Solar Maximum

Effects on GNSS Operations Plus Ionospheric Monitoring

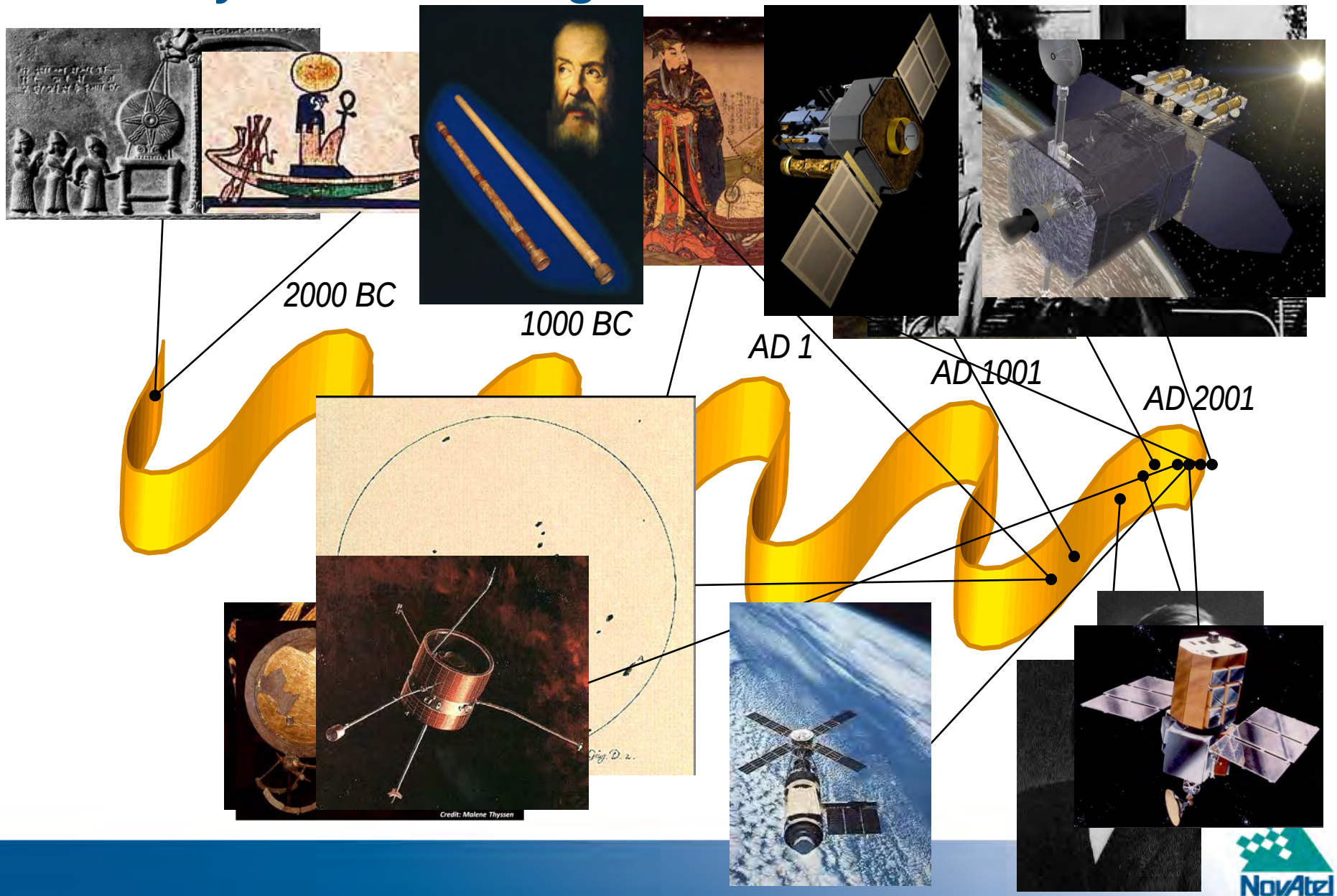
Thomas Morley, Product Manager

June, 2012

Solar Max and GNSS - Outline

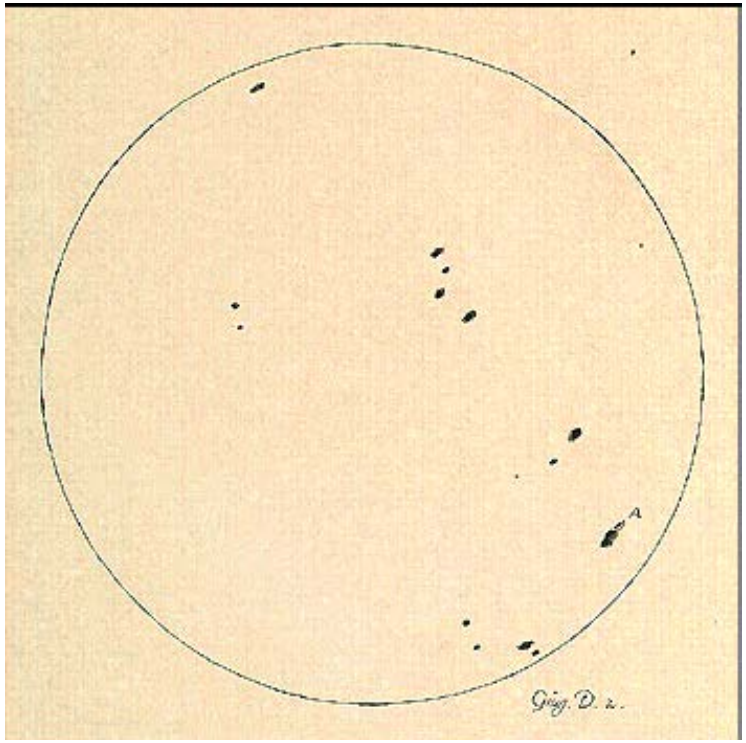
- Sun 101
  - History of knowledge of the Sun
  - Structure of the Sun
  - Behaviour of the Sun
- Earth 101
  - Structure and behaviour of the magnetosphere and ionosphere
- Implications to GNSS
- Ionospheric monitoring using GNSS

History of Knowledge of the Sun



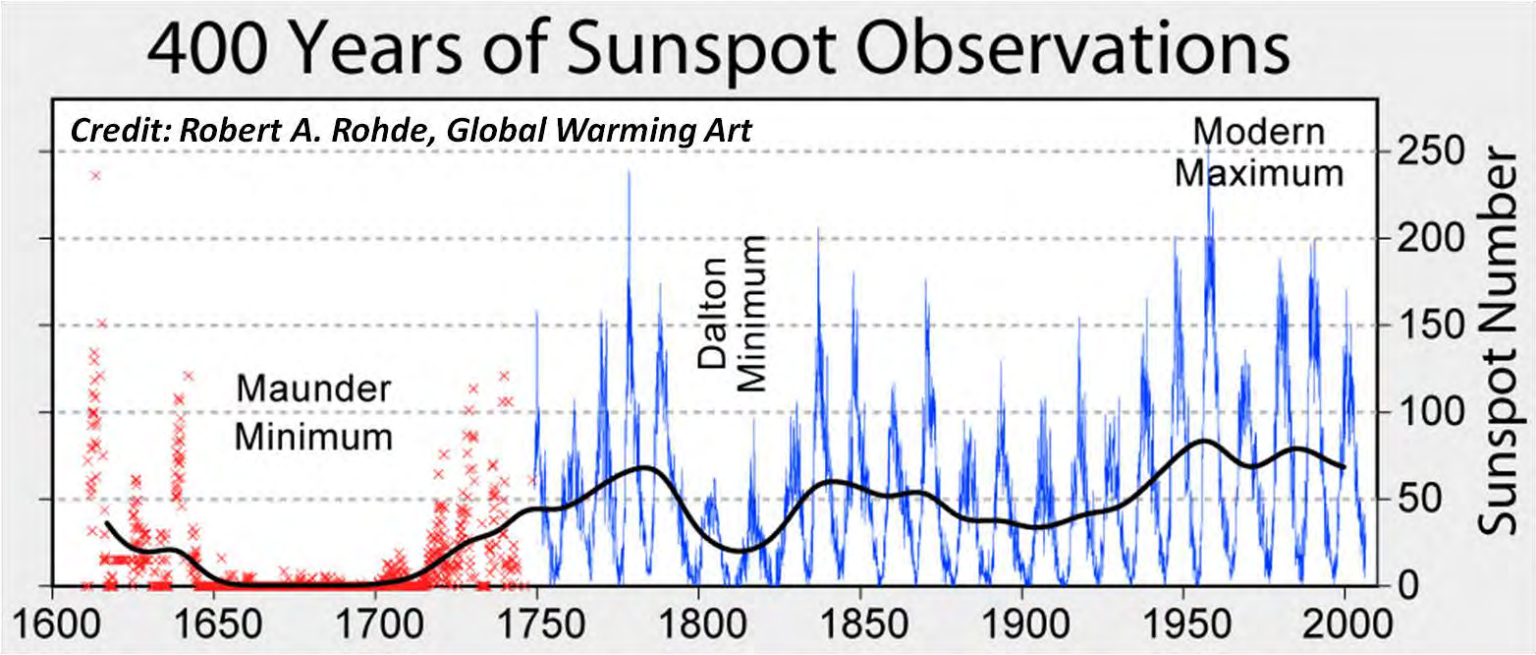
The Sun – What Have We Learned

- Sunspots
  - documented by Galileo in June-July of 1612
  - rarely appear outside of ±30° of the solar equator
  - originally thought to be cloud-like structures in the solar atmosphere
  - also thought to be an opening in the Sun's luminous atmosphere

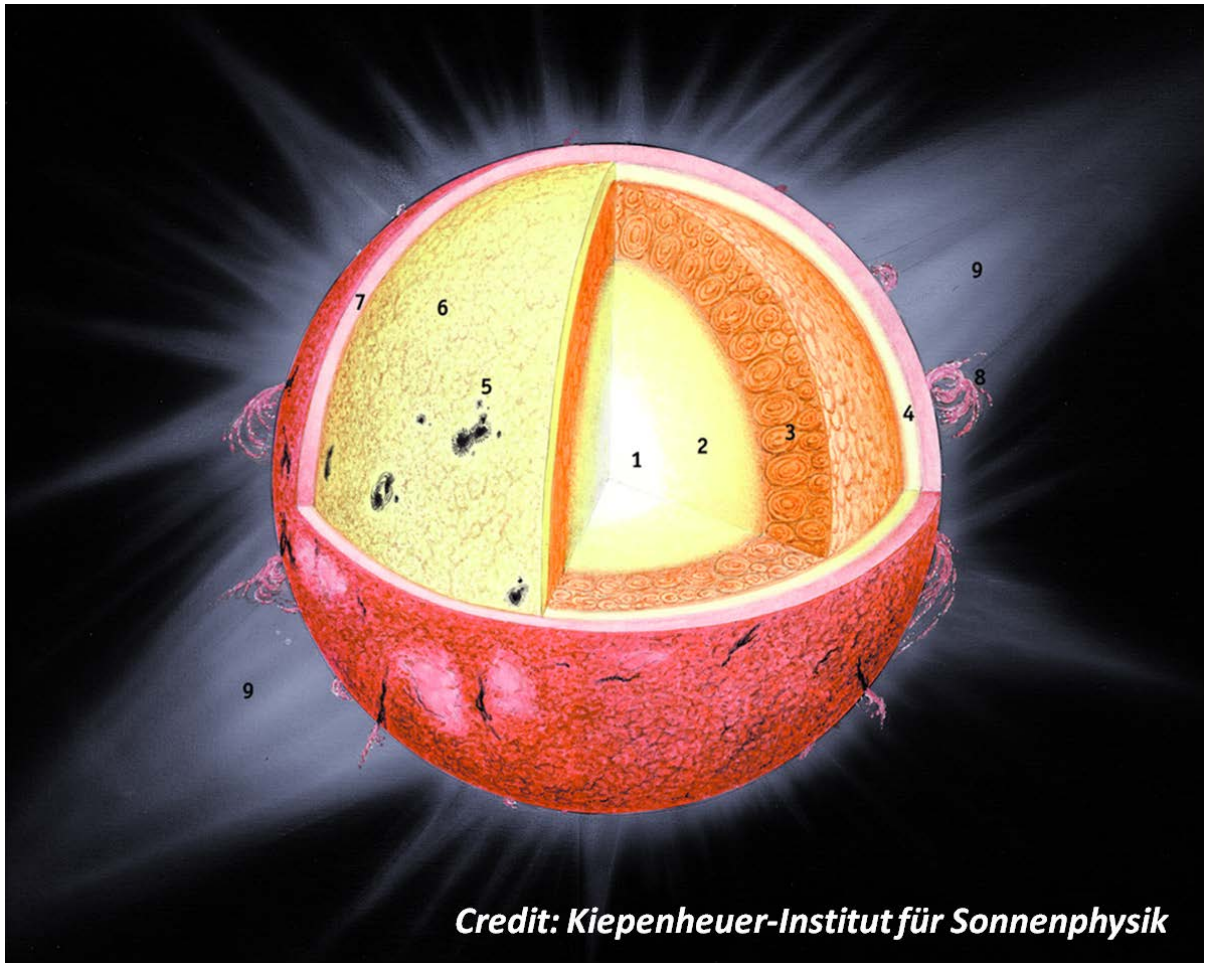


The Sun – What Have We Learned

- Sunspots and the Solar cycle
  - 1843 by Samuel Heinrich Schwabe
    - Based on 17 years of observations
    - Cycle originally estimated at 10 years in duration



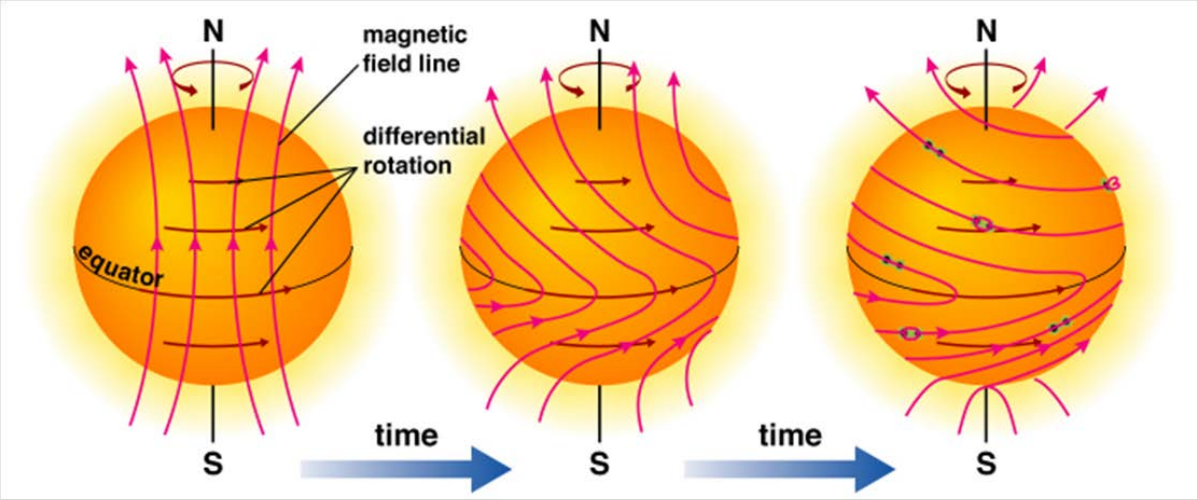
The Sun - Structure



1. Core
2. Radiation zone
3. Convection zone
4. Photosphere
5. Sunspots
6. Granulation
7. Chromosphere
8. Prominences
9. Corona

The Sun – Differential Rotation

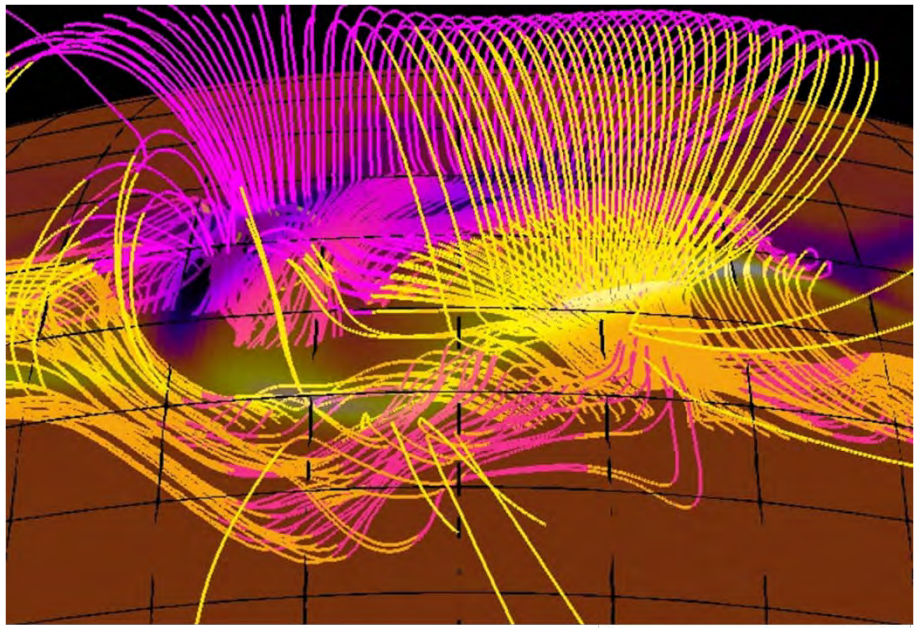
- Rotation period
  - at equator: ~26 days
  - at poles: ~38 days
- Shear creates a current and magnetic field
  - Magnetic field lines twist together over time
- Sun's magnetic field reverses around solar maximum



Credit: Allison Wesley

The Sun – Magnetic Fields

- Magnetic field loops
- “Flux tubes” in convection zone
  - Inhibits convection
  - Cooler (and darker) than surrounding photosphere
- Prominences associated with field loops

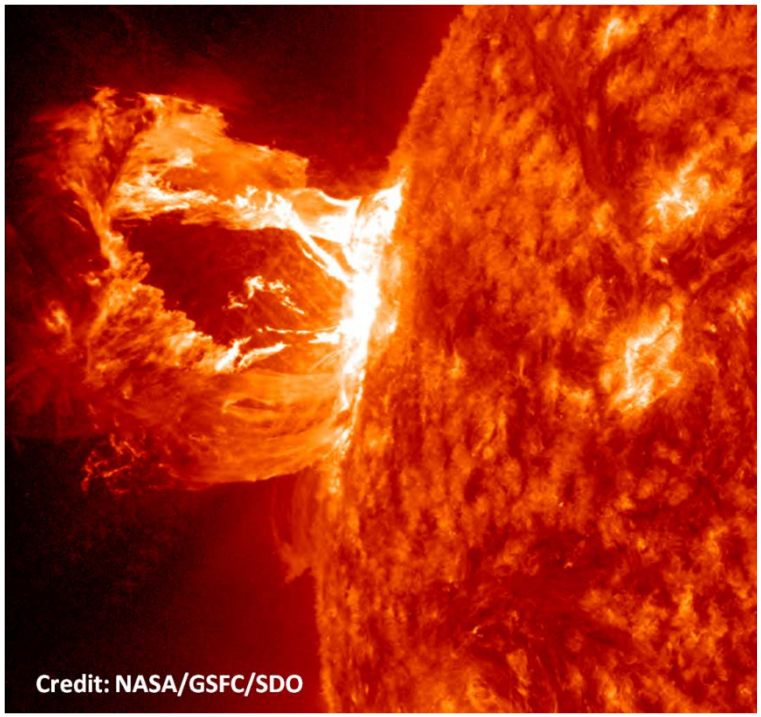


Credit: Jouve and Brun

The Sun – Magnetic Reconnection

- Spontaneous rearrangement of magnetic field lines
- Magnetic energy converted to:
  - kinetic energy
  - thermal energy
  - particle acceleration
- May release (in minutes) energy that was stored over many days

The Sun – Coronal Mass Ejection

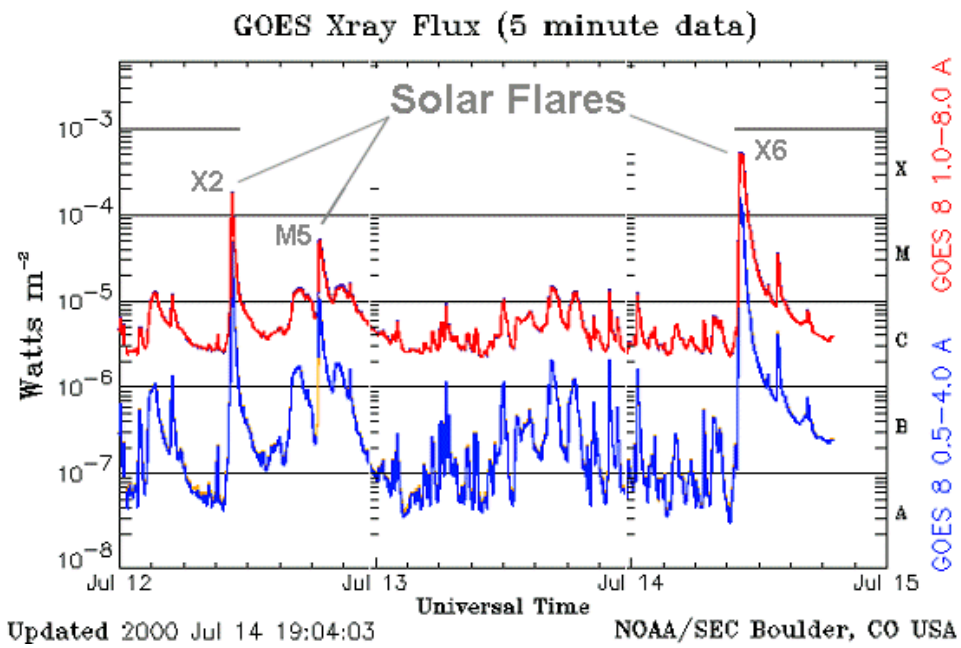


- Massive burst of energy rising above the corona
  - Solar Maxima: ~ 3.5 CME per day
  - Solar Minima: ~ 1 CME every 5 days

The Sun – Coronal Mass Ejection

- Releases huge quantities of plasma and electromagnetic radiation
  - Radiation travels at ~ 300,000 km/s
    - Reaches Earth in ~ 500 seconds (~ 8.3 minutes)
  - Plasma travels at ~ 20 to 3,200 km/s
    - Reaches Earth in ~ 2-3 days

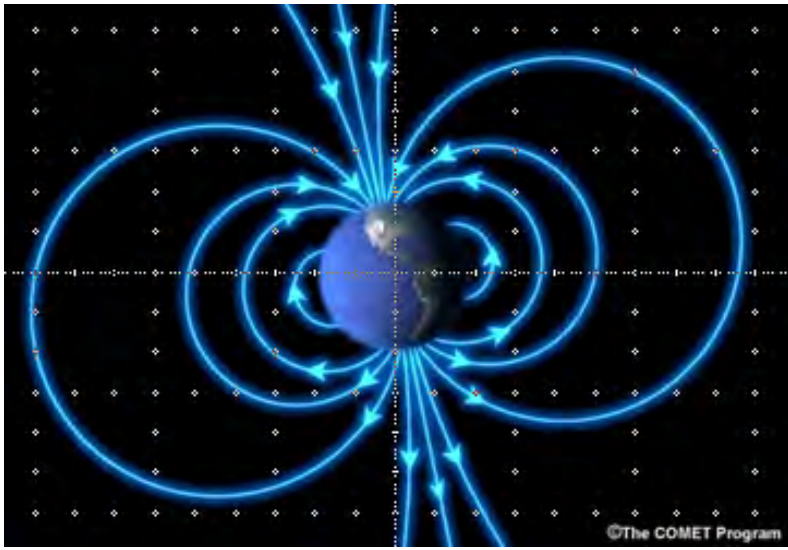
The Sun – Coronal Mass Ejection



- Classified according to peak flux (W/m^2) of X-rays measured by the GOES satellites
  - A: $<10^{-7}$
  - B: 10^{-7} to 10^{-6}
  - C: 10^{-6} to 10^{-5}
  - M: 10^{-5} to 10^{-4}
  - X: $>10^{-4}$

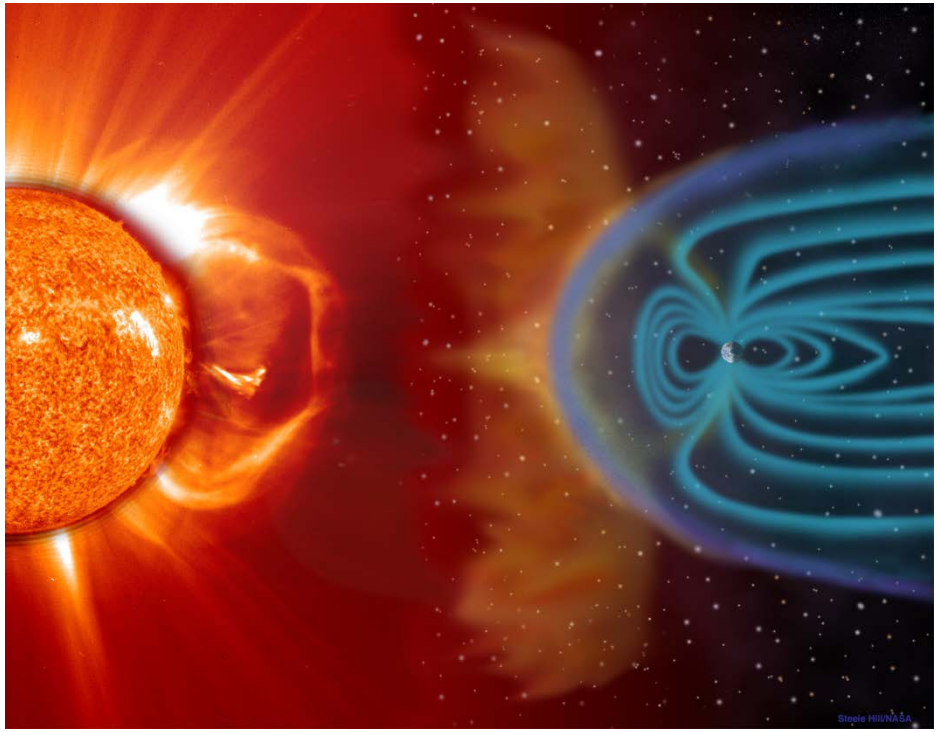
The Earth – Magnetic Field

- Tilted at approximately 11° from the Earth's rotational axis
- Generated by the motion of molten iron alloys in the outer core
- Deflects most of the particles in the solar wind
- Magnetic field intensity is greatest near the poles

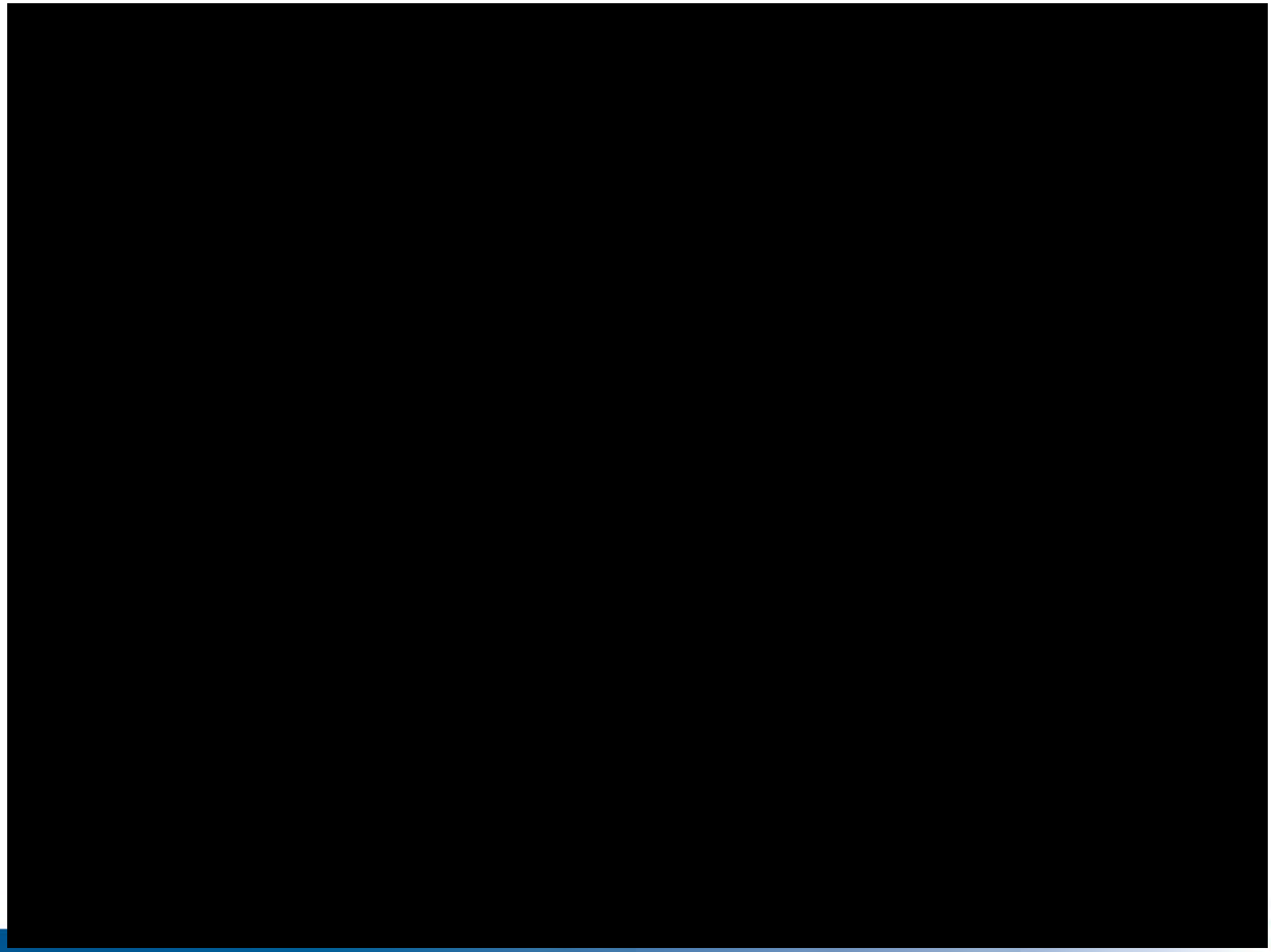


The Earth – Magnetosphere

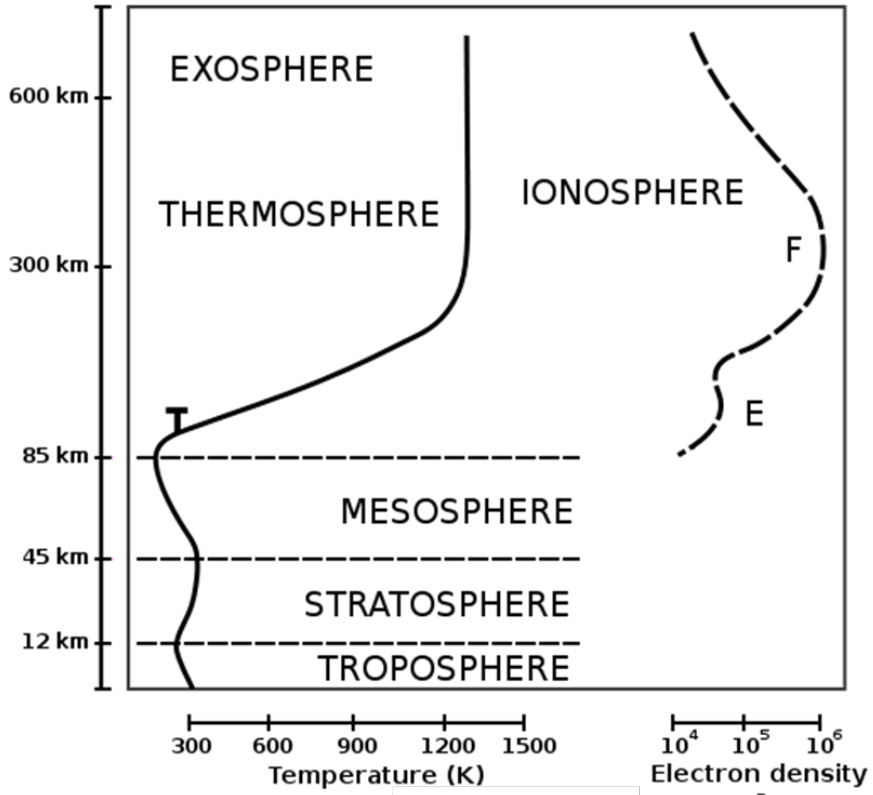
- Extends to a boundary with the solar wind
  - Compressed on day side
  - Long tail on the night side



Magnetic Recombination



The Earth – Ionosphere

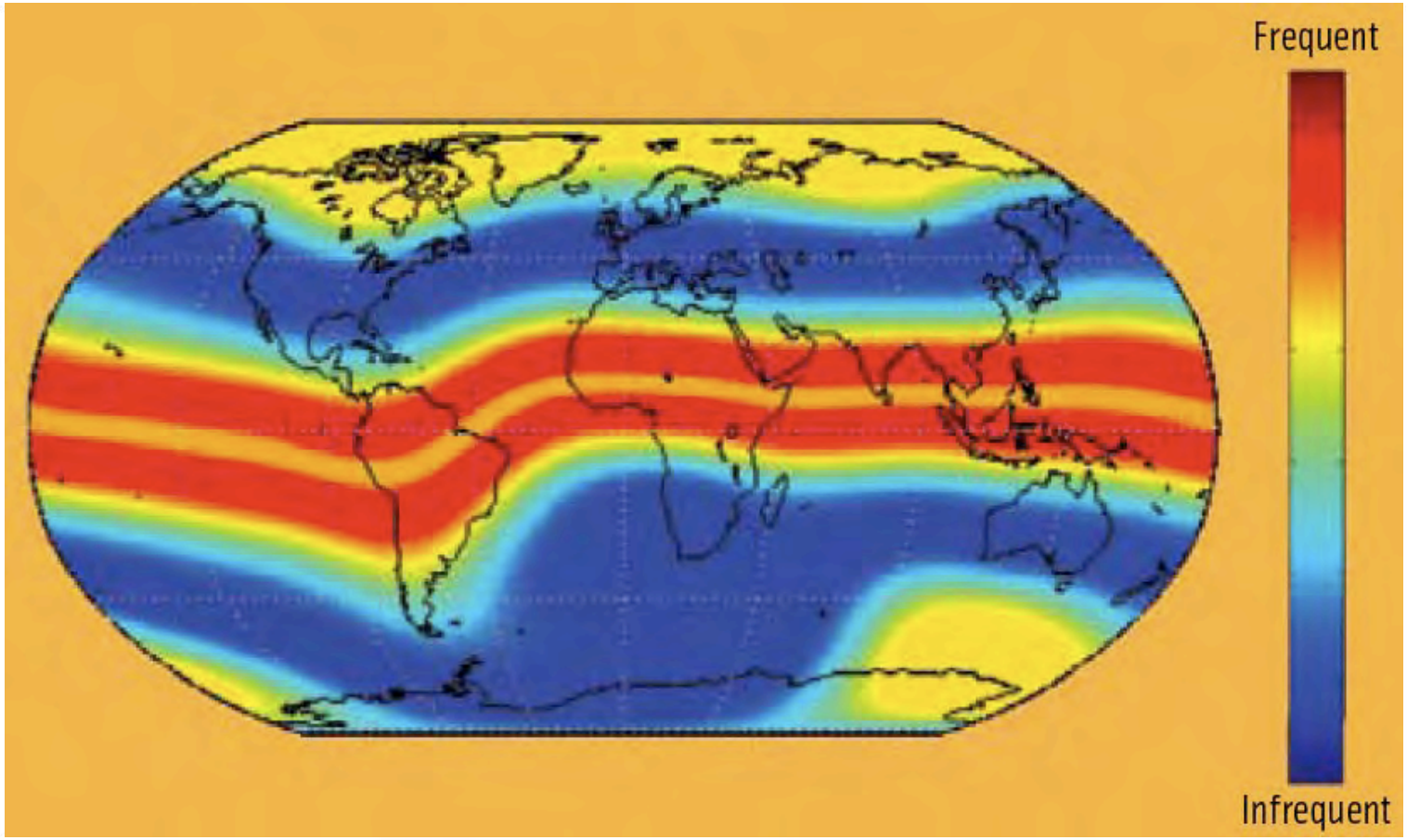


Credit: Bhamer

- Upper portion of Earth's atmosphere
- Extends from 85km to 600km (approx)
- Ionized by solar radiation (primarily UV and X-ray)

Ionospheric Disturbances and Variations

- Due to tilt, rotation, interaction with magnetic field, rate of ionization

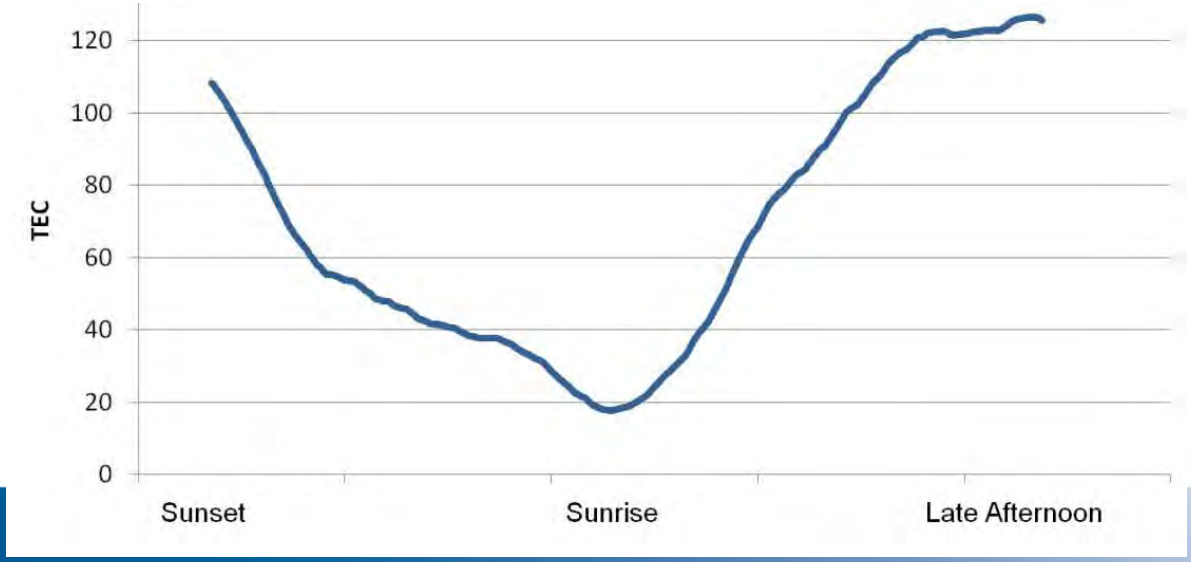


Implications to GNSS – Signal Delay

- Satellites orbit at ~26,500km
- Signals must pass through ionosphere
- Propagation delay is:
  - frequency dependant
    - L1: 1575.42 MHz
    - L2: 1227.60 MHz
    - L5: 1176.45 MHz
  - a function of the amount of ionization (density)
- **Delay = time error = position error**

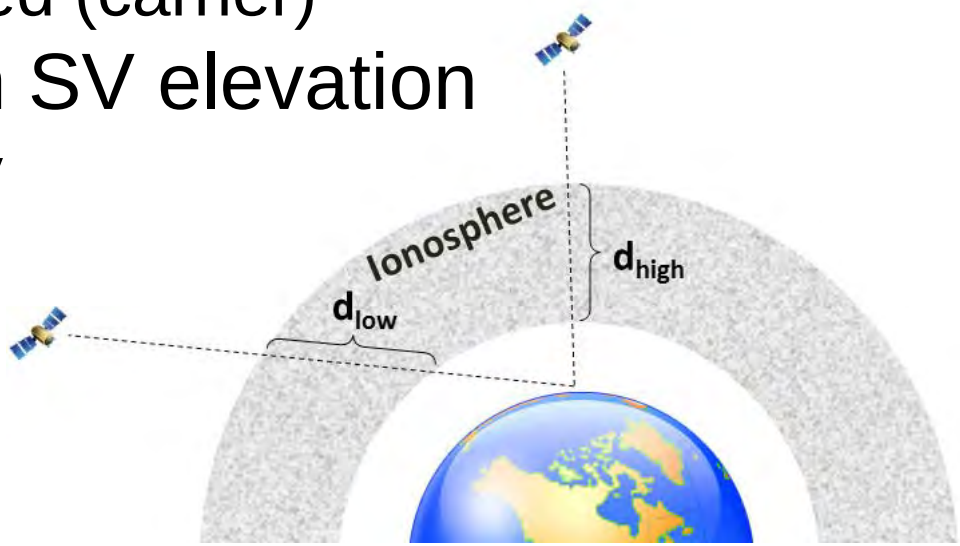
Total Electron Content (TEC)

- A measure of the number of electrons between the satellite and the user's antenna
  - 1 TECU = 10^{16} electrons per m^2
  - 1 TECU = 16.3cm delay at L1
  - 1 TECU = 10.5cm differential delay (L1-L2)
  - 1 TECU = 0.35ns differential delay (L1-L2)



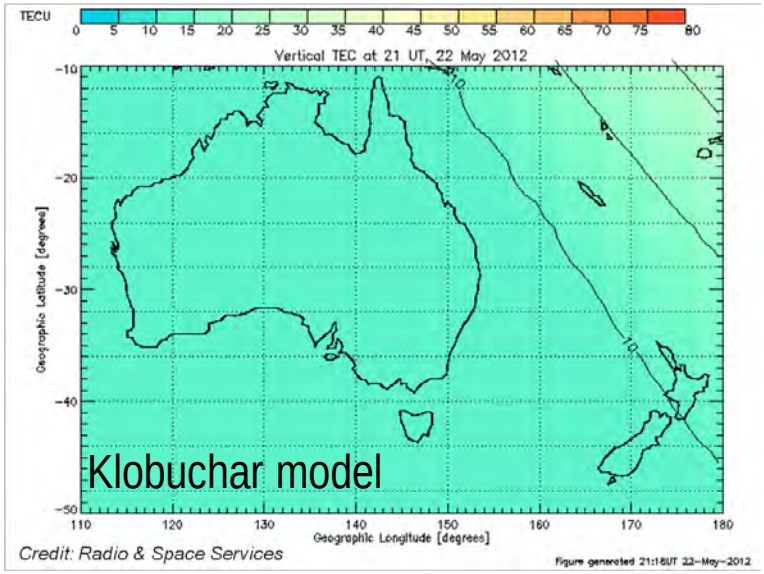
TEC Impact on GNSS

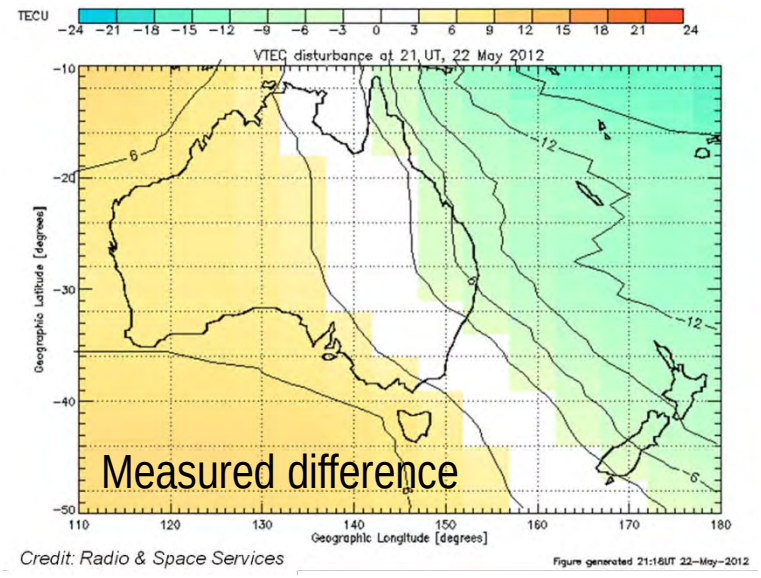
- Code and carrier affected differently
  - Code is delayed (group velocity reduced)
  - Carrier is advanced (phase velocity increased)
- Range measurements are impacted
  - Pseudorange is lengthened (code)
  - Carrier range shortened (carrier)
- TEC delay varies with SV elevation
  - d_{low} – more TEC delay
  - d_{high} – less TEC delay



Klobuchar Model – TEC Estimation

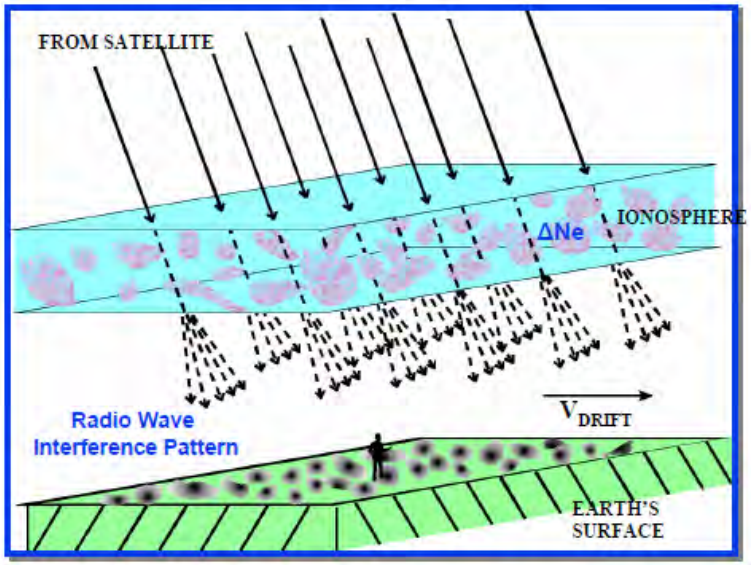
- Parameters broadcast by satellites
- Global model
  - Removes ~50%-60% of ionospheric delay
  - Does not account for local variation

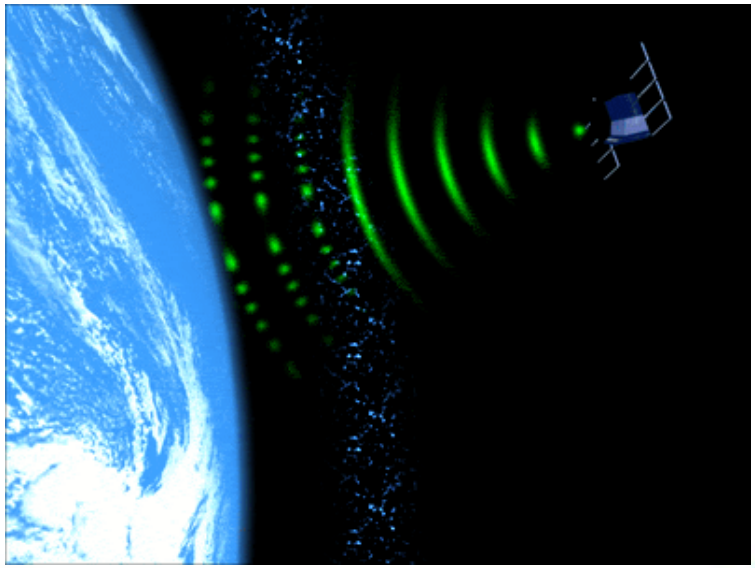




Ionospheric Scintillation

- Occurs when radio waves encounter steep gradients in refractivity
- Rapid temporal fluctuations of signal
  - Amplitude & phase
- Induced by random irregularities
  - Localized pockets
- Can cause both refraction / diffraction





Scintillation Impact on GNSS

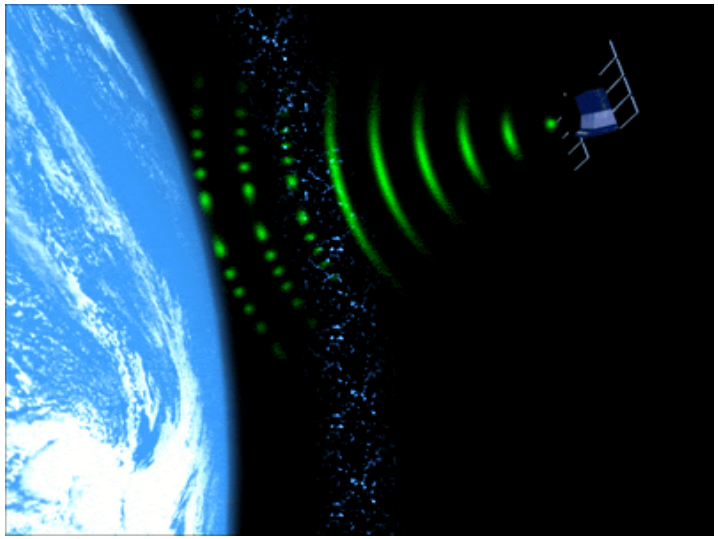
- Amplitude scintillation directly impacts C/No
  - Signal amplitude decreases and increases
    - Signal fades of up to 30 dB can be observed
  - Degraded signal quality: pseudorange & carrier phase
- Phase scintillation will stress the PLLs
  - Can cause cycle-slips and loss of lock

Three Fundamental Parameters

- *Total Electron Content (TEC)*
  - Amount of ionization in ionosphere
- *S4*
  - Variation in received signal strength
- *Sigma-Phi*
  - Variation in signal quality of carrier

NovAtel's GPStation-6™ Receiver

- Next-generation GNSS Ionospheric Scintillation and TEC Monitor (GISTM) receiver
  - 120-channel OEM628 GNSS engine
  - Integrated ultra-low phase-noise OCXO
  - Multi-constellation multi-frequency support
  - Advanced GISTM SW algorithms / outputs

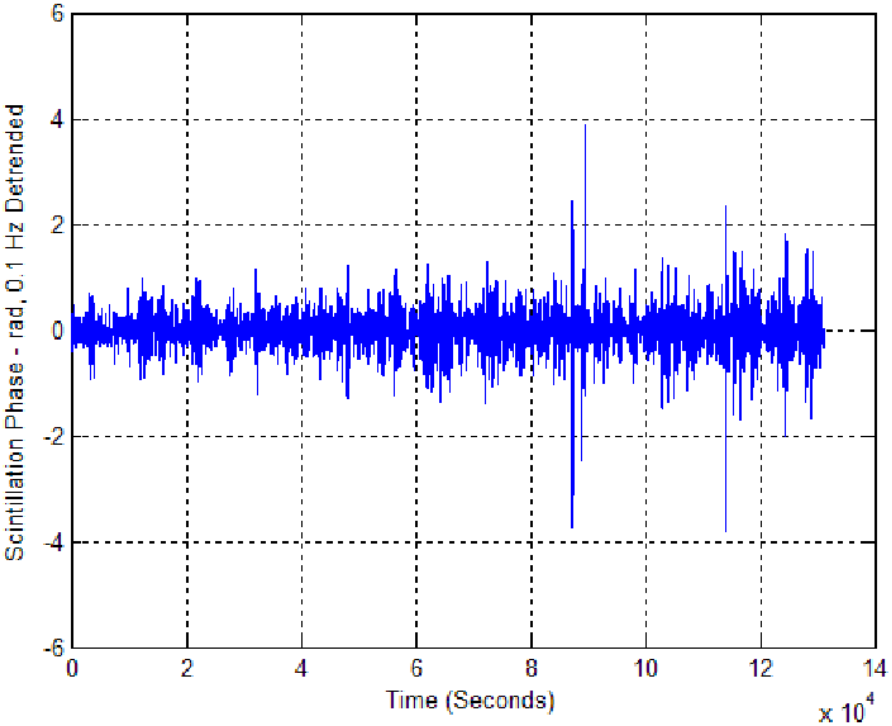


Limitations of a Standard Rx

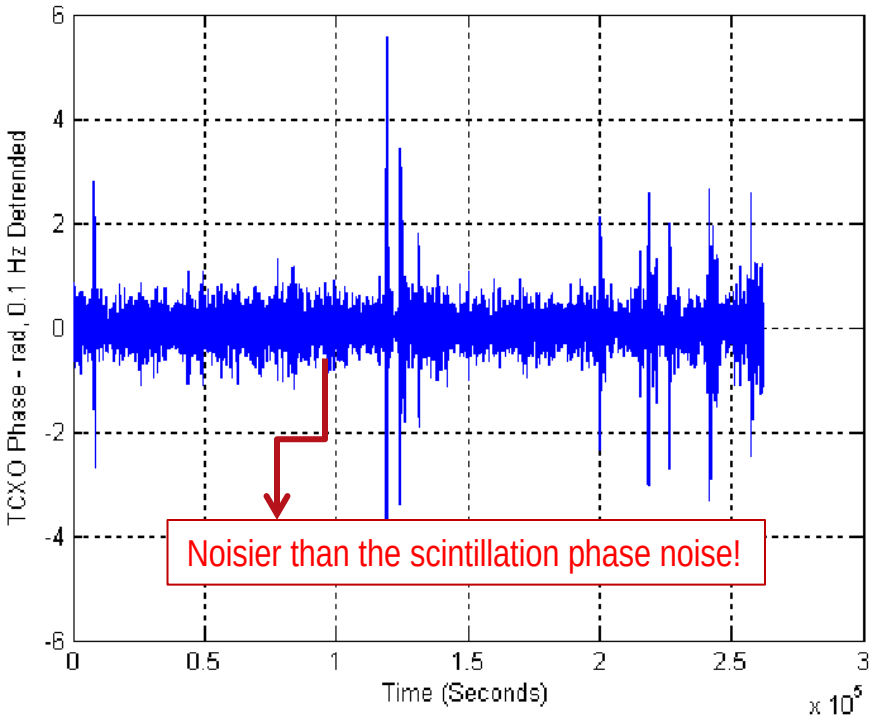
- On-board clock noise limitations
  - TCXO phase noise too high to allow for phase scintillation observations during phase lock
- Ionospheric measurement statistics not available directly
  - Code and carrier TEC, slant TEC
  - Scintillation indices
    - S4 – amplitude scintillation index
    - Sigma-phi (σ_ϕ) – phase scintillation index
- Sampling rate and signal support may be limited

Standard Receiver Phase Noise

- Comparison between a ionospheric scintillation phase noise and Receiver(TCXO)

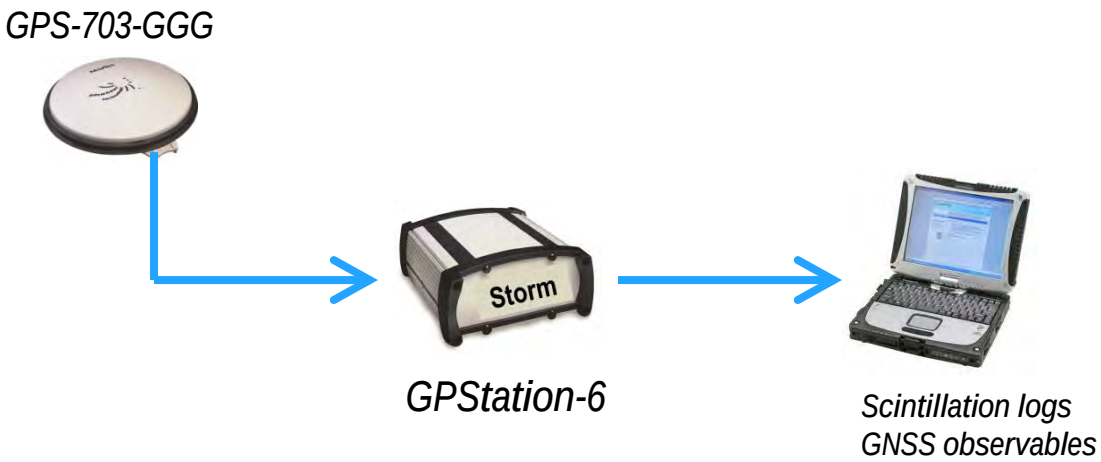


Signal phase noise disturbed by ionospheric scintillation



TCXO phase noise

Example 1: Equatorial Scintillation

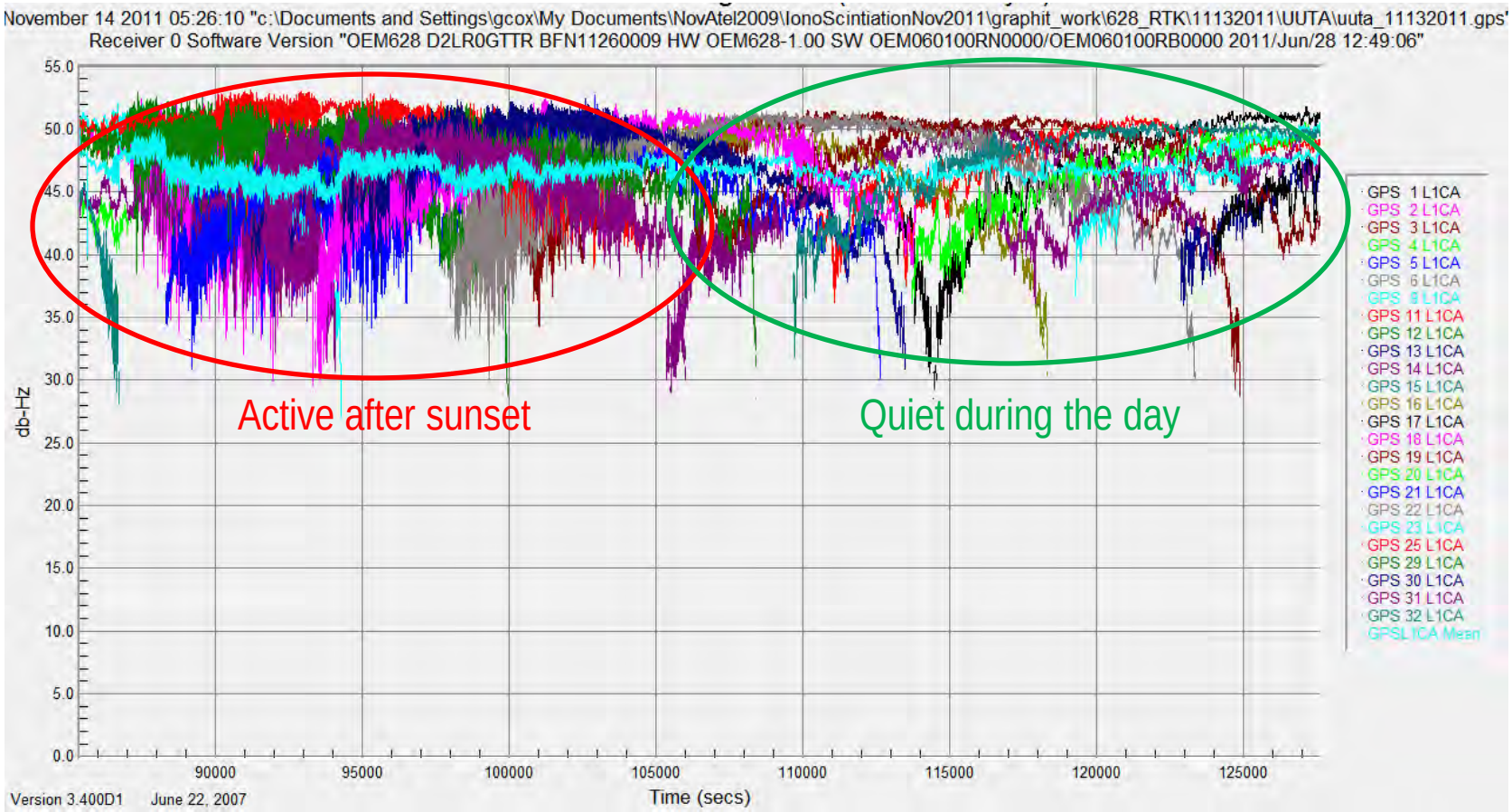


- GNSS data were recorded Nov 14-18, 2011
- GPStation-6 with GPS-703-GGG antenna
- Northern Chile, in close proximity to geomagnetic equator
- Active especially during post sunset period
- Both amplitude and phase scintillation
- Extending up to several hours

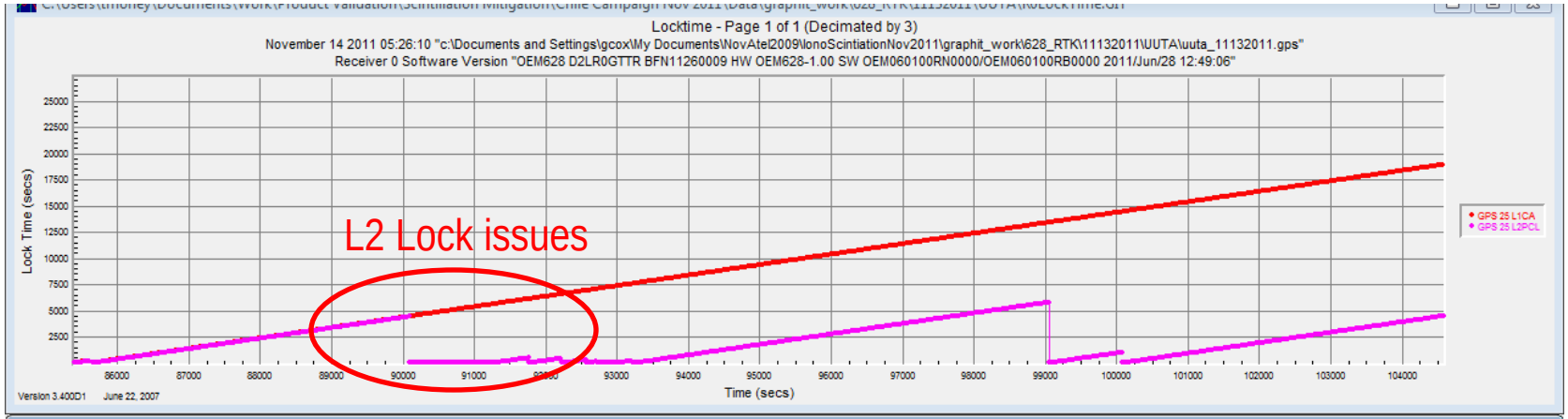
Potential Effects of Ionospheric Activity

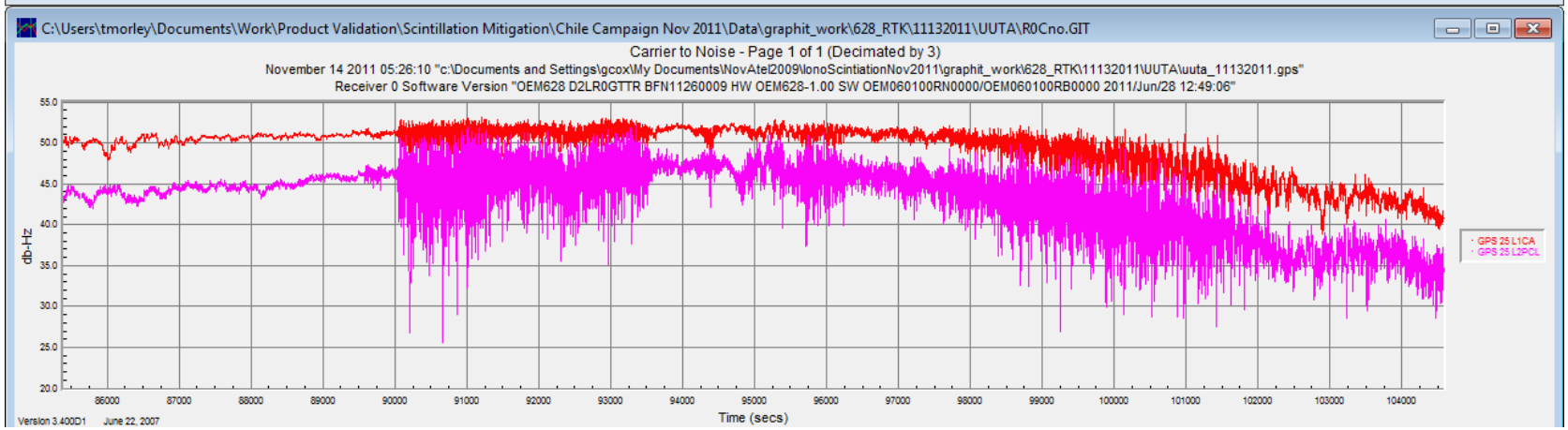
- Depending on severity, ionospheric activity can result in:
  - Degraded pseudorange and/or carrier phase accuracy
  - Cycle slips and loss of lock
  - Degraded navigation solution due to satellite outages or selective exclusion
  - Signal power fading and complete loss of lock

Signal to Noise Ratio (C/N_o)

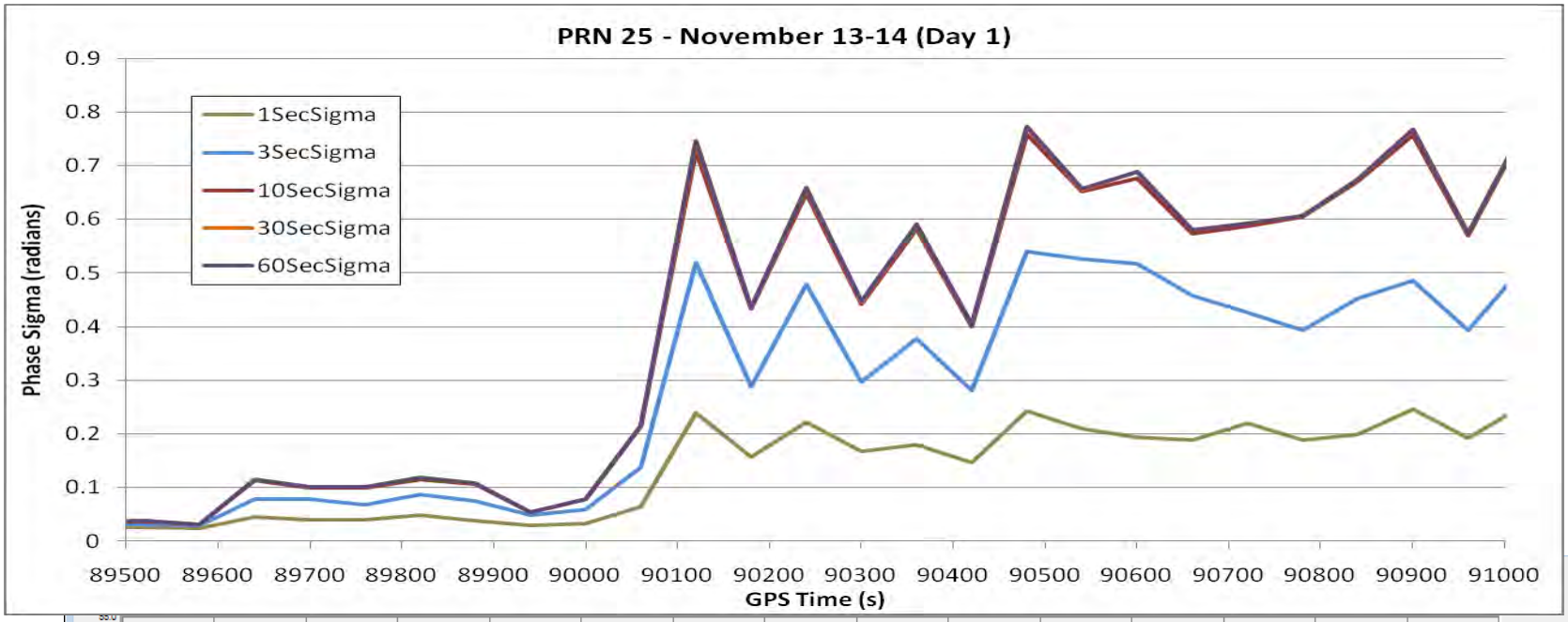


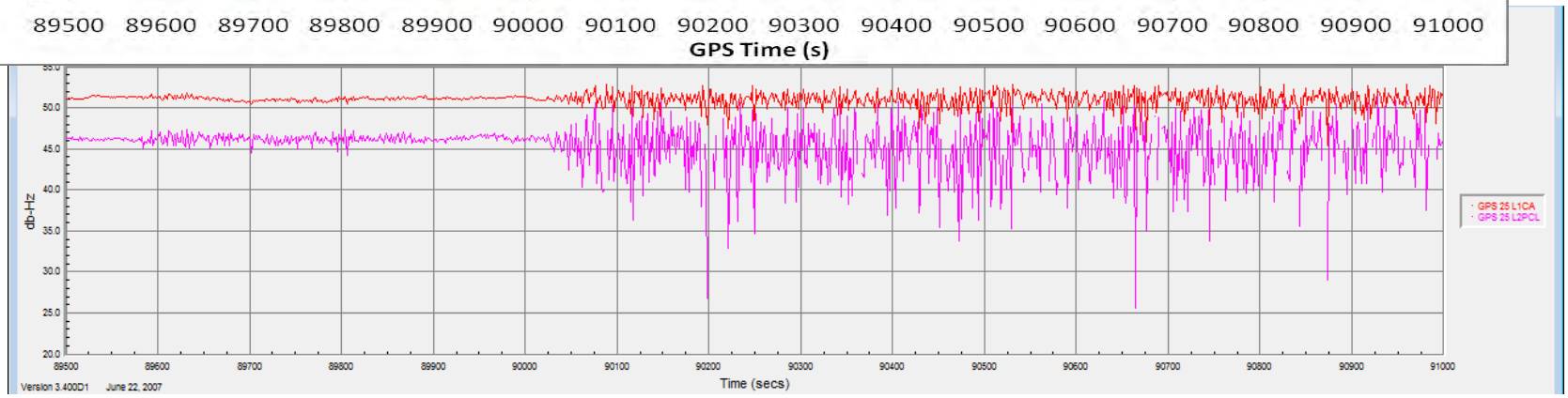
PRN 25 Lock Time and C/N_o



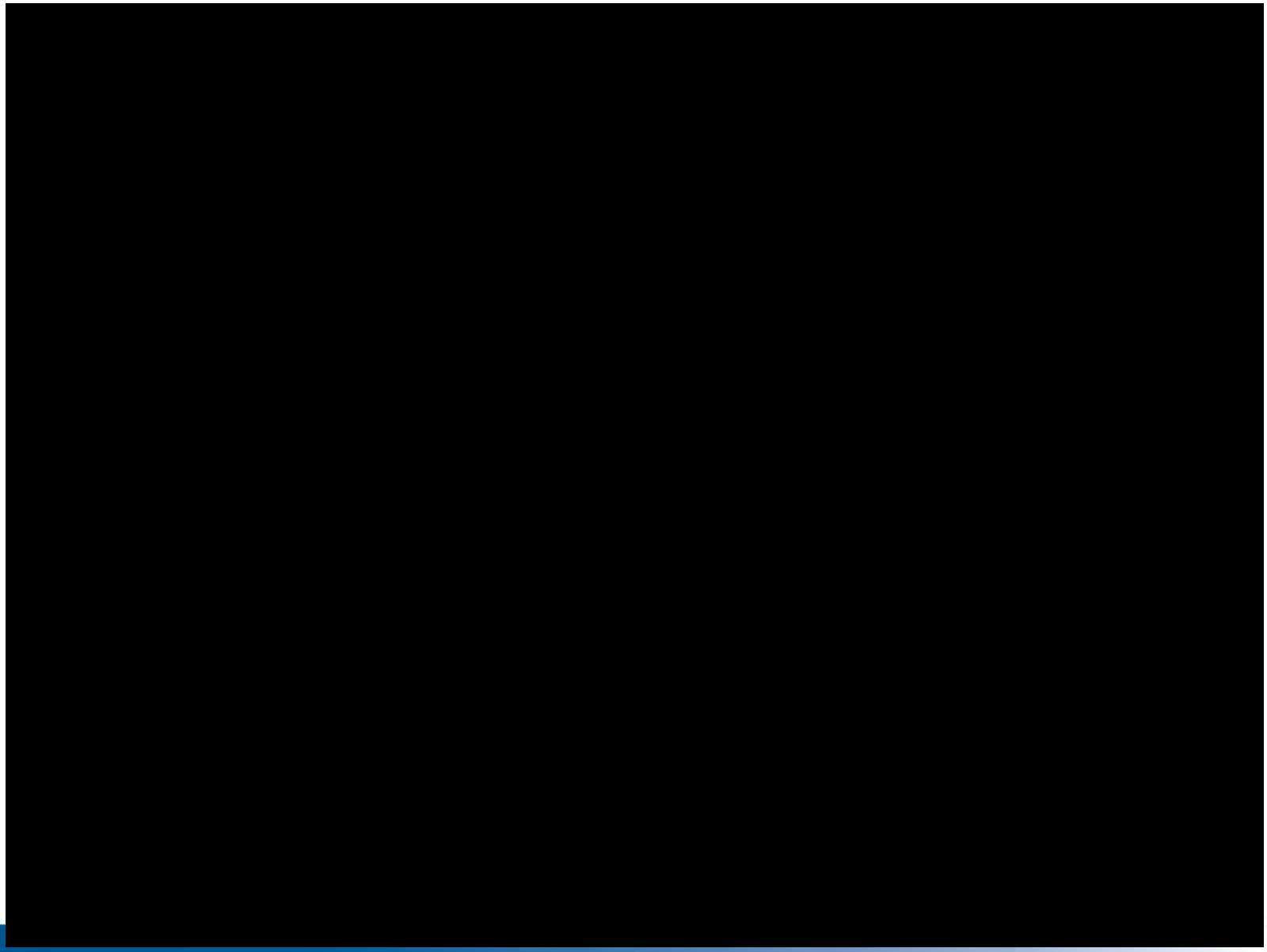


PRN 25 Phase Variation and C/N_o

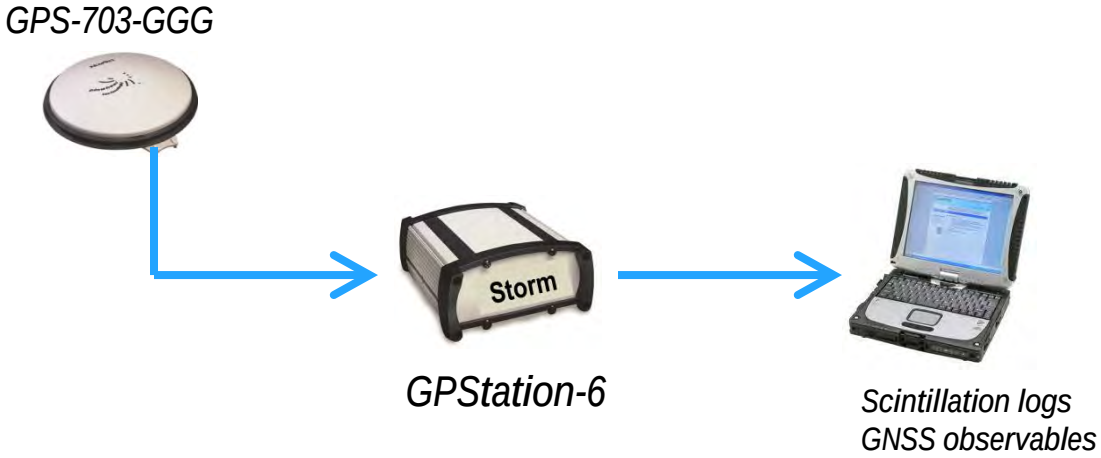




Ionospheric Scintillation – Nov 16-17

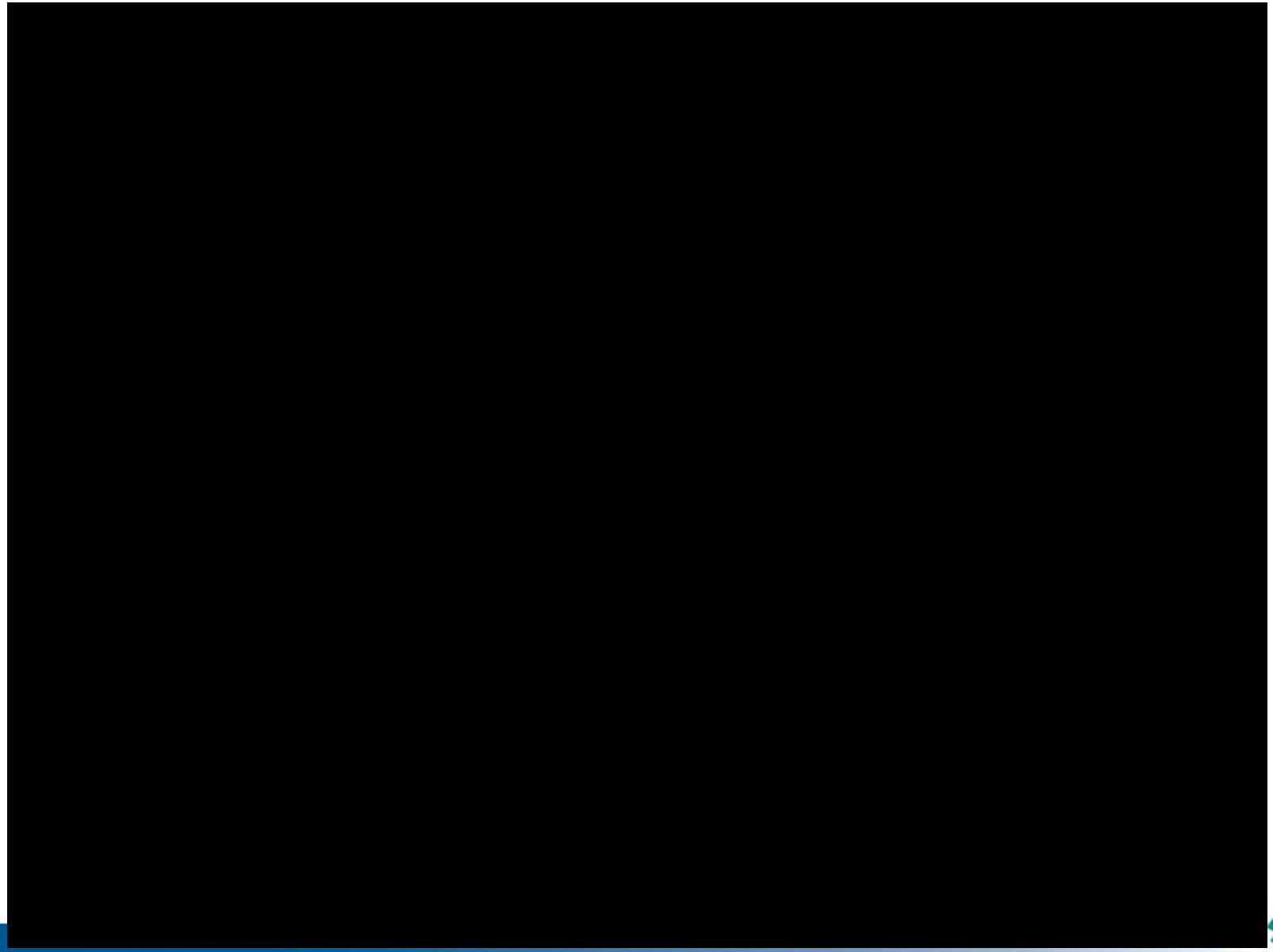


Example 2: Auroral Scintillation

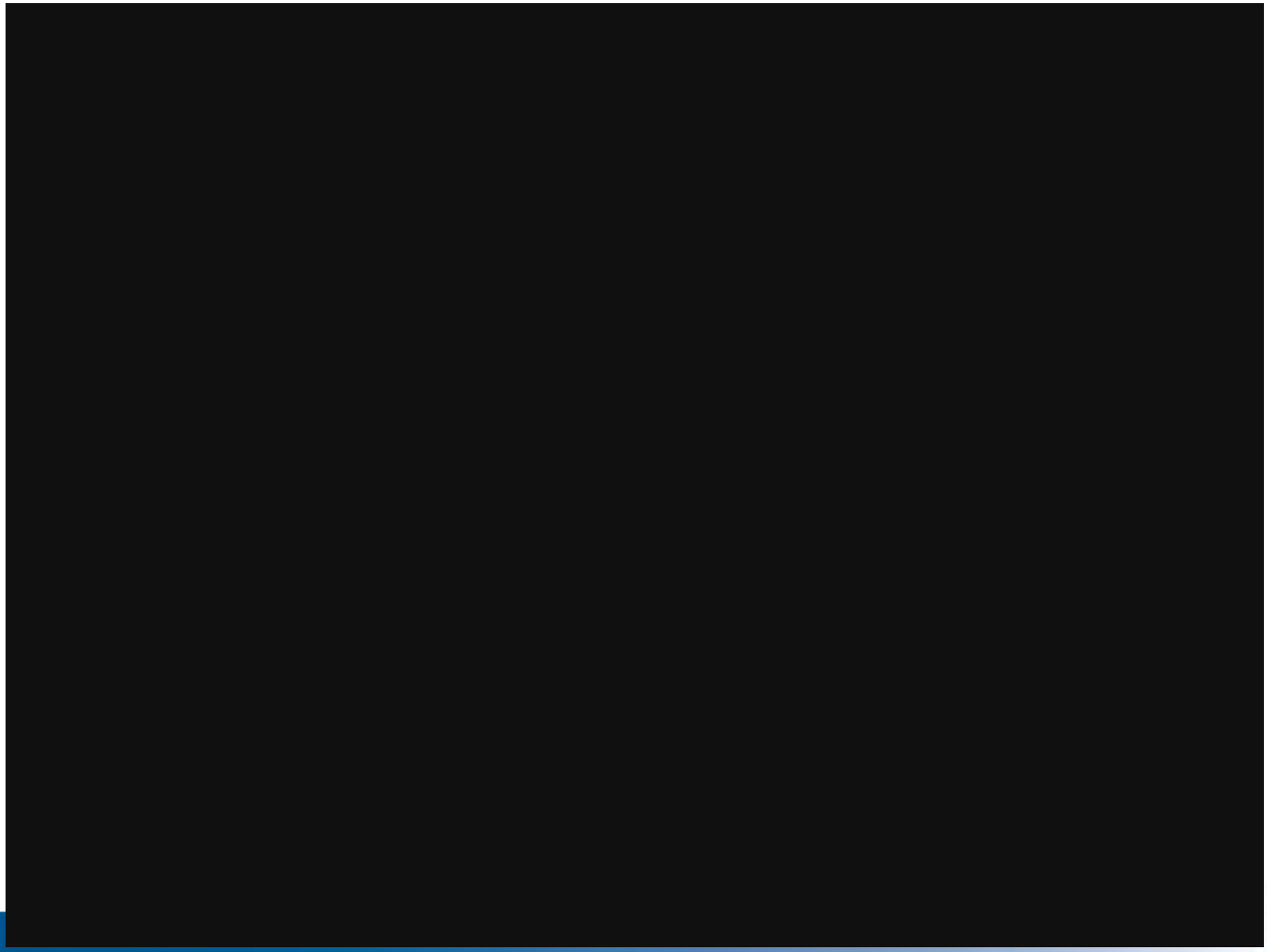


- GNSS data were recorded March 8-9, 2012
- GPStation-6 with GPS-703-GGG antenna
- Calgary (51° N)
- Impact of CME from March 7 X5.4 event
- Only phase scintillation observed
- Phase disturbance for several hours

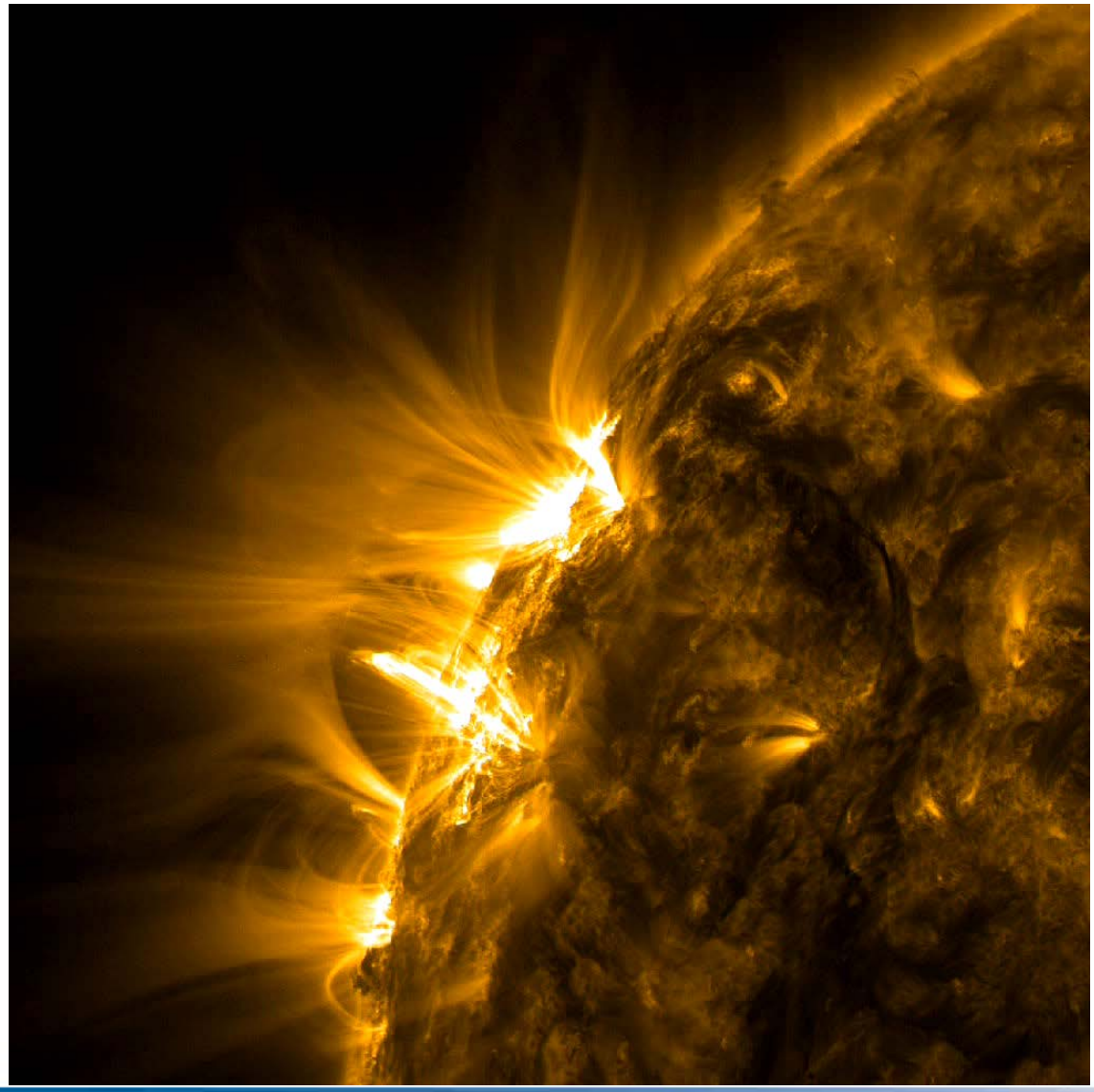
March 7, 2012 – X5.4 Coronal Mass Ejection



March 8-9, 2012 – CME Impact



Summary



Summary

Summary

[redacted]

Thank you!