Solar Maximum

Effects on GNSS Operations
Plus Ionospheric Monitoring

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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

AD 1001 – AD 2001

2000 BC

1000 BC

AD 1

AD 1001

AD 2001

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

Credit: Kiepenheuer-Institut für Sonnenphysik
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/m²) 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

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

*Credit: Bhamer*
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
  - $d_{\text{low}}$ – more TEC delay
  - $d_{\text{high}}$ – 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 ($\sigma_\phi$) – phase scintillation index

• Sampling rate and signal support may be limited
Standard Receiver Phase Noise

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

Signal phase noise disturbed by ionospheric scintillation

TCXO phase noise

Noisier than the scintillation 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/N₀)

Active after sunset
Quiet during the day
PRN 25 Lock Time and C/N₀

L2 Lock issues
PRN 25 Phase Variation and $C/N_0$
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
Summary
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Thank you!