Operational Impacts of Space Weather

R. Lambour, A. J. Coster, R. Clouser,
L. E. Thornton, J. Sharma, and A. Cott

MIT Lincoln Laboratory

2001 Space Control Conference

3 April 2001
Outline

- Introduction – Space Weather
  - Effects on Space-Based Systems
  - Effects on Ground-Based systems
  - Conclusions
Space Weather

• Definition:
  
  "Conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can affect performance and reliability of space-based and ground-based technological systems."*

*National Space Weather Program Strategic Plan, NSF
Effects of Space Weather on Earth

Solar Flare of 14 July 2000
Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects
Effects of Space Weather on Earth

Solar Flare of 14 July 2000
Biggest Solar Storm in Nine Years

Caused very large magnetic storm and ionospheric effects

SOHO – Solar Flare

SOHO – Coronal Mass Ejection

Estimated Planetary K Index (3 hour data)

Updated 2000 Jul 18 23:45:05
NOAA/SSEC Boulder, CO USA

Visible Imaging System/POLAR
The University of Iowa
Effects of Space Weather on Earth

Solar Flare of 14 July 2000
Biggest Solar Storm in Nine Years
Caused very large magnetic storm and ionospheric effects

Near peak of 11 Year solar cycle
Activity on Sun, magnetosphere and ionosphere will be a maximum for the next 2-3 years
Outline

• Introduction – Space Weather

Effects on Space-Based Systems
  – Space-Based Visible sensor
    South Atlantic Anomaly
    Transient effects
    Long-term (?) effects

• Effects on Ground-Based systems

• Conclusions
SBV Sensor

- 15 cm high straylight rejection telescope
- 4 - 420x420 Lincoln Laboratory CCD
- 1.4 x 1.4 deg field of view per CCD
- Staring sensor
SBV Sensor

- 15 cm high straylight rejection telescope
- 4 - 420x420 Lincoln Laboratory CCD
- 1.4 x 1.4 deg field of view per CCD
- Staring sensor

- Target and star detection
- Clutter rejection
- Data compression
South Atlantic Anomoly (SAA)

Energetic particle enhancement at low altitudes due to offset of magnetic field

Flux contours of E > 50 MeV Protons at 500 km
SAA Effects on SBV

Protons with energy > 10 MeV affect SBV focal plane and inhibit ability to observe valid target streaks
Transient Effects: 14 July 2000 Solar Proton Event

NOAA Geosynchronous Space Environment Summary
Transient Effects: 14 July 2000 Solar Proton Event

- Solar flare occurred at end of pinch point CONOPS testing
- One DCE produced no data (day 197)
- Decrease in valid streaks over polar regions seen
- Decrease not attributable to anomalies
Transient Effects: 14 July 2000 Solar Proton Event

- False streaks per frameset increased significantly after solar flare
Transient Effects: 14 July 2000 Solar Proton Event

- False streaks per frameset increased significantly after solar flare

Influx of solar protons over poles degraded SBV performance
Long Term (?) Space Environment Effects

SAA
Long Term (?) Space Environment Effects
Long Term (?) Space Environment Effects

- Area with reduced detections south of SAA noticed in 1998-1999
- Effect investigated by looking geographic distribution of valid and false streaks
Long Term (?) Space Environment Effects

Region of interest

Valid Streaks per Look

False Streaks per Look

day 001 to 090, 2000

SAA
Long Term (?) Space Environment Effects

SAA

Region of interest

Area of degraded performance persists into 2000
Energetic Particle Source Regions

> 6900 keV proton data from NOAA POES MEPED sensor

- NOAA baseline plots show increase in trapped outer-zone protons south of SAA in recent years
- Consistent with location of degraded SBV performance

0°-detector

90°-detector
Outline

• Introduction – Space Weather
• Effects on Space-Based systems

Effects on Ground-Based systems
  – Range Delay
  – Scintillation
  – July 14-15th storm

• Conclusions
Ionospheric Refraction

- Cylinder of Cross-Sectional Area = 1 m²
- Ionospheric Shell Height
- Total Electron Content (TEC) Shown as Dotted Outline of Cylinder, in el/m²
- IRI-95 Profile
- Receiver

MIT Lincoln Laboratory
Illustration of Atmospheric Effects

Range Delay

\[ n_{\text{ionosphere}} \approx 1 - \frac{AN_e}{f^2} \]

\[ \Delta R_{\text{ion}}(\text{meters}) = \frac{40.3}{f^2} \int_0^R N_e \, dr \]
Illustration of Atmospheric Effects

Range Delay

\[ n_{ionosphere} \approx 1 - \frac{AN_e}{f^2} \]

\[ \Delta R_{ion} (meters) = \frac{40.3}{f^2} \int_0^R N_e \, dr \]

<table>
<thead>
<tr>
<th>Range Delay</th>
<th>S-Band</th>
<th>L-Band</th>
<th>UHF</th>
<th>VHF</th>
<th>Elev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionosphere</td>
<td>6 m</td>
<td>32 m</td>
<td>280 m</td>
<td>2 km</td>
<td>&lt; 20 °</td>
</tr>
</tbody>
</table>
GRIMS: GPS Real-Time Ionospheric Monitoring System

- MIT Lincoln Laboratory built the first real-time ionospheric monitoring system based on GPS (1991).
  - Purpose: Part of a radar calibration system. Operational systems online at FPS-85, ALTAIR, and Millstone satellite tracking radars.

TEC as Function of Azimuth and Elevation around Millstone Hill Radar, MA
Scintillation can cause additional errors.

For GPS, the primary issue is loss of lock. For radars, the primary issue is degradation of coherent integration capabilities.
ALTAIR VHF Observations on CAL Sphere 2826:
Normal Conditions versus Severe Scintillation

ALTAIR VHF Tracks
Calibration Sphere 2826
.5 m diameter, 850 km circular orbit

Normal Spectrum

Spectrum in Severe Scintillation
Solar Flare of 14 July 2000

Biggest Solar Storm in Nine Years
Strikes Earth
Solar Flare of 14 July 2000

Biggest Solar Storm in Nine Years
Strikes Earth

Est. Planetary Kp (3 Hr.) Begin: 2000 Jul 14 0000 UT

NOAA/SEC Boulder, CO USA
TEC Disturbances on 15 July 2000

UTC Time (Hours) starting at day 197
TEC Disturbances on 15 July 2000

UTC Time (Hours) starting at day 197

TEC Disturbances on 15 July 2000

UTC Time (Hours) starting at day 197

TEC Units

POR4
WES2
NRC1
MHR3
EGL2

0 5 10 15 20 25 30
GPS Loss of Lock at Ottawa and Millstone Hill

- **GPS Loss of Lock at Ottawa**

- **Local Westward Ion Velocity at Millstone Hill**

- **Zenith TEC Over Millstone Hill**

- Loss of Lock on GPS L2 signal
Range Residuals on Calibration Sphere 7646
FPS-85 Florida

Typical Residuals

July 15th storm effects
Summary

- **Space-Based Visible sensor sensitive to proton radiation environment (e.g., SAA)**
  - Transient effects (solar proton events) can degrade SBV performance
  - Long-term changes in the radiation environment may also affect performance of space-based sensors

- **Ground-based radar measurements: ionosphere introduces errors**
  - Range Delay and Angle Errors
  - Scintillation

- In general, geomagnetic storms make these errors larger and harder to model

- Understanding of space environment facilitates future space-based and ground-based systems