COLLAGE 2023

Lecture 08: Space Weather Impact on Radio Waves

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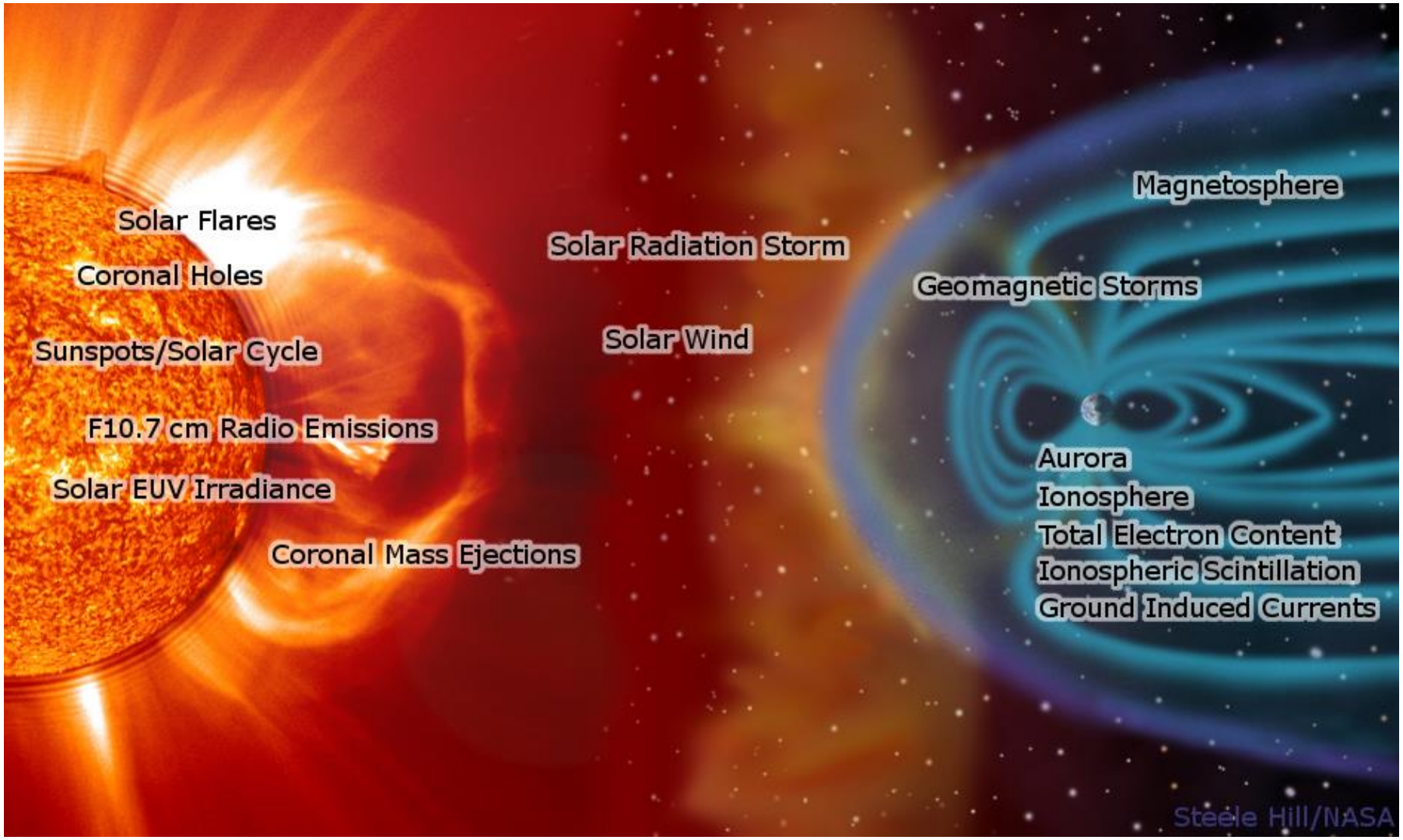
Source materials partially from Jade Morton, Thomas Berger, and Robert Marshall

Overview

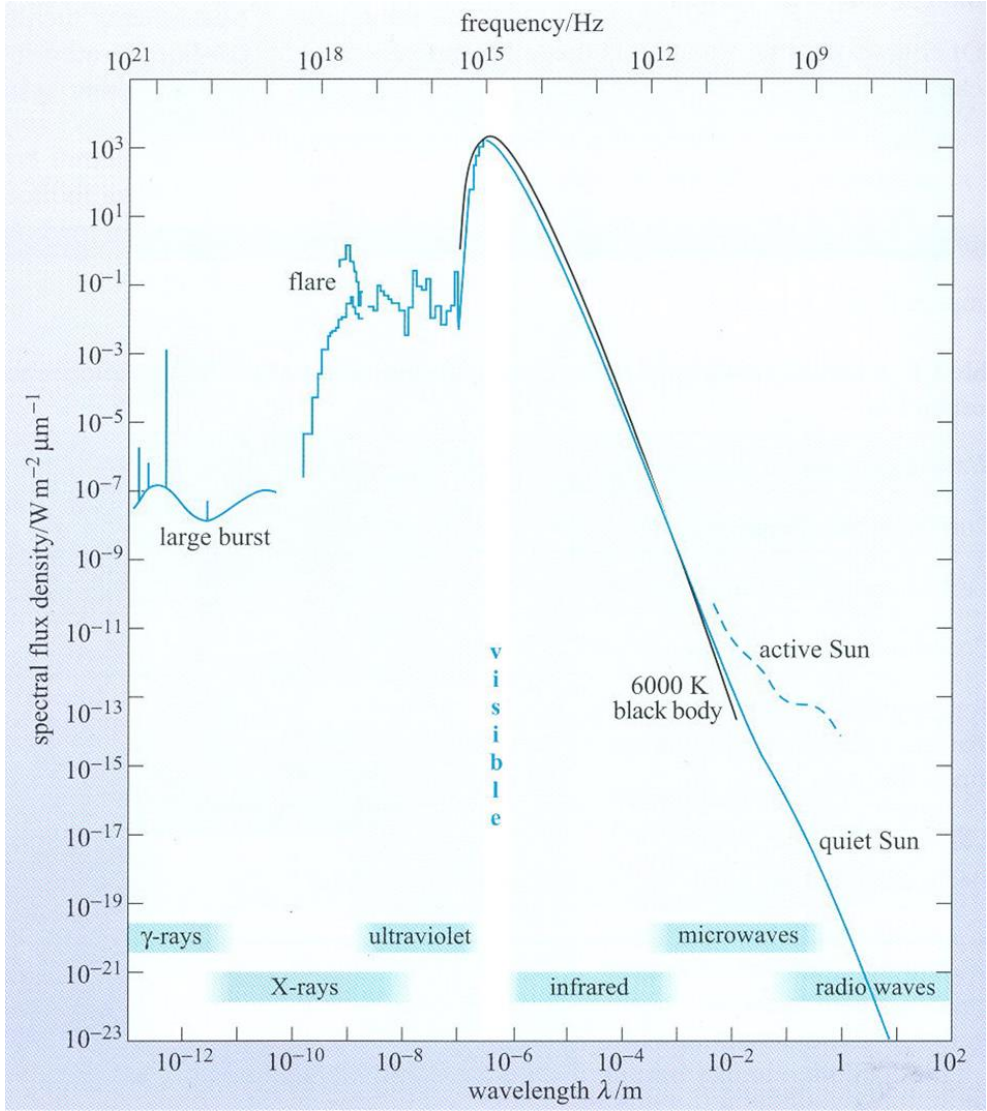


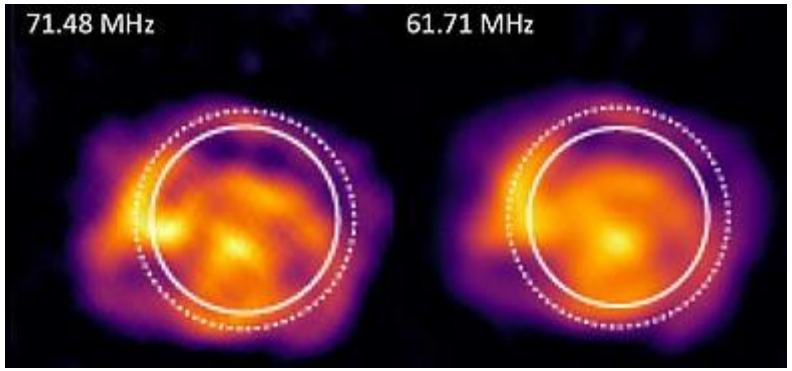
- **Solar radio emission interference**
- **Ionospheric effects and radio wave propagation**

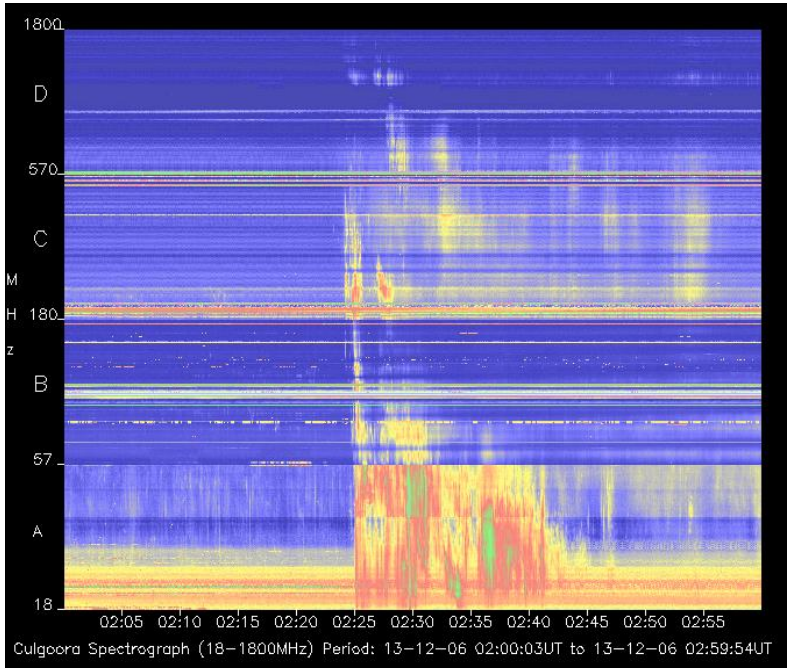
- HF communications
- Satellite Navigation (GNSS)
- Others radio systems

- **Mitigations**

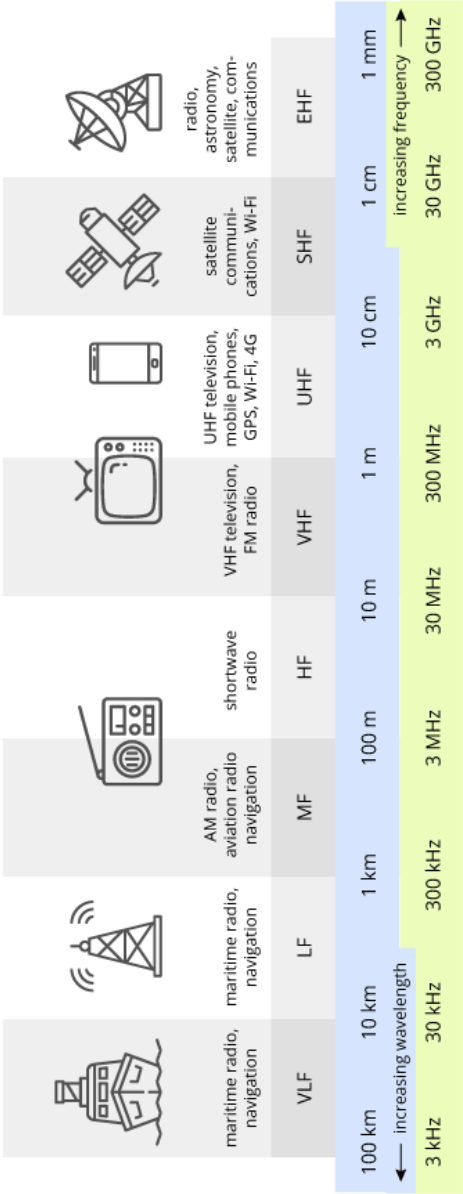
Solar Radio Emission



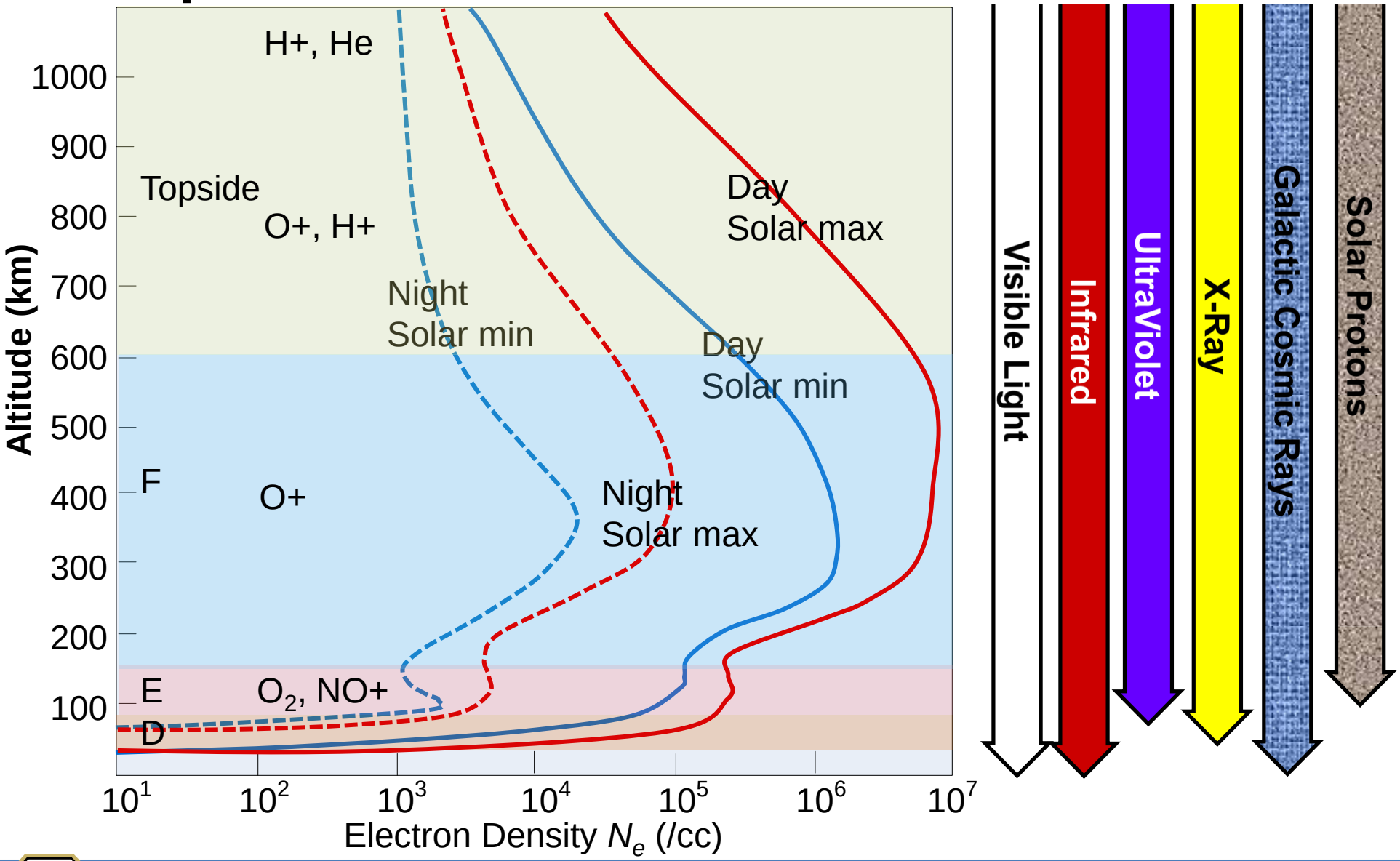




13-Dec-2006 solar flare radio spectrum



Atmosphere Ionization



Radio Wave Propagation in Plasma (or the Ionosphere)

Plasma Oscillation & Frequency

The plasma frequency is the frequency at which the electrons in the plasma naturally oscillate relative to the ions and typically has values between 2 - 20 MHz for conditions in Earth's ionosphere.

$$f_p = \frac{1}{2\pi}\sqrt{\frac{N_e e^2}{m_e \varepsilon_0}}$$

vacuum permittivity

EM wave into plasma, ignore B

$$v_p = \frac{c}{n} = \frac{c}{\sqrt{\varepsilon_r}}$$

$$n = 1 - \frac{f_p^2}{f^2}$$

Index of Refraction

Simplified Appleton-Hartree Equation

$$X = \left(\frac{f_p}{f}\right)^2 \ll 1$$

$$Y = \frac{f_g}{f} \ll 1$$

$$n_\varphi = 1 - \frac{X}{1 - \frac{Y^2 \sin^2\theta_B}{2(1-X)} \pm \sqrt{\frac{Y^4 \sin^4\theta_B}{4(1-X)^2} + Y^2\cos^2\theta_B}}$$

$$n_\varphi \approx 1 - \frac{X}{2} \pm XY|\cos\theta_B| - \frac{1}{4}X\left(\frac{X}{2} + Y^2(1+\cos^2\theta_B)\right)$$

Vacuum | 2nd order | 3rd order

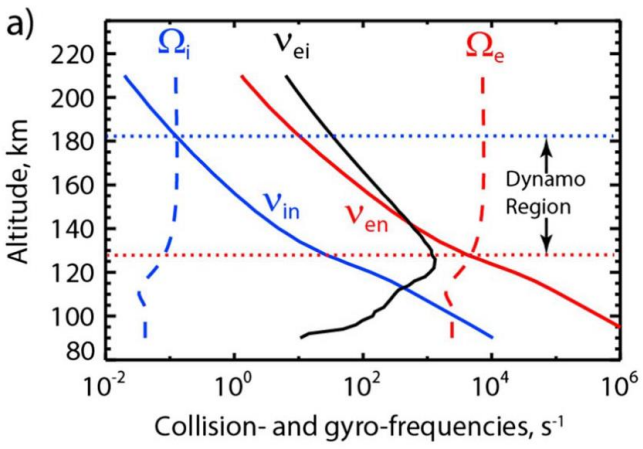
$$\boxed{n_j \gg 1 - \frac{X}{2} \gg 1 - \frac{e^2}{2m\varepsilon_0 f^2}N_e = 1 - 40.3\frac{N_e}{f^2}}$$

$$f_g = \frac{|e|B}{2\pi m_e} \approx 28\times10^9 B \approx 1MHz$$

Radio Wave Propagation in Plasma (or the Ionosphere)

D Region Absorption

Electrons randomly collide with neutral; Radio wave energy converts to electron kinetic energy and then to neutral thermal energy (i.e., neutrals are “heated”)

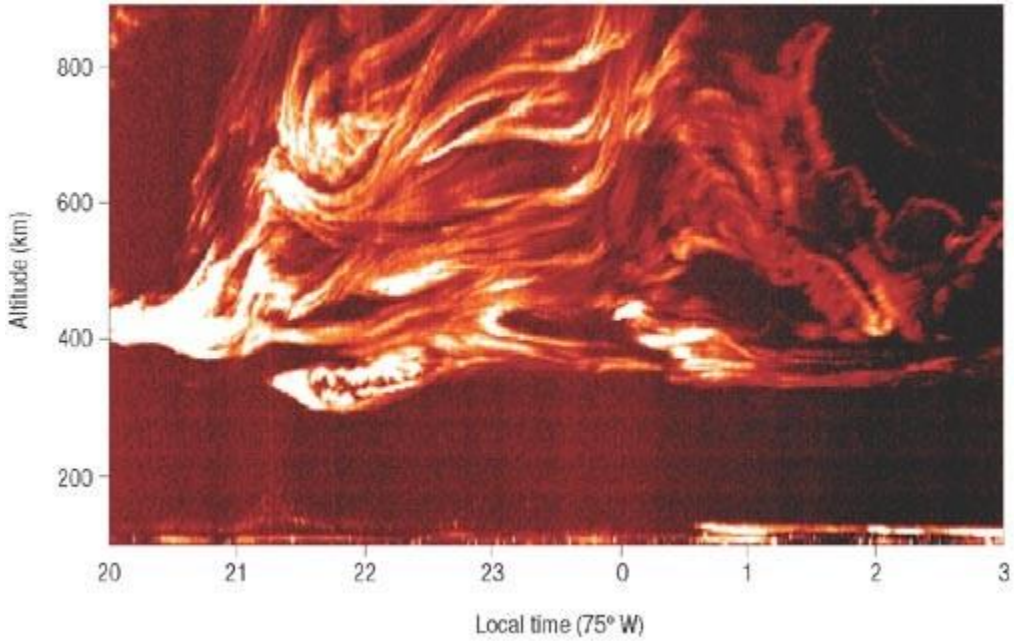


$$\frac{dA}{dl} = 4.6 \times 10^{-5} \frac{n_e v}{(2\pi f)^2}$$

$$\langle \nu_{e,\mathrm{O}} \rangle = 1.37 \times 10^{-16} N(\mathrm{O}) \left(1 + 3.32 \times 10^{-4} \mathrm{T_e}\right) \mathrm{T_e^{\frac{1}{2}}}$$

$$\langle \nu_{e,\mathrm{N_2}} \rangle = N(\mathrm{N_2}) \left(4.02 + 2.37 \left(1 - 1.54 \times 10^{-4} \mathrm{T_e}\right) \mathrm{T_e}\right) \times 10^{-17}$$

Wave Diffraction/Scintillation

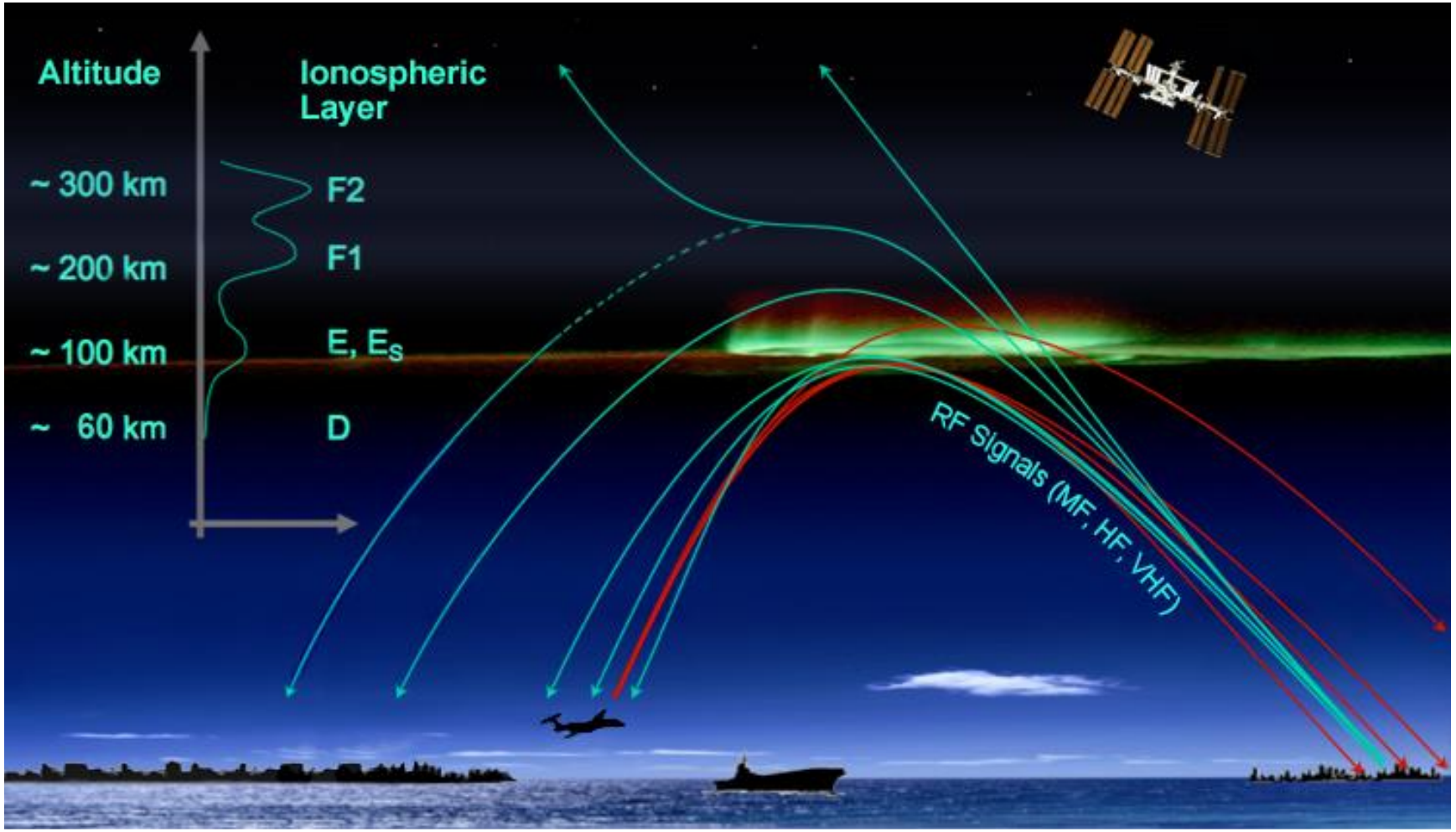


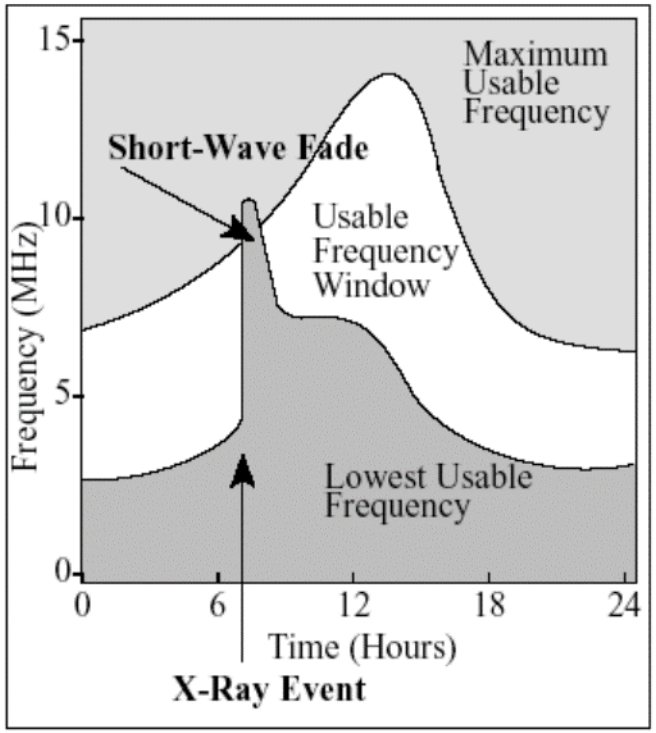
Height-time-SNR map of ionospheric irregularities observed in the E and F regions by the Jicamarca radar

Over-the-horizon Radar/Radio Communication

HF, located between 3MHz and 30MHz

$$f_p = \frac{1}{2\pi}\sqrt{\frac{N_e e^2}{m_e \varepsilon_0}}$$



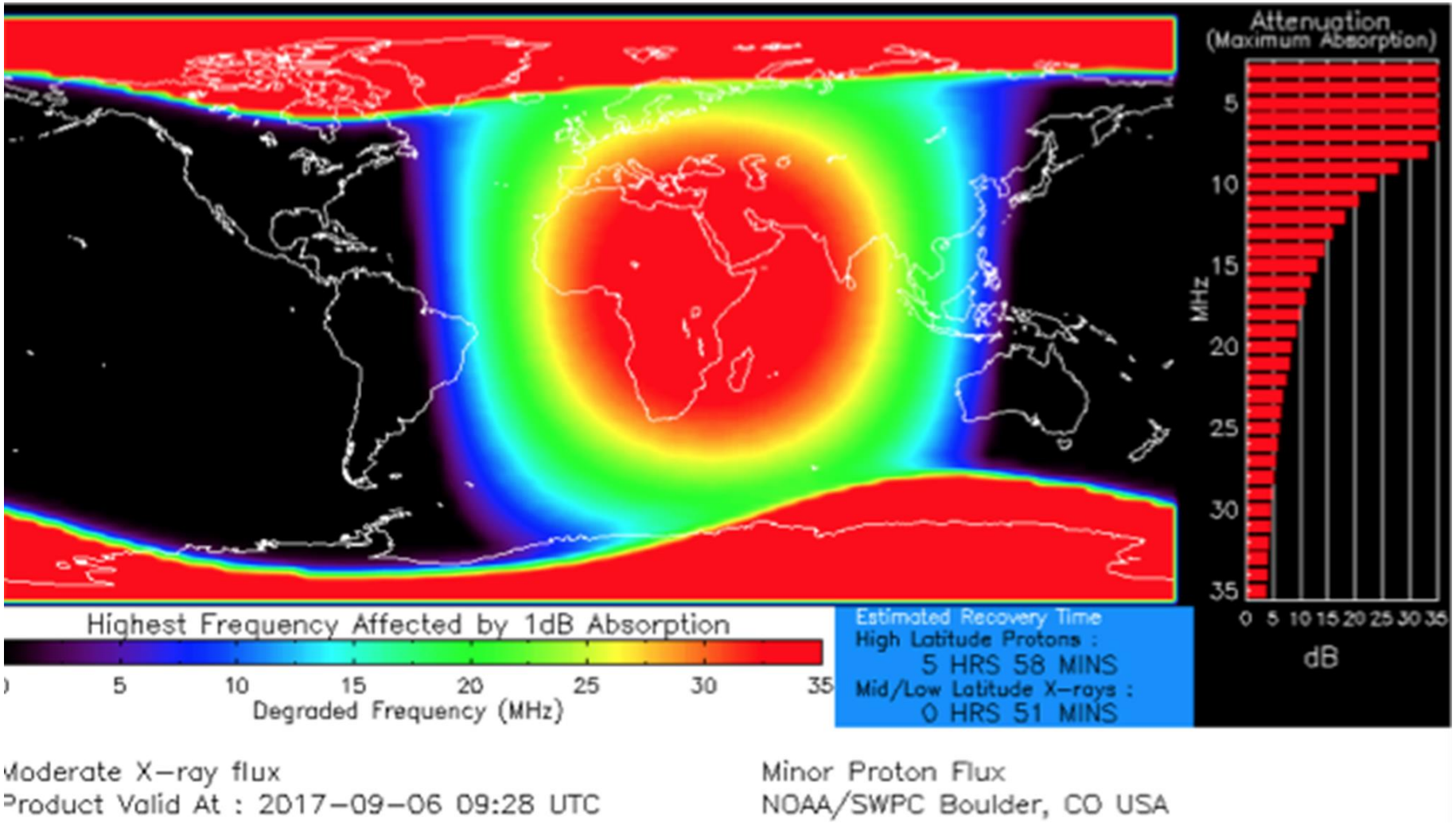


$$\frac{dA}{dl} = 4.6 \times 10^{-5}\frac{n_e \upsilon}{(2\pi f)^2}$$

$$\langle \nu_{e,O} \rangle = 1.37 \times 10^{-16} N(O)\left(1 + 3.32 \times 10^{-4} T_e\right) T_e^{\frac{1}{2}}$$

NOAA SWPC D-region Absorption Prediction

HF, located between 3MHz and 30MHz

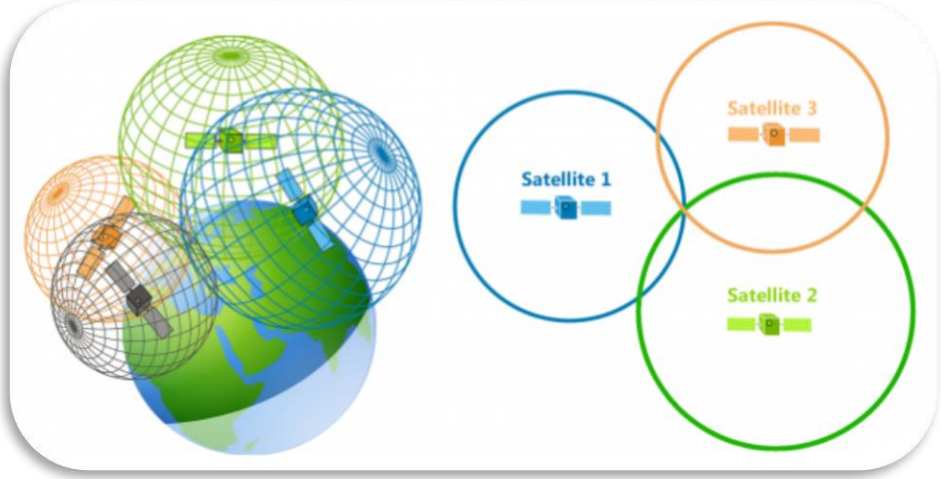


Global Navigation Satellite Systems (GNSS)

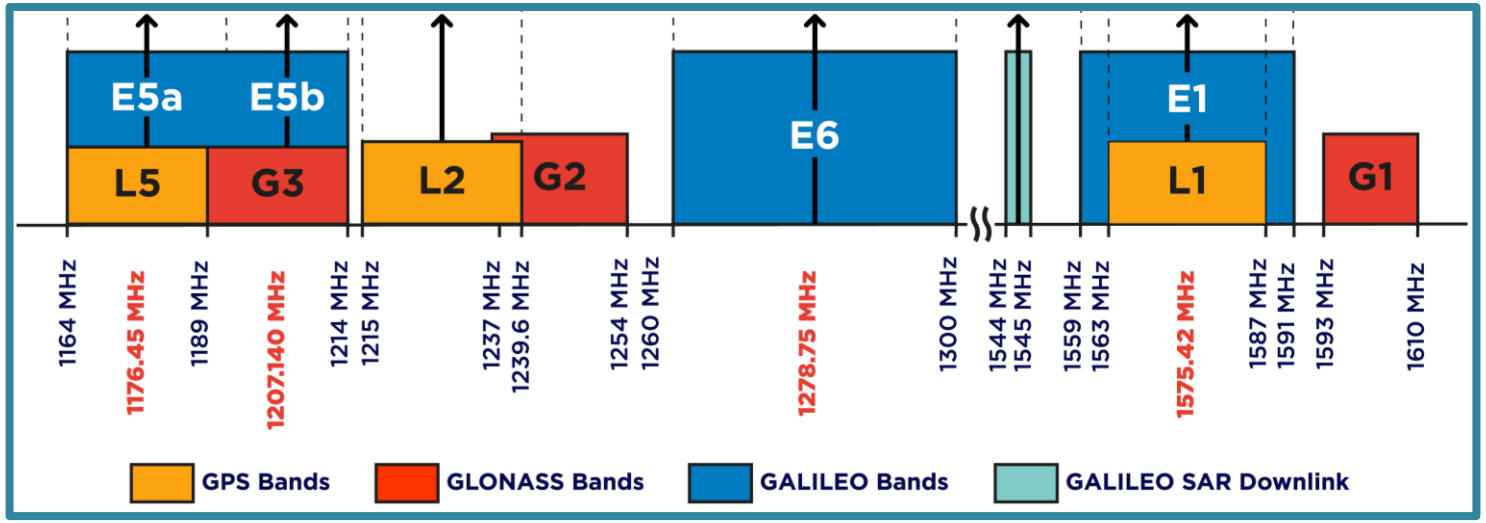
- **US Global Positioning System**
- Russian GLONASS
- European Galileo
- Chinese BeiDou

What does GNSS offer?

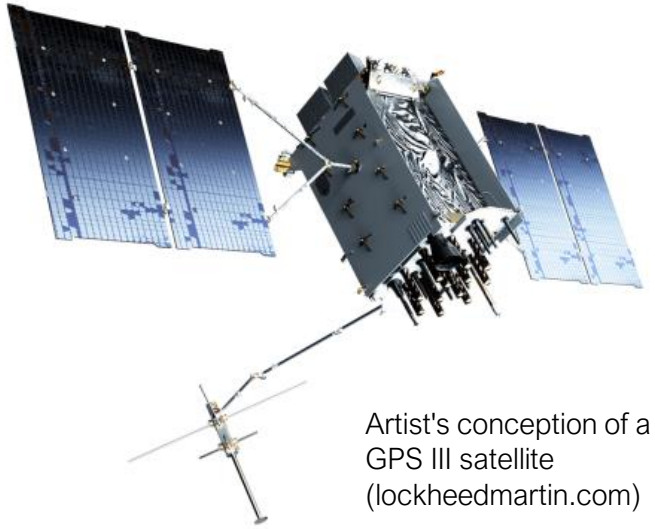
- **P**osition
- **N**avigation
- **T**iming



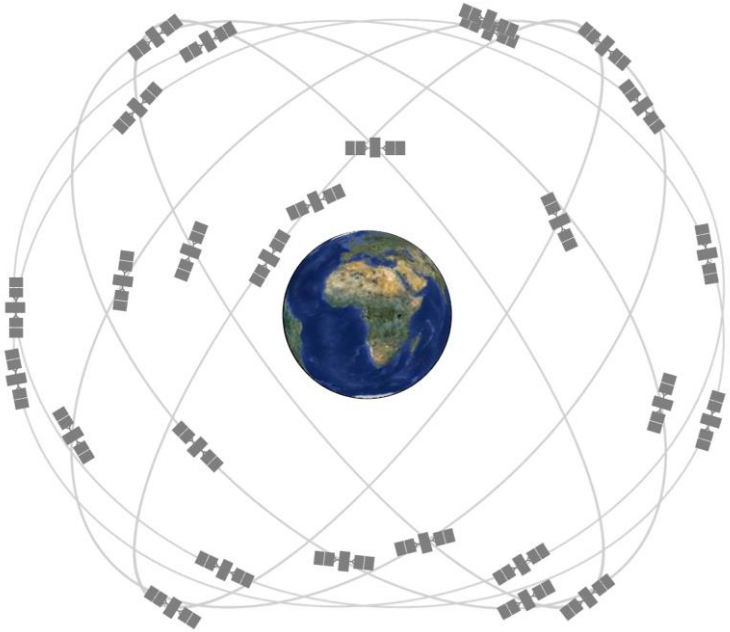
Trilateration with GNSS. Courtesy: gisgeography.com



GNSS frequency bands. Courtesy. tualcom.com



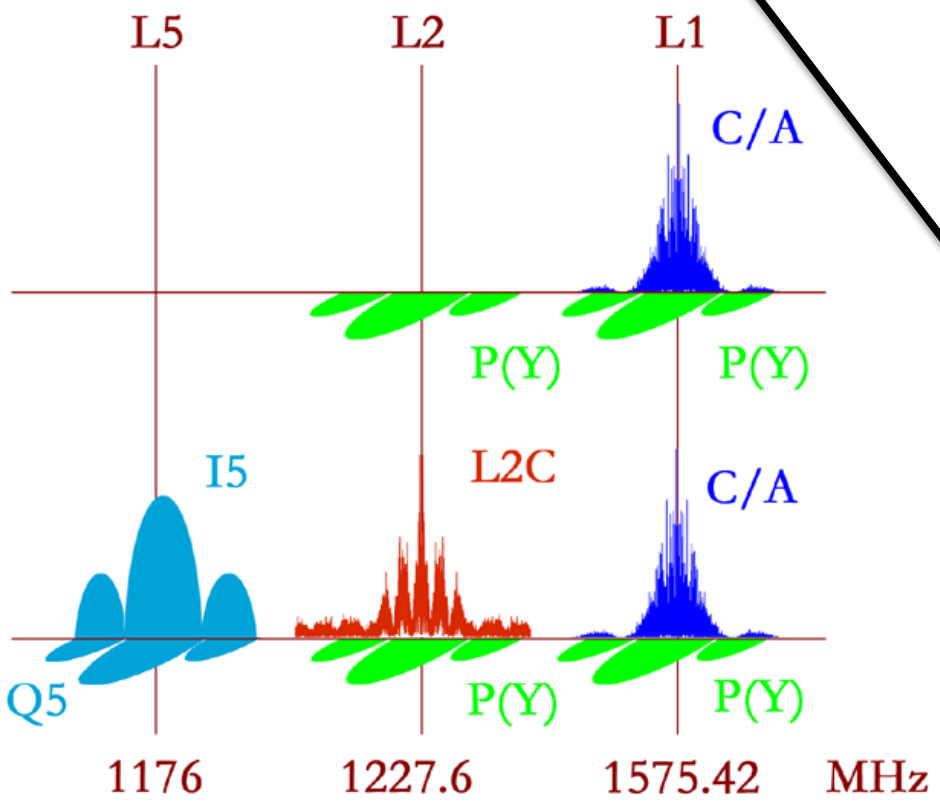
Artist's conception of a GPS III satellite (lockheedmartin.com)



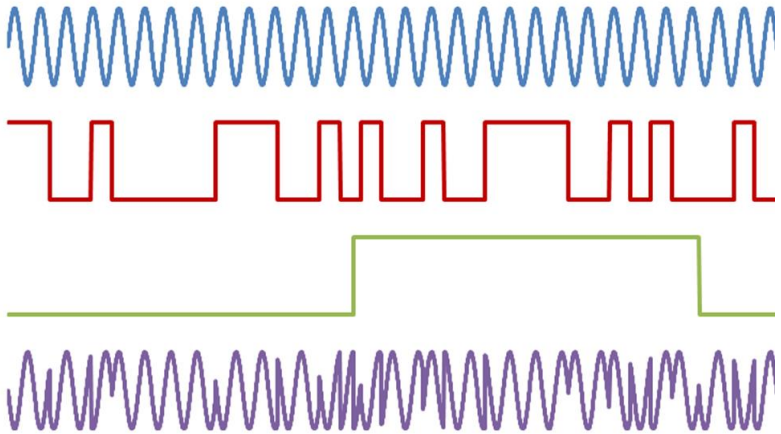
GPS Constellation (gps.gov)

GPS Signal and Measurements

The key to **Trilateration** is **RANGE**, which is from the GNSS **Radio Signal**.

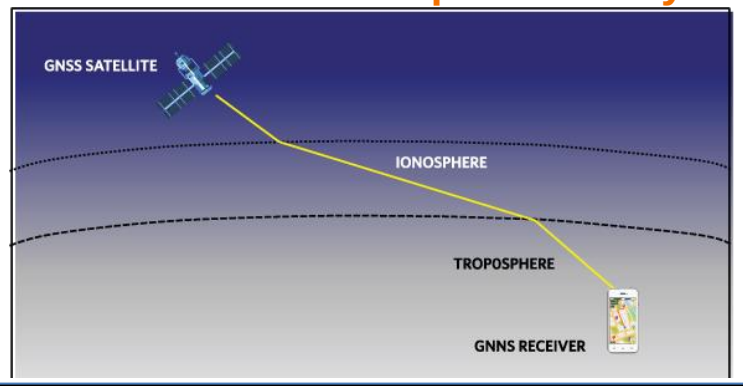


$$\boldsymbol{S_{L1}}(t) = \sqrt{P_c}\, C(t)\, D(t)\ \cos(2\pi f_{L1} t + \emptyset)\text{+others}$$

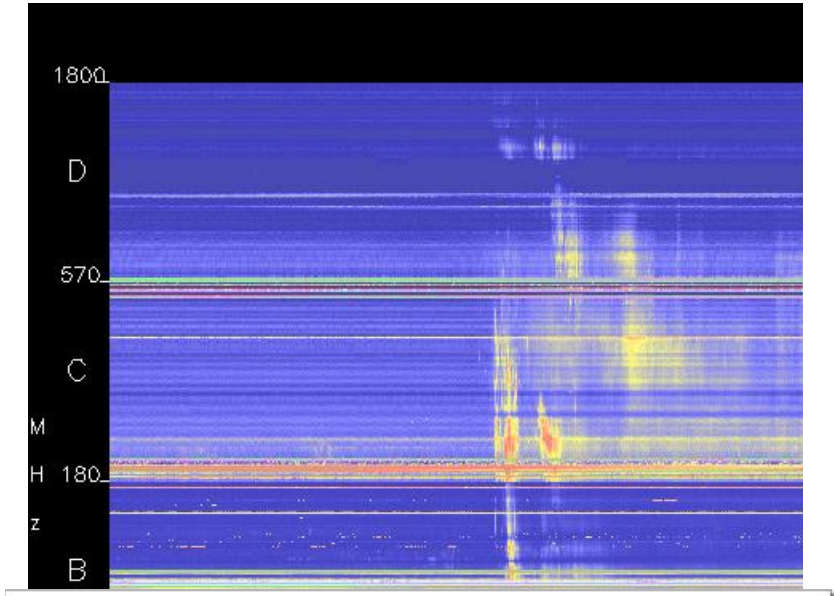


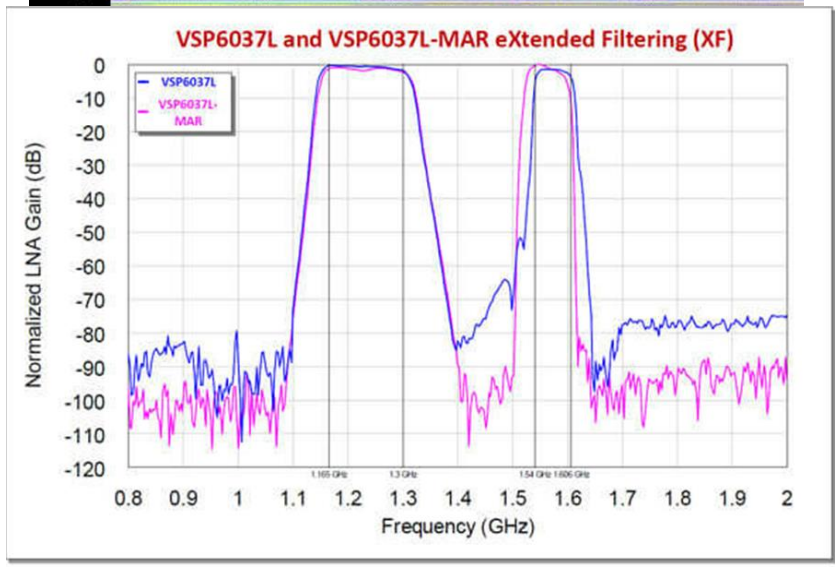
$$\rho^i_{L1}(t) = \left|\vec{r}_{\mathrm{Rx}}(t) - \vec{r}^{\,i}_{\mathrm{Tx}}(t)\right| + b_{\mathrm{Rx}}(t) - b^i_{\mathrm{Tx}}(t) + \underline{I(\mathrm{t})} + T(\mathrm{t}) + \varepsilon(\mathrm{t})$$

Ionospheric Delay



How does Solar Flare/Radio Burst impact GPS/GNSS





Radio Signal:

$$\boldsymbol{S_{L1}}(t) = \sqrt{P_c}\, C(t)\, D(t)\ \cos(2\pi f_{L1} t + \emptyset) + \text{others}$$

"Direct" Impact

$$+ \int \sqrt{P(f)} \cos(2\pi f t + \emptyset_j) df$$

Range:

$$\rho_{L1}^{i}(t) = \left|\vec{r}_{\mathrm{Rx}}(t) - \vec{r}_{\mathrm{Tx}}^{\,i}(t)\right| + b_{\mathrm{Rx}}(t) - b_{\mathrm{Tx}}(t) + \underline{I(\mathrm{t})} + T(\mathrm{t}) + \varepsilon(\mathrm{t})$$

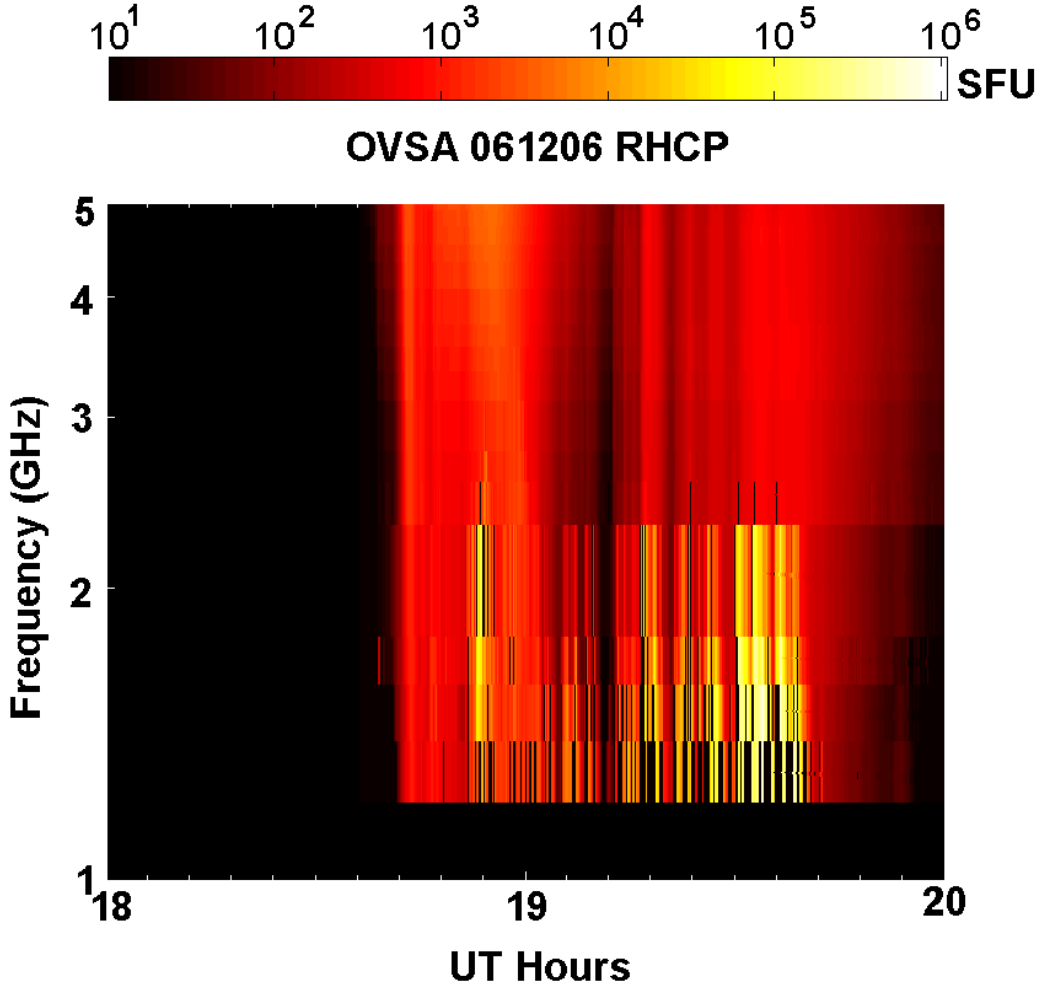
Ionospheric Delay

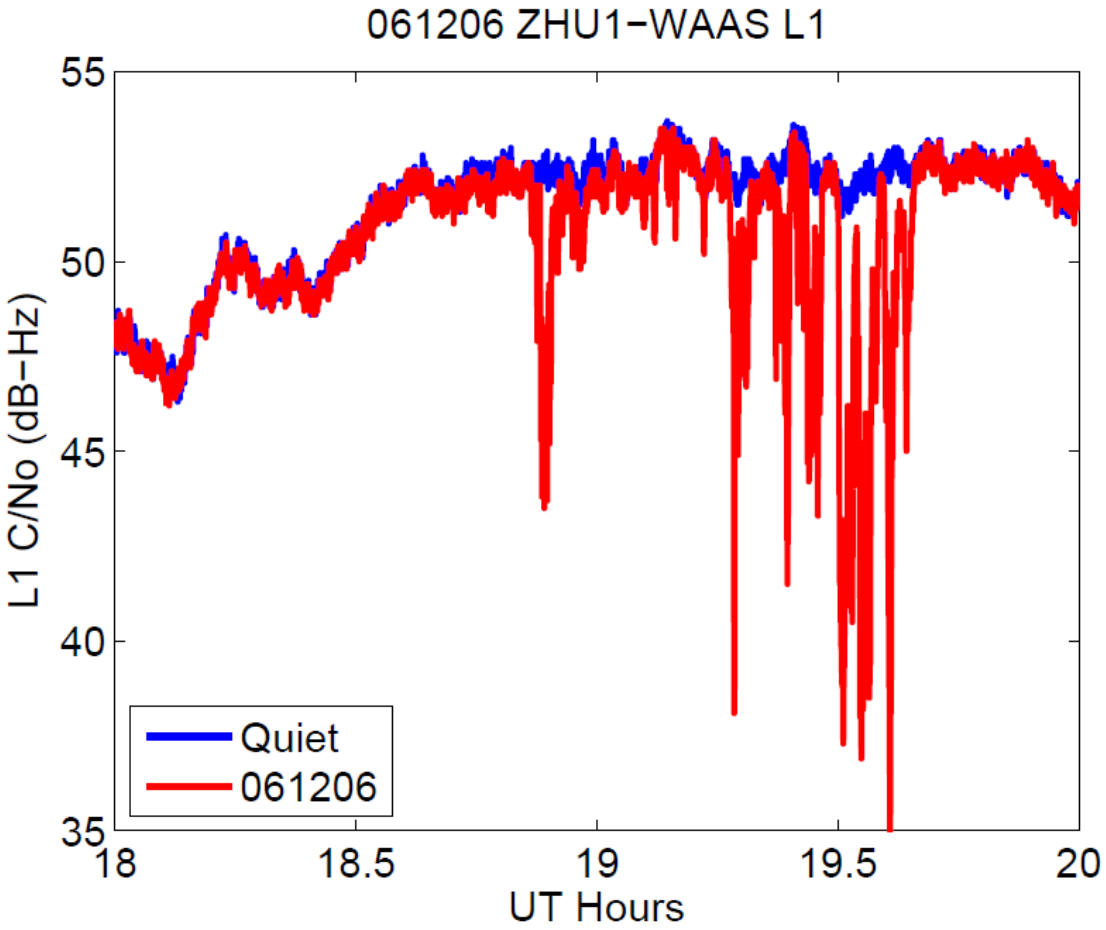
"Indirect" Impact

Enhanced Ionospheric Effects:

- **Refraction -> increased $I(\mathrm{t})$**
- **Diffraction -> Scintillation!**

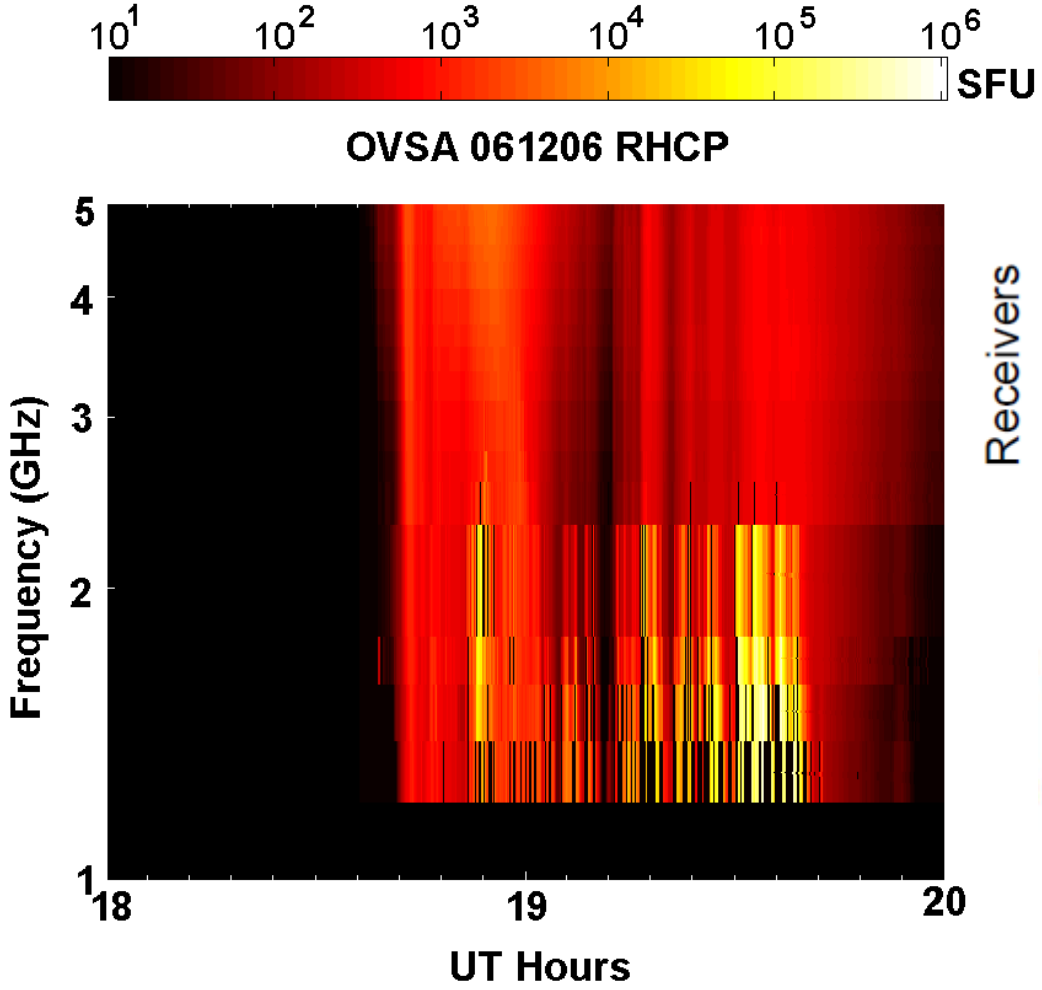
Example of "Direct" Impact on GPS/GNSS

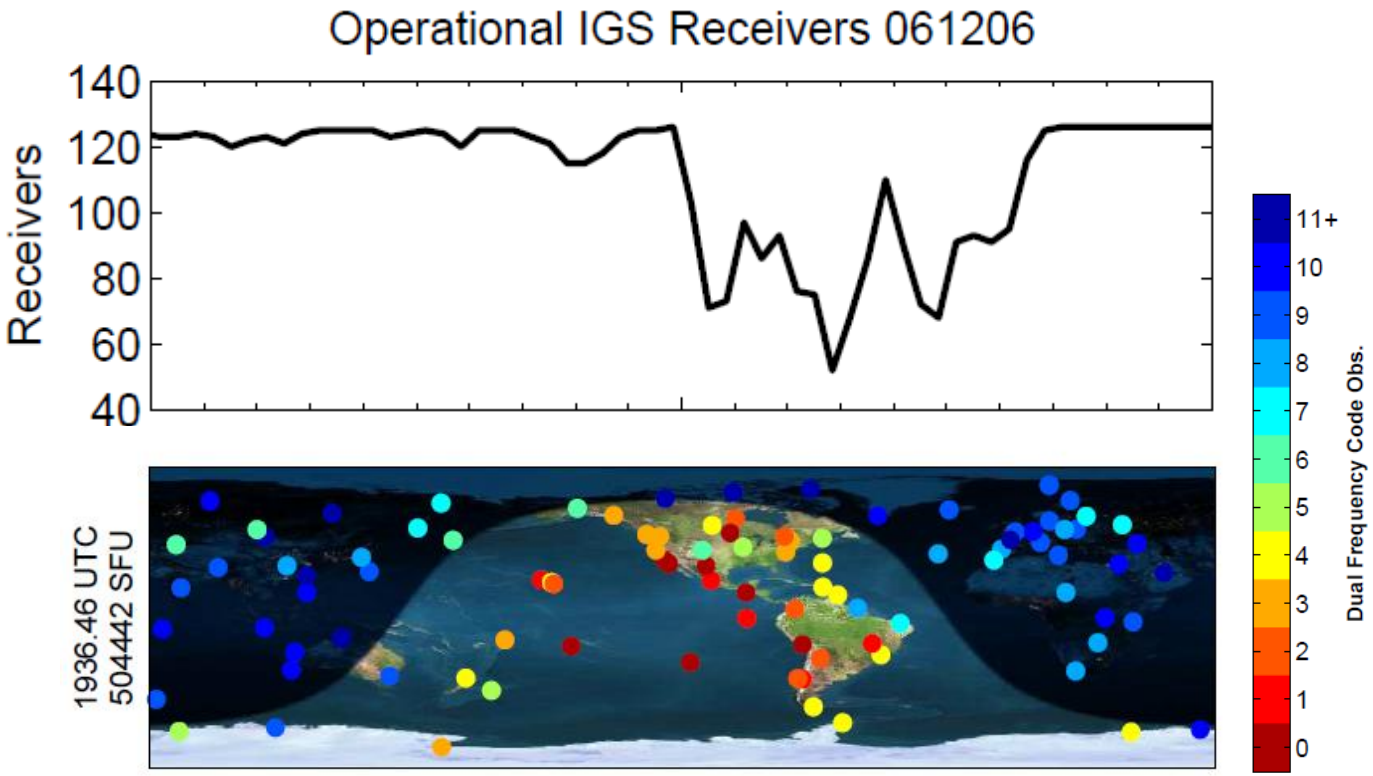




Left: Solar radio burst flux density on 6 December 2006 as measured at the Owens Valley Solar Array.
Right: Response of a GPS receiver to the solar radio burst. The red line corresponds to C=N0 on 6 December 2006 and the blue line corresponds to the previous sidereal day. Cerruti et al. (2007).

Example of "Direct" Impact on GPS/GNSS

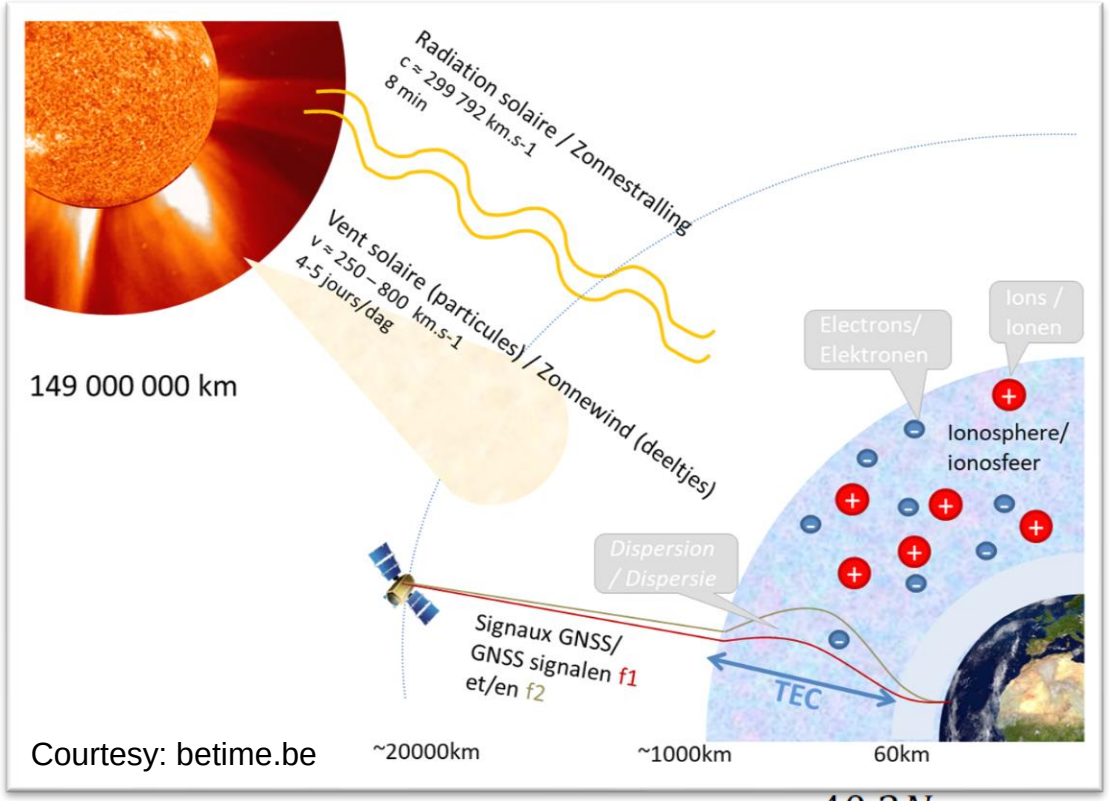




Left: Solar radio burst flux on 6 December 2006 as measured at the Owens Valley Solar Array. Cerruti et al. (2008).
Right: IGS GNSS Network on December 6, 2006. Cerruti et al. (2007).

Solar Flare "Indirect" Impact on GPS/GNSS

Ionospheric Refraction



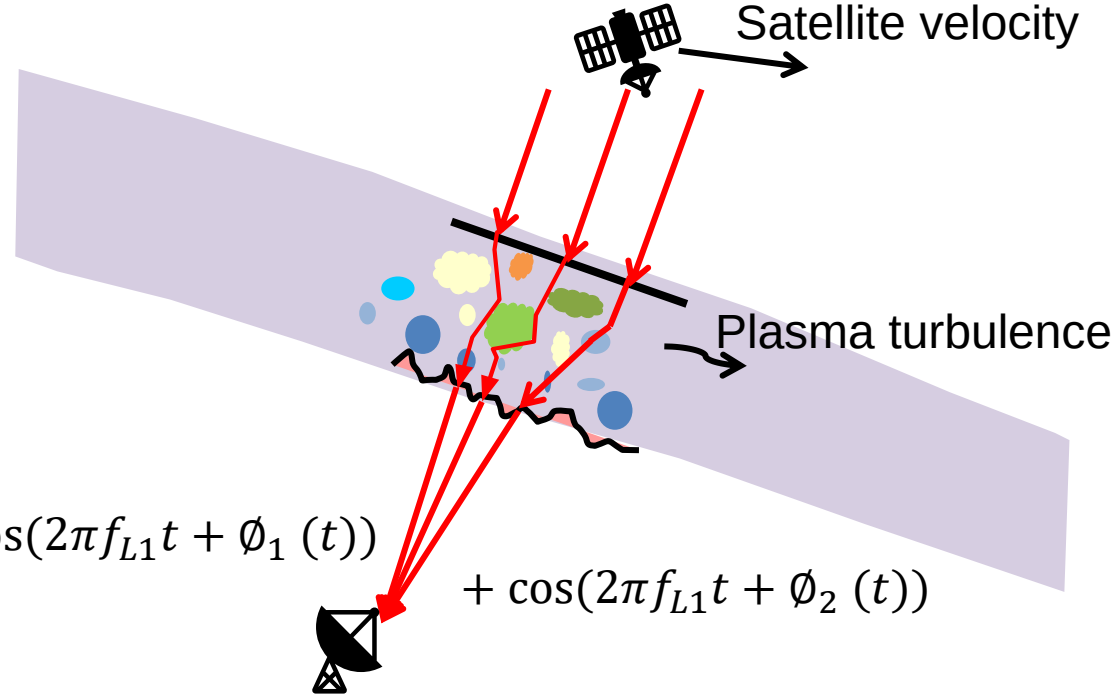
Courtesy: betime.be

Ionosphere Refractive Index $n_p = 1 - \frac{40.3 N_e}{f^2}$

Simplified from Appleton-Hartree equation.

Ionospheric Delay: $I = \frac{40.3}{f^2} \int_S^R Ne\, dl = \frac{40.3}{f^2} TEC$

Ionospheric Scintillation



$$\cos(2\pi f_{L1} t + \emptyset_1(t)) + \cos(2\pi f_{L1} t + \emptyset_2(t))$$

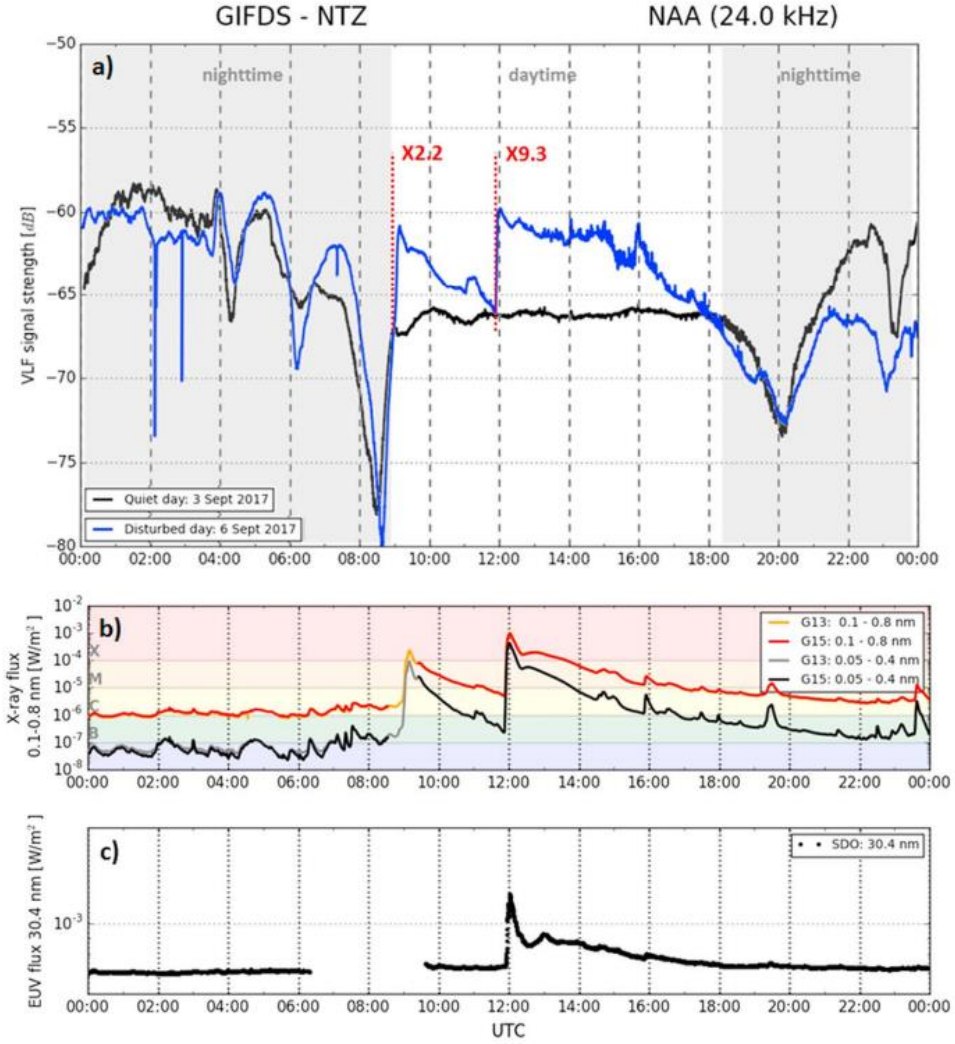
$$= 2\cos\left(2\pi f_{L1} t + \frac{\emptyset_1(t) + \emptyset_2(t)}{2}\right)\cos\left(\frac{\emptyset_1(t) - \emptyset_2(t)}{2}\right)$$

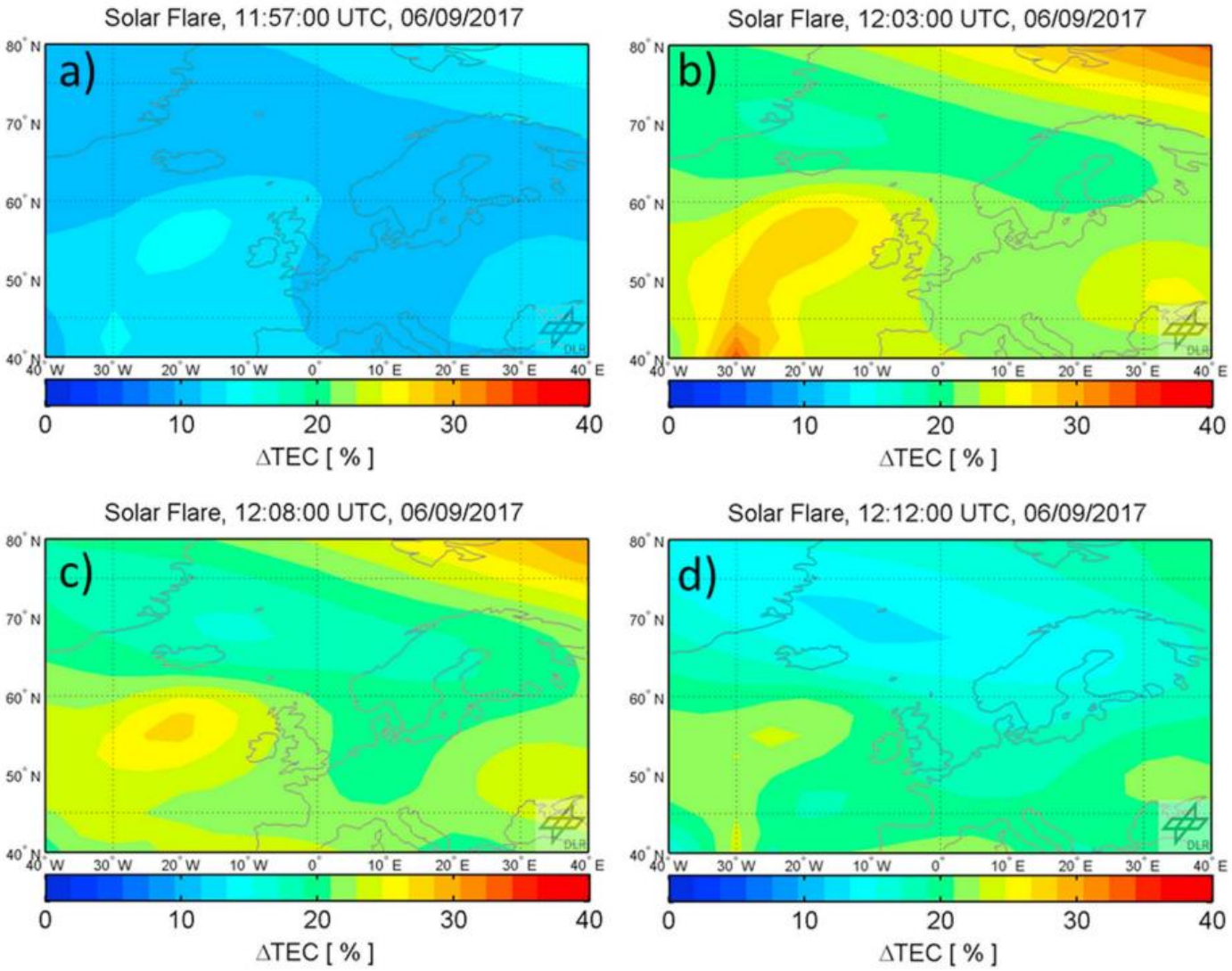
- Rate of TEC Index (ROTI)

$$ROTI = \sqrt{E\left[\frac{|TEC(t+\delta t) - TEC(t)|^2}{\delta t^2}\right]}$$

Example of “Indirect” Impact on GPS/GNSS

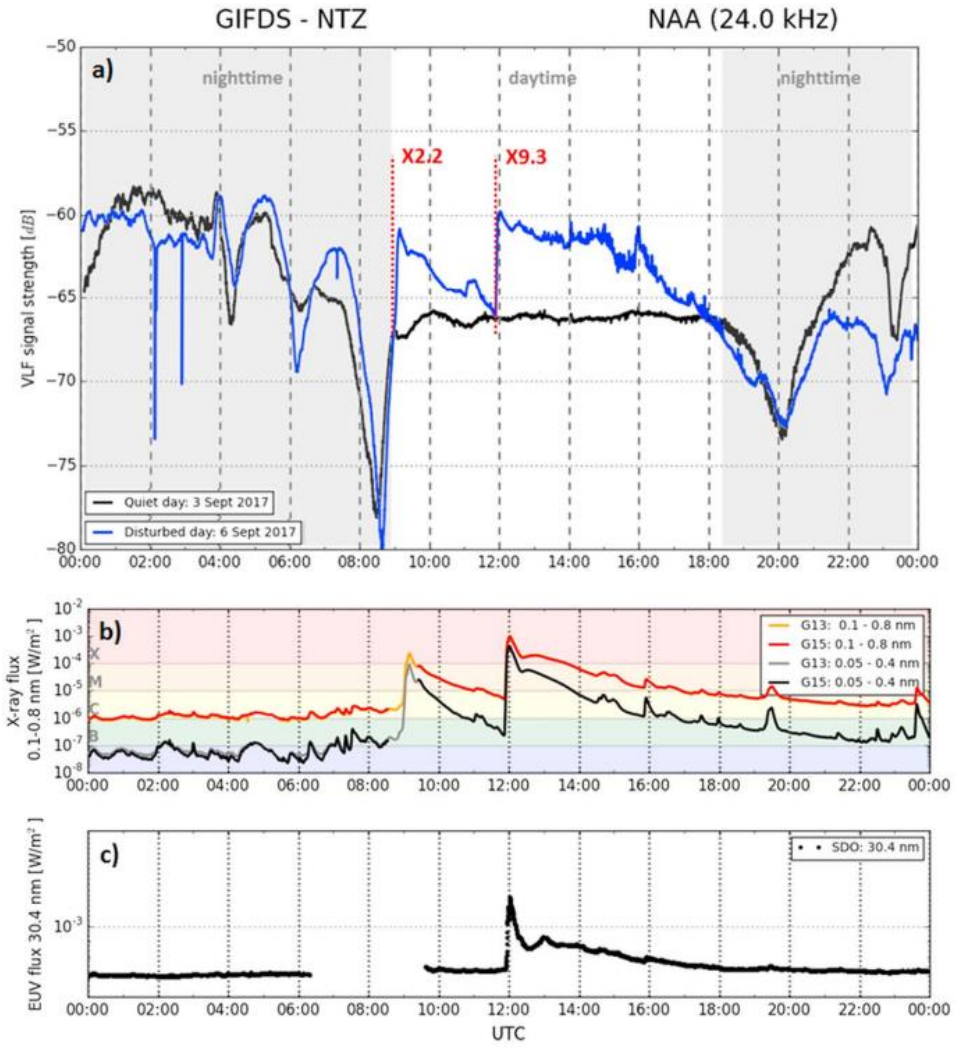
X9.3 flare on September 06, 2017

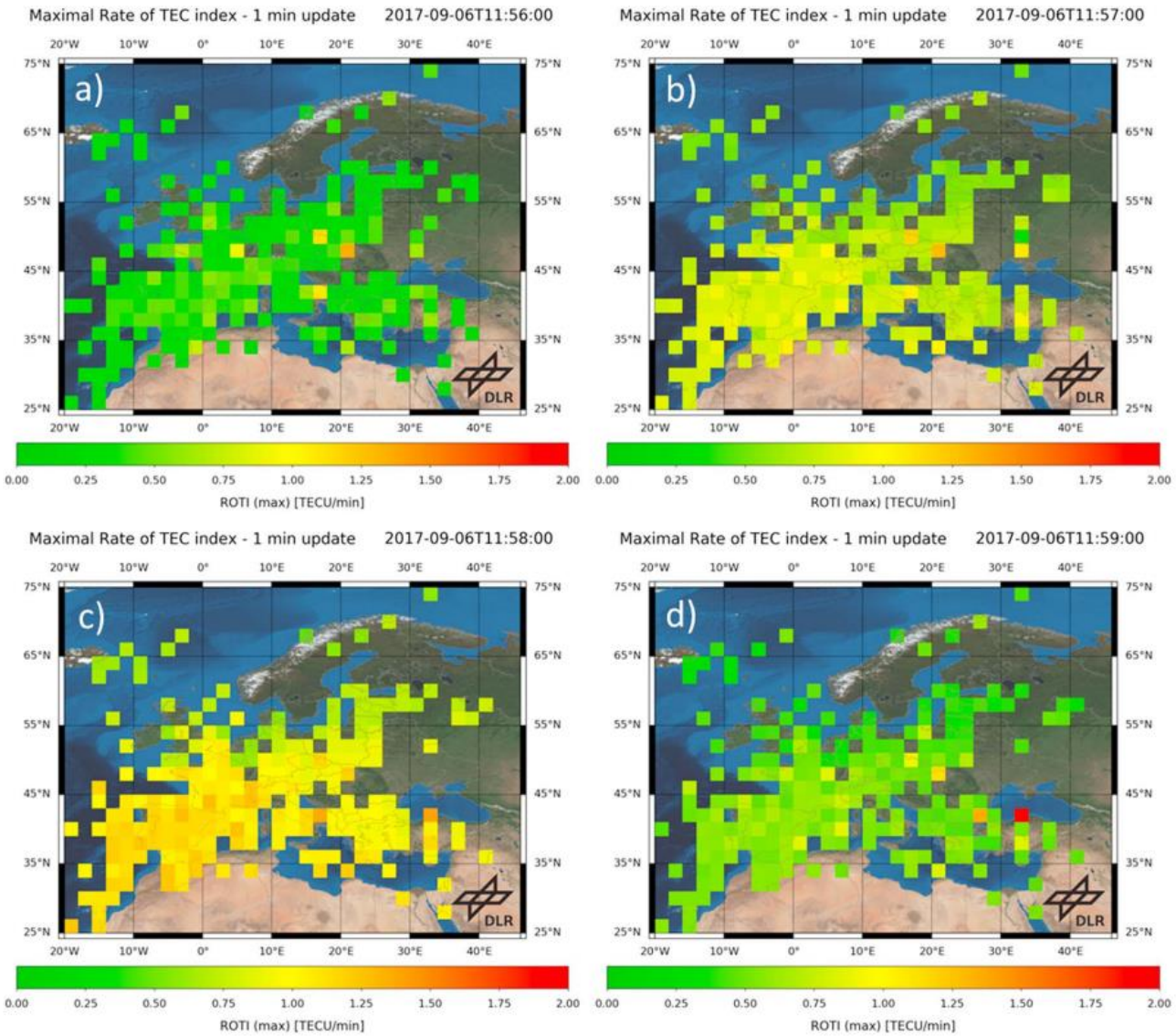




Example of “Indirect” Impact on GPS/GNSS

X9.3 flare on September 06, 2017





Example of “Indirect” Impact on GPS/GNSS

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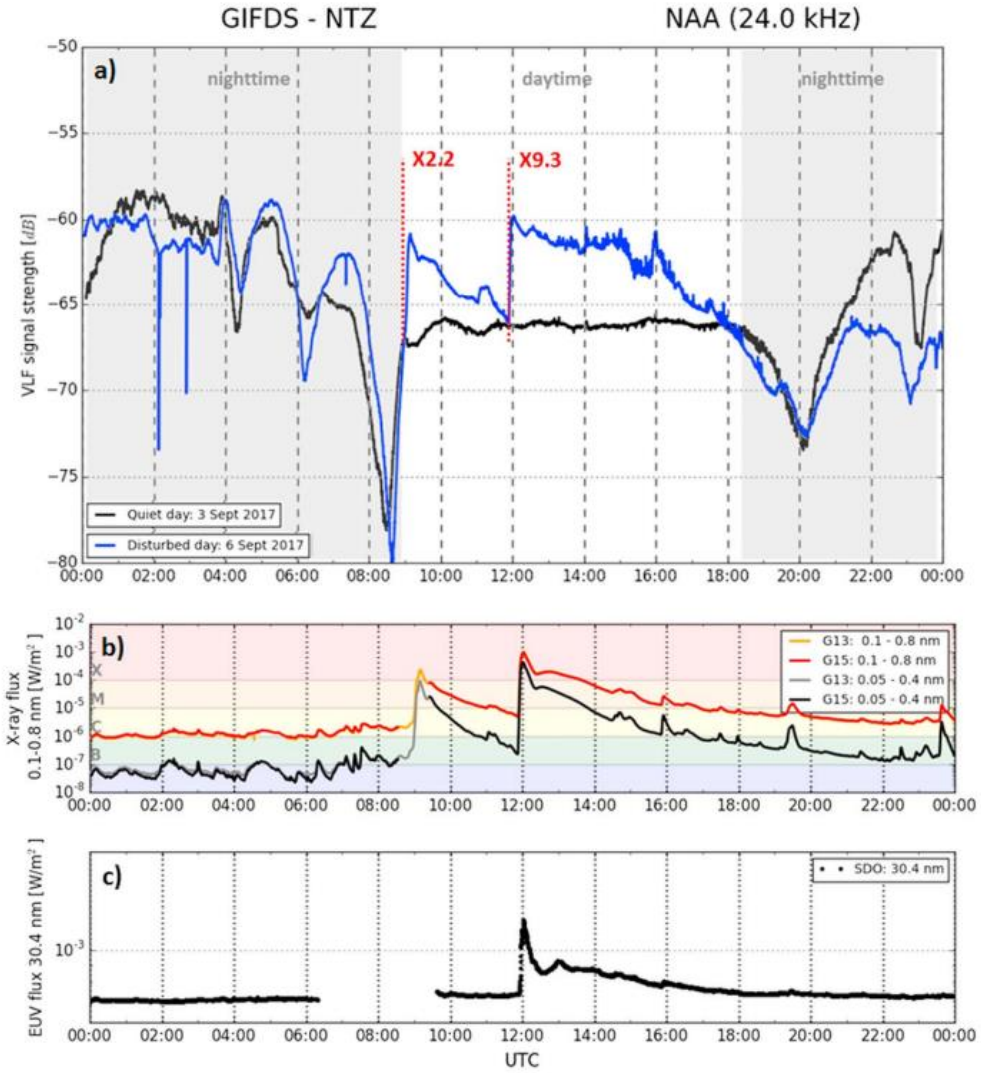
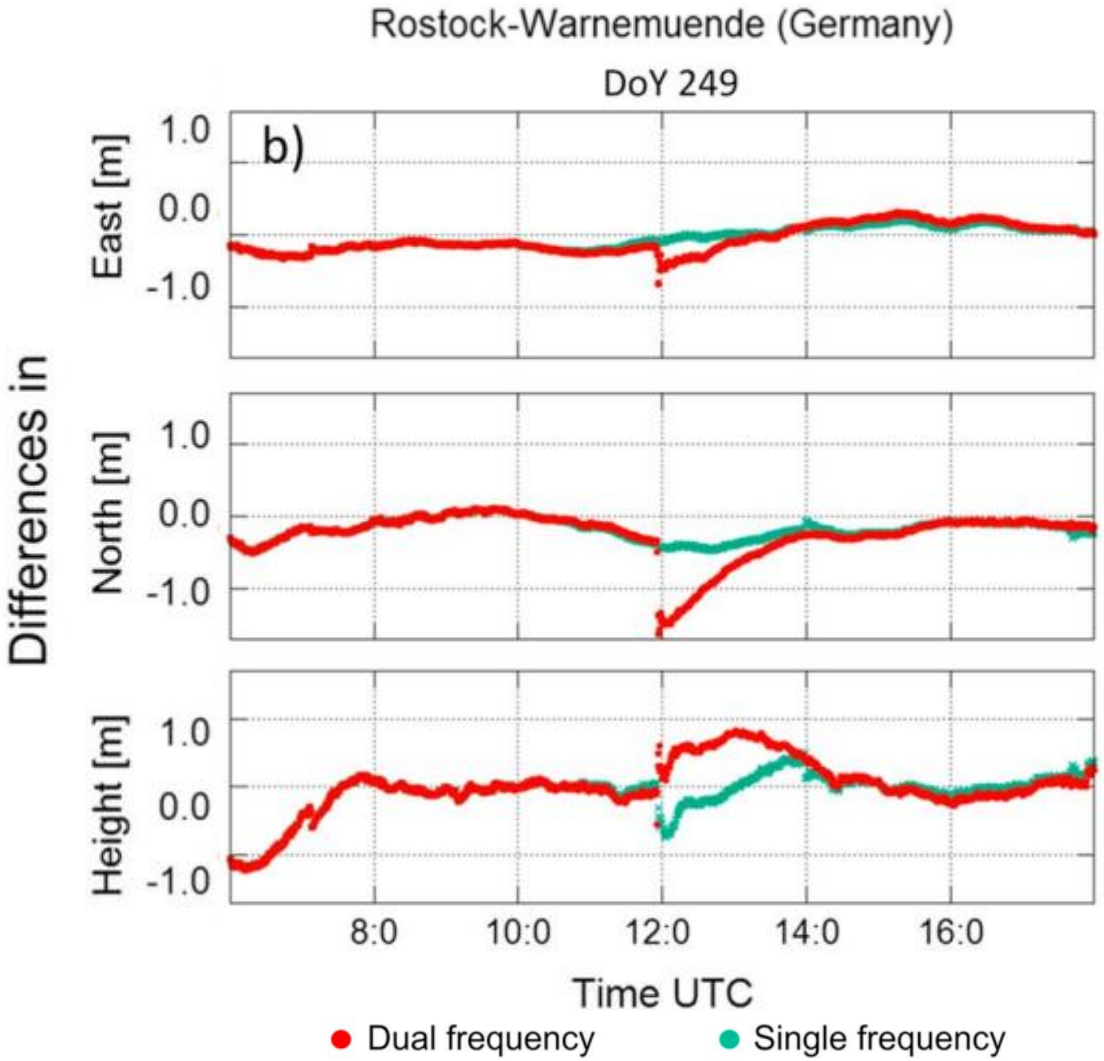
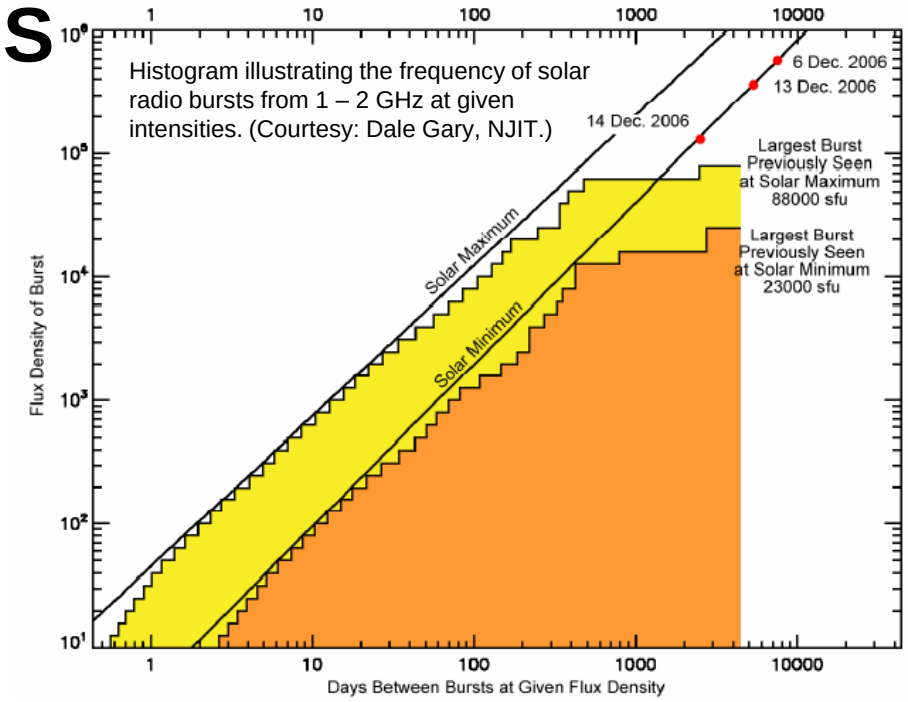


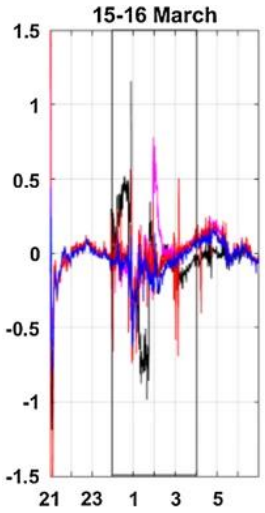
Precise Point Positioning

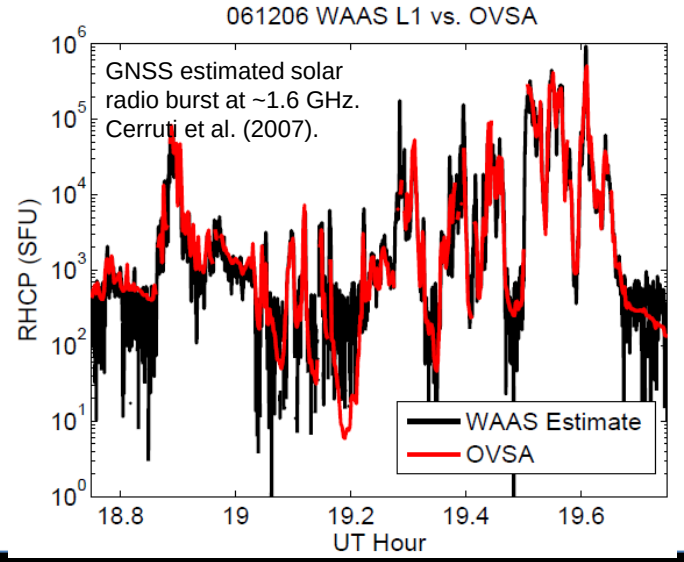


Summary of Solar Flare Impacts on GNSS

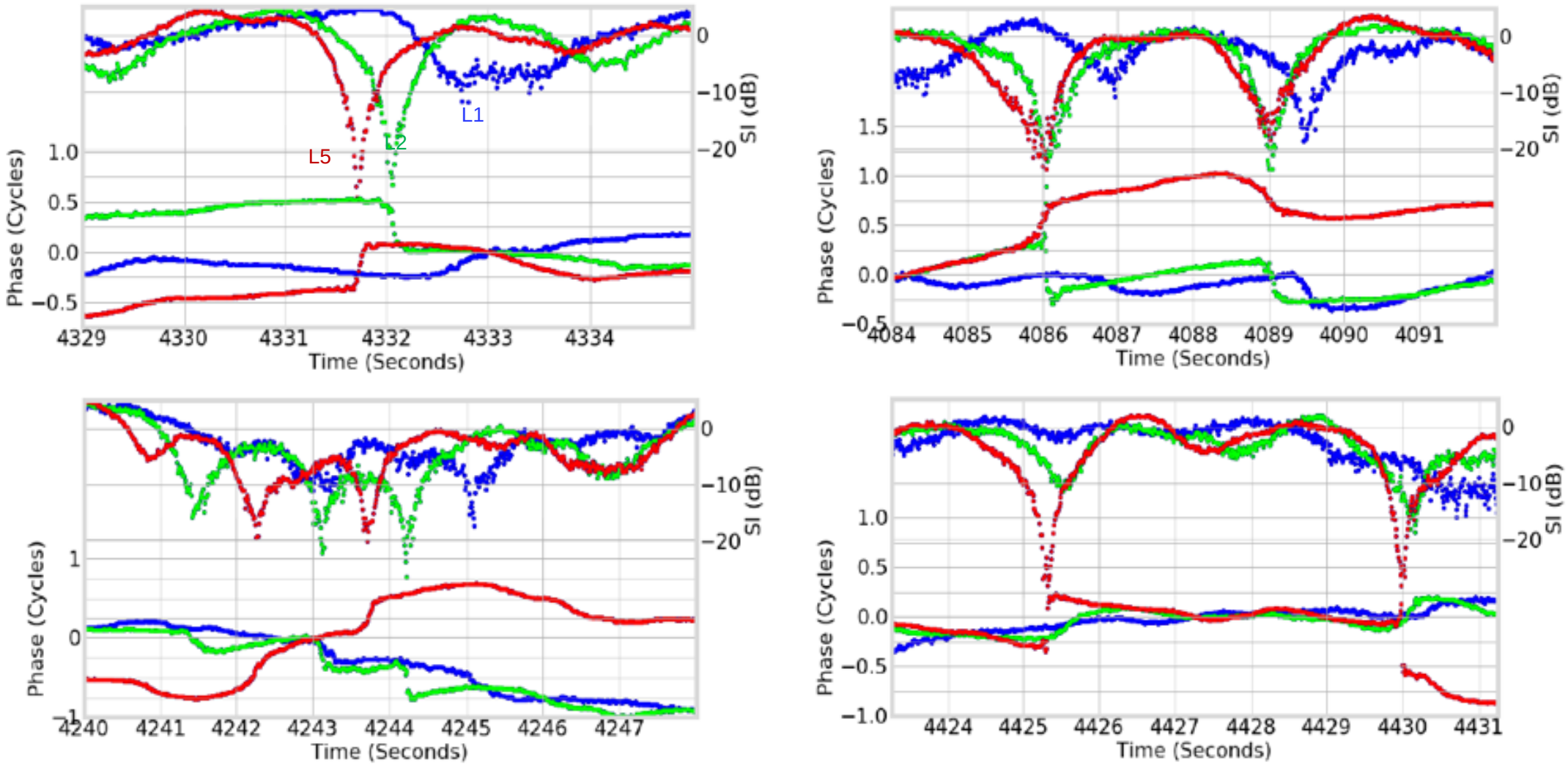
- **Solar radio bursts with severe impacts on GNSS do not happen frequently.**
- **Solar radio bursts challenge the ability of the receiver by significantly decreasing the carrier-to-noise ratio.**
- **Solar flares enhance the atmosphere ionization (EUV & X-ray), increase the ionospheric error in GNSS range measurements, and may also cause scintillation.**
- **The scintillation impacts from solar flares are considered mild comparing with those from ionosphere geomagnetic perturbations.**
- **GNSS networks can be used to monitor 1.1-1.6 GHz Solar radio bursts.**





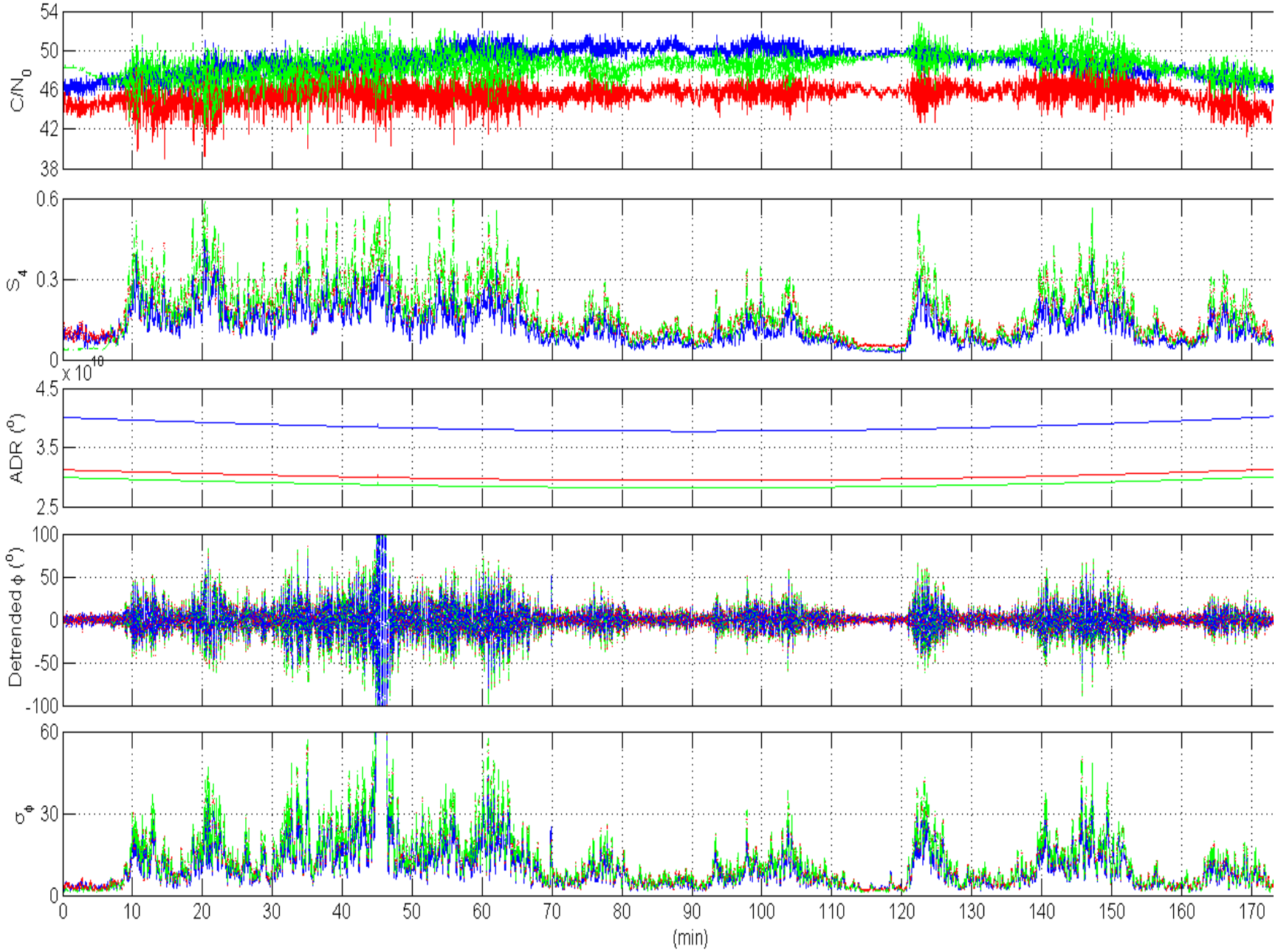


An Example of a Real Scintillation



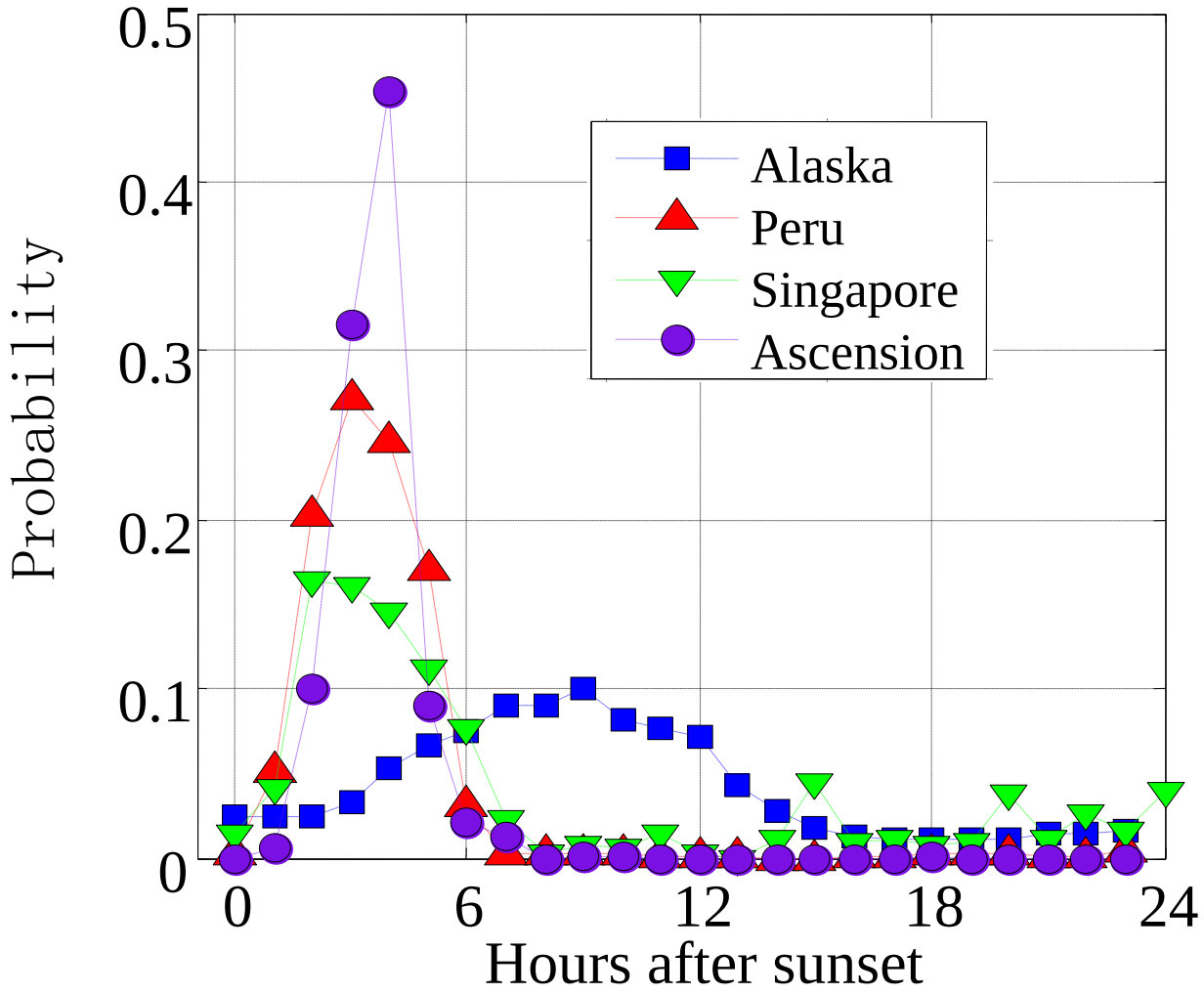
Low Latitude Scintillation Example

Peru
3/11/2013
13:30UTC



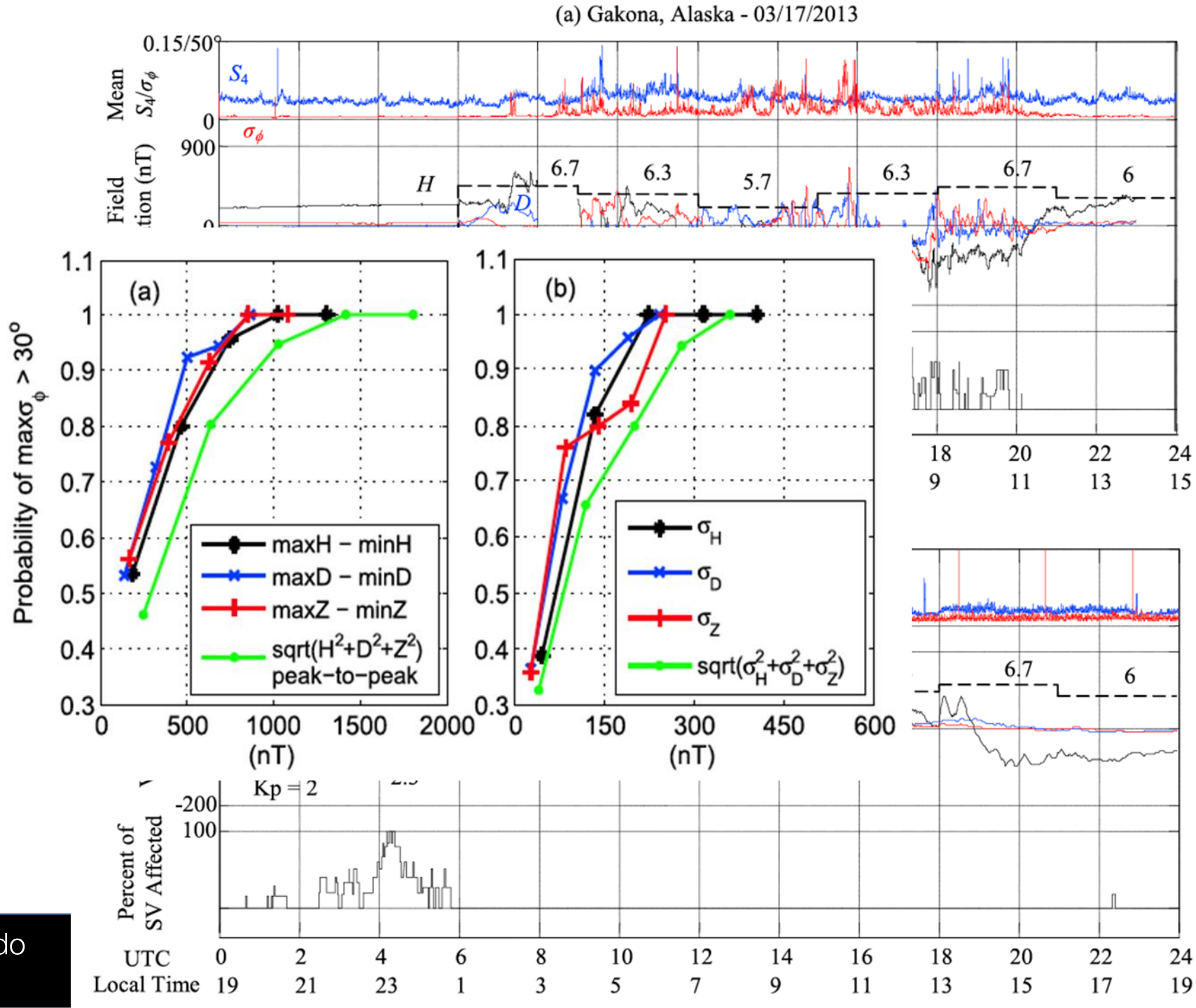
Scintillation Characteristics

High vs Low Latitude: Atmospheric Disturbance Diurnal Pattern



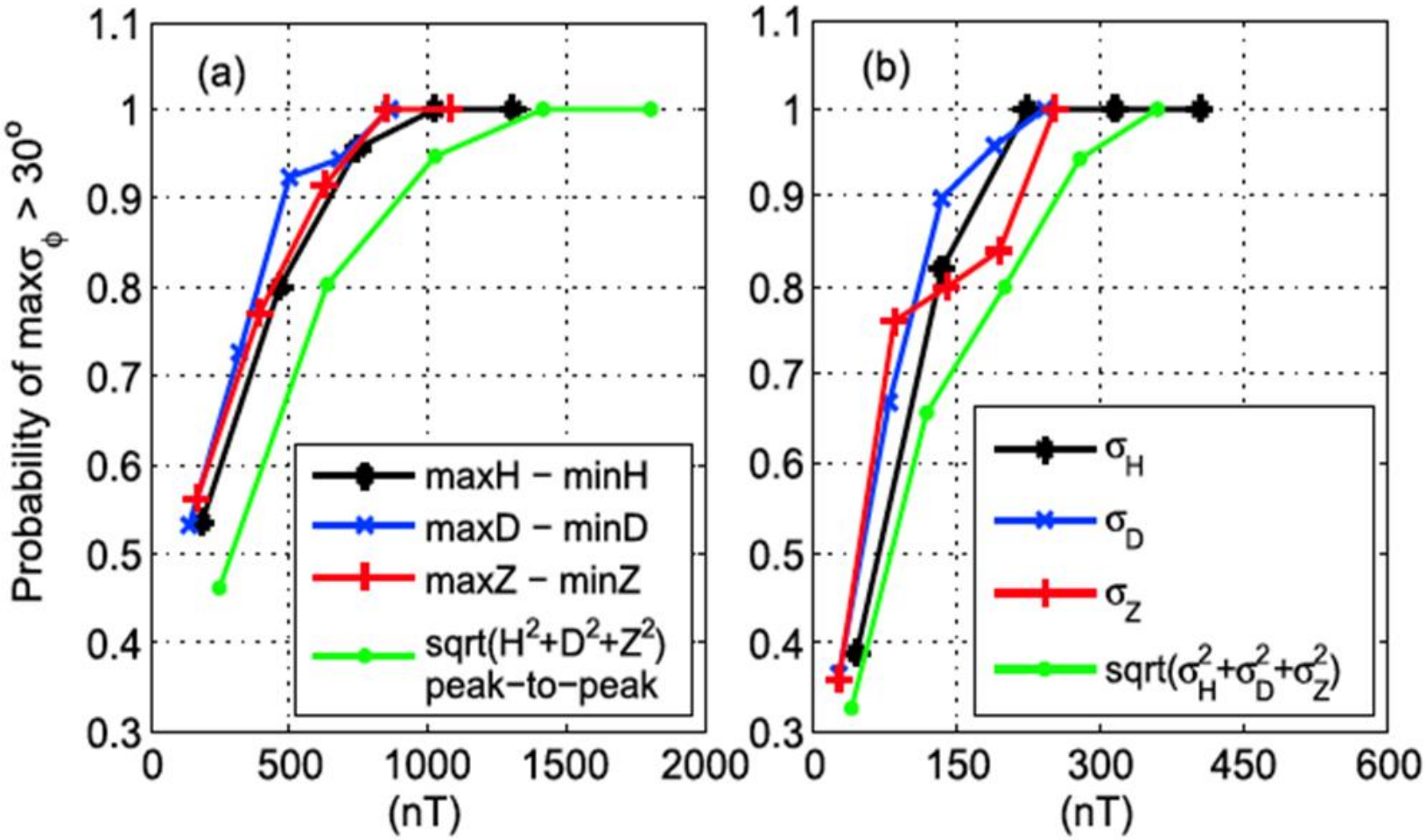
Scintillation Characteristic

Geomagnetic Dependency

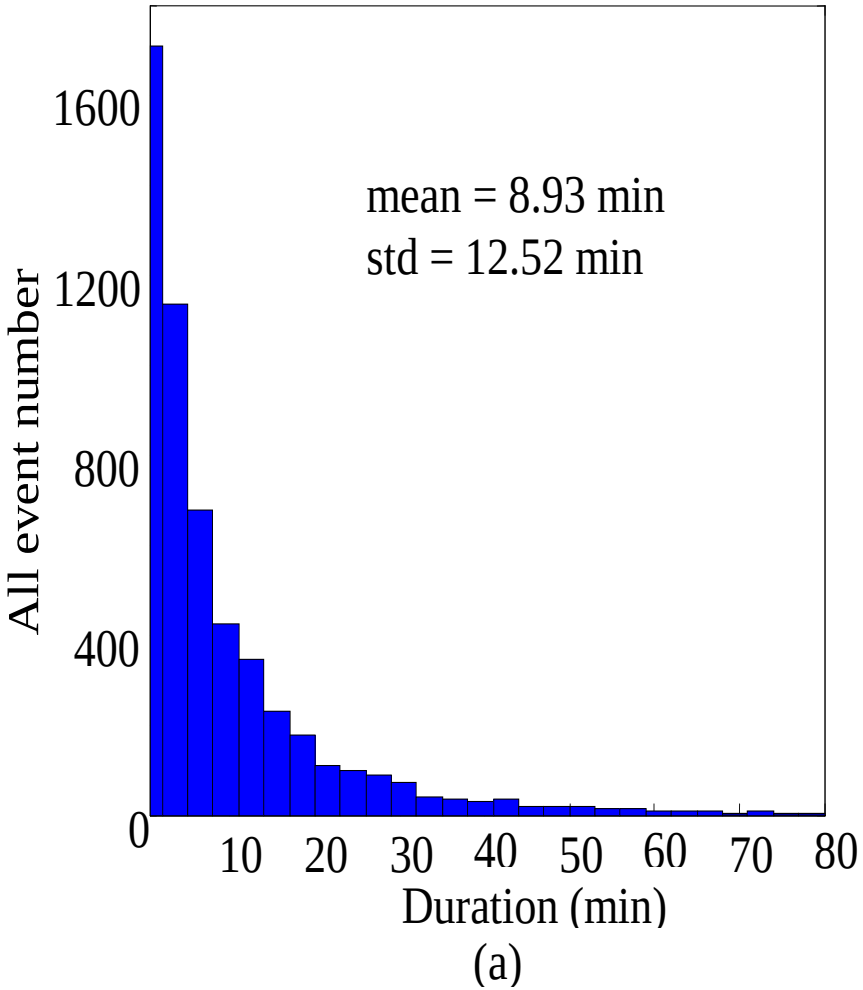


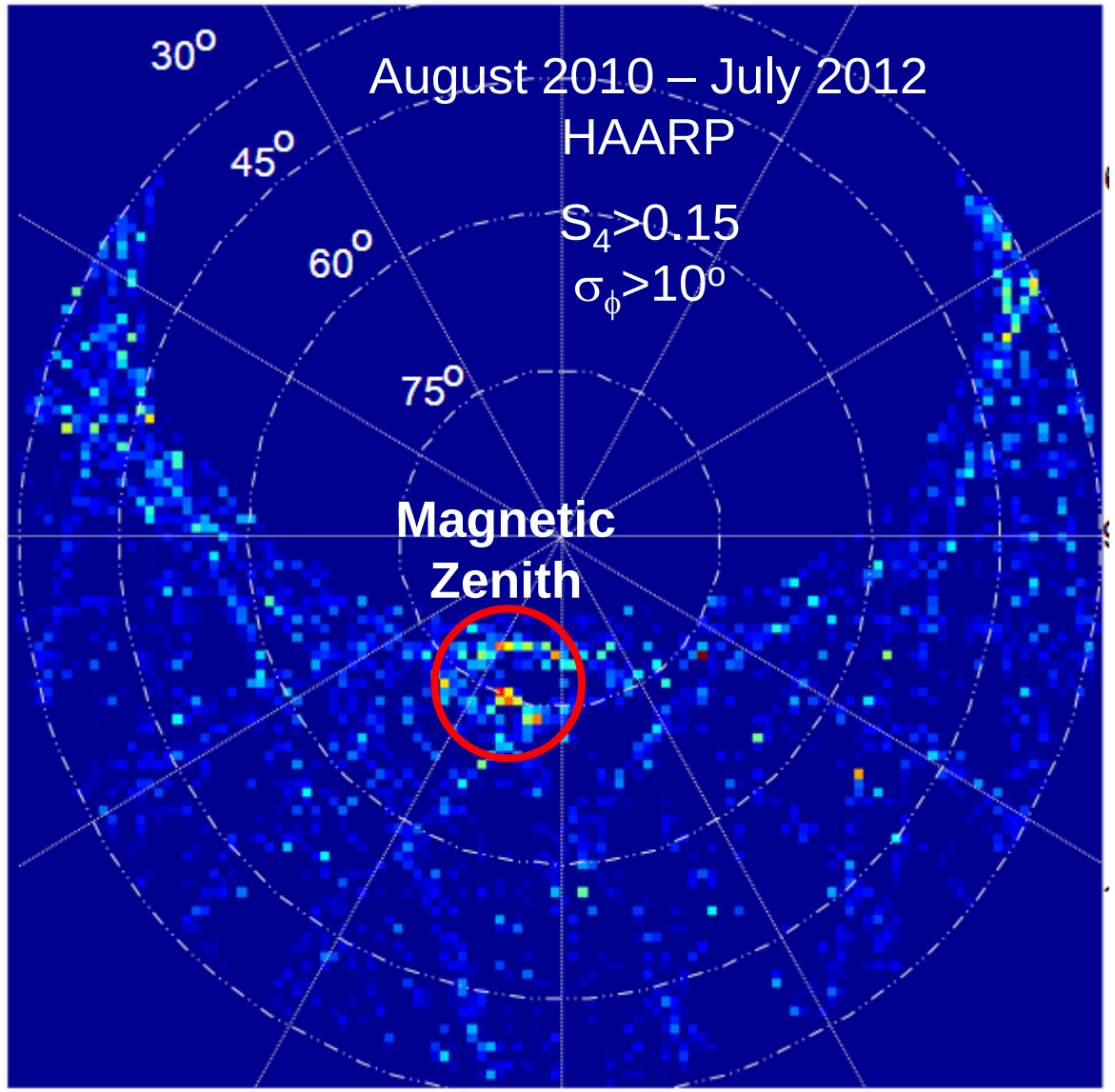
Scintillation Characteristics:

Geomagnetic Dependency

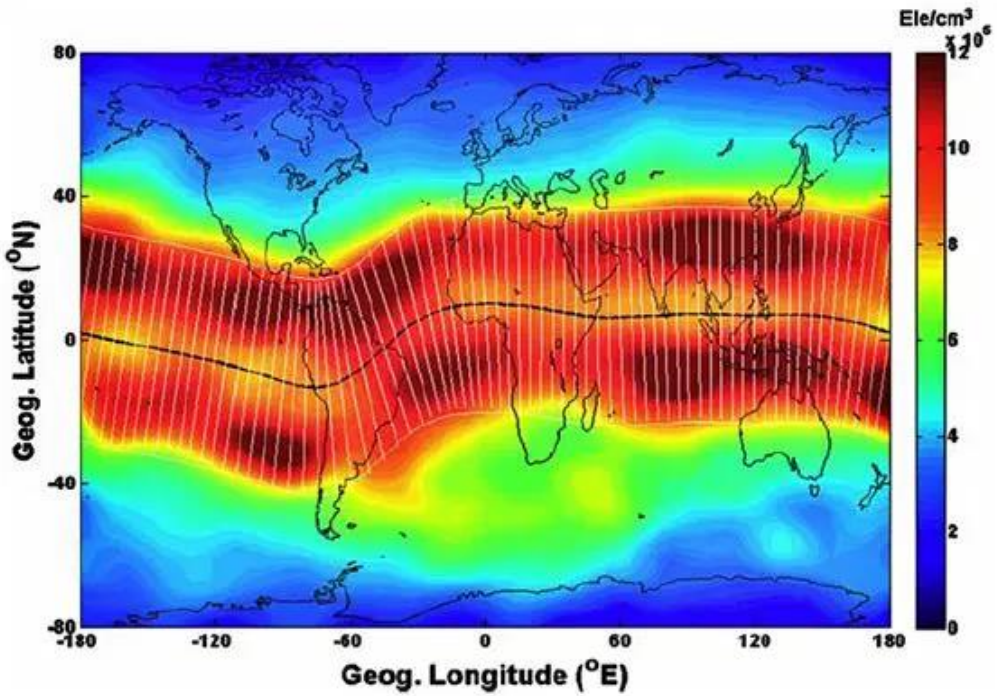


High Latitude Scintillation Spatial Distribution





Equatorial Scintillation



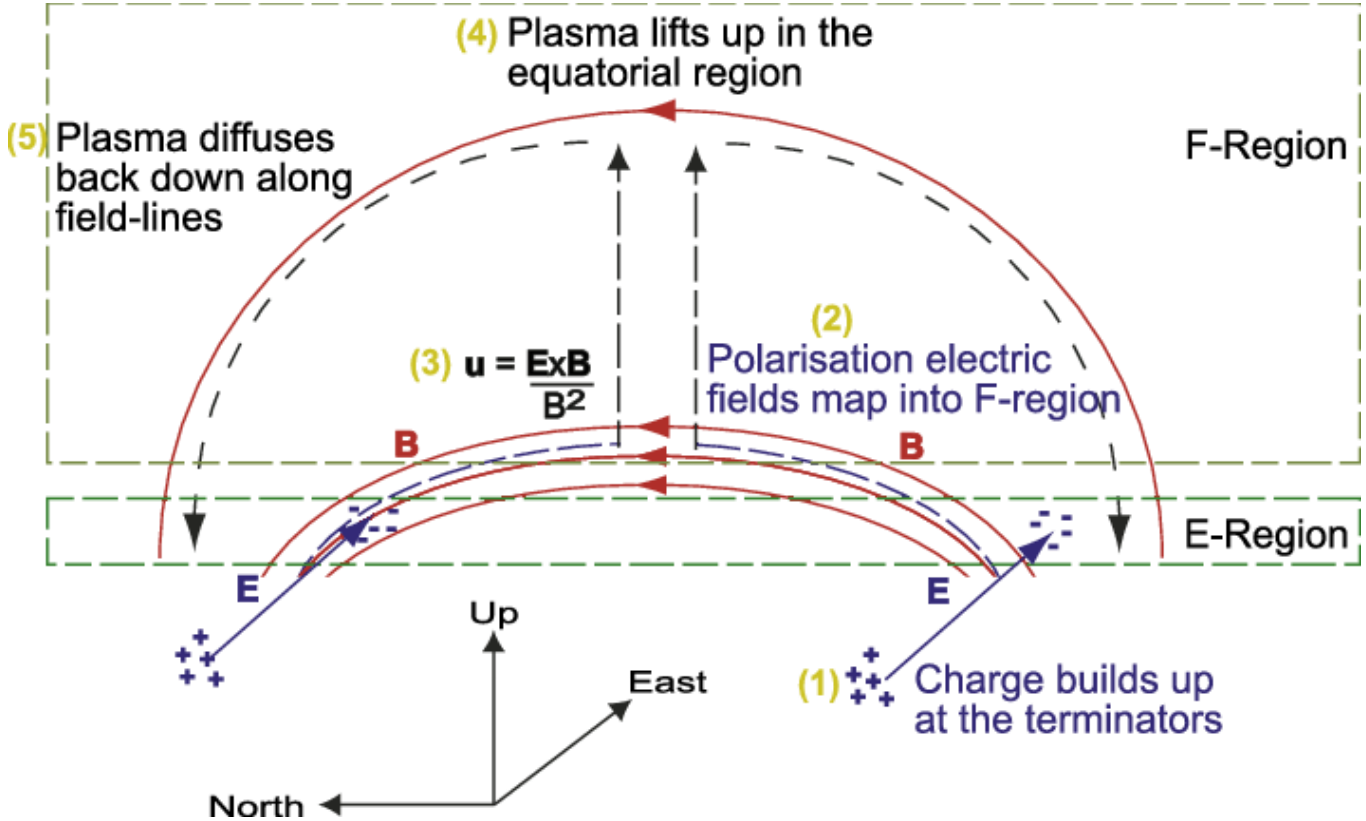


Diagram describing the development of the equatorial ionospheric anomaly, the magnetic and electric fields that combine to produce it.

(1) The E-region dynamo, driven by neutral wind-E-layer interaction, produces an eastward electric field across the dayside.

(2) These fields are transmitted upward along magnetic field lines into the F-region, causing the plasma to ExB drift upward (3, 4) at the magnetic equator.

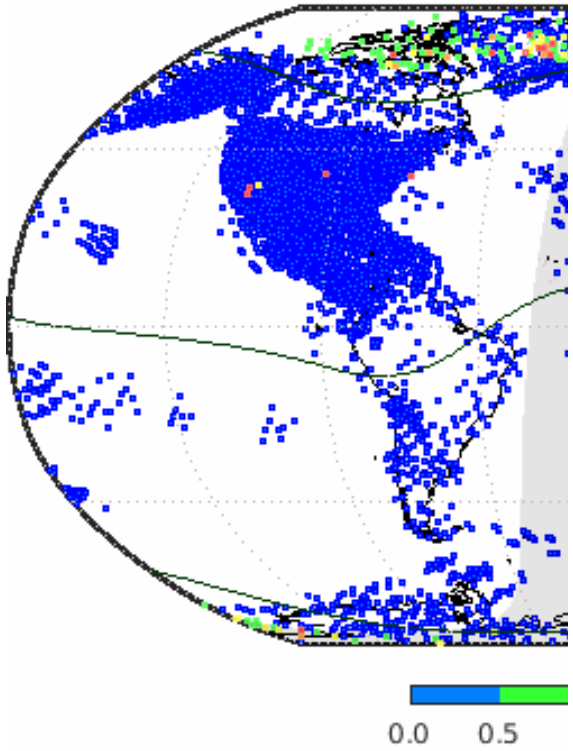
(5) Through diffusion and gravitational sedimentation, the upward lifted plasma settles along the magnetic field to locations north and south of the equator.

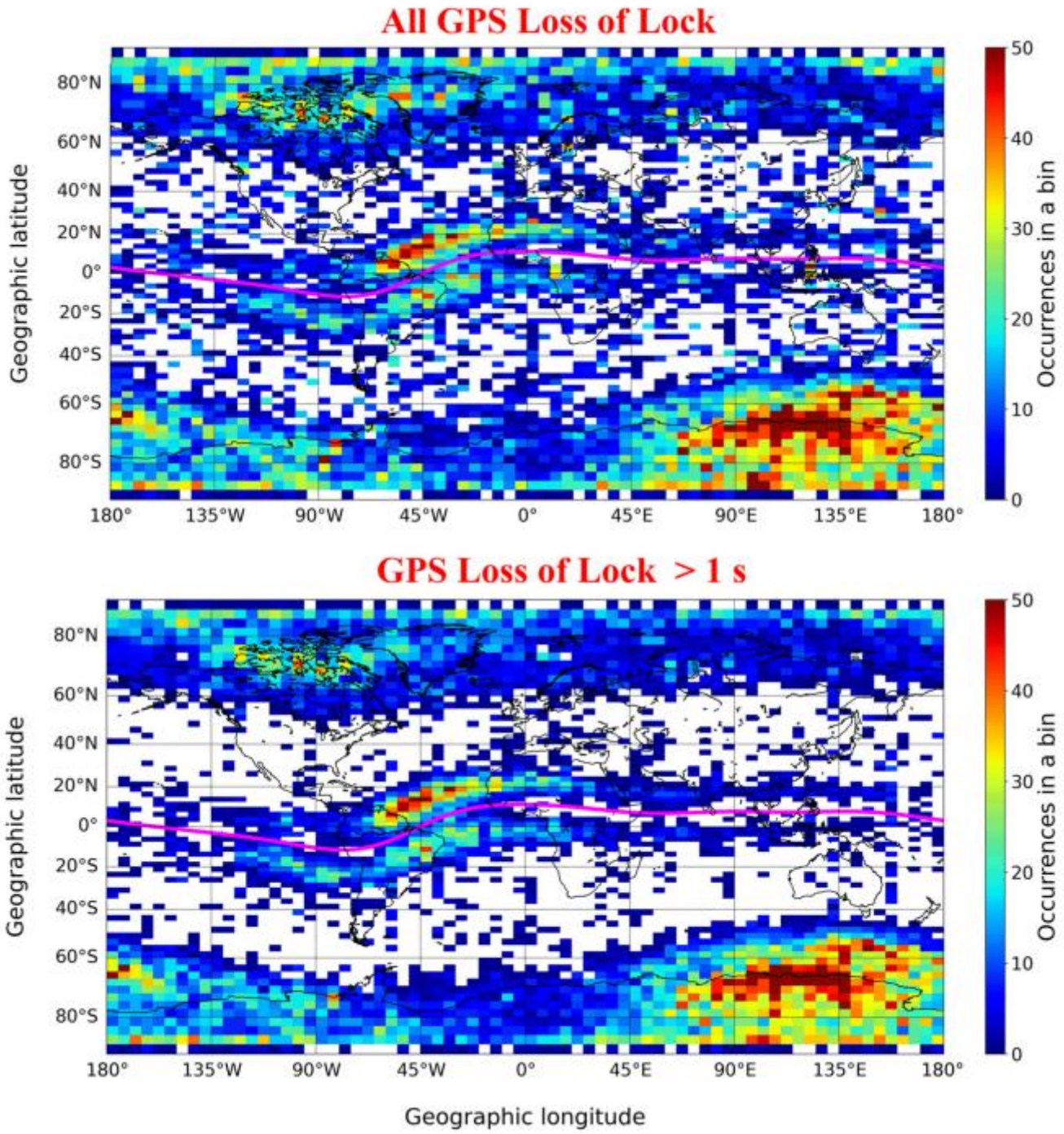
Immel et al. 2006

Ionosphere D

ROTI: Ionospher

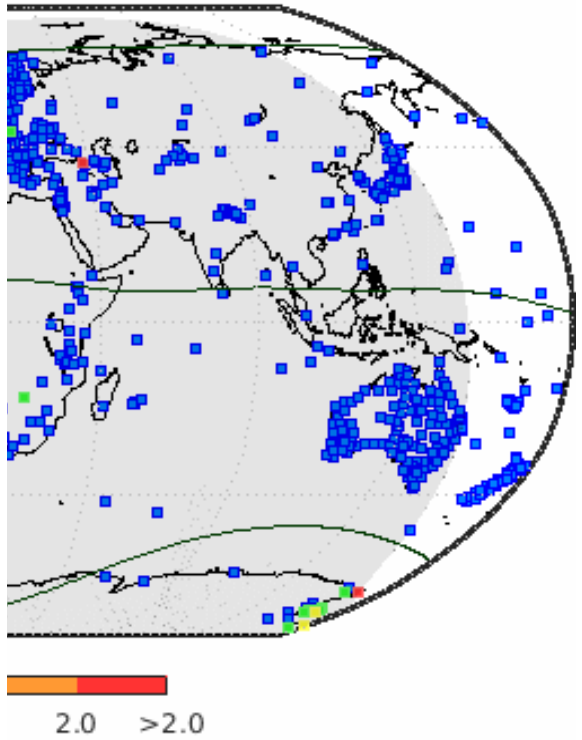
09/07/2



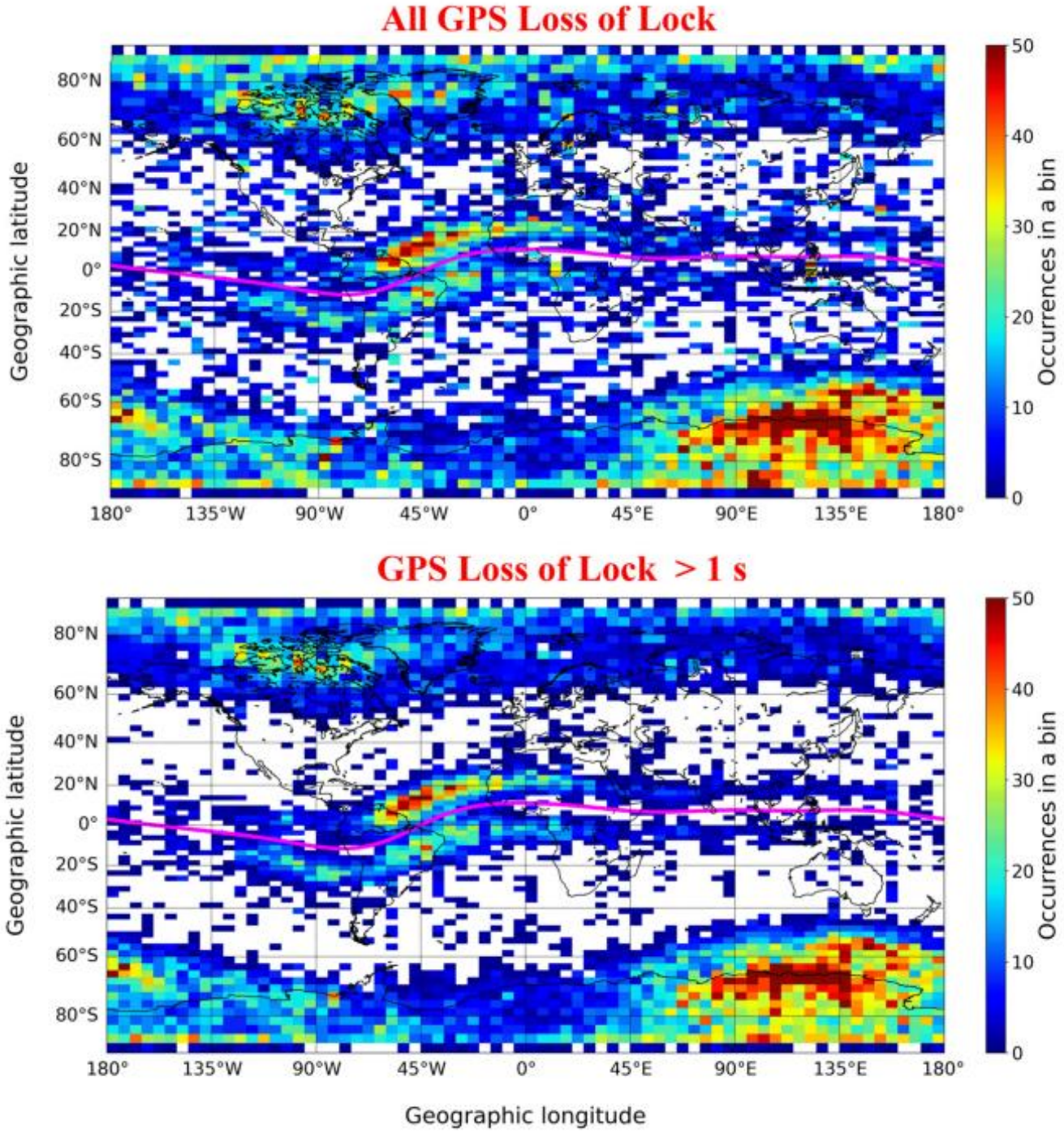


rrors

0:00 UT



Ionosphere Disturbance Impact at LEO

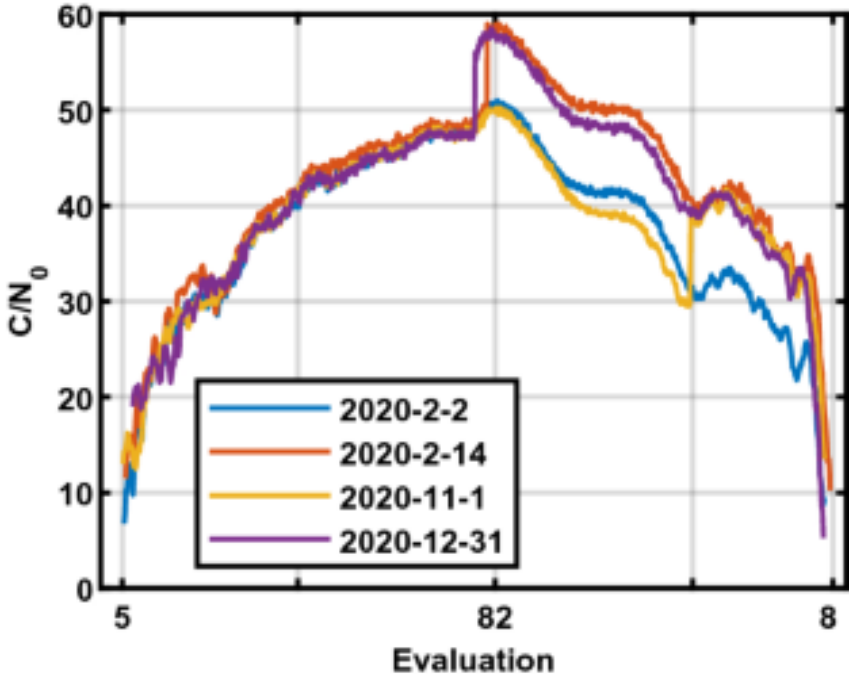


Pezzopane et al. 2021

Mitigation of Space Weather Impacts on GNSS

Increase Signal Transmission Power

The New Flex Power Mode:
From GPS IIR-M and IIF Satellites



GPS P(Y) code Signal of PRN 5 received by IGS BAIE

Warning System for GNSS Users

SRB WARNING SYSTEM FOR GNSS APPLICATIONS IN EUROPE

Contact: *iono@oma.be*

To receive real-time alert emails, please contact us to be added to the mailing list.

Last update : 2017-09-06 13:30:00 UTC	L1	L2
Last 15min		
Last 24h		
Last week		

Events of the last 30 days:

Frequency	Date of the maximum fade	Maximum fade (in dB-Hz)	Beginning of the event	End of the event
L1	2017-09-06 13:07:30	-1±0.5		
L1	2017-09-06 13:05:00	-1±0.52		
L2	2017-09-06 13:03:30	-2.75±0.91		
L2	2017-09-06 12:20:30	-1±0.52		
L2	2017-09-06 12:08:30	-2±1.08		
L2	2017-09-06 12:02:30	-6.25±1.6		
L1	2017-09-06 12:01:30	-1±0.61		

Improve GNSS Receiver Design and Signal Tracking

- Higher quality oscillator
- Robust tracking loop design
- Adaptive filter tuning and integration time adjustment
- Integration with external sensors, such as IMU.