to a much more significant and rapid change in the amount of absorption. The absorption can increase so much that the D-region becomes opaque to HF radio waves. Generally, radio waves at lower frequencies in the HF band are most affected. The degree of absorption at any frequency depends on the angle at which the radio wave enters the D-region.

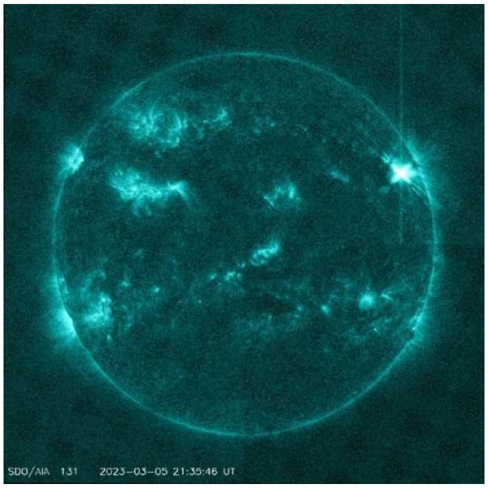

Figure 3 ~ Snapshot of the Sun and a solar flare at 131 Å (13.1 nm) wavelength as recorded by the Solar Dynamics Observatory (SDO) on 5 March 2023 at 2135 UTC. This wavelength shows the hottest material in a flare. The flare intensity was M5.0 and is the bright area near the northwest (upper-right) limb. The flare produced a radio blackout at Anchorage on 15 MHz (see text). Image source: NASA

Solar X-ray flares radiate over a very wide range of wavelengths, but it is the 0.1 – 0.8 nm wavelength range (often called *soft x-ray band*) that is significant to ionospheric radio propagation. Radiation at these wavelengths is able to penetrate the upper ionosphere and reach the D-region. The D-region ionization by solar x-rays is greatest above the *sub-solar point* (the point on Earth's surface where the Sun is directly overhead). The amount of ionization and absorption decreases with distance from the sub-solar point, reaching zero at the day and night solar terminators (gray lines). The night-side of the Earth's ionosphere is not directly affected by solar flares, but flares have been observed on the night-side in the HF radio band under very rare circumstances {Typinski}.

Flares are rated C, M, or X according to the flux radiated at 0.1 – 0.8 nm wavelengths. Spacecraft (for example, GOES) are used to measure these wavelengths because they cannot be measured from the ground. The C, M, and X classification is based on the full-disk x-ray emission from the sun. C-class flares are the most common but least intense and X-class are the least common but most intense, and M-class are in-between. During periods of high solar activity, such as around solar maximum, the background flux may increase to C-class levels for days at a time even without flare activity. The ionosphere's D-region electron density is determined by the total x-ray flux regardless of the source, so these periods of high background flux can significantly affect radio propagation.

The depths of absorption are predicted by Space Weather Prediction Center by estimating the effects of the flare x-ray radiation and energetic protons on the ionosphere [Sauer]. These are plotted as D-Region Absorption Predictions (D-RAP) (figure 4) and are available on the SWPC Radio Dashboard {SWPC}. The absorption predicted in the D-RAP plot resulted in a 15 MHz radio blackout as recorded at Anchorage, Alaska (figure 5).

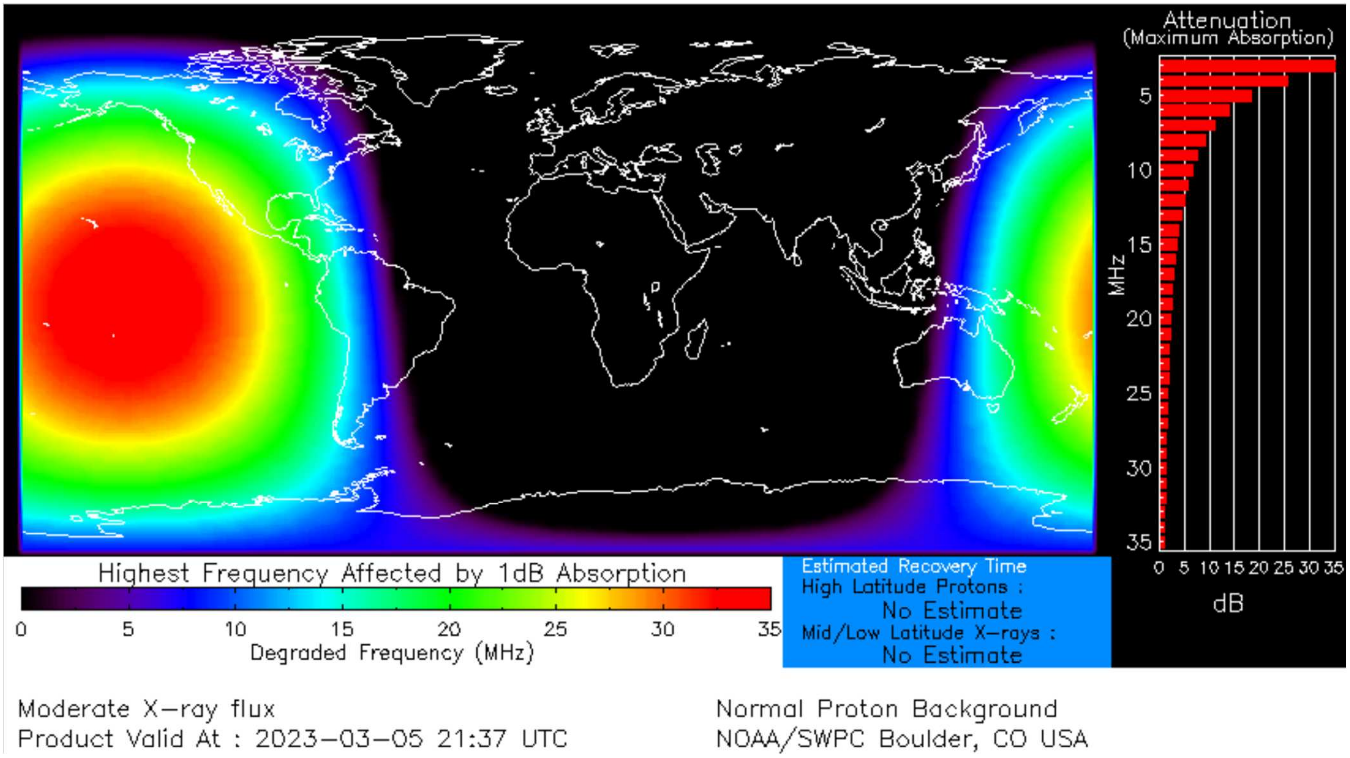

Figure 4 ~ The D-RAP image from 5 March 2023, shows the result of an M5.0 x-ray flare that affected trans-Pacific radio paths. The colors show the highest frequency that experiences 1 dB of absorption but they also indicate the amount of absorption at lower frequencies (the absorption usually affects lower frequencies more than higher frequencies). The histogram on the right shows the predicted absorption in frequency increments of 1 MHz. For example, the absorption at 20 MHz was about 2.5 dB while at 5 MHz the absorption was about 18 dB. Image source: Space Weather Prediction Center

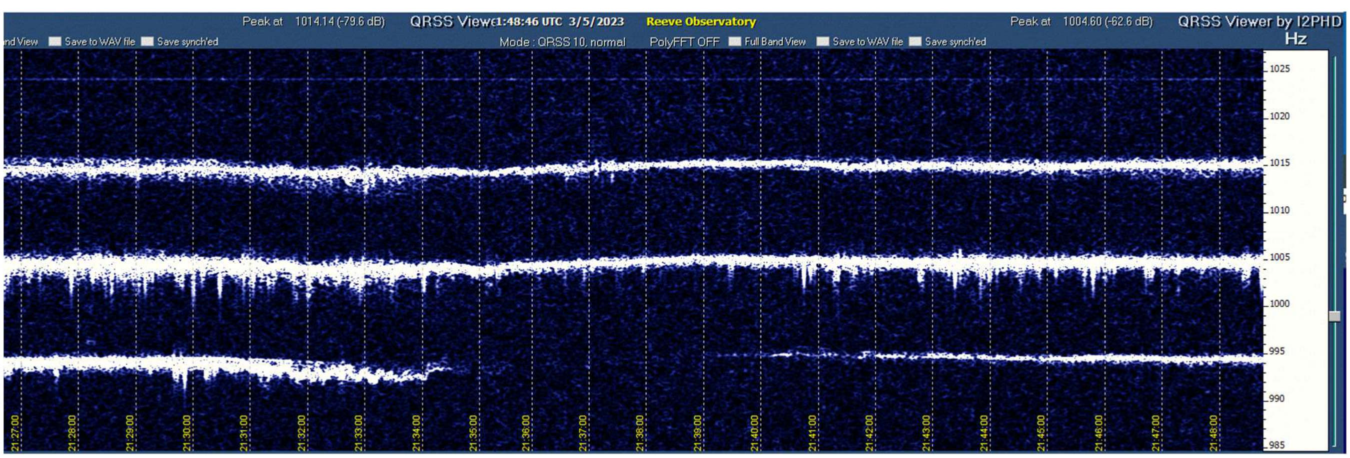

Figure 5 ~ Argo plot for the same time period as the previous figure. Three traces are shown. The lower trace at 995 Hz is the demodulated signal from WWV or WWVH at 15 MHz, and it is seen to blackout at 2134 with partial recovery around 2142 UTC. The middle trace at 1005 Hz is the demodulated signal from WWV or WWVH at 20 MHz. It does not blackout but the signal characteristics do change during the same time period. The upper trace at 1015 Hz is the demodulated signal from WWV at 25 MHz. As with 20 MHz, it does not blackout but there is a slight change in the received signal characteristics. The three receivers that produced the signals for this plot were set to LSB mode and tuned 995, 1005 and 1015 Hz above the carrier frequencies of 15, 20 and 25 MHz, respectively.

3. High Latitudes

Solar flares typically do not affect higher latitudes in the same way as lower latitudes. It is interesting that during winter months at higher latitudes, the absorption is 2x or 3x higher than found under similar conditions during the summer months at those latitudes, and the absorption is much more variable from day to day during winter. At higher latitudes, the absorption from flare radiation is lower because the radiation obliquely penetrates the atmosphere and passes through more of it, and the radiation loses considerable energy before it reaches the D-region (figure 6).

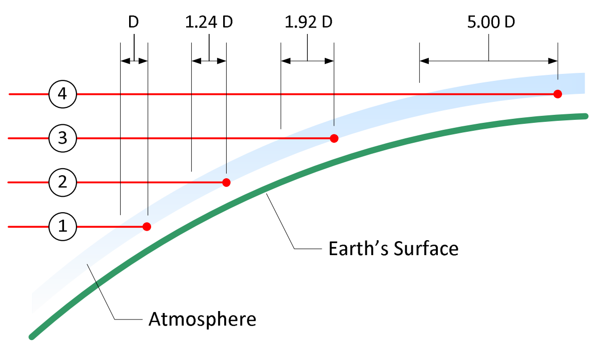

Figure 6 ~Exaggerated effect of incidence angle on radiation intensity received by the D-region. These examples show the Sun's radiation (red lines) hitting the upper atmosphere at arbitrary lower and higher latitudes. At lower latitudes ①, the distance traveled by the radiation through the atmosphere is D, but at higher latitudes ④, the distance traveled is 5 D and much more of the radiation is absorbed before reaching the D-region. Drawing not to scale. Image © 2023 W. Reeve

The relative absorption varies with the solar zenith angle X according to $(\cos X)^n$ where n has been found to vary from 0.7 to 1.0. For example, in the simple case where n = 1, if the Sun's zenith angle is 38° (elevation angle of 52°, which it reaches on the summer solstice at Anchorage, Alaska), the relative absorption is about 79%. If the zenith angle is 75° (15° elevation), the value is much lower at 26%, indicating that the D-region is not nearly as absorptive at the lower elevation angle because the flare's radiation energy is reduced by more atmosphere. It is for this reason that radio blackouts at high latitudes usually are not caused by the x-ray radiation from a flare.

Instead of flare radiation, radio blackouts at high latitudes usually are caused by *Solar Energetic Particle* (SEP) events, also called *Solar Particle Event*, SPE, and *Solar Radiation Storm*. Solar energetic particles consist of protons, mostly from hydrogen and some other atomic nuclei, and electrons ejected by the Sun during a flare and accelerated to near light speed. These particles usually reach Earth in less than an hour.

The geomagnetosphere normally shields the Earth from these protons. However, during geomagnetic disturbances, the interaction between the interplanetary magnetic field (IMF) and Earth's magnetic field allows the protons to easily enter the high latitude region around the geomagnetic pole called the *auroral zone*. The SEPs that are involved have energies ranging from 1 to 200 MeV. By assuming the energy is entirely kinetic, the particle velocities can be calculated with a relativistic kinetic energy calculator. If the protons in question are hydrogen nuclei with a rest mass of 1.66×10^{-27} kg, the corresponding velocities range from about 14×10^6 m s^{-1} for 1 MeV particles to 170×10^6 m s^{-1} for 200 MeV particles, or approximately 5% to 57% of the speed of light.

When the protons collide with the atmospheric particles, they release their energy by stripping electrons from the atoms and molecules, thus increasing the electron density and radio wave absorption at high latitudes. This is called *Polar Cap Absorption*, PCA (figure 7). PCA usually leads to a complete blackout of transpolar radio propagation. The duration of a PCA event can range from several hours to days and depends on the proton flux levels. Studies have shown a close correlation between PCAs and Type IV solar radio noise storms.

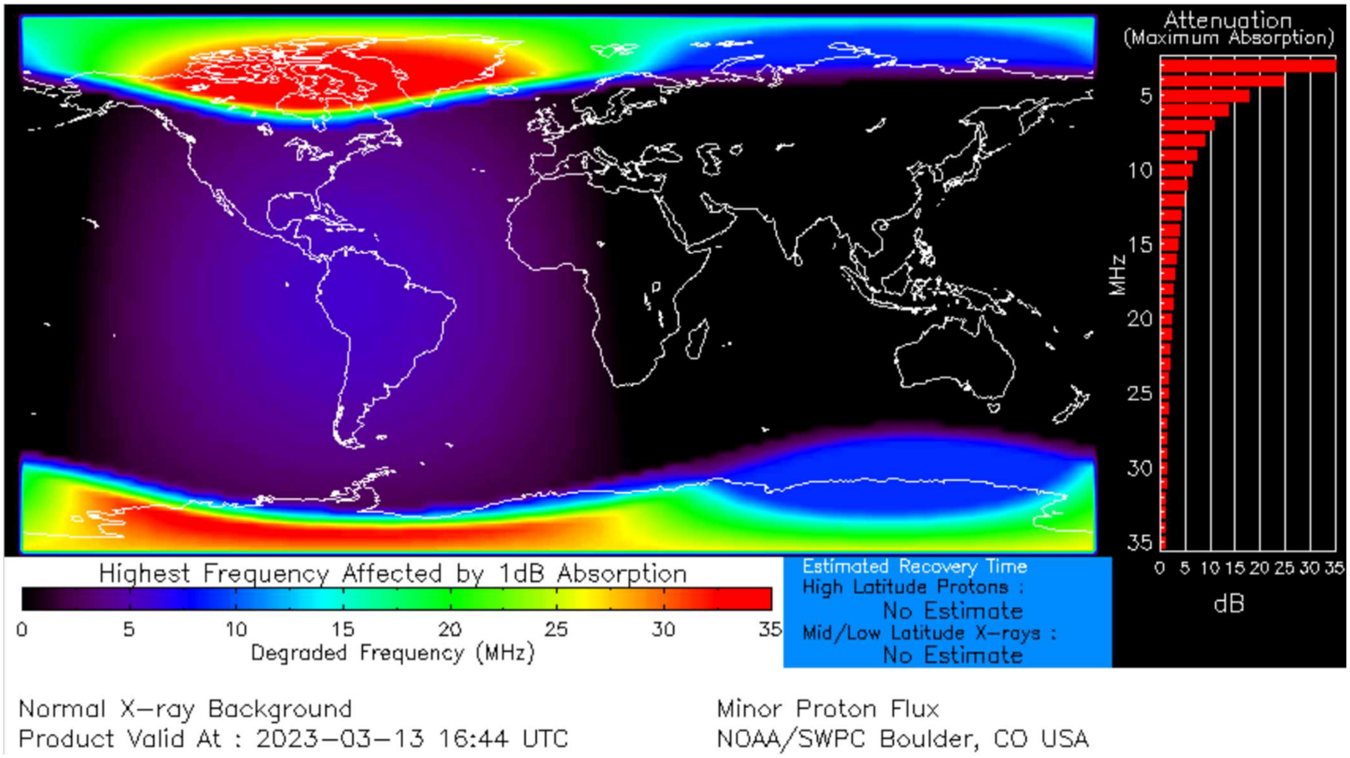

Figure 7 ~ D-RAP image from 13 March 2023 shows the strong absorption at high latitudes caused by an SEP event, which led to a Polar Cap Absorption event. The SEP event was associated with a full-halo CME that erupted on the far-side of the Sun and was first visible in LASCO C2 imagery at 0336 UTC. The SEP required about 1 h to propagate from the Sun to Earth's vicinity. The highest frequencies for 1 dB absorption are shown by the colors in the main panel (absorption at lower frequencies is higher). The histogram on the right shows the absorption in 1 MHz increments at the time of the snapshot. This snapshot at 1644 UTC is representative of the absorption that varied throughout the UTC day. This event had no obvious effect on propagation from WWV or WWVH to Anchorage (Anchorage is below the edge of the absorption region at upper-left) but likely affected transpolar radio paths. Image source: Space Weather Prediction Center

The electron density enhancement from an SEP event depends on several complex factors including the incident proton flux at the top of the atmosphere, the rate at which electrons are produced through ionization and the rate at which the free electrons are subsequently lost by recombination with ions and attachments to other atoms and molecules. All of these depend on the neutral particle and electron densities prior to the event.

The level of geomagnetic disturbance usually determines the extent and duration of a PCA. The 3-hour K-Index, which is determined from ground magnetometers, generally provides a reliable indication of geomagnetic activity. However, in the case of the 13 March 2023 event discussed above, the geomagnetic activity was relatively low throughout the day, possibly because the flare and associated CME that produced the SEP event were on the far side of the Sun and did not directly affect the IMF and its interaction with Earth's magnetic field. This illustrates that solar events and their effects on Earth fall into a statistically *wide* range.

Another example of a PCA event caused by solar energetic particles, or radiation storm, occurred on 8 May 2023 (figure 8). Although the two plots in this figure were taken at 2026 UTC, the event lasted most of that day and for three days afterwards. The upper image shows both the predicted PCA and the coincidental global D-region absorption caused by an M2.3 x-ray flare. The lower image shows the North Pole effects for the same time period. Compare the 8 May plot, which predicted at least 5 dB absorption as high as 31 MHz, with the previous plot for 13 March, which predicted 5 dB of absorption at only 11 MHz.

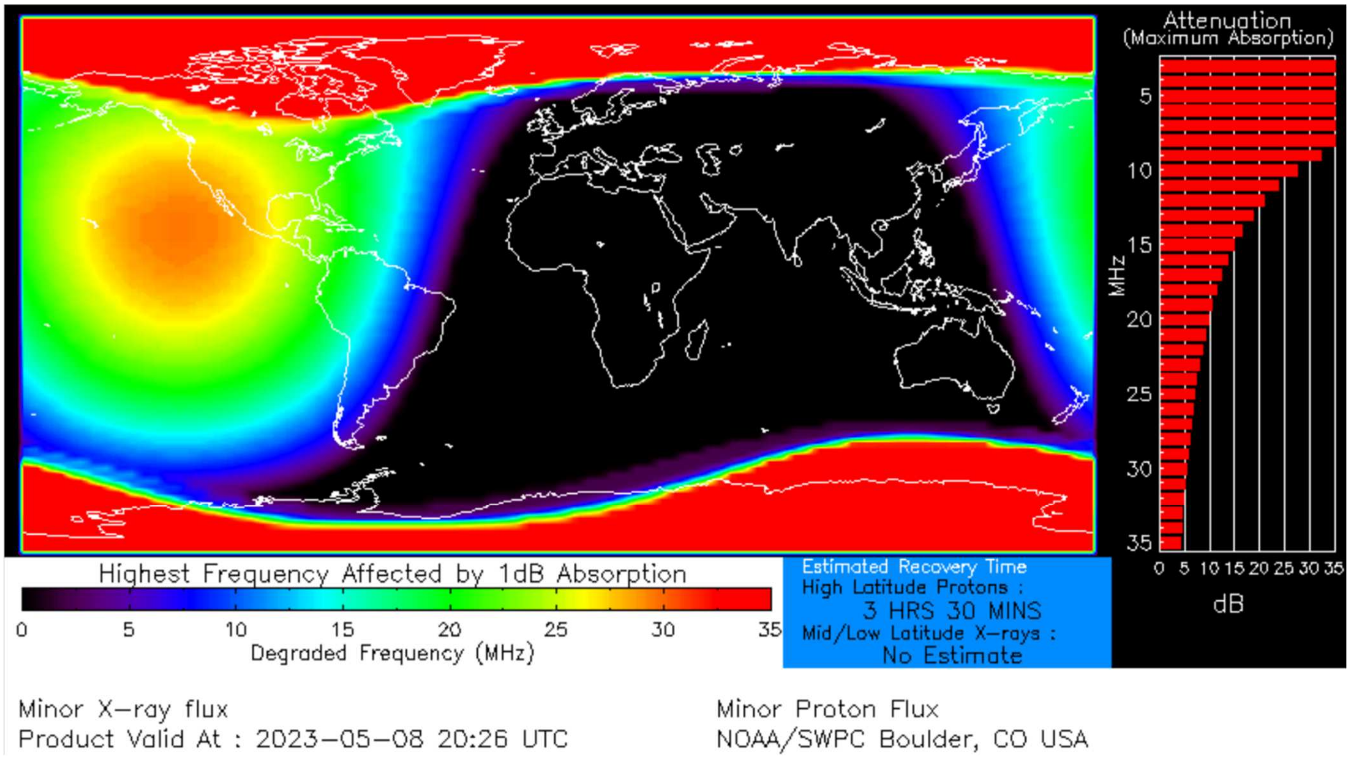

Figure 8.a ~ D-RAP image from 8 May 2023 shows the strong absorption at high latitudes caused by an SEP event, which led to a Polar Cap Absorption event. This snapshot at 2026 UTC is representative of the PCA that persisted until mid-UTC day on 11 May. This event had no obvious effect on propagation from WWV or WWVH to Anchorage. Image source: Space Weather Prediction Center

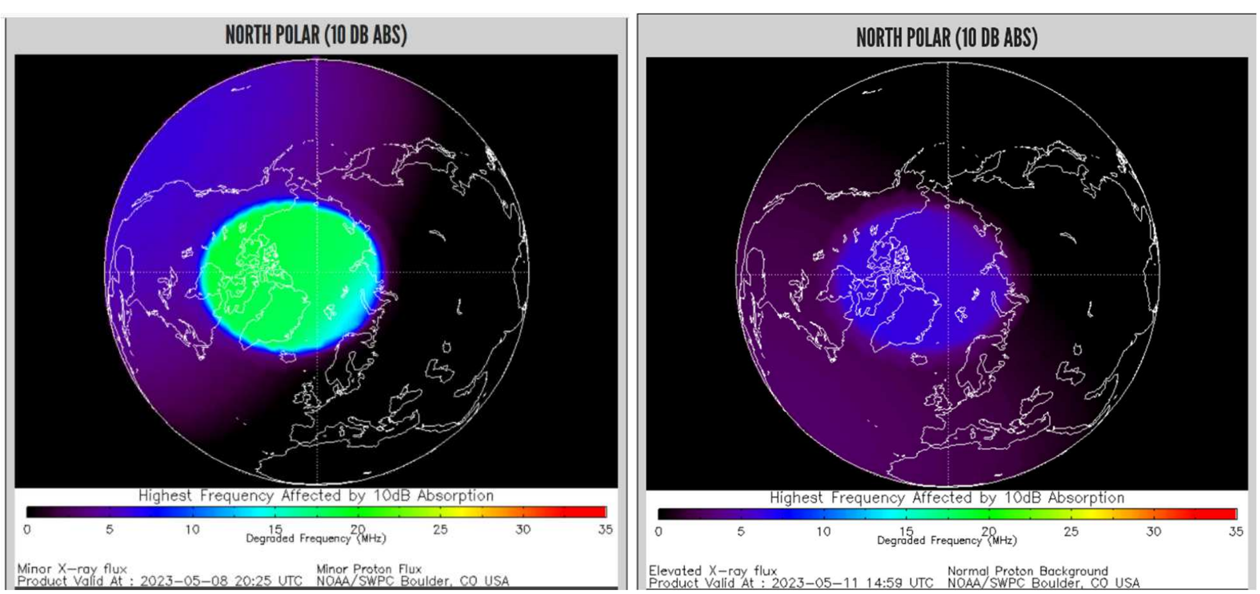

Figure 8.b ~ Left: DRAP plot of absorption at the north polar region resulting from the SEP event of 8 May 2023 and predicted at the same time as the global plot. Note that the polar plot differs from the global DRAP plots in that the basic absorption level is 10 dB for the polar plot and 1 dB for the global plot. In the event shown here, 10 dB of absorption was predicted for approximately 22 MHz. Lower frequencies would incur higher absorption. Right: DRAP plot just after mid-UTC day on 11 May as the radiation storm's effects were subsiding. Image source: Space Weather Prediction Center

The 8 May flare coincidentally produced sudden frequency deviations starting just after 2019 UTC and lasting for several minutes (figure 9). SFDs occur when the radio propagation path length is abruptly changed as the electron density in the ionosphere is enhanced by a strong flare and the reflection region is rapidly moved upward or downward. Although a radio blackout was predicted by the D-RAP program for the date shown, the only effects observed at 15 and 20 MHz at Anchorage were the SFDs.

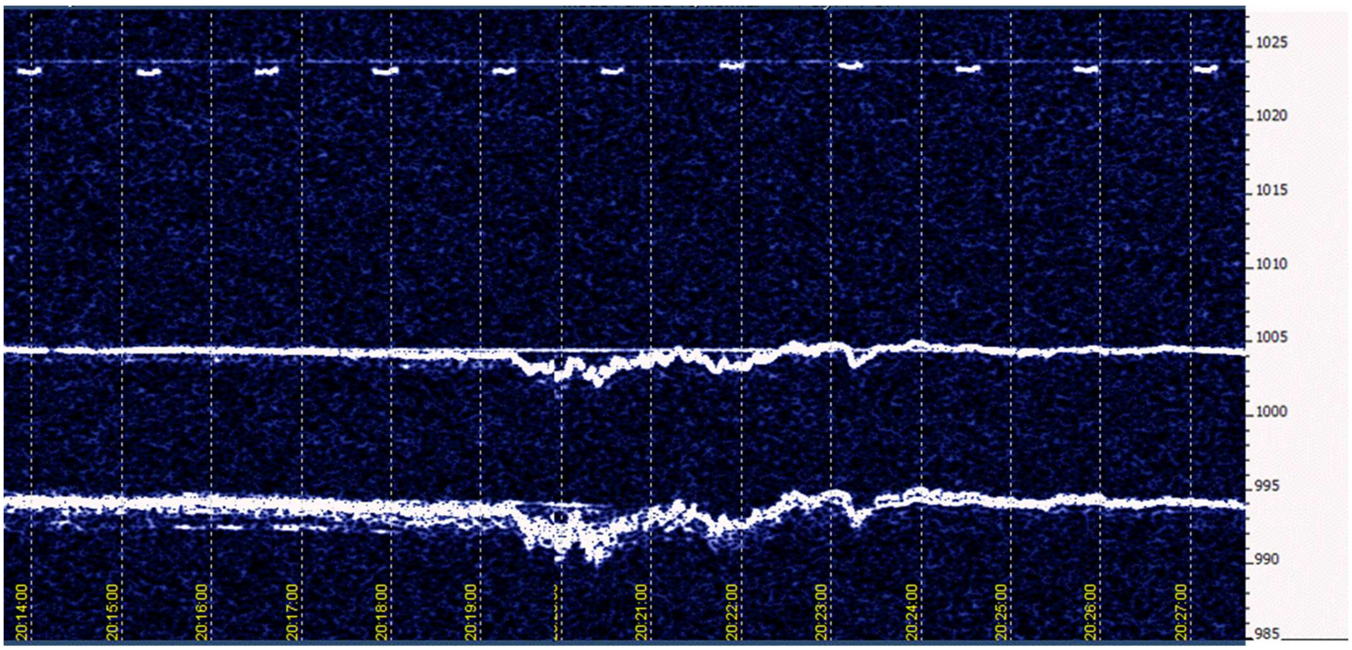

Figure 9 ~ Argo plot showing the demodulated signals at 15 MHz (lower trace at 995 Hz) and 20 MHz (middle trace at 1005 Hz). If signals had been received at 25 MHz, there would be an upper trace at 1015 Hz but 25 MHz propagation to Anchorage was unsupported by the ionosphere at the time. The dashed traces near the top are spurious signals. The sudden frequency deviations resulting from the M2.3 x-ray flare, which began at 2011 UTC and peaked at 22025, are not particularly severe (about 4 Hz at 15 MHz) but are long-lasting.

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4. References

[Davies] Davies, K., Ionospheric Radio, Institution of Engineering and Technology, United Kingdom, 1990 (earlier versions are less expensive)

[Sauer] Sauer, H., Wilkinson, D., Global Mapping of Ionospheric HF/VHF Radio Wave Absorption Due to Solar Energetic Protons, 2008, https://doi.org/10.1029/2008SW000399

{SWPC} Space Weather Prediction Center, Radio Dashboard: https://www.swpc.noaa.gov/communities/radio-communications

{Typinski} A Solar Radio Burst at Night, observed by Dave Typinski in Florida and reported in the 23 March 2023 issue of Spaceweather.com:
https://spaceweather.com/archive.php?view=1&day=23&month=03&year=2023

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