



Operational Impacts of Space Weather

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L. E. Thornton, J. Sharma, and A. Cott**

MIT Lincoln Laboratory

2001 Space Control Conference

3 April 2001



Outline



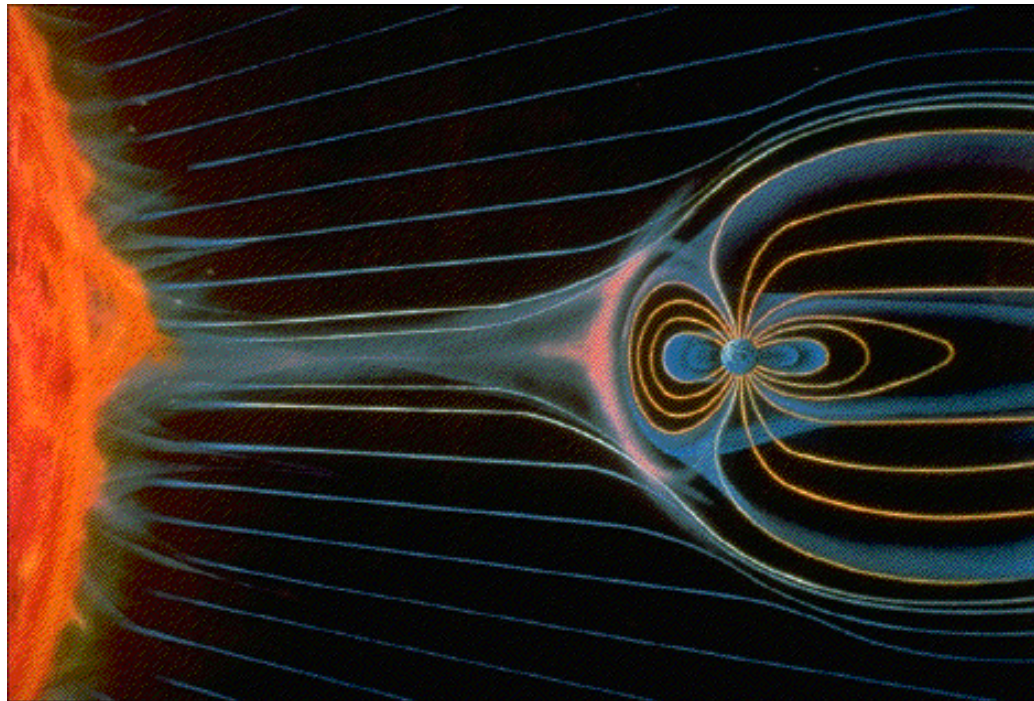
Introduction – Space Weather

- **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.”****

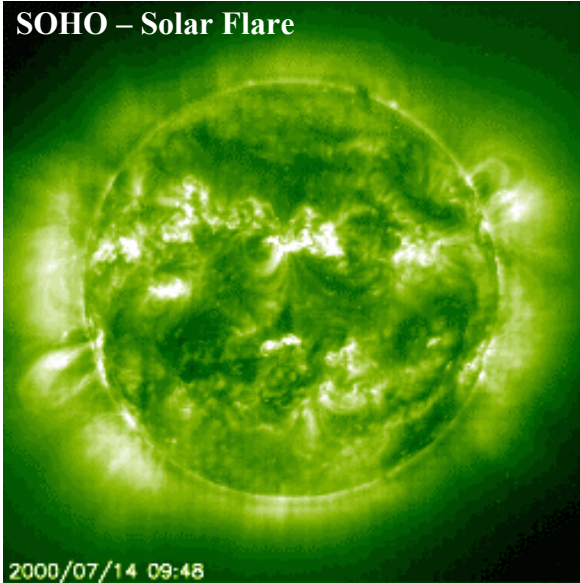


*National.Space.Weather.Program.Strategic.Plan,.NSF

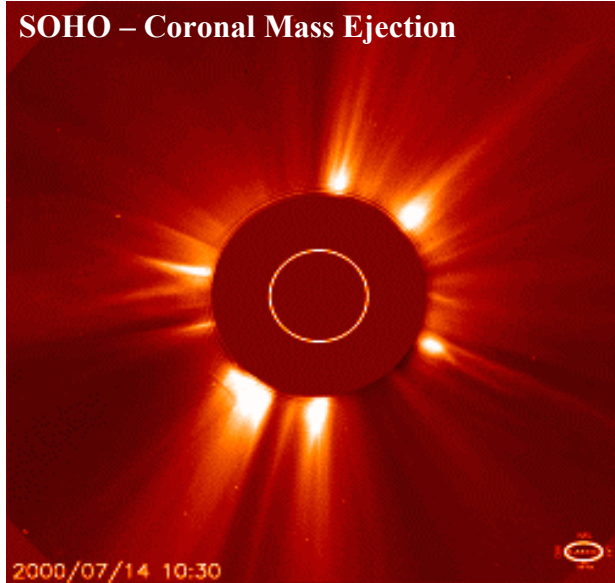


Effects of Space Weather on Earth

SOHO – Solar Flare



SOHO – Coronal Mass Ejection

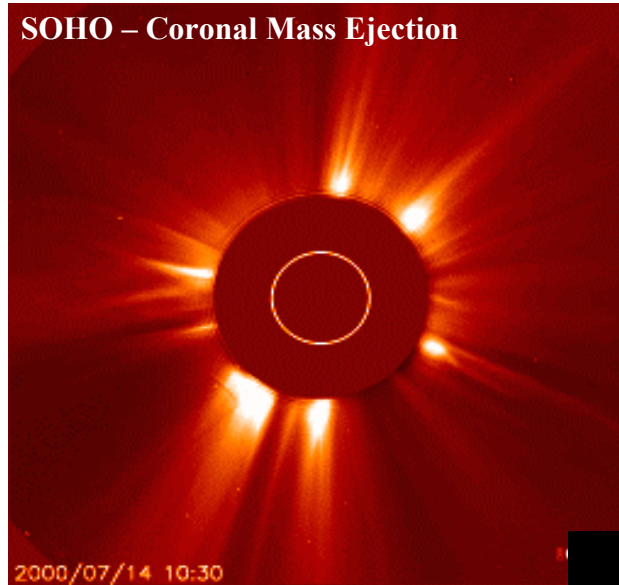
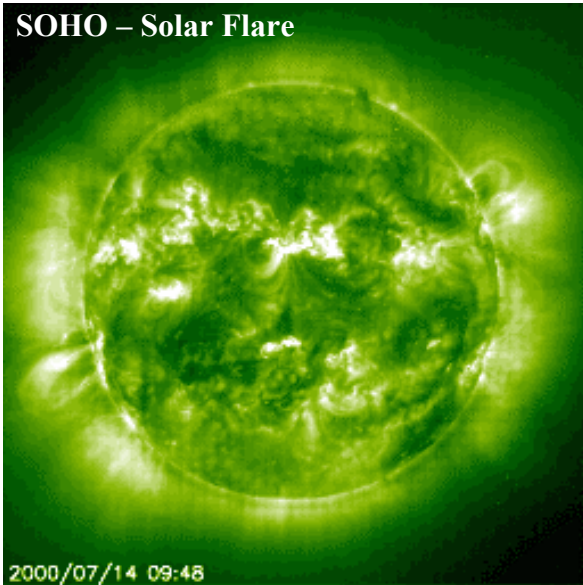


**Solar Flare of 14 July 2000
Biggest Solar Storm in
Nine Years**

**Caused very large
magnetic storm and
ionospheric effects**

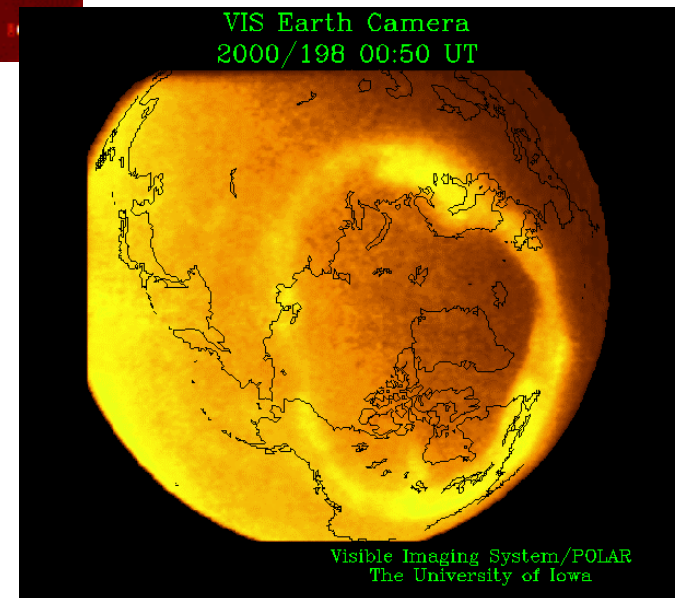
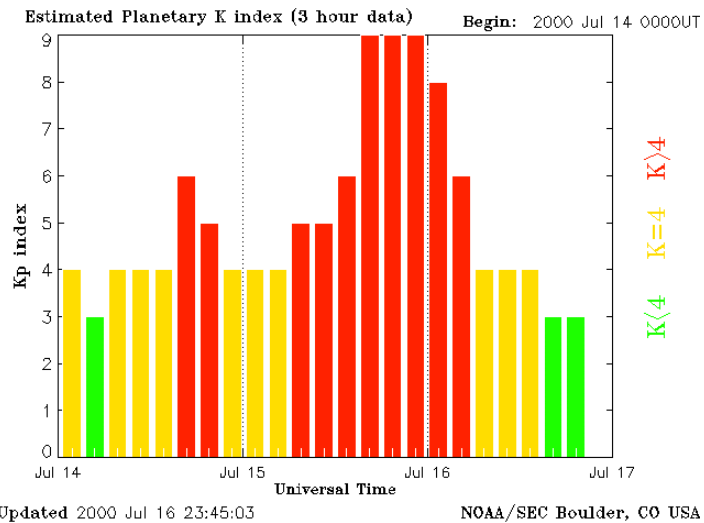
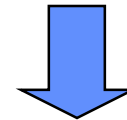


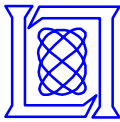
Effects of Space Weather on Earth



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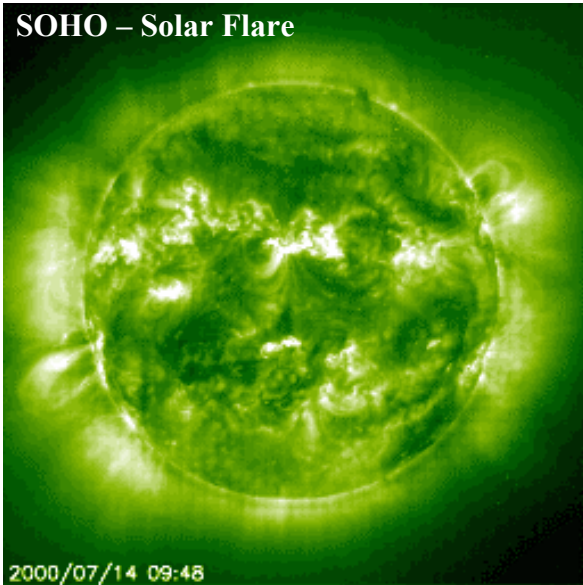
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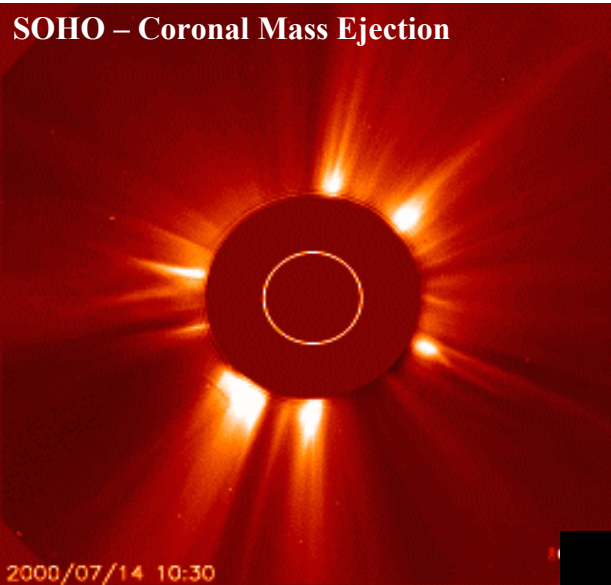


Effects of Space Weather on Earth

SOHO – Solar Flare

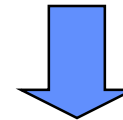


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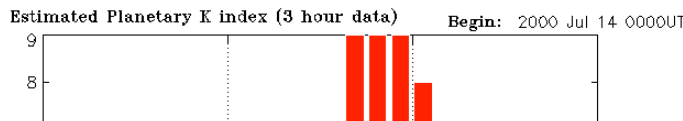


**Solar Flare of 14 July 2000
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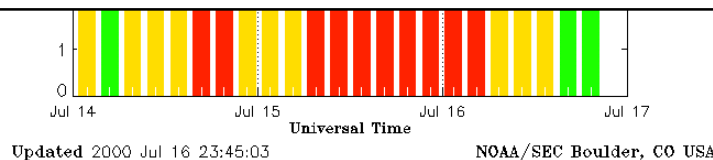


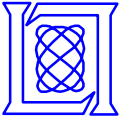
VIS Earth Camera
2000/198 00:50 UT



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

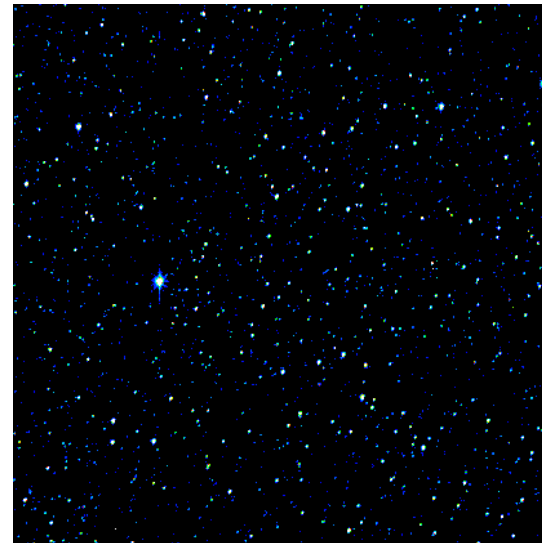
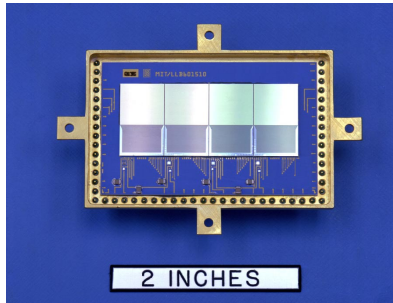
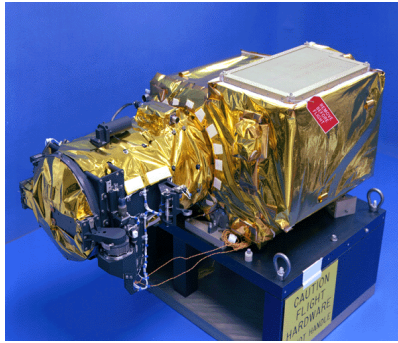
- Transient effects

- Long-term (?) effects

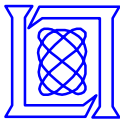
- **Effects on Ground-Based systems**
- **Conclusions**



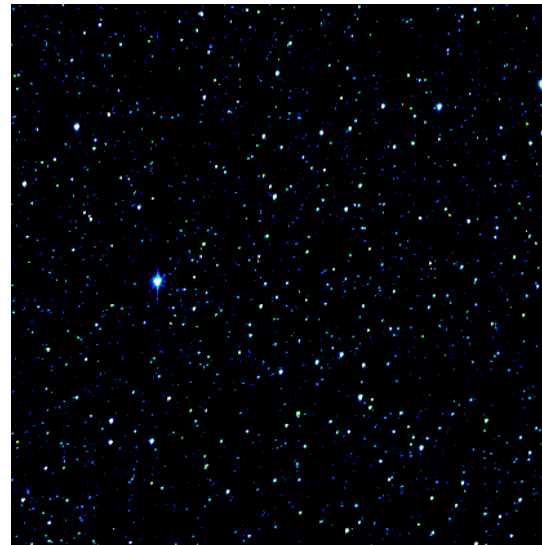
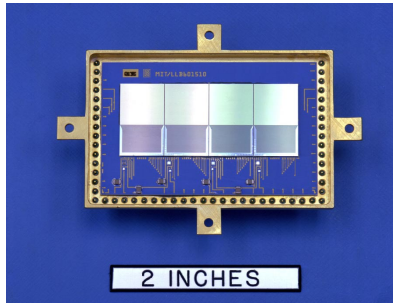
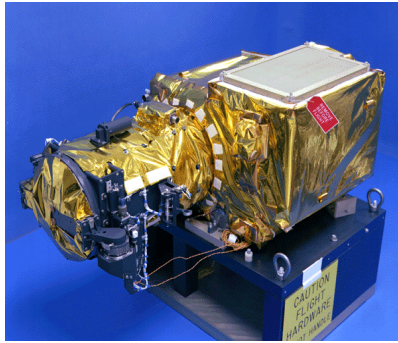
SBV Sensor



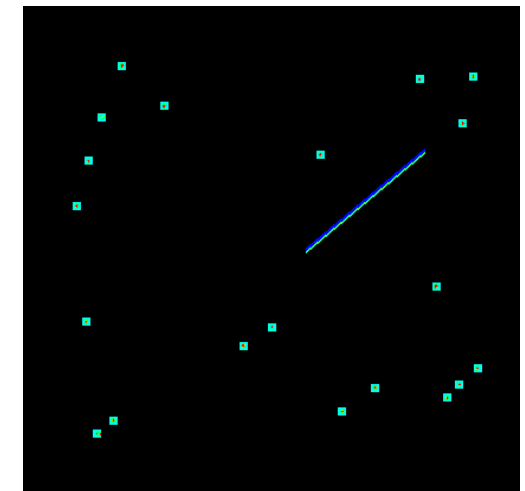
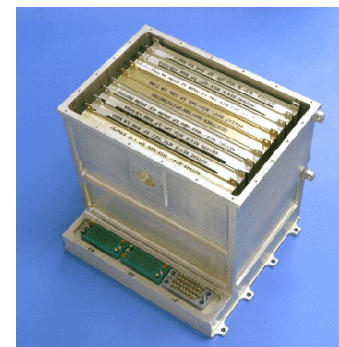
- 15 cm high straylight rejection telescope
- 4 - 420x420 Lincoln Laboratory CCD
- 1.4 x 1.4 deg field of view per CCD
- Staring sensor



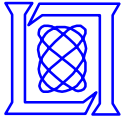
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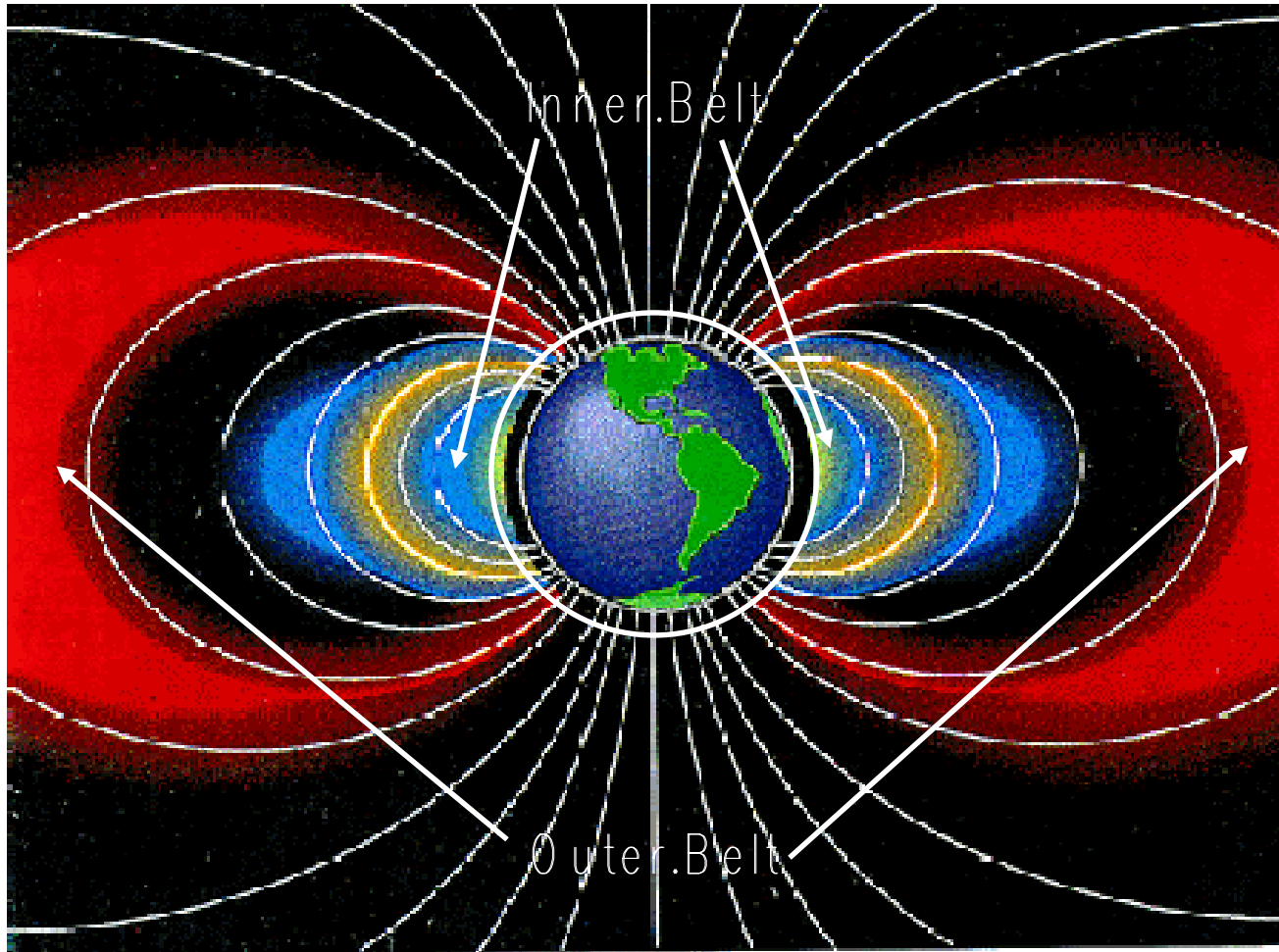
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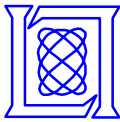


- Target and star detection
- Clutter rejection
- Data compression



Space Environment Effects on SBV

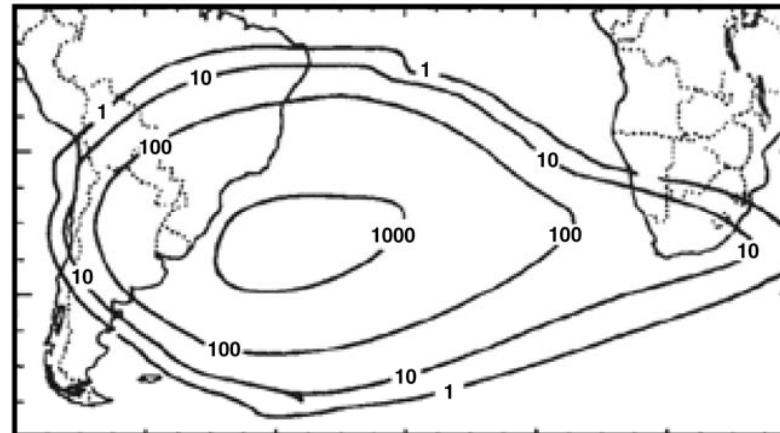




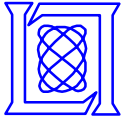
South Atlantic Anomaly (SAA)



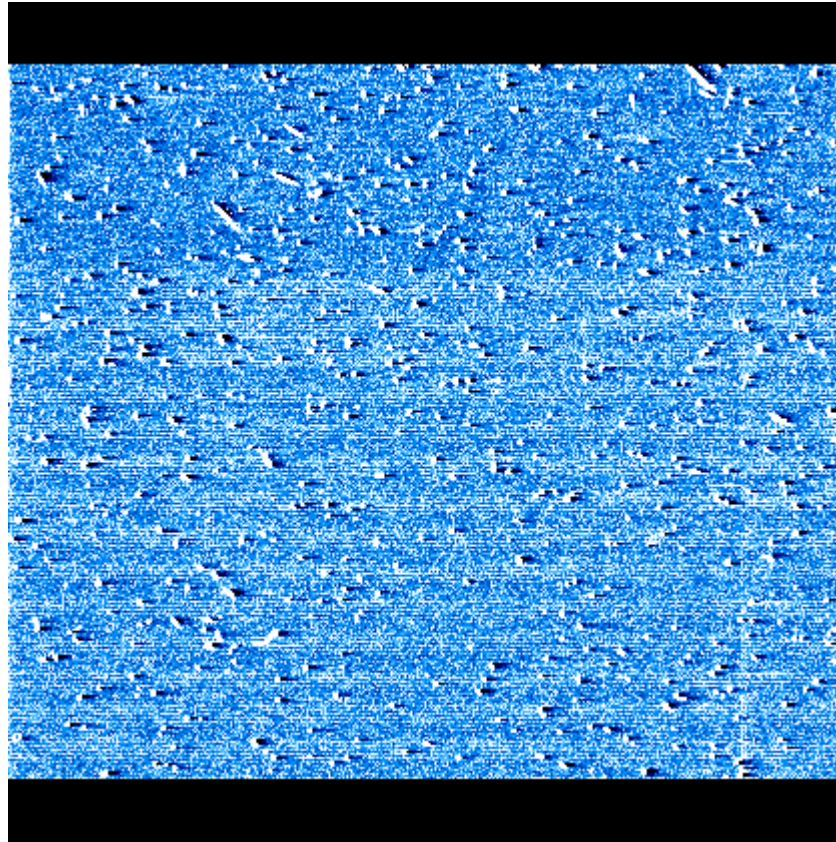
Flux contours of $E > 50$ MeV Protons at 500 km



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



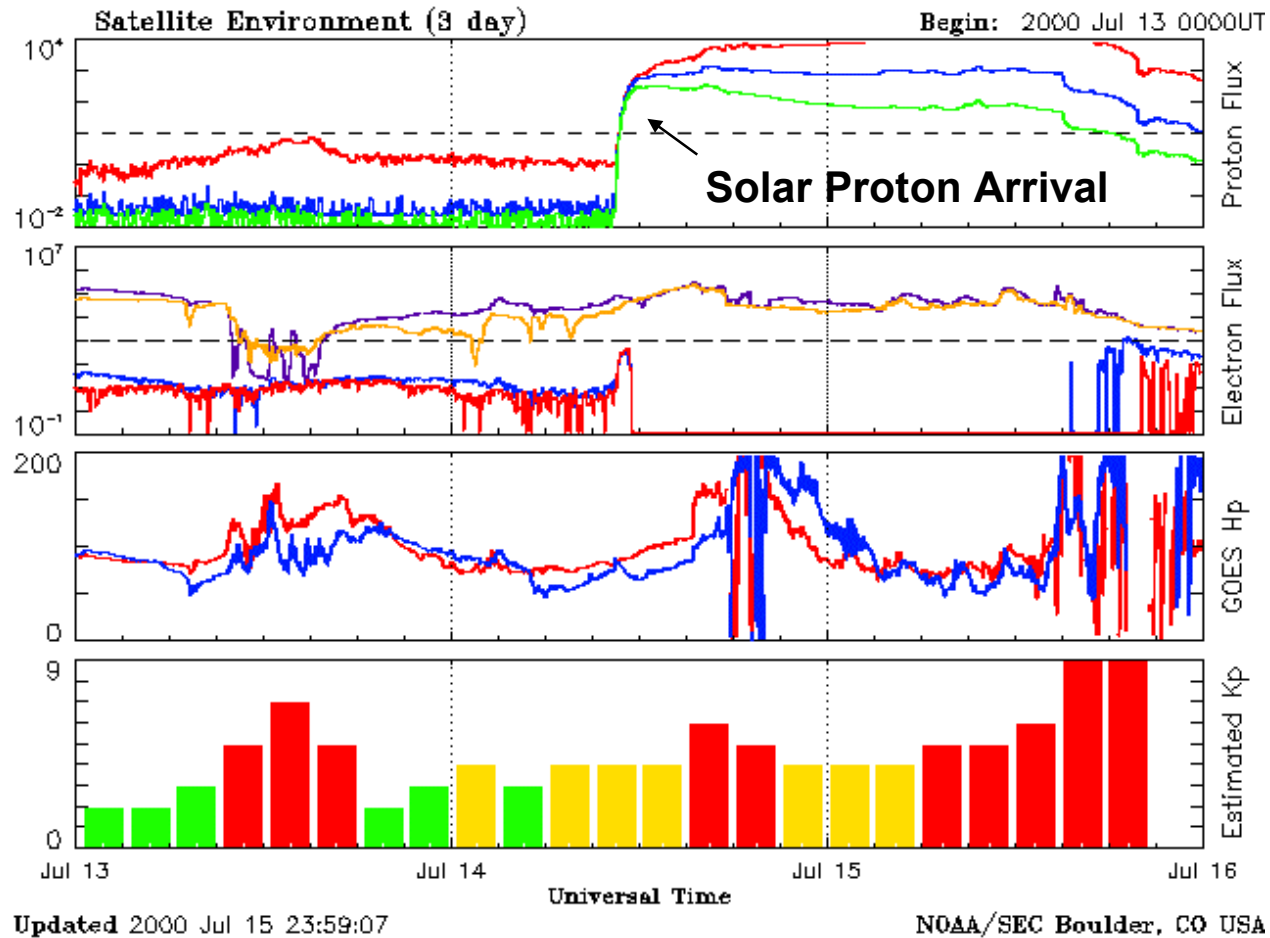
SAA Effects on SBV



**Protons with energy > 10 MeV affect SBV focal plane
and inhibit ability to observe valid target streaks**



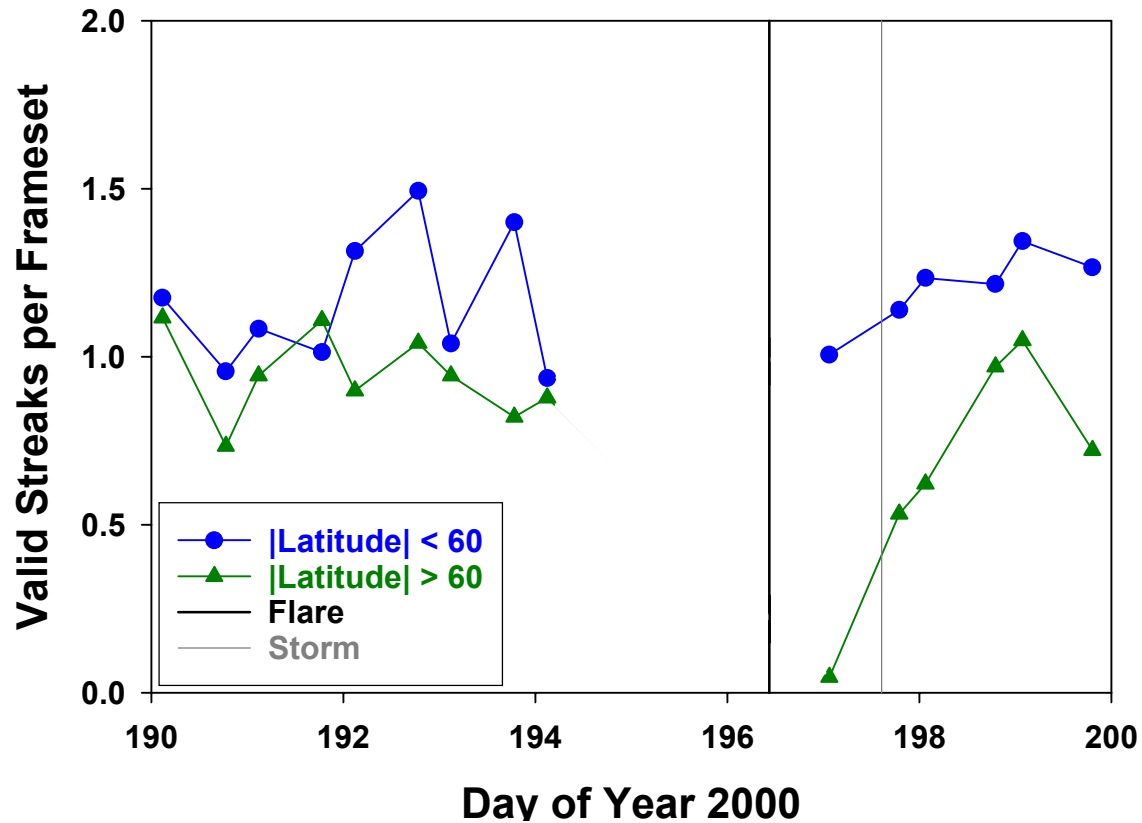
Transient Effects: 14 July 2000 Solar Proton Event



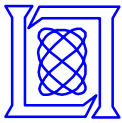
NOAA Geosynchronous Space Environment Summary



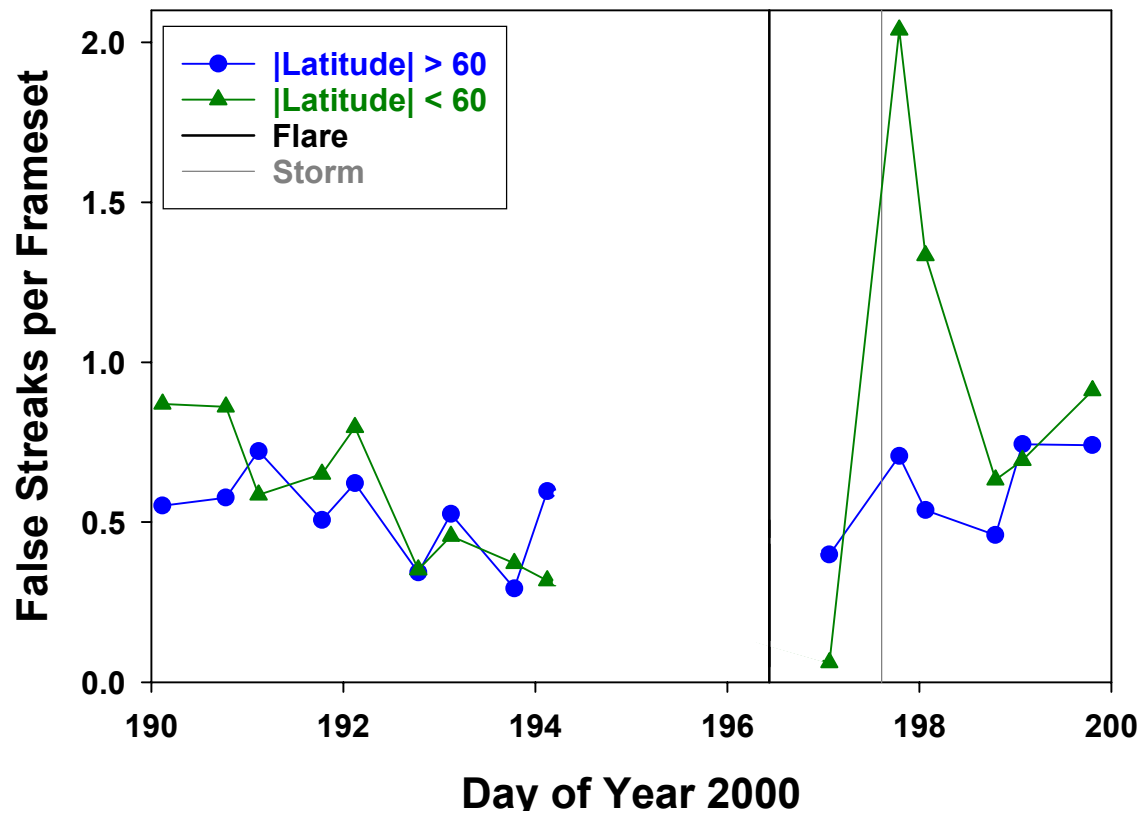
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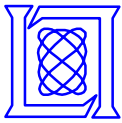
- Solar flare occurred at end of pinch point CONOPS testing
- One DCE produced no data (day 197)
- Decrease in valid streaks over polar regions seen
- Decrease not attributable to anomalies



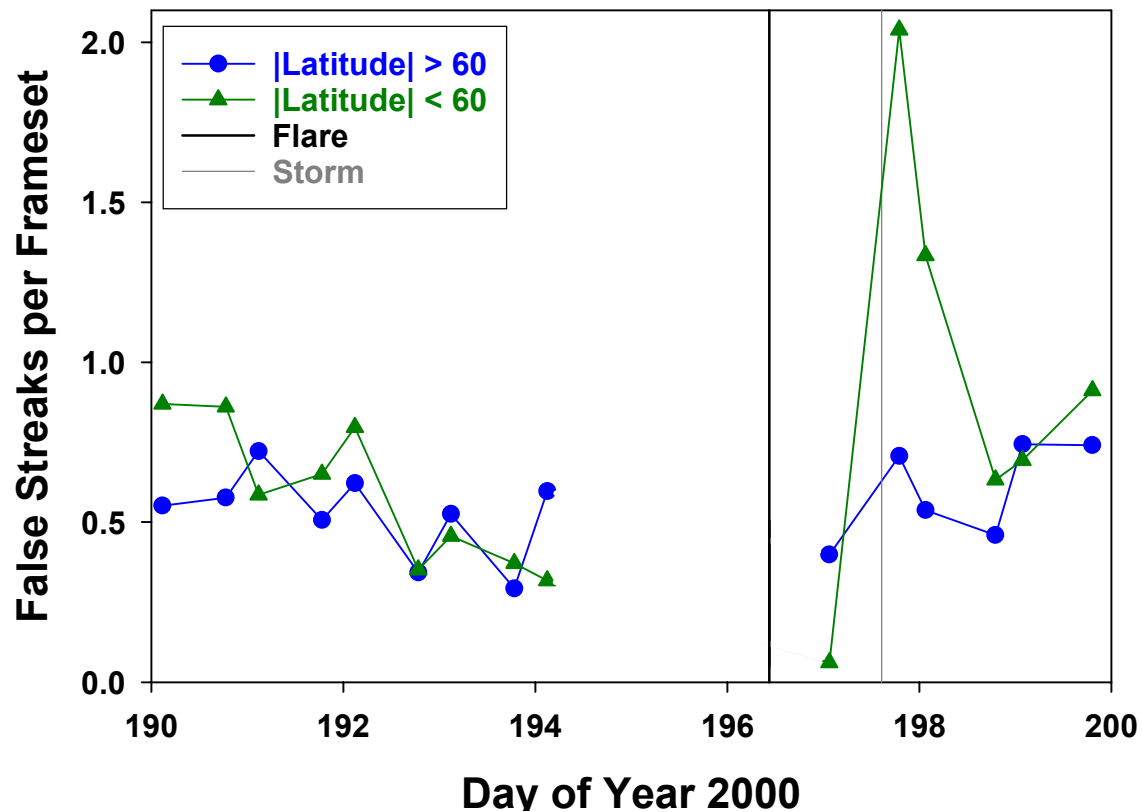
Transient Effects: 14 July 2000 Solar Proton Event



- False streaks per frameset increased significantly after solar flare



Transient Effects: 14 July 2000 Solar Proton Event

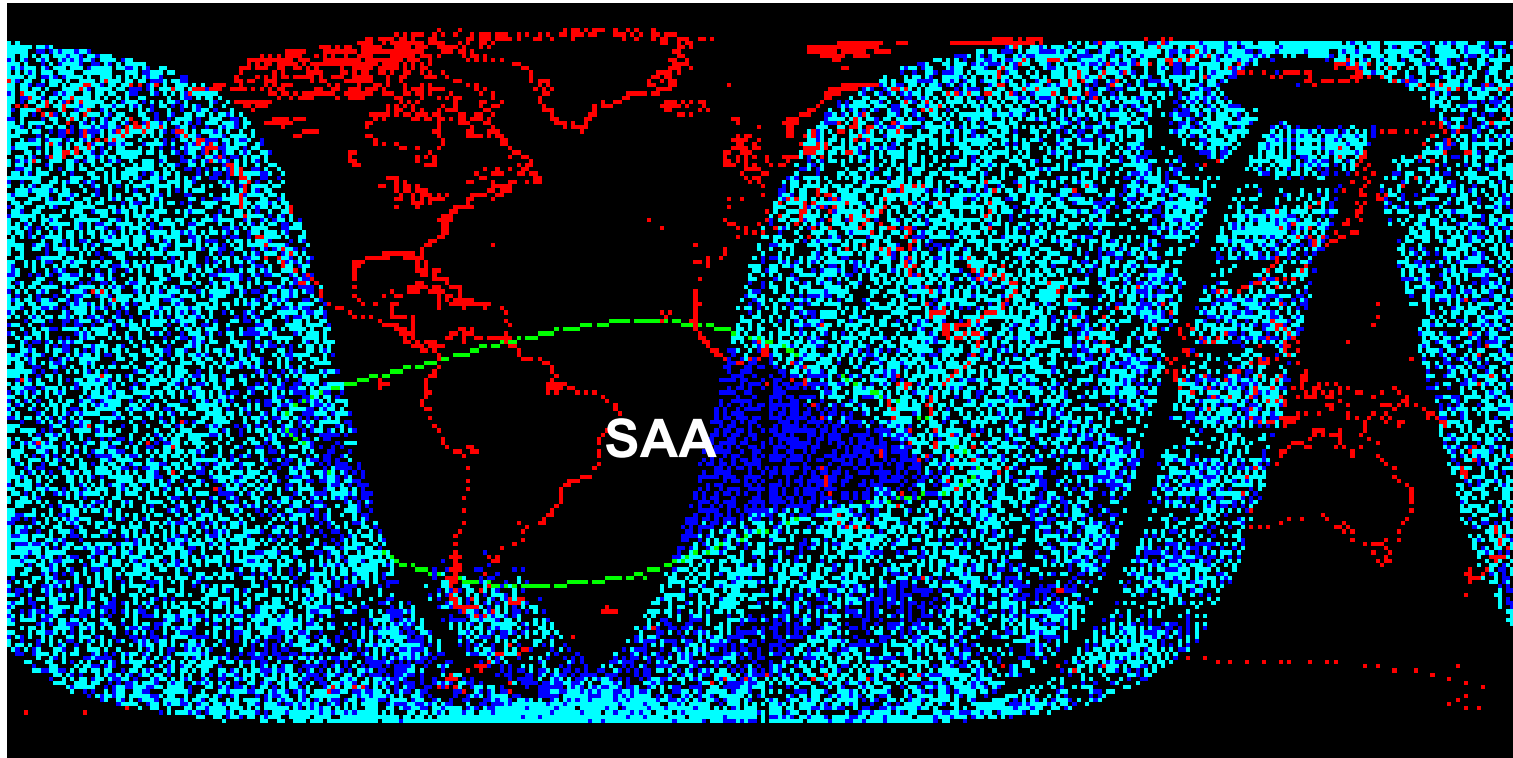


- False streaks per frameset increased significantly after solar flare

Influx of solar protons over poles degraded SBV performance

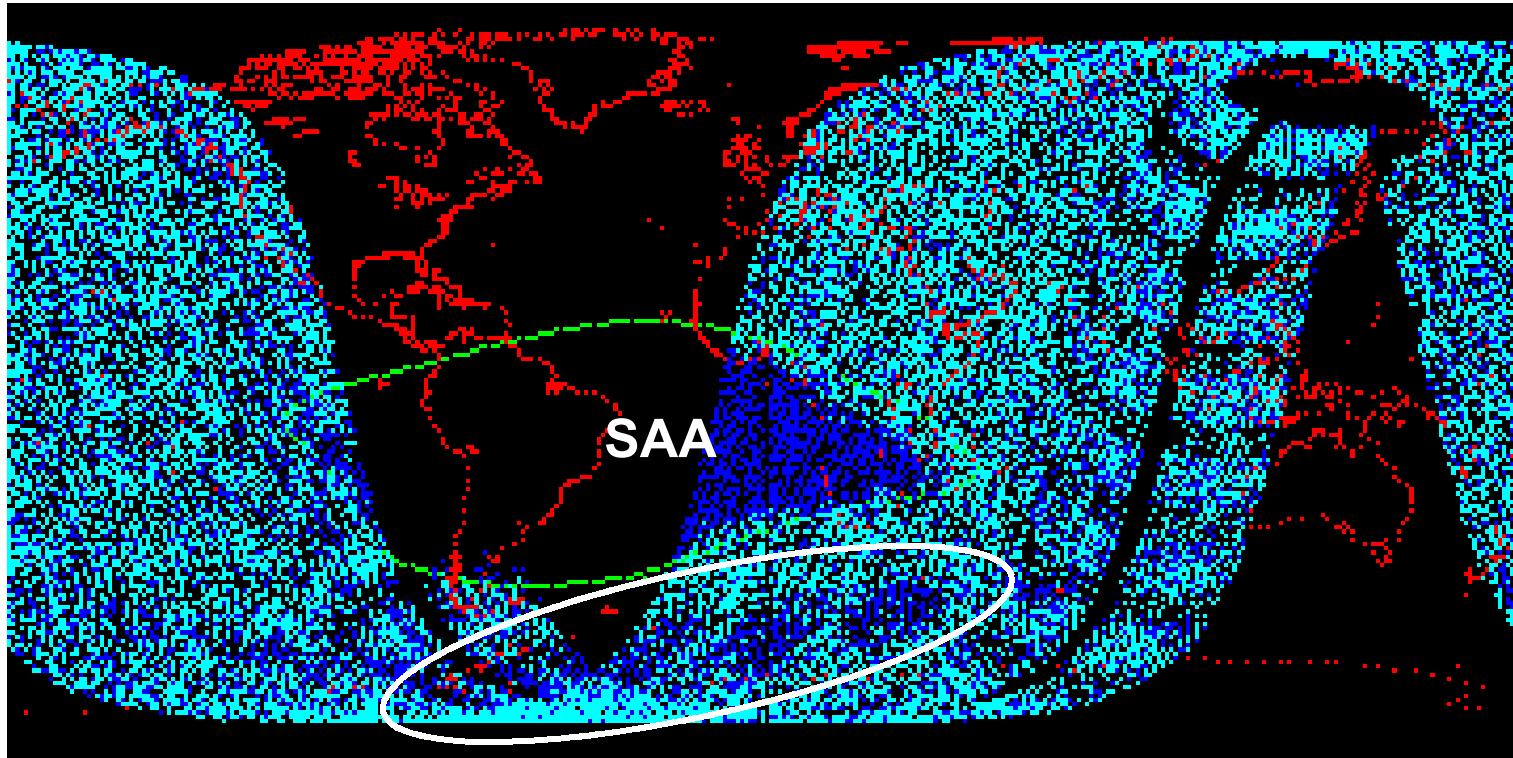


Long Term (?) Space Environment Effects



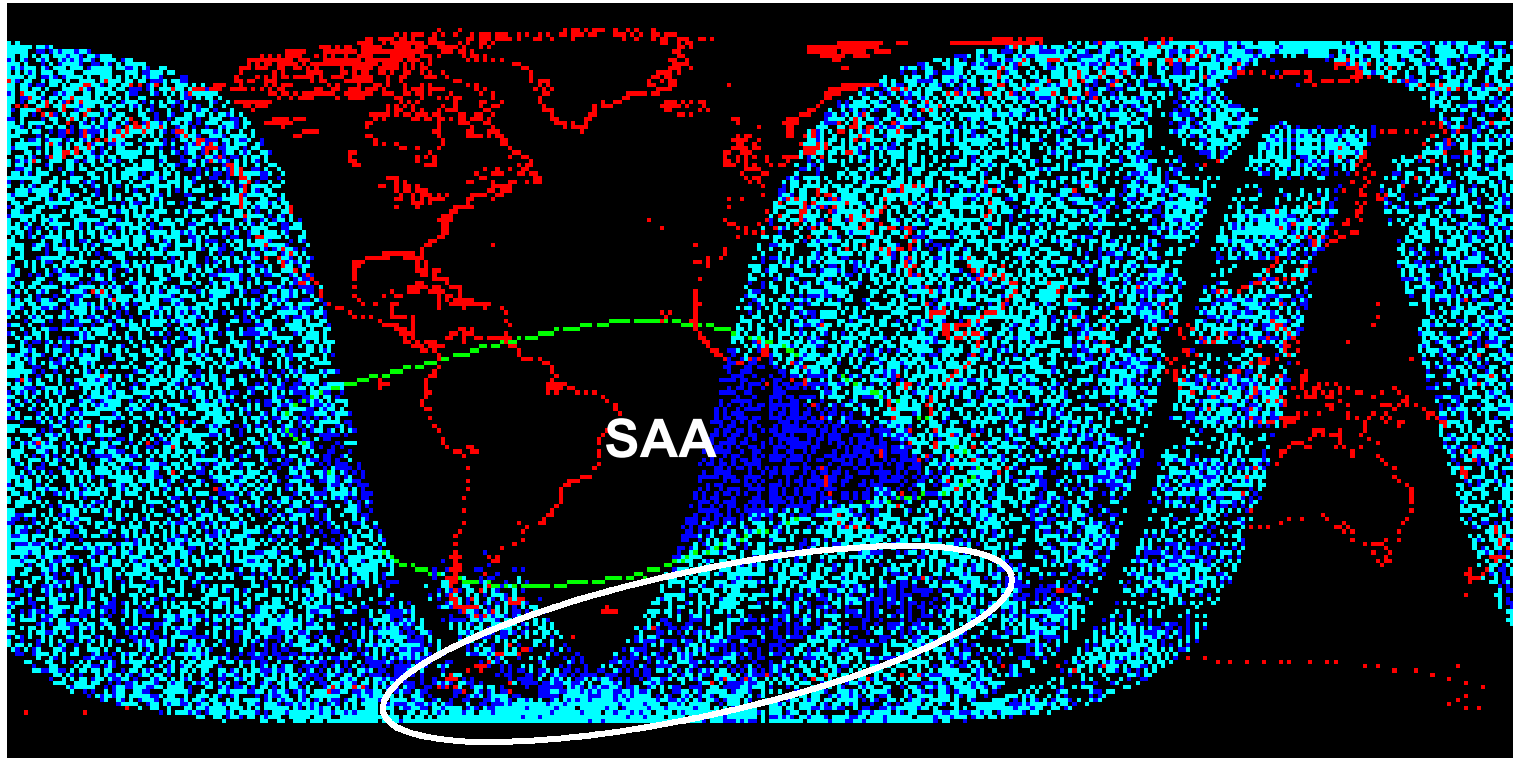


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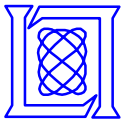




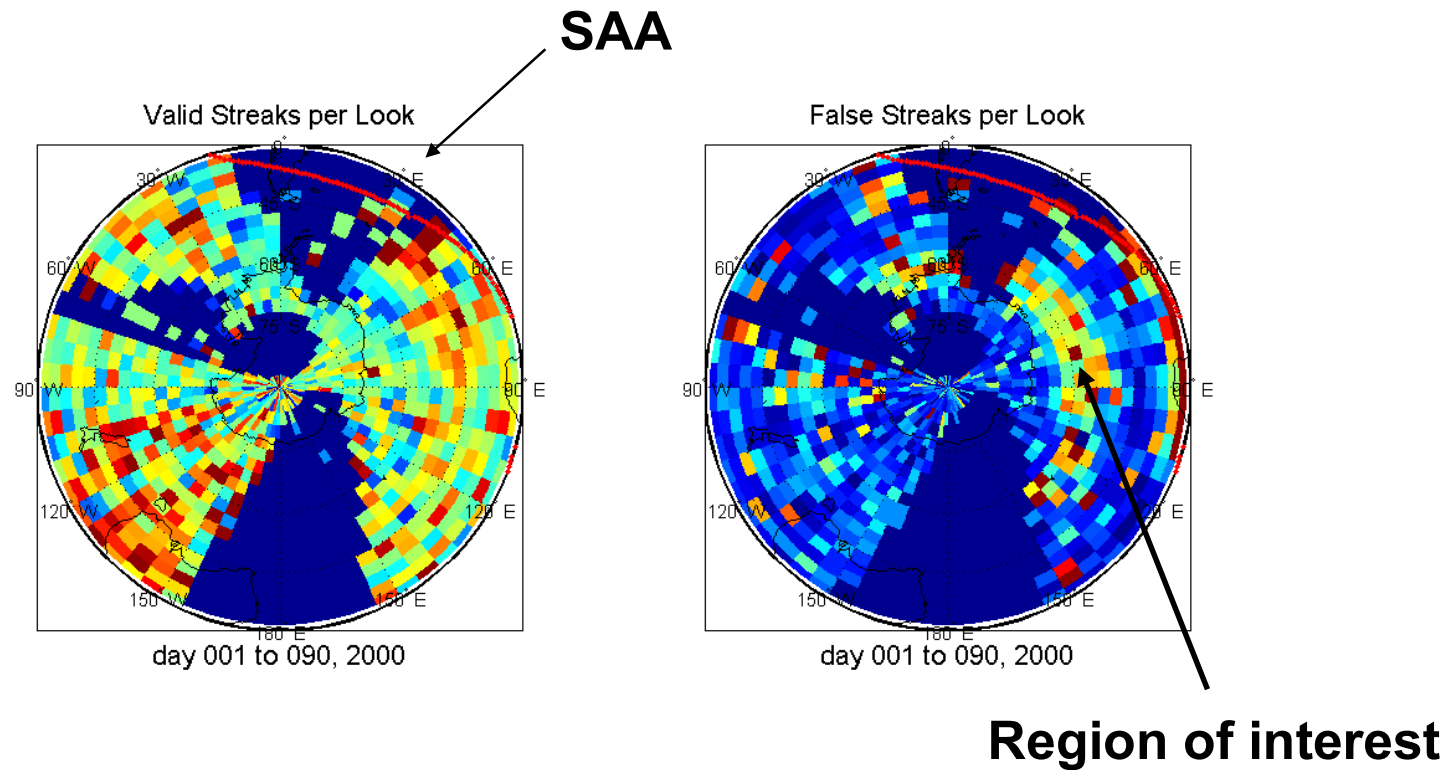
Long Term (?) Space Environment Effects



- **Area with reduced detections south of SAA noticed in 1998-1999**
- **Effect investigated by looking geographic distribution of valid and false streaks**

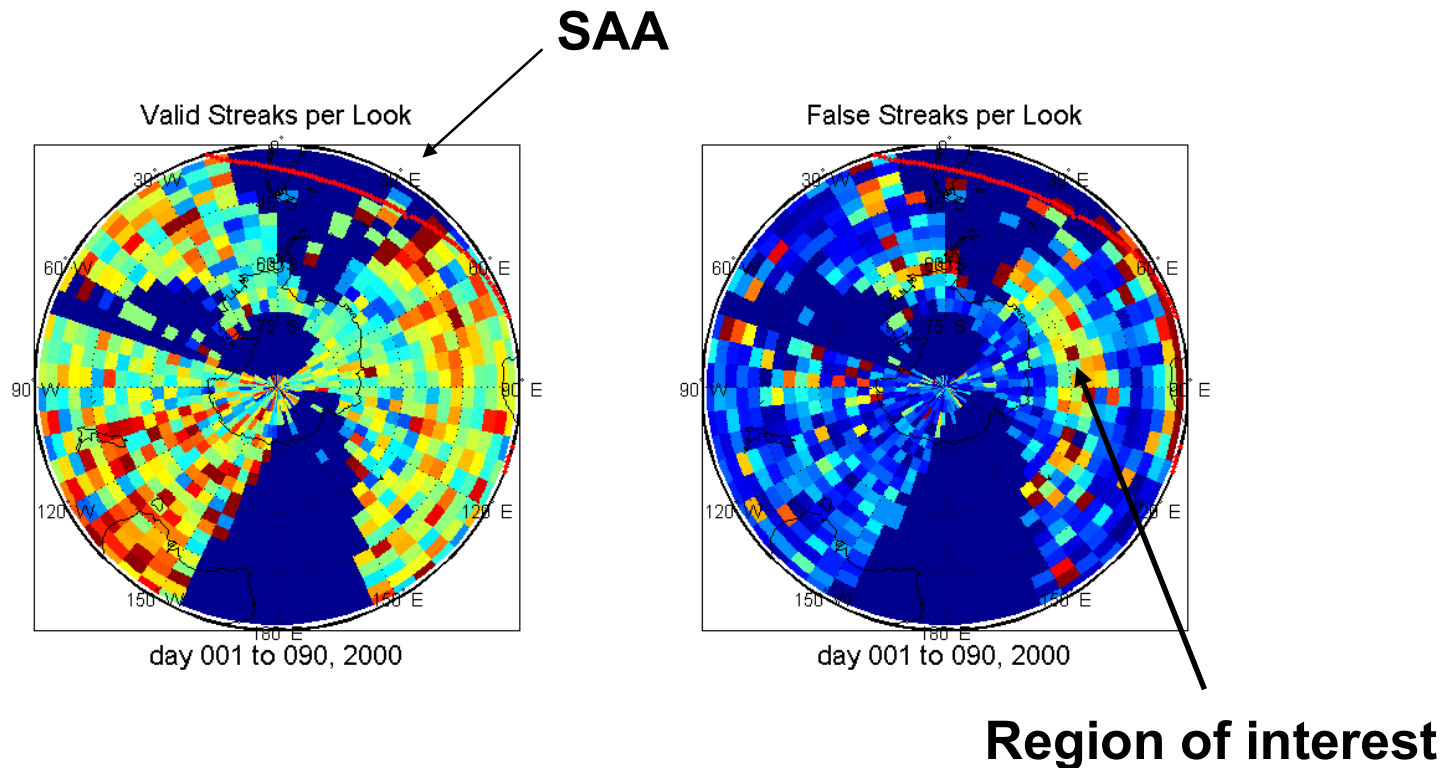


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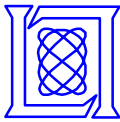




Long Term (?) Space Environment Effects

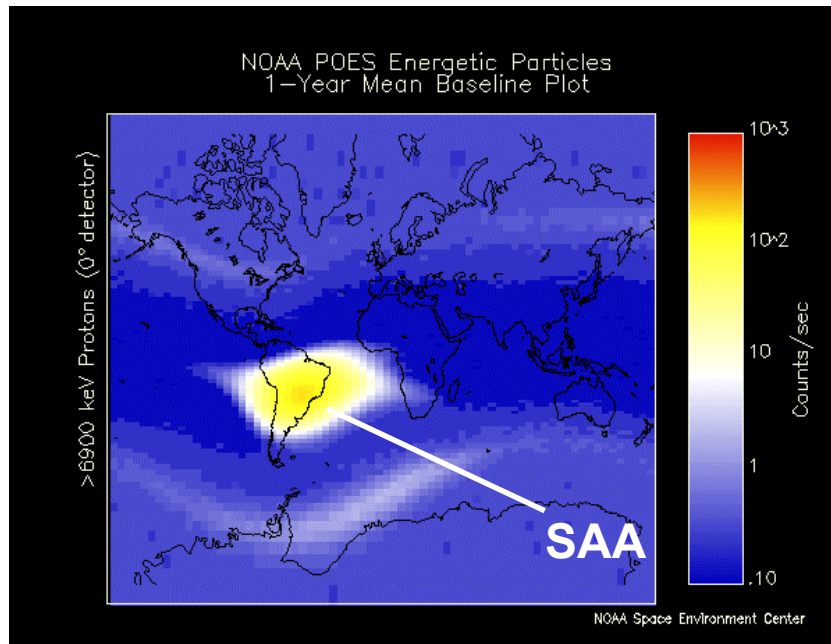


Area of degraded performance persists into 2000

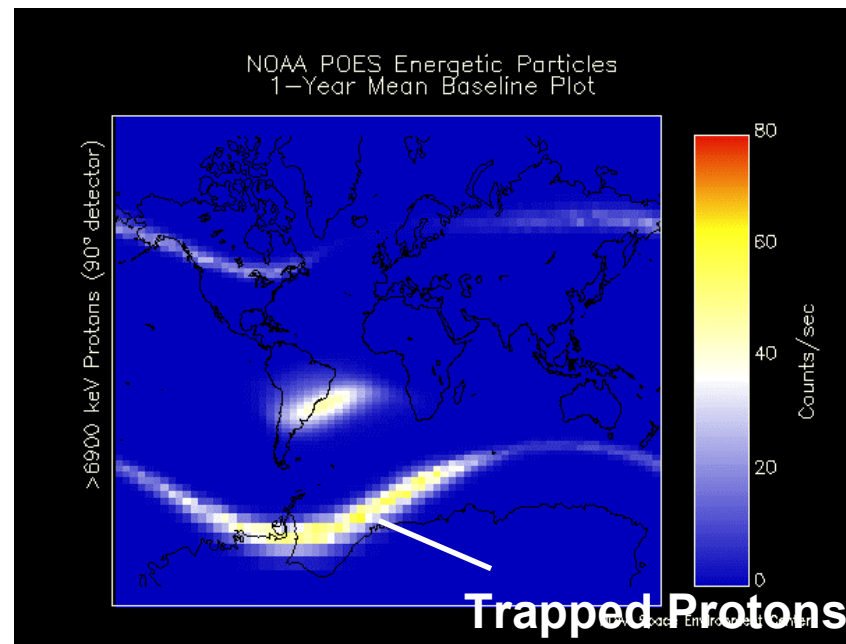


Energetic Particle Source Regions

> 6900 keV proton data from NOAA POES MEPED sensor



0°-detector



90°-detector

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



Outline

- **Introduction – Space Weather**
- **Effects on Space-Based systems**
- **Effects on Ground-Based systems**
 - **Range Delay**
 - **Scintillation**
 - **July 14-15th storm**
- **Conclusions**





Ionospheric Refraction

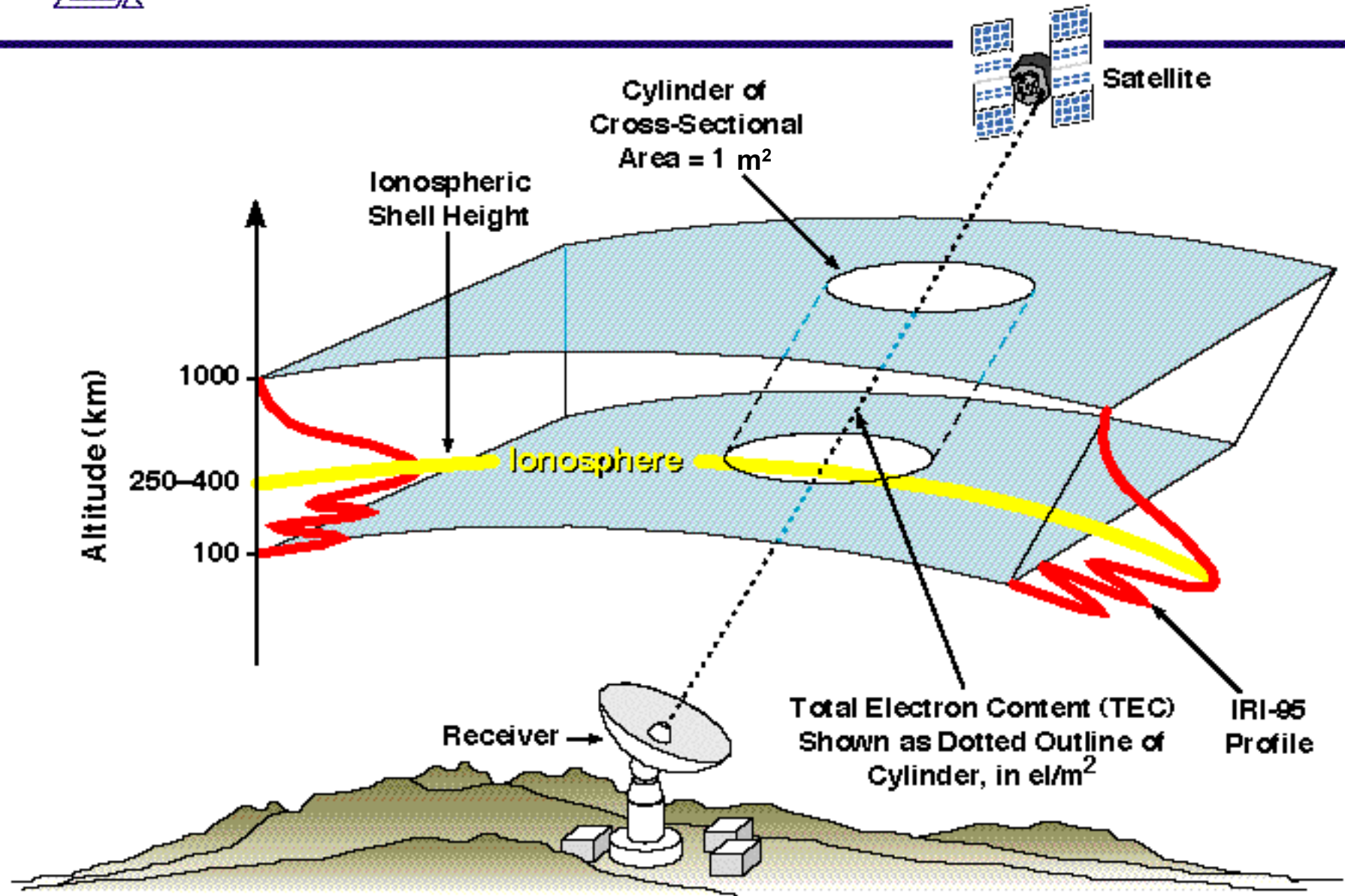
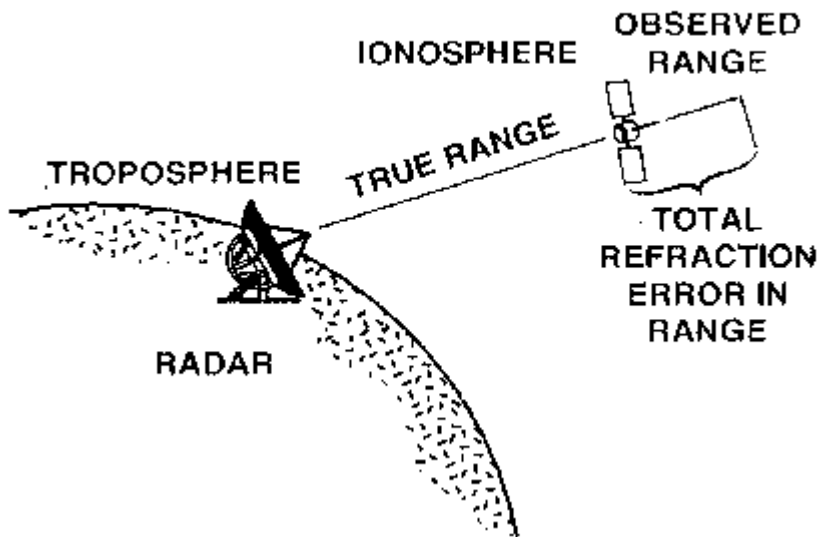




Illustration of Atmospheric Effects

Range Delay



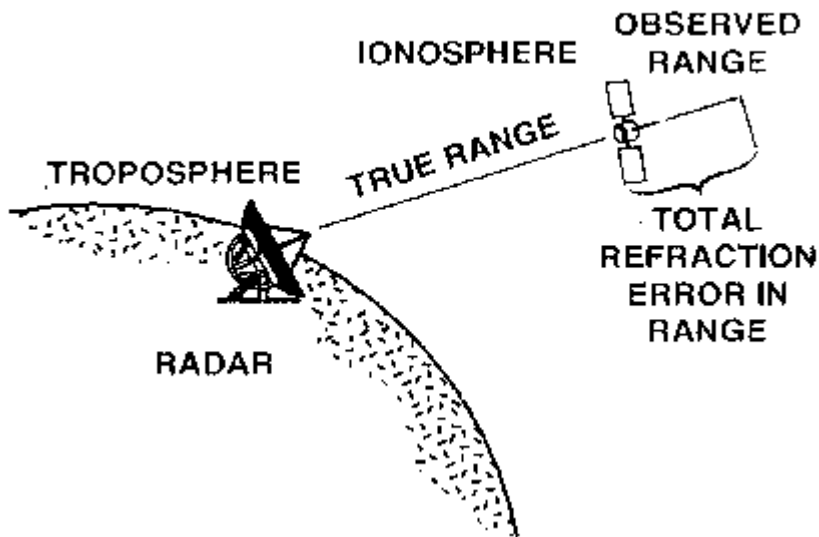
$$n_{\text{ionosphere}} \approx 1 - \frac{AN_e}{f^2}$$

$$\Delta R_{\text{ion}} (\text{meters}) = \frac{40.3}{f^2} \int_0^R N_e dr$$



Illustration of Atmospheric Effects

Range Delay



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

$$\Delta R_{\text{ion}} (\text{meters}) = \frac{40.3}{f^2} \int_0^R N_e dr$$

Range Delay

Ionosphere

S-Band

6 m

L-Band

32 m

UHF

280 m

VHF

2 km

Elev

< 20 °

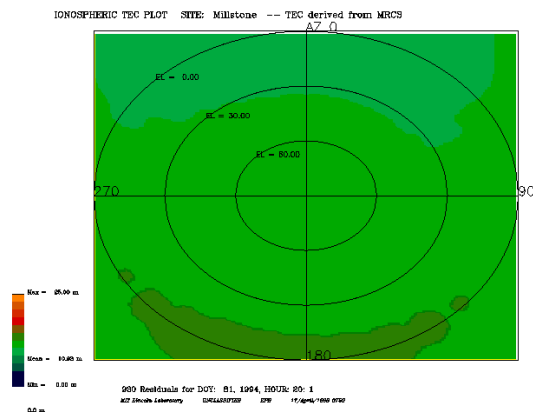


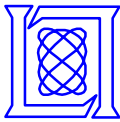
GRIMS: GPS Real-Time Ionospheric Monitoring System

- 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.



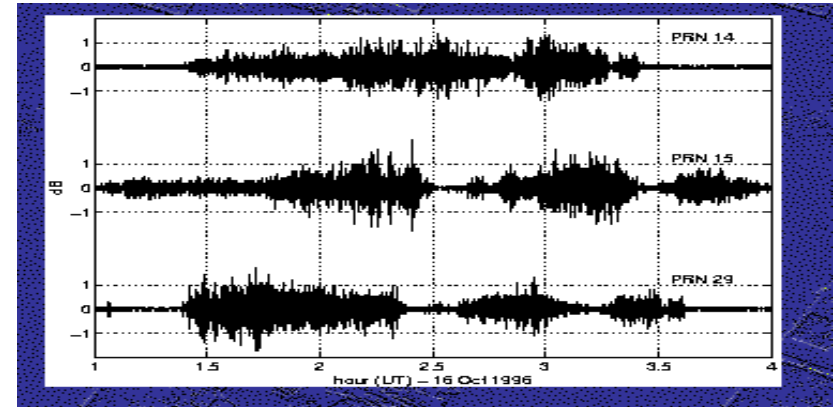
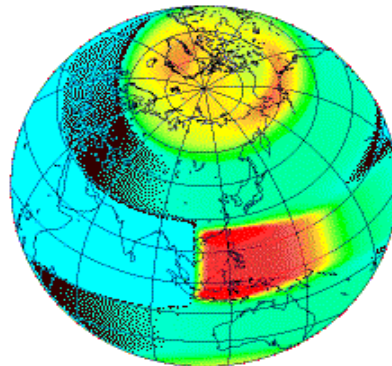
TEC as Function of Azimuth and Elevation around Millstone Hill Radar, MA





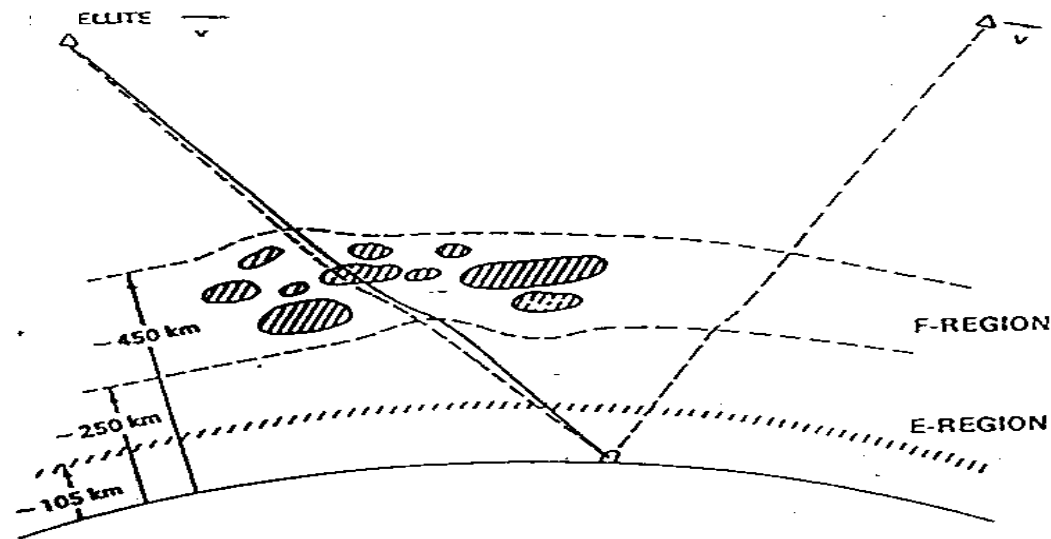
Scintillation

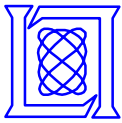
Scintillation can cause additional errors.



For GPS, the primary issue is loss of lock. For radars, the primary issue is degradation of coherent integration capabilities.

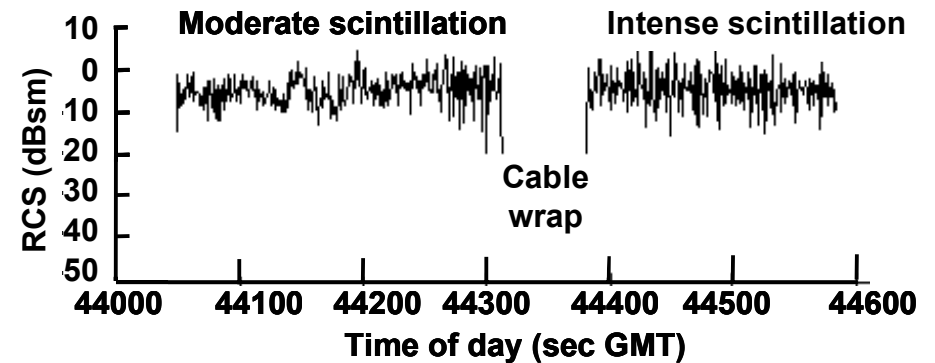
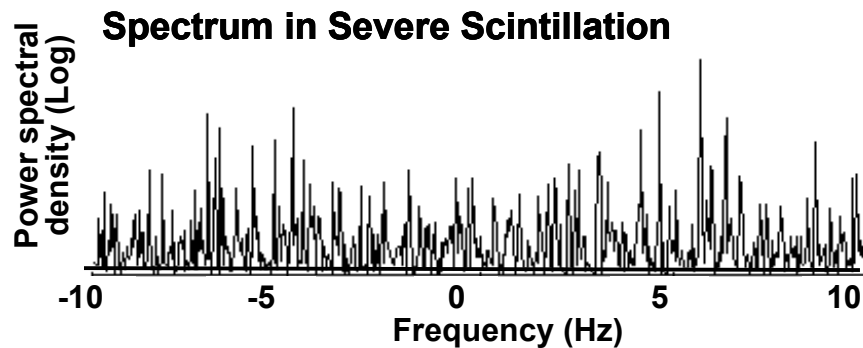
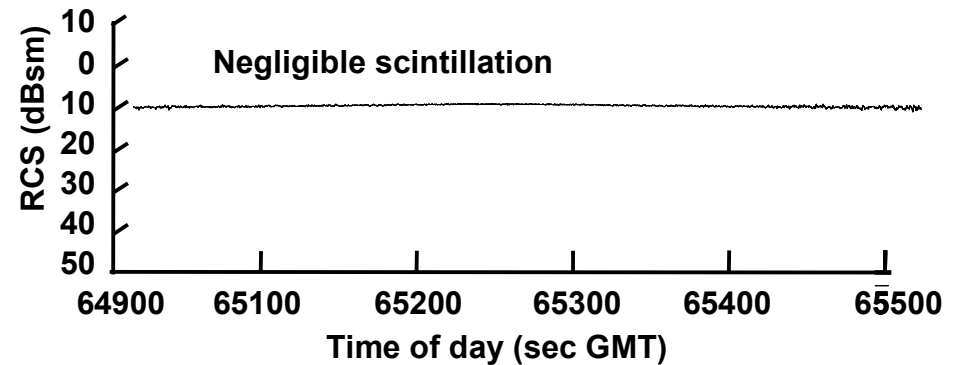
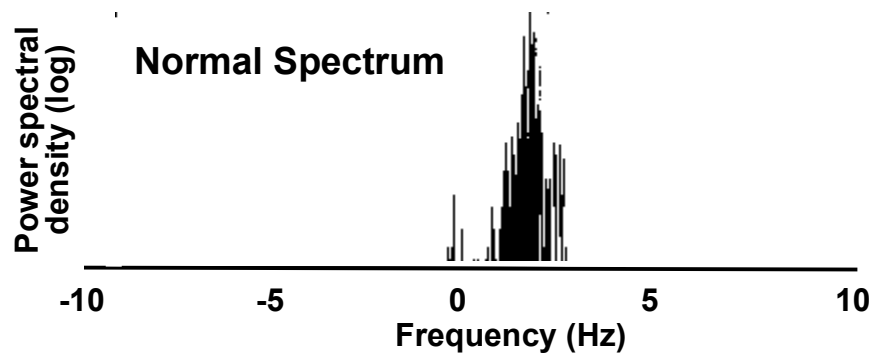
IONOSPHERE WITH IRREGULARITIES

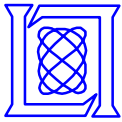




ALTAIR VHF Observations on CAL Sphere 2826: Normal Conditions versus Severe Scintillation

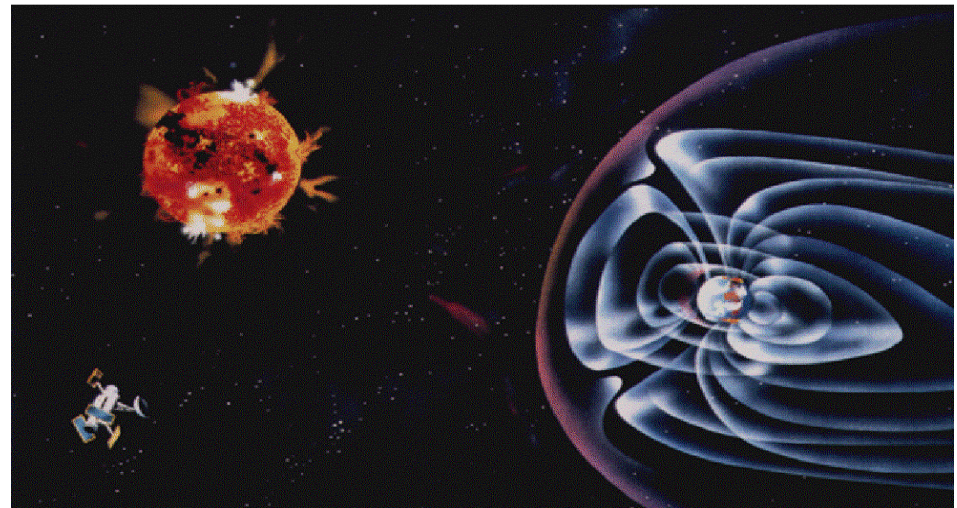
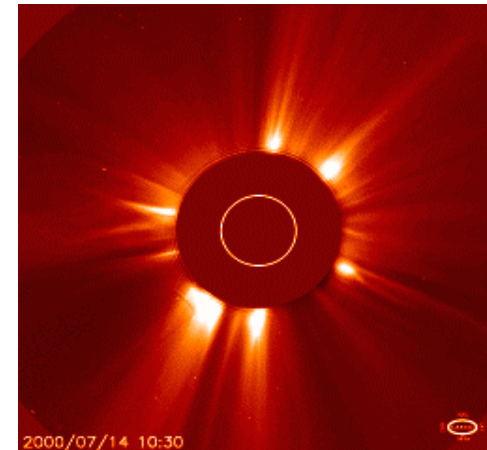
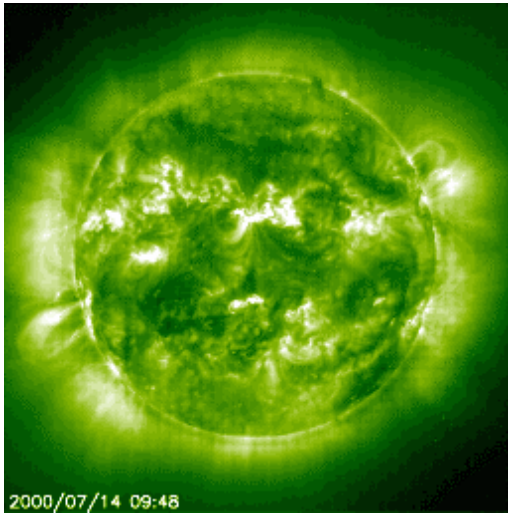
ALTAIR VHF Tracks
Calibration Sphere 2826
.5 m diameter, 850 km circular orbit





Solar Flare of 14 July 2000

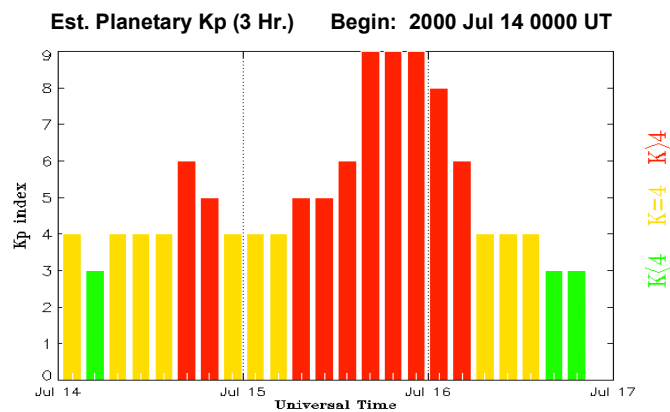
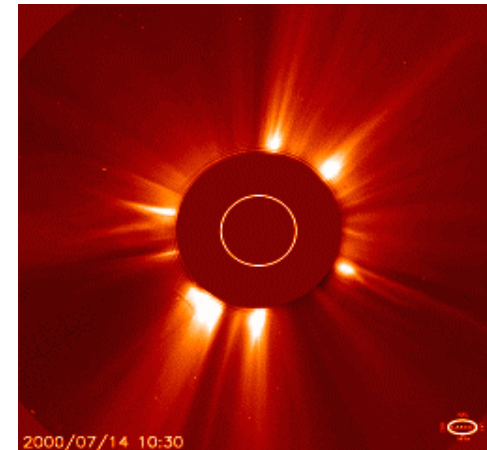
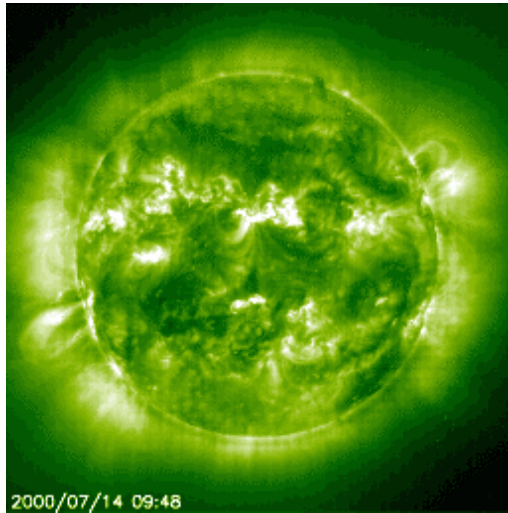
Biggest Solar Storm in Nine Years Strikes Earth



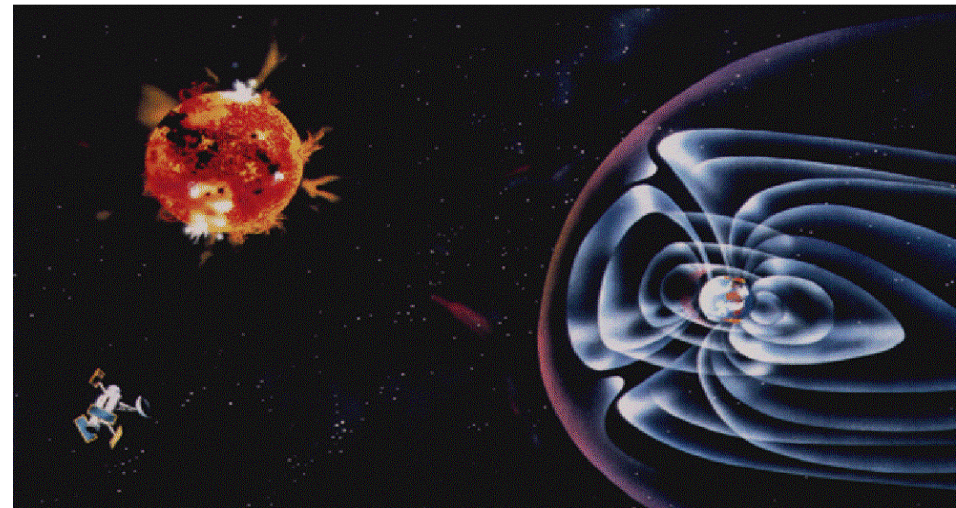


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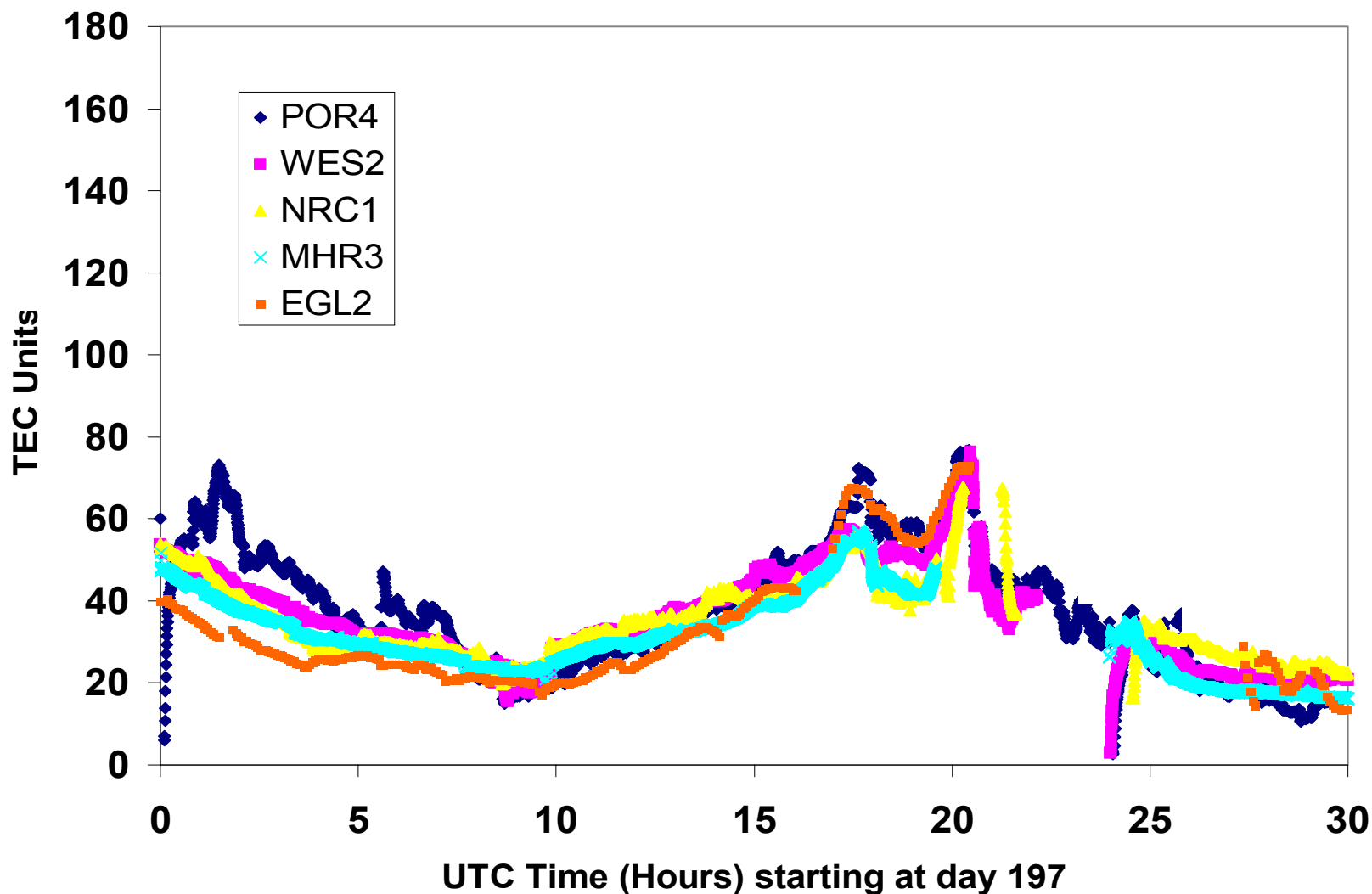


NOAA/SEC Boulder, CO USA



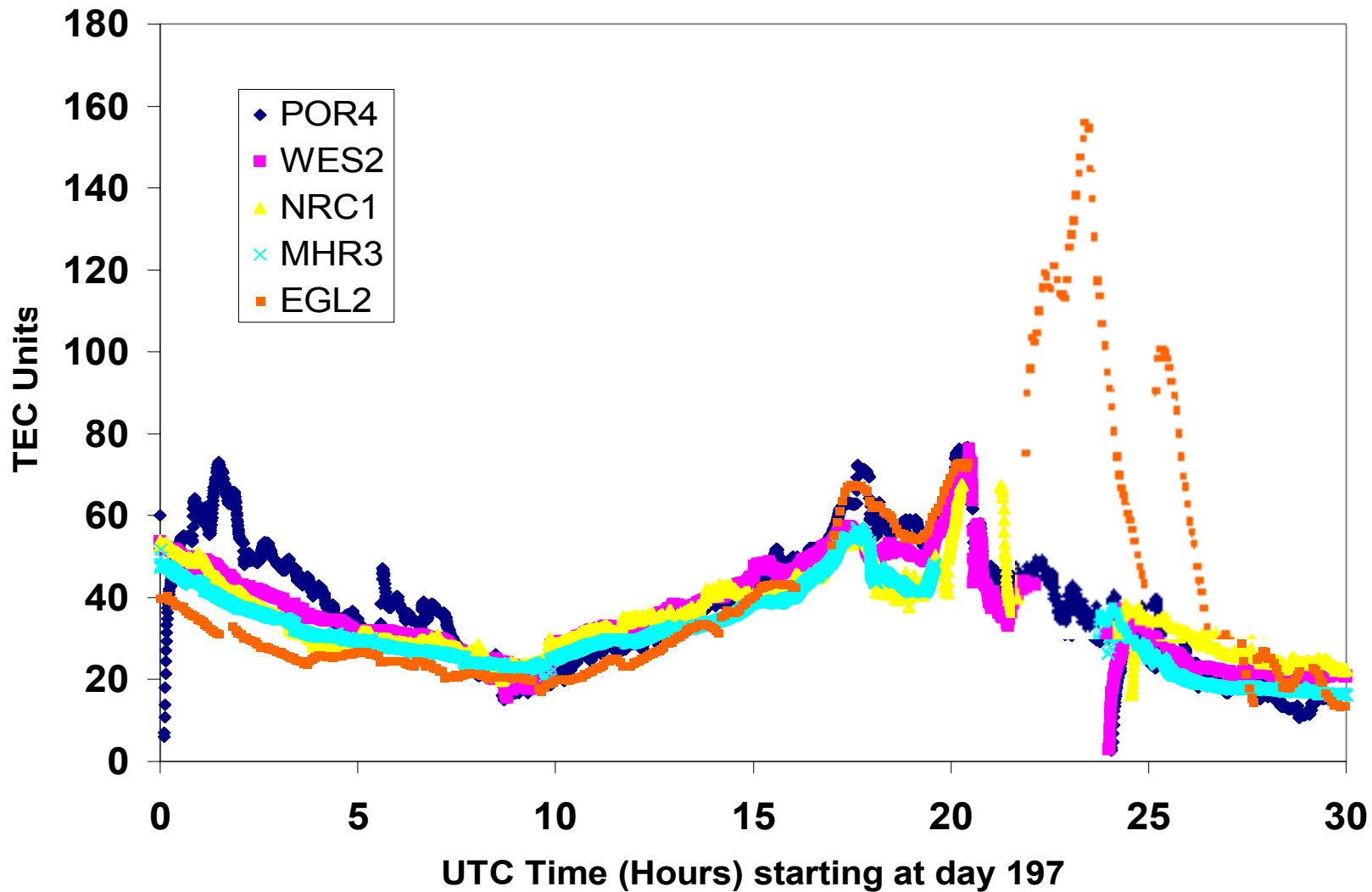


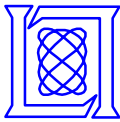
TEC Disturbances on 15 July 2000





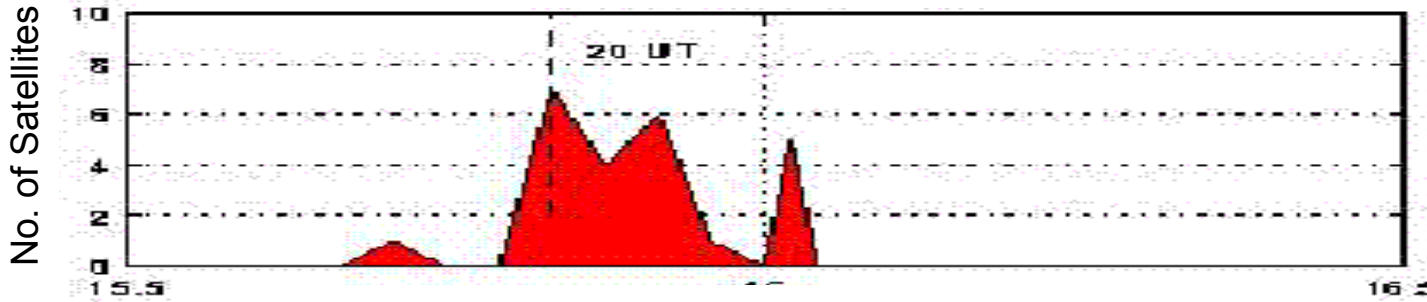
TEC Disturbances on 15 July 2000



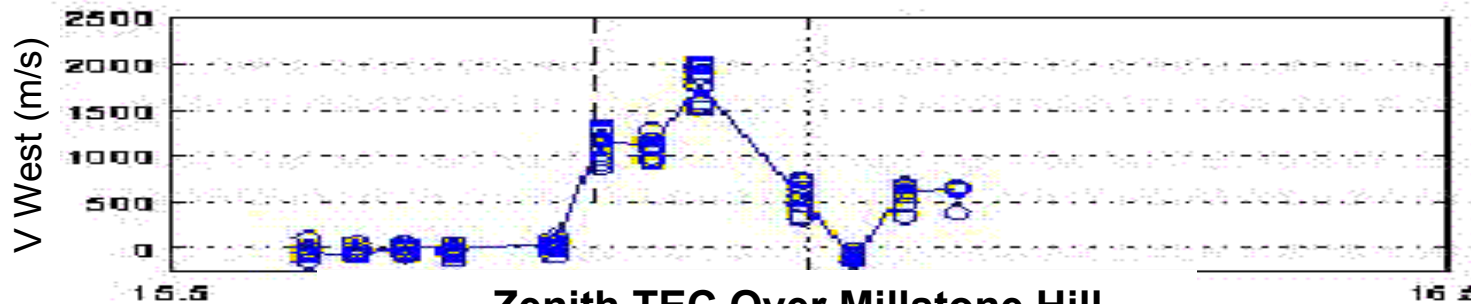


GPS Loss of Lock at Ottawa and Millstone Hill

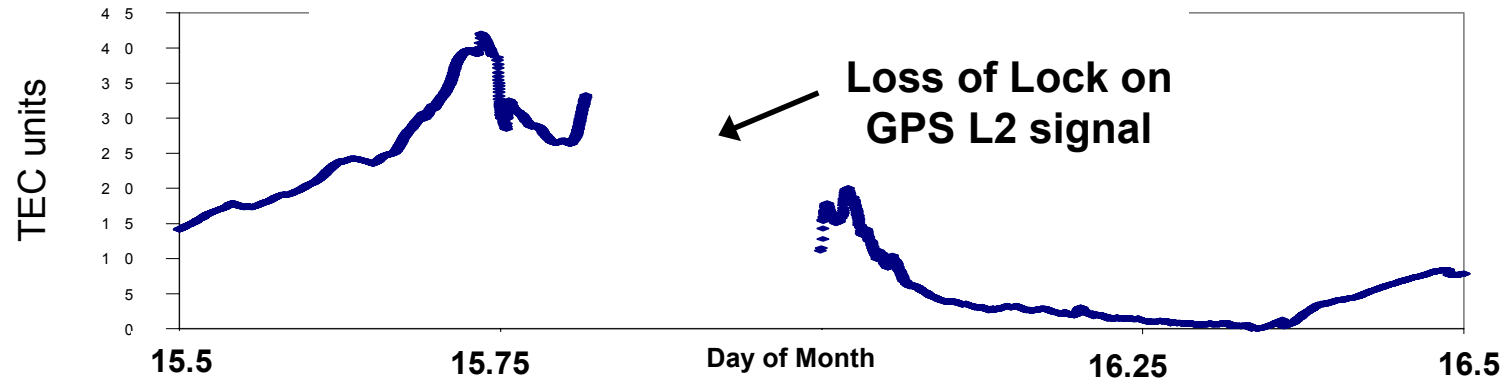
GPS Loss of Lock at Ottawa



Local Westward Ion Velocity at Millstone Hill

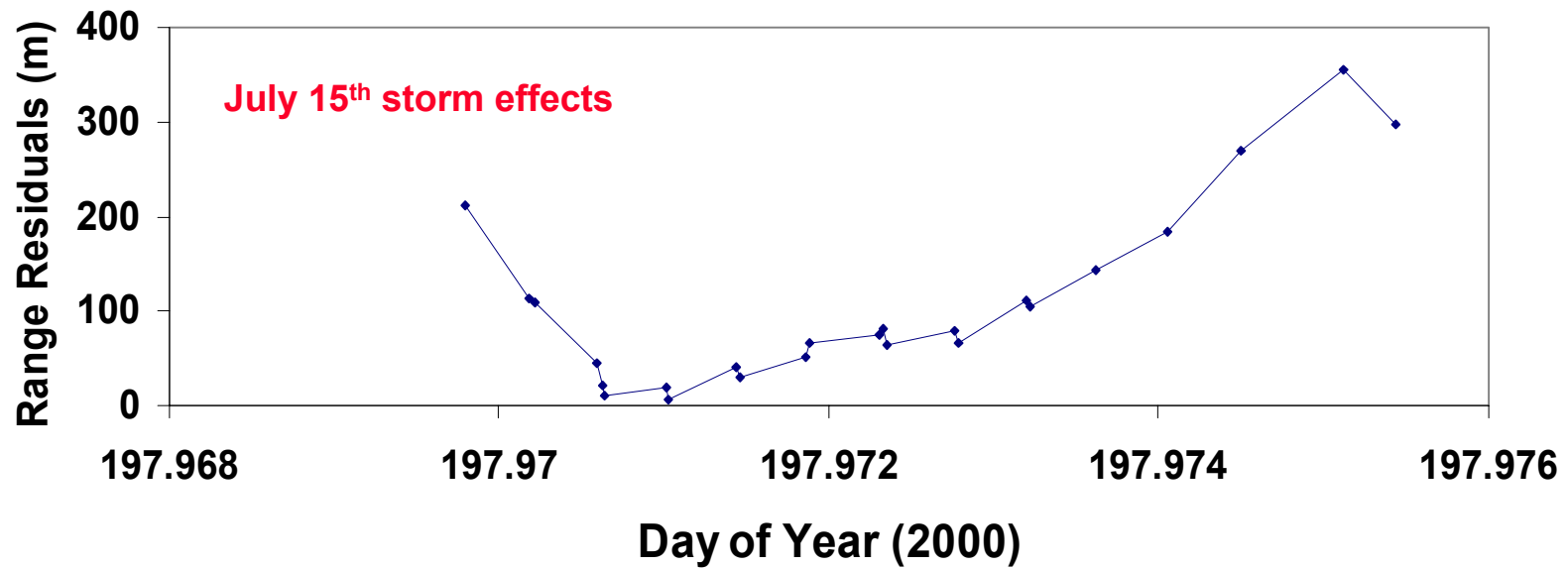
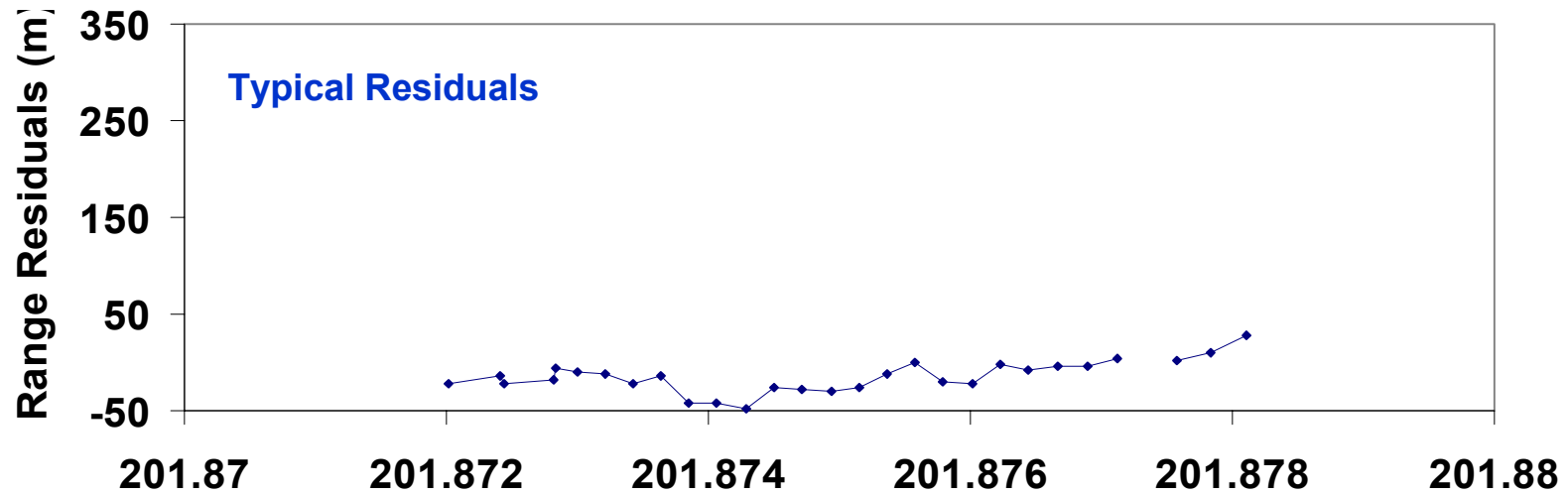


Zenith TEC Over Millstone Hill





Range Residuals on Calibration Sphere 7646 FPS-85 Florida





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**