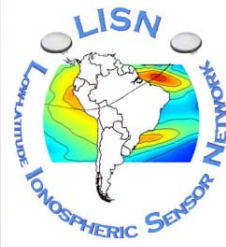




A Couple's Journey through Fifty Year's of Ionospheric Space Weather Research



Sunanda Basu and Santimay Basu*
Boston College

CEDAR Workshop
Boulder, CO
23-28 June 2013

****Deceased 16 April 2013***

***Santimay Basu's Obituary appeared in
SPA Newsletter dated May 1, 2013***

Scope of Presentation

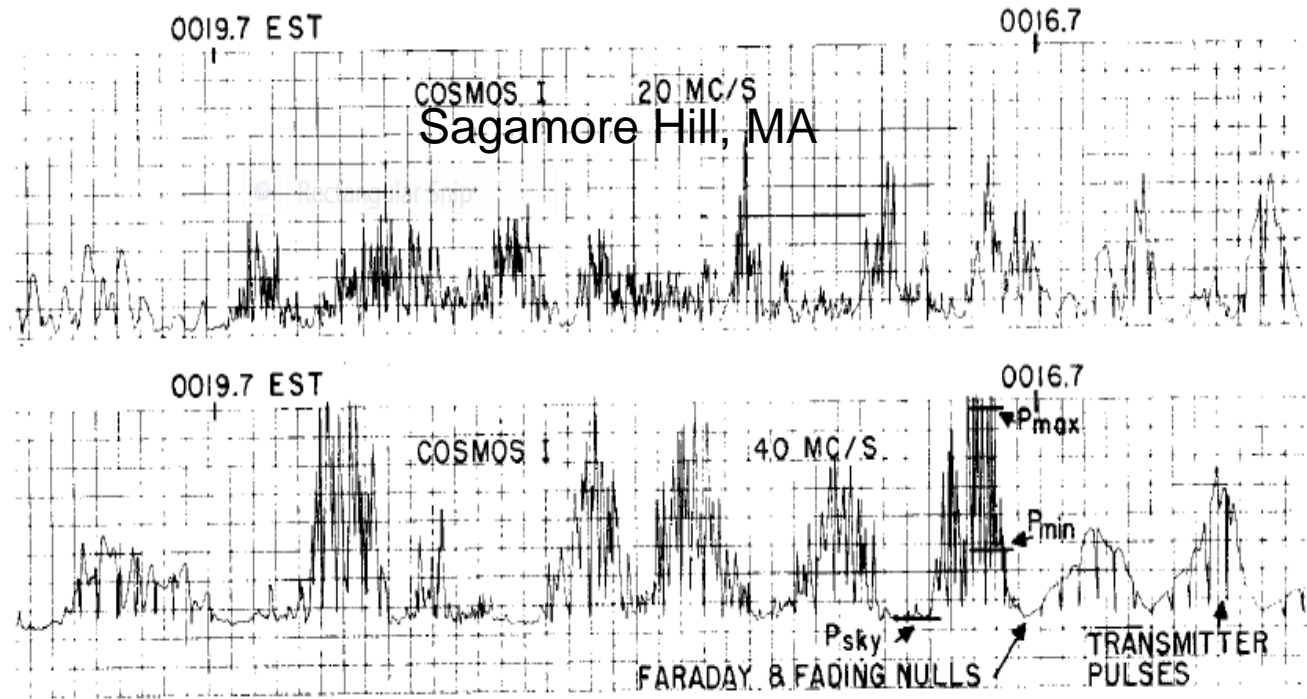


Boston Globe
Photo June 1963

- Sunanda's Grad Student Years
 - Master's in US – awesome discovery!
 - Ph.D. in India (a son born in between)
- Santi's Beacon Receiver Building Phase
 - In India with his grad students
- Sunanda's Exciting NRC Post-doc Research
- Sunanda and Santi Partnership Phase 1
- Sunanda's NSF Decade – AER/CEDAR
- Sunanda and Santi Partnership Phase 2

Study of High Latitude Scintillations by Receiving Signals from Artificial Satellites

One of the first studies of high latitude scintillations using satellites was made at Boston, MA in the early sixties by Jules Aarons and his group. The Soviet satellite Cosmos 1 and American satellite Transit 4A were used. Dependence of irregularities on signal frequency, latitude and magnetic activity were determined.

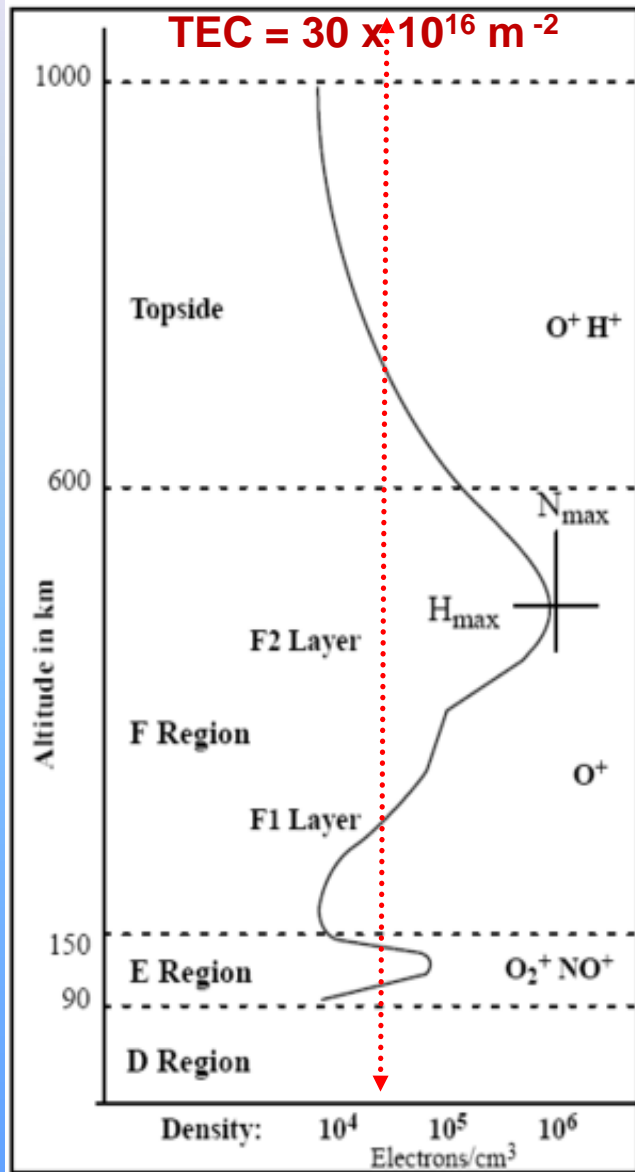


REVOLUTION 404 APRIL 12, 1962

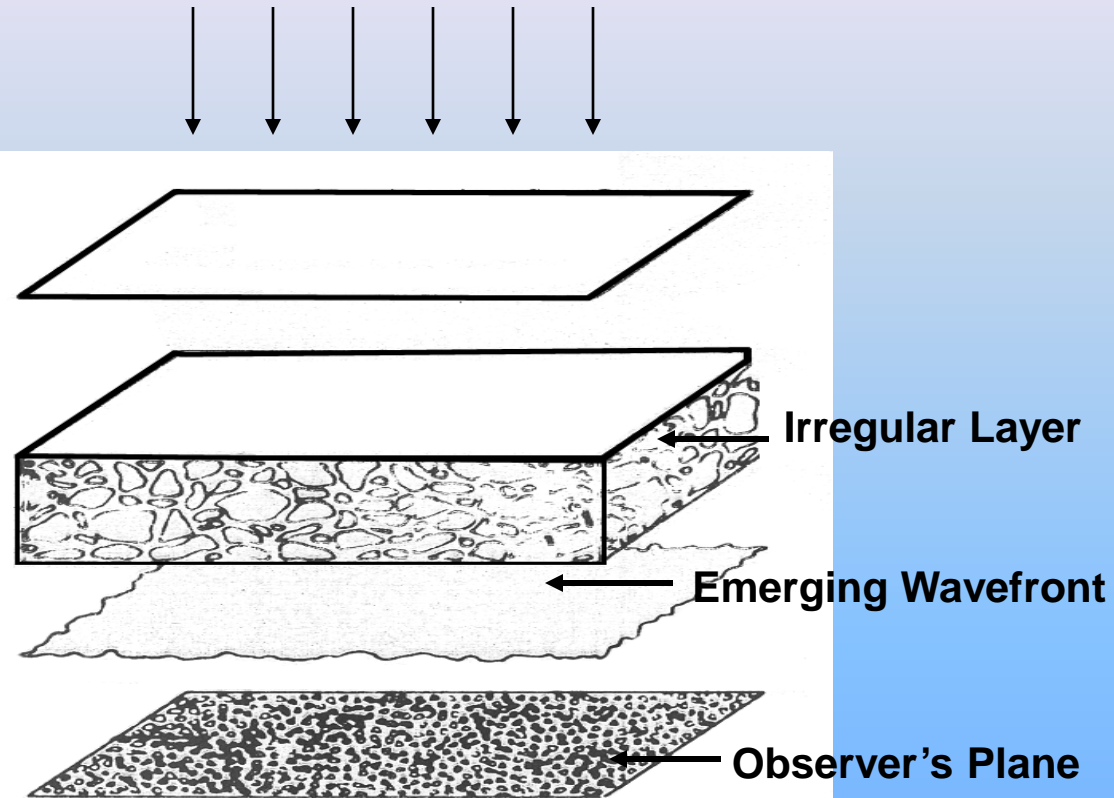
<u>TIME EST</u>	<u>LONG. (W)</u>	<u>LAT. (N)</u>	<u>ALTITUDE (km)</u>
0016.7	69.6°	40.8°	757
0019.7	64.1°	43.3°	739

Sunanda Basu, MS Thesis, Boston Univ., 1963
 Advisor: Gerald Hawkins
 Su. Basu et al., JATP, 1964; Aarons, Mullen and Basu, JGR, 1963;1964.

Vertical profile of the ionosphere



Incident Plane Wave

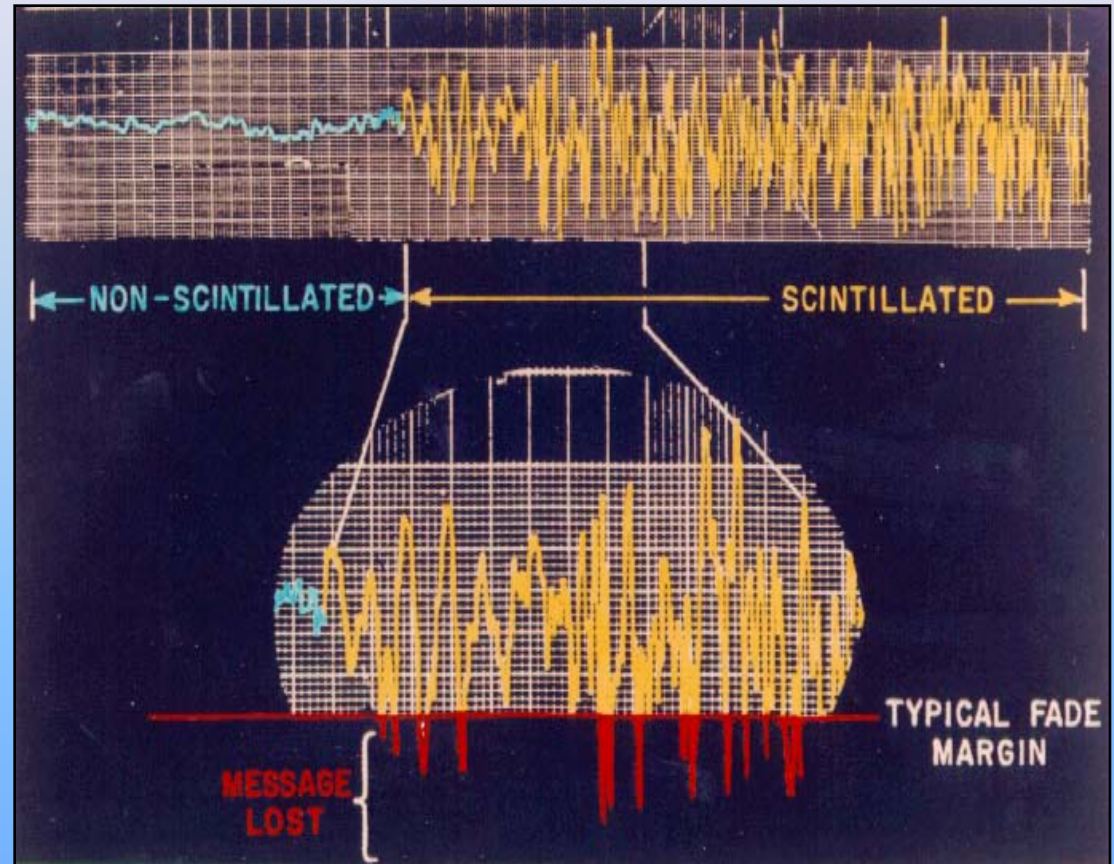


Pictorial illustration of the phase fluctuations imposed on a wave-front traveling away from an irregular layer for a vertical radio path.

For Scintillation Theory, see CEDAR Tutorial 2003 by Santimay Basu

What are the major impacts of scintillation?

Advantage of scintillation technique is in simplicity of the receiving system that can be used when the source is a satellite (high signal strength). Thus suitable also for developing countries (awesome discovery!)

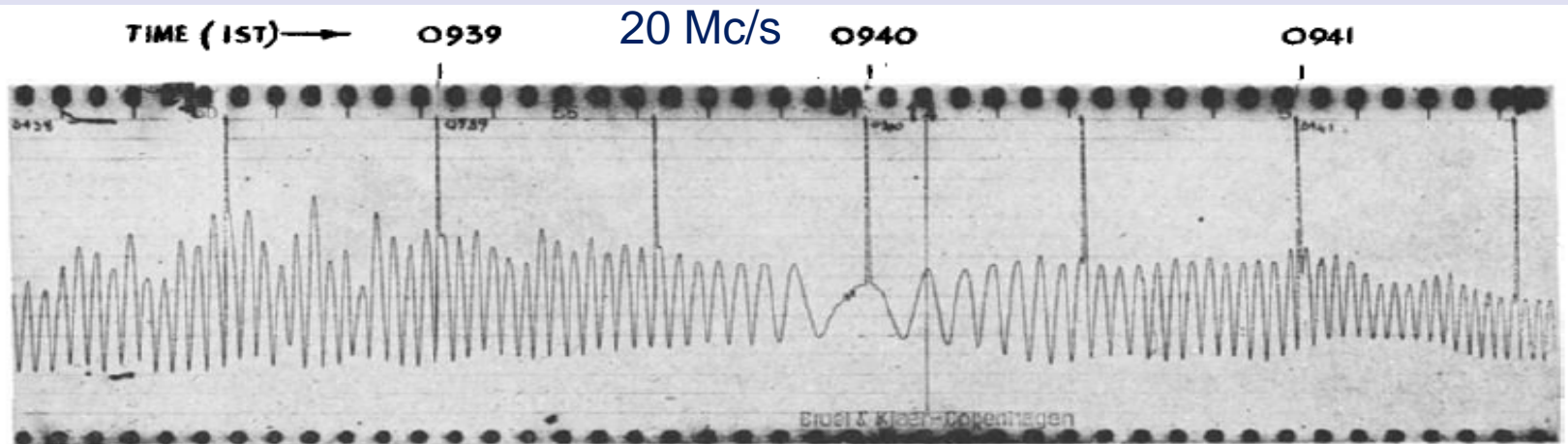


- Regional UHF Communication outages for extended periods (hours)
- Increased Global Positioning Satellite (GPS) navigation errors
- Degraded High Frequency (HF) radio communication

Obstacles on the path to Sunanda's Ph.D.

- Expectation was that I would teach under-graduate Physics at a college for women – no opportunity to combine with research
- Research in Radio Physics only possible at Calcutta University where Santi was on the faculty
- Head of the Dept. there said he wouldn't admit a woman
- I was equally adamant that I would do research (we decided to have a baby while waiting for an opening!!)
- Six months after the birth of our son, we found another University in Calcutta called Jadavpur where the Head of Telecommunication Engg. was more open minded
- I started work there with a junior fellowship from the UGC in June 1965 – a group of one with the expectation that Santi would provide guidance – and I haven't stopped doing research since!

Satellite signals received at Jadavpur & Haringhata



BEC

REV. No. 6197

Su. Basu, JGR, 1967

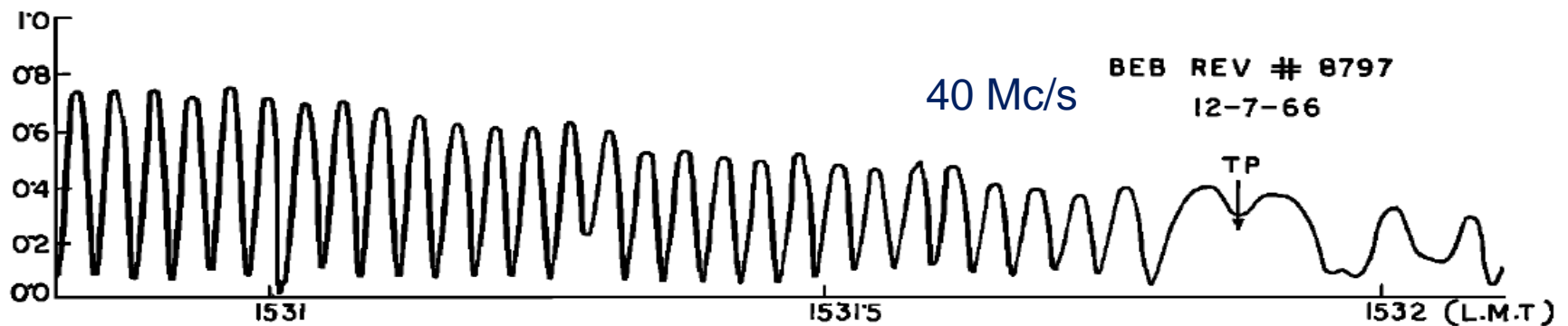


Fig. 1. Faraday fading records obtained from satellite S-66 showing the transverse point.

Basu & Das Gupta, JGR, 1967

Latitude Variation of TEC

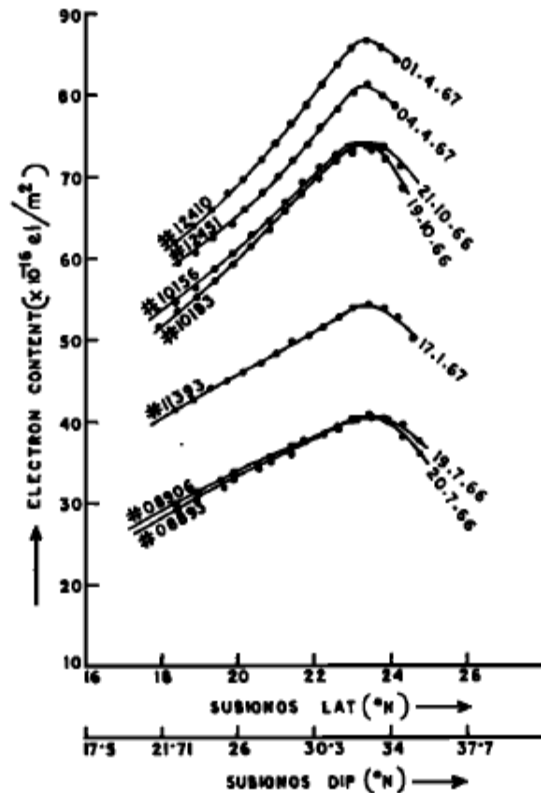
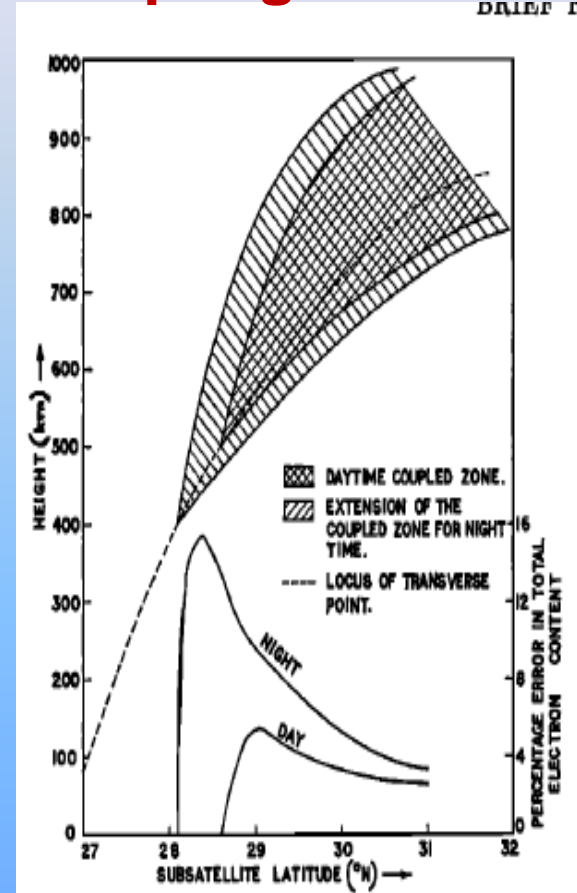


Fig. 1. Variation of electron content with latitude under magnetically quiet conditions in different seasons.

Basu & Das Gupta, JGR, 1967

Magneto-ionic Mode Coupling



Su. Basu & S. Basu, JGR, 1969

Summary of Scientific Studies in Space Weather at Calcutta during 1965-1975

- Calcutta is located under the Northern Crest of the Equatorial Anomaly
- Total Electron Content variation with satellites BE-B and BE-C measured at Haringhata could map the equatorial anomaly and its variations with magnetic activity
- Magneto-ionic mode coupling and studies on refraction correction in the low latitude ionosphere were also performed at Jadavpur University

(Some Publications: *Su. Basu, JGR, 1967; S. Basu and DasGupta, JGR, 1967, 1968, 1969; Su. Basu and S. Basu, JGR, 1969, 1971, 1972; DasGupta and S. Basu, Ann. Geophys, 1973*)



Dr. Jules Aarons with Prof. M. K. DasGupta, S. Basu and former students, A. DasGupta, S. Mitra and B.K. Guhathakurta at the Field Station in February, 1969.

Susanto Basu, our son the future economics prof at age 4, not too thrilled to be in the company of grazing sheep in the Calcutta Maidan!

Photo taken by Jules Aarons during his 1969 Calcutta visit

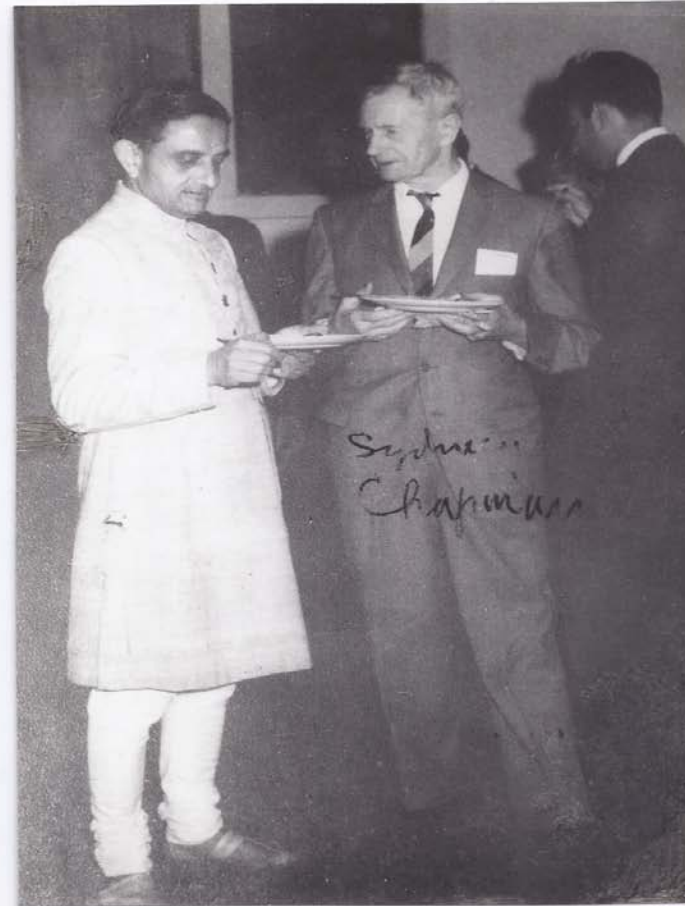


Third International Symposium on Equatorial Aeronomy, Ahmedabad, India, 1969



Chapman
1888-1970

Su.
Basu



Sarabhai
1919-
1971

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Model of Equatorial Scintillation

From Satellite In-Situ Measurements



- The OGO-6 Retarding Potential Analyzer (RPA) data were made available to us in Calcutta by Prof. W.B. Hanson in 1974 (30 lb. data)
- The in-situ measurements of F-region irregularity amplitude and ambient electron density made by the RPA on OGO-6 near the perigee altitude of 400 km was utilized to determine the electron density deviation over the equatorial region.
- A model of equatorial scintillation was developed in the framework of diffraction theory and 3-D irregularity power law index 4.
- The occurrence contours of 140 MHz scintillations during 19 – 23 MLT for Nov-Dec period were derived. A pronounced longitude variation of the scintillation belt width and the occurrence was obtained in agreement with observations.
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826

BASU, BASU, AND KHAN

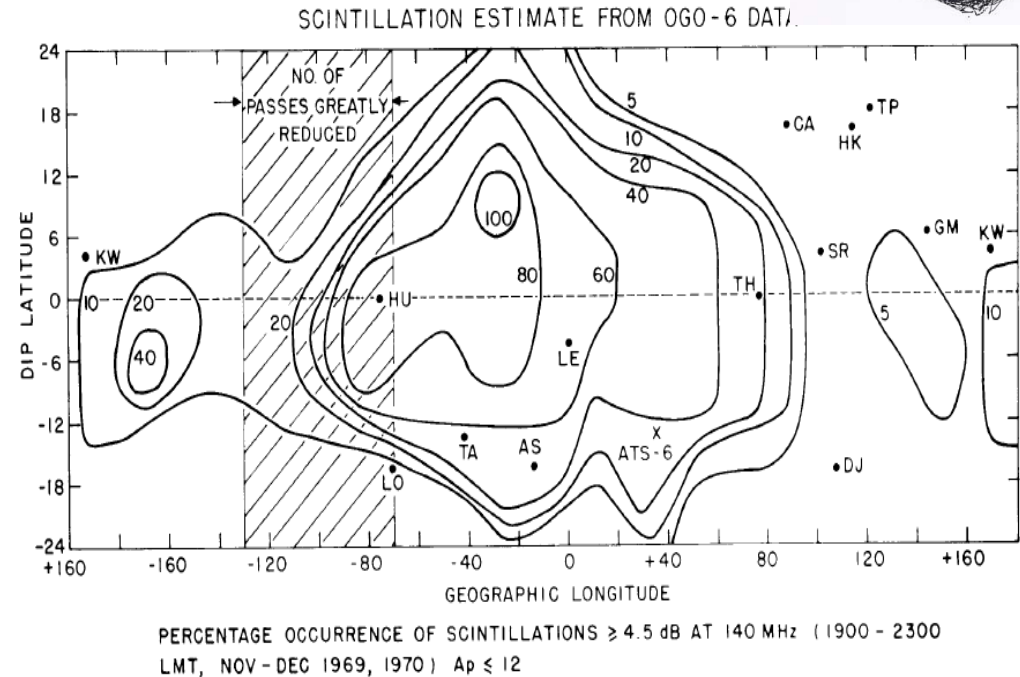


Fig. 5. Model of estimated scintillations ≥ 4.5 dB over the equatorial region (model parameters are given in the text). The contours equivalently represent the percentage occurrence of electron density deviation $\Delta N \geq 10^{10} \text{ m}^{-3}$.

(Su. Basu et al., Radio Sci., 1976)

This was our first exposure to in-situ data and was followed by work with AE-D, AE-E and DE-2 all made available to us by Bill Hanson.

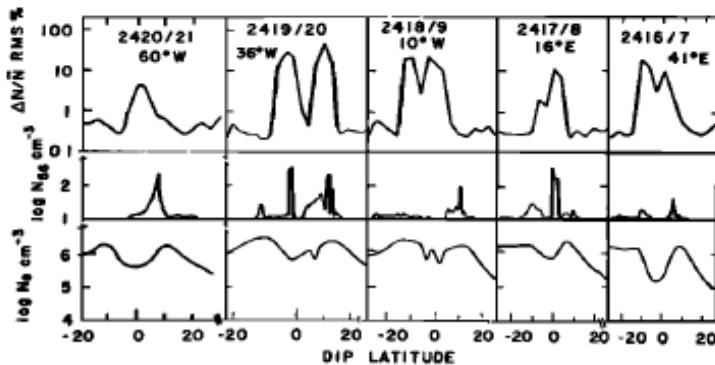
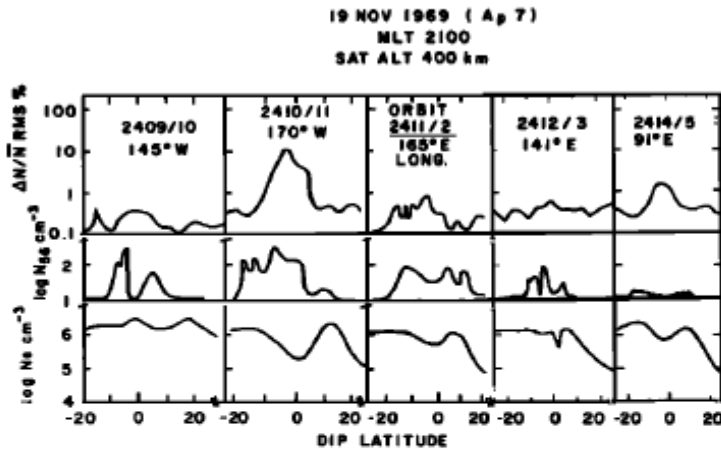


Fig. 4. Typical set of OGO-6 orbits over the equatorial region on November 9, 1969, at 2100 MLT showing longitudinal variation of irregularity structure.

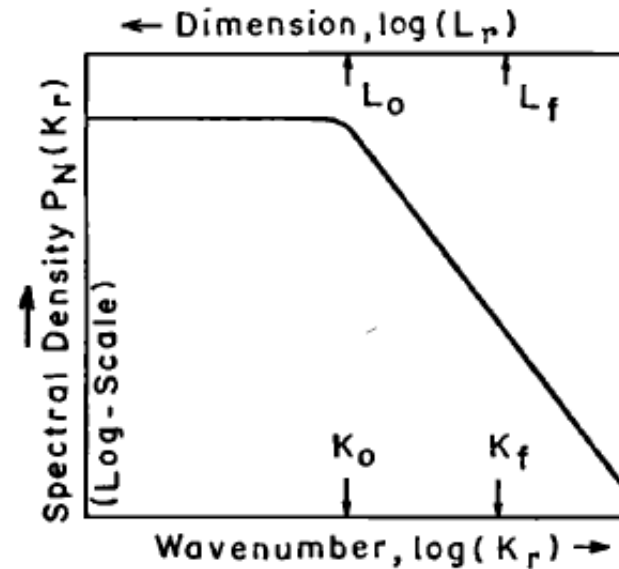


Fig. 3. Schematic representation of irregularity power spectrum with outer-scale wavenumber $K_0 \ll K_f$, the Fresnel wavenumber.

Scintillations are most sensitive to density irregularities of sizes of Fresnel dimension $L_f \sim 1$ km at VHF. Here outer scale $L_0 \sim 20$ km, distance traveled by satellite in 3 sec, over which dN/N computed by OGO-6. Thus spectral shape has to be assumed to compute PSD at L_f . A 3-D power law irregularity power spectrum with spectral index $p = 4$ used to compute scintillation (Rufenach, Radio Sci., 1975).

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Coordinated Jicamarca Radar and Scintillation Measurements at the Magnetic Equator

In 1977, we performed for the first time co-ordinated 50 MHz radar and 137 MHz scintillation through a common ionospheric volume at the magnetic equator. It established that at the onset of spread-F, 3-m (50 MHz radar) and km-scale (137 MHz scintillation) irregularities attain saturation amplitude simultaneously. Later in the evening meter scale irregularities decay faster than km-scales owing to scale-length dependent cross-field diffusion coefficients.

This confirmed Gerhard Haerendel's theory of equatorial spread F (unpublished manuscript, 1974) that mother and daughter irregularities attain maturity at the same time because the growth rate of smaller irregularities is faster.

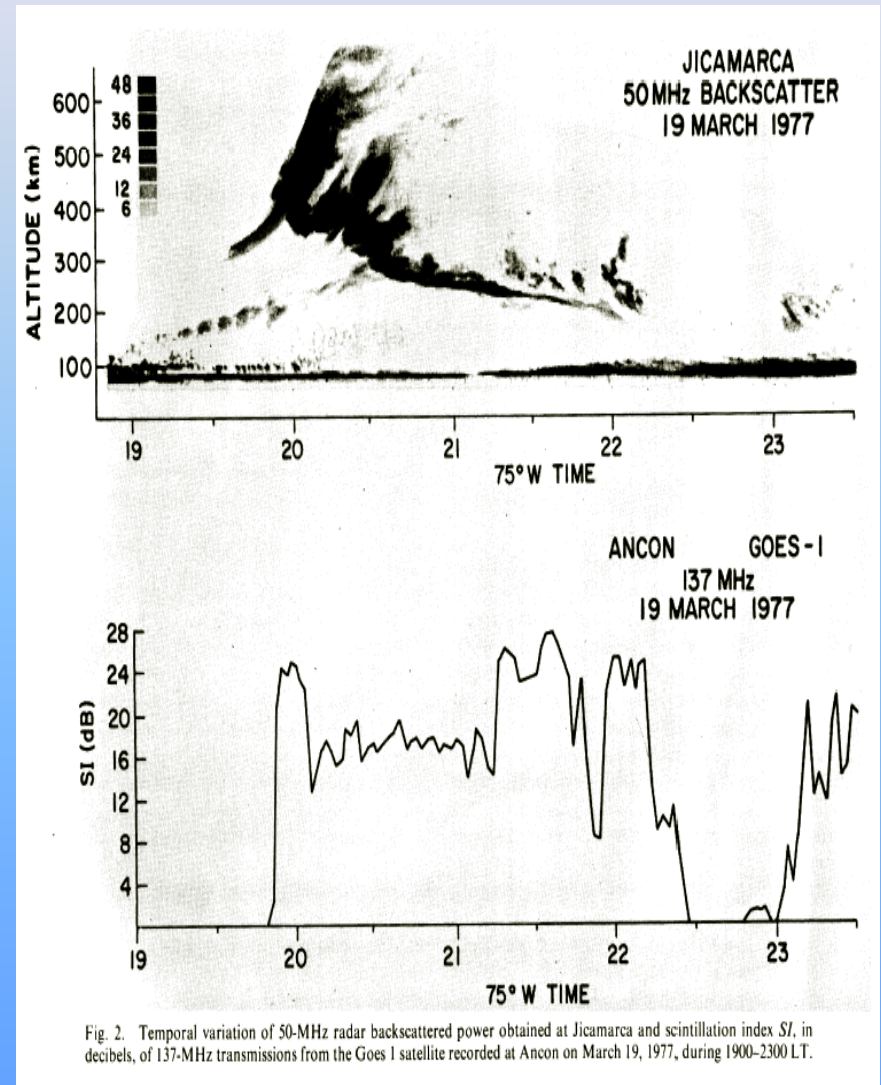
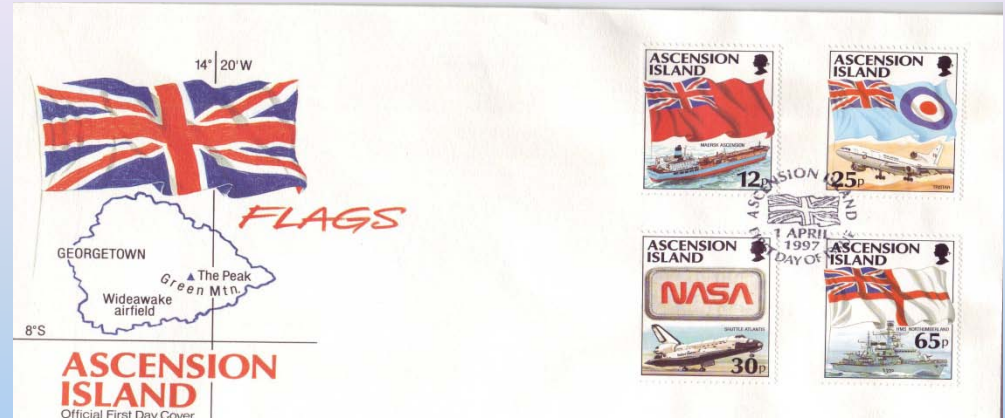


Fig. 2. Temporal variation of 50-MHz radar backscattered power obtained at Jicamarca and scintillation index SI , in decibels, of 137-MHz transmissions from the Goes 1 satellite recorded at Ancon on March 19, 1977, during 1900–2300 LT.

Observing Sites in the Equatorial Region used by AFRL to Determine Ionospheric Constraints on Communication and Navigation Systems

Ascension Island in the South Atlantic has one of the most strongly turbulent ionospheres. Since the mid-seventies AFRL has used this ground station as the test bed for studying the robustness of communication and navigation systems. The multi-frequency scintillation input allowed the development of user-oriented scintillation models



A First Day cover showing the tiny size of Asc. Is.

Jicamarca radar, in Peru, at the magnetic equator allows us to study the initiation of equatorial plasma turbulence. Campaigns were conducted starting in the mid-seventies to understand F-region dynamics

The fully steerable Altair radar has been used by AFRL starting in the eighties to study the physics of ionospheric turbulence and assess their impact on space surveillance.



ALTAIR Radar 46m dish at VHF/UHF



Jicamarca Radar at 49.9 MHz uses 18,432 dipoles

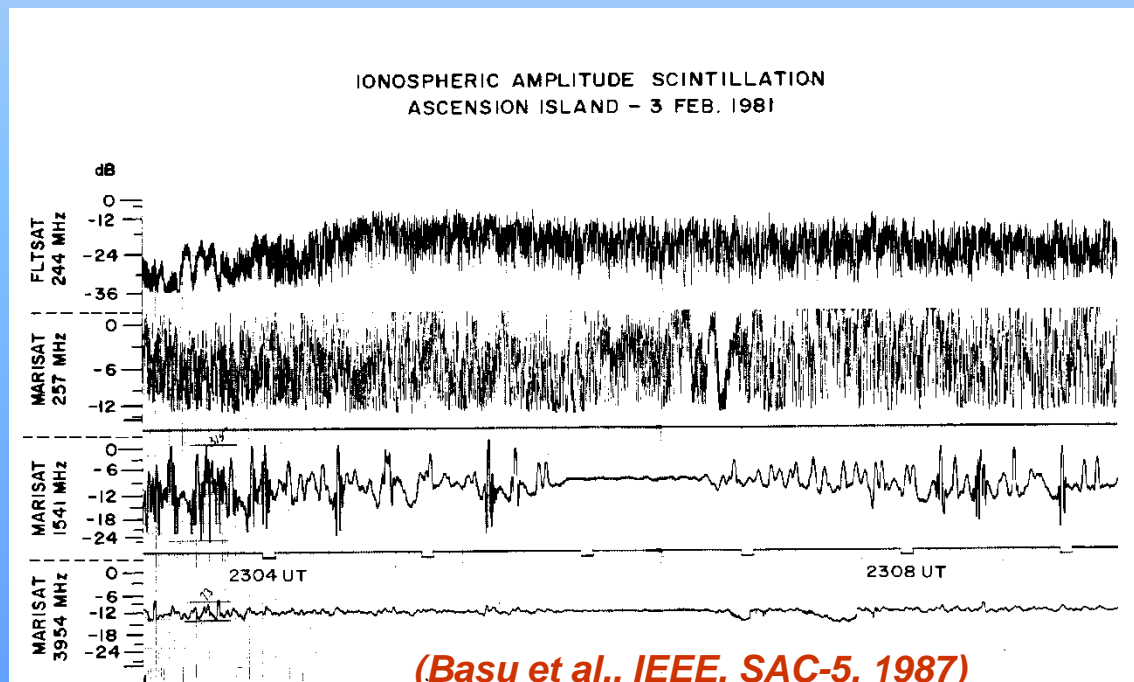
Quiet-time Space Weather: Intense Scintillation Event at Ascension Island

The AFSATCOM system provides Critical Satellite Communications support to the civilian community and military .

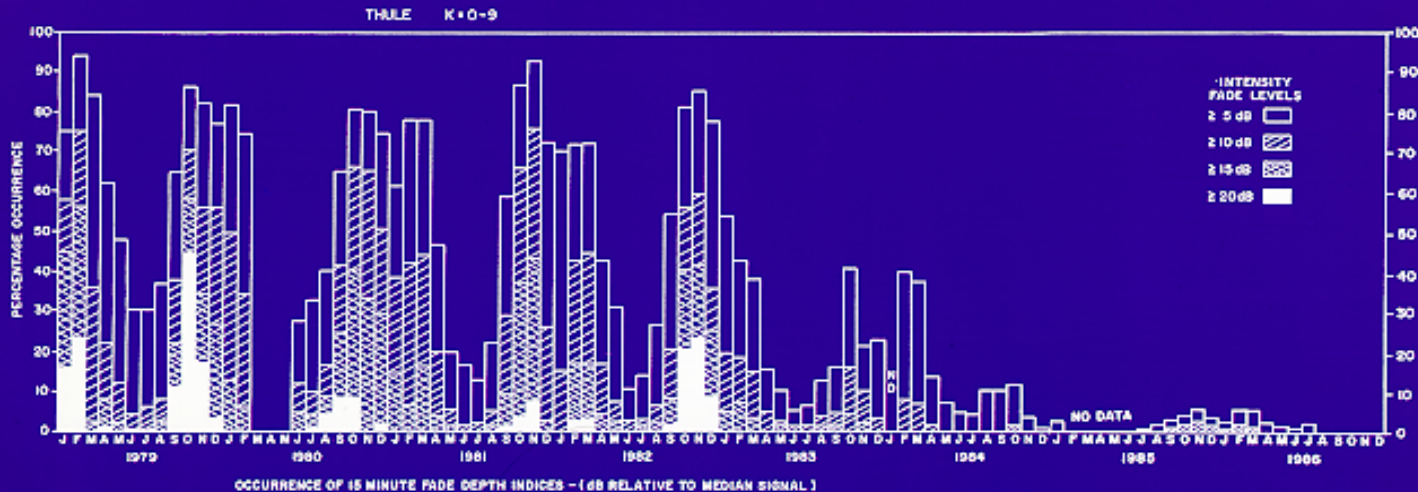
“We are learning that space weather can have a significant effect on our communications.....We must provide either reliable communications or at least a forecast of when there will be disruptions.....”

**Chief,
AFSATCOM Systems Division**

Under solar maximum conditions, 20 decibel signal fadings at 1.5 GHz (GPS frequency band) and 6 decibel fadings at 4 GHz are routinely encountered at places like Ascension Island. Voice communication becomes choppy, and GPS position errors become unacceptable.



Polar Cap VHF Scintillation Variation with Solar Cycle



(Basu et al., Radio Sci., 1988)

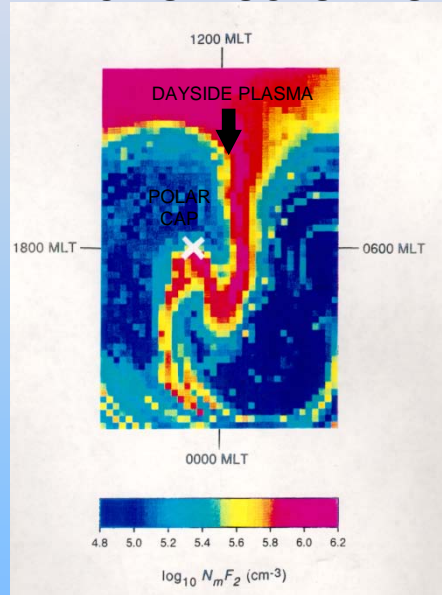
Polar Cap Patches

Model plasma transport
 By induced IMF variation
 UT and seasonal effects

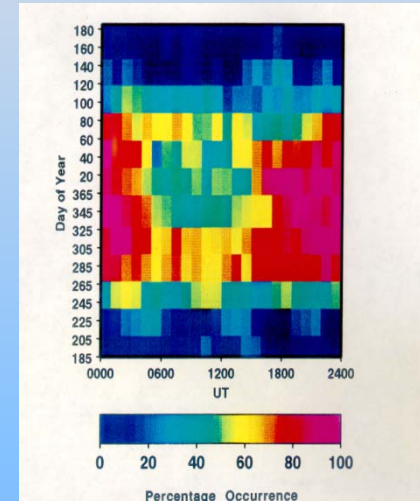
- Model reproduces observed effects

Gradient drift structuring
 causes observed scintillation

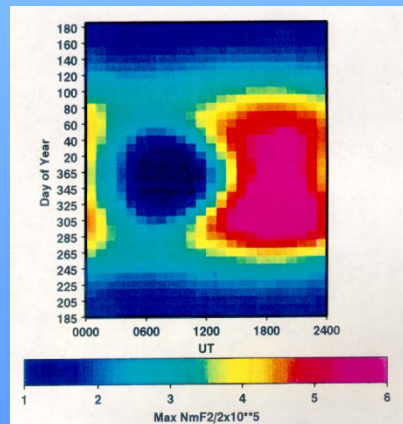
PATCH STRUCTURING



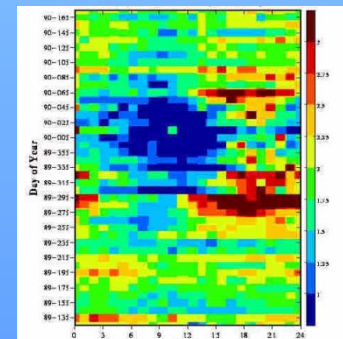
OBSERVED UHF SCINTILLATION



MODEL NmF2



OBSERVED NmF2

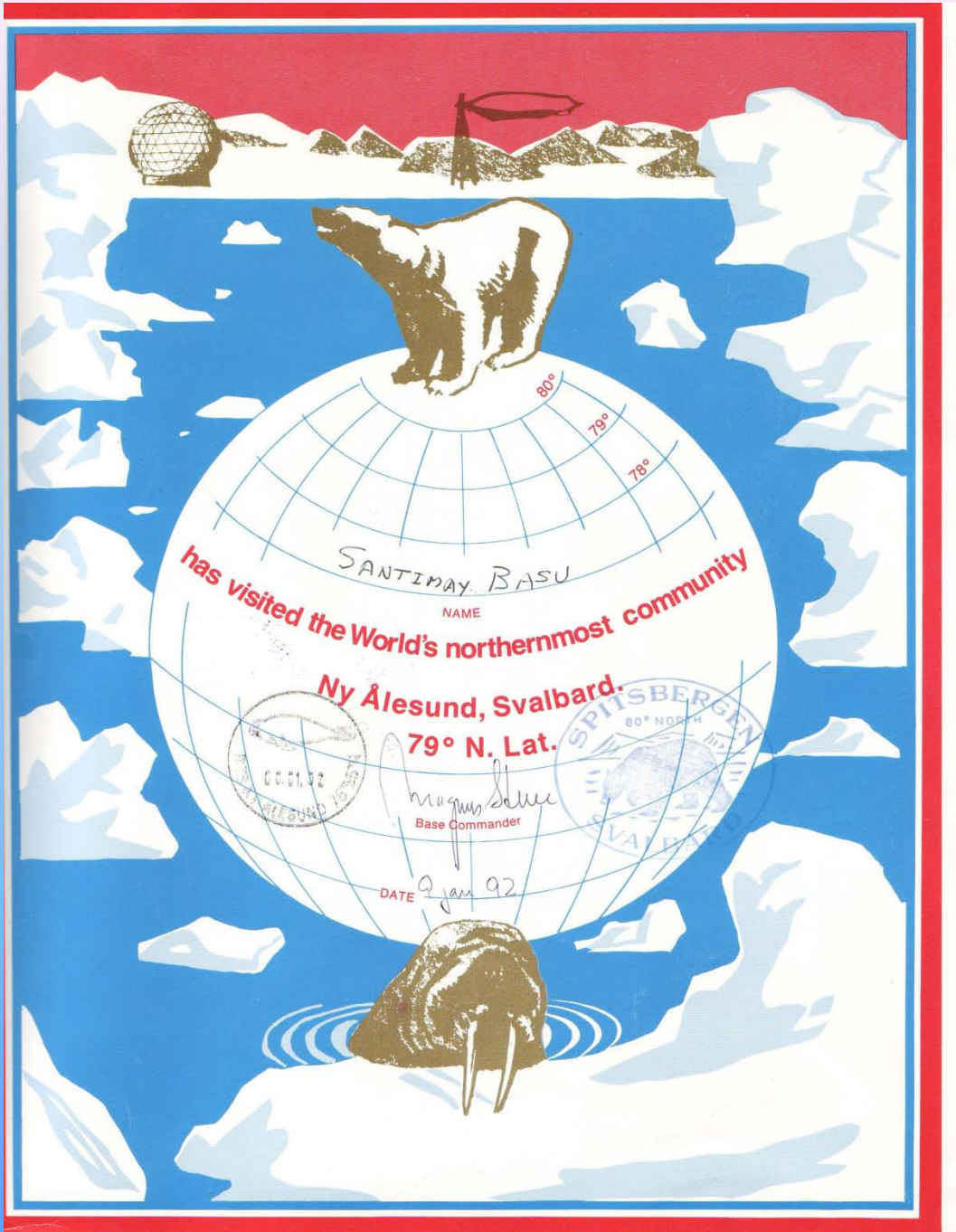


(Basu et al., GRL, 1995)

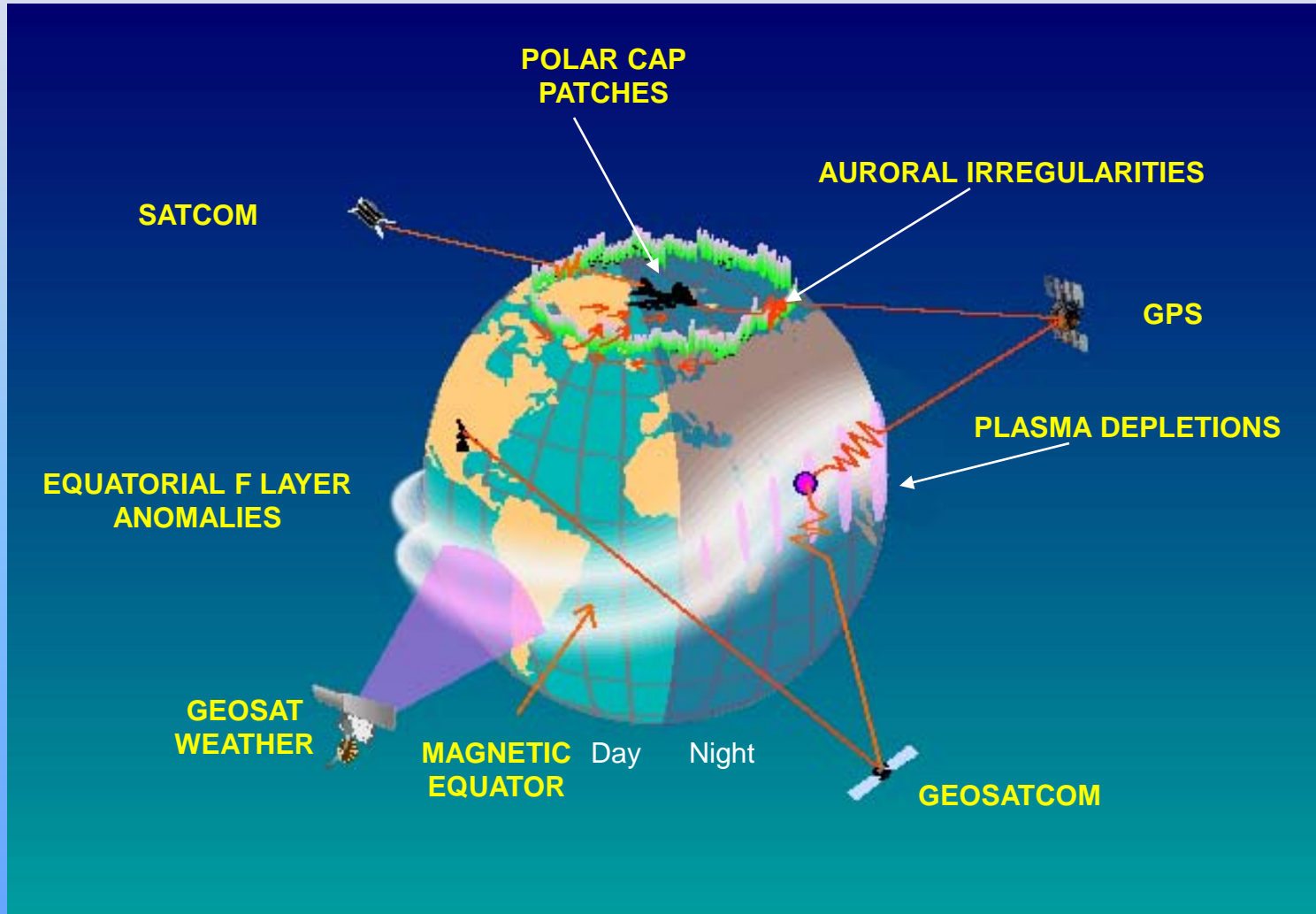
Experiments in the Dark Cusp

Ny Alesund, at the dayside cusp, is the entry point of polar cap patches and the seat of intense scintillation. We went on a 2-week campaign, obtained good data and left the instruments there. AFRL continues to perform round-the-clock scintillation and optical observations throughout the polar region in winter (**Basu, et al., Radio Sci., 1994**)

It is also Polar Bear country, particularly in winter, when we make our observations. We were asked to carry a gun when going off the base!

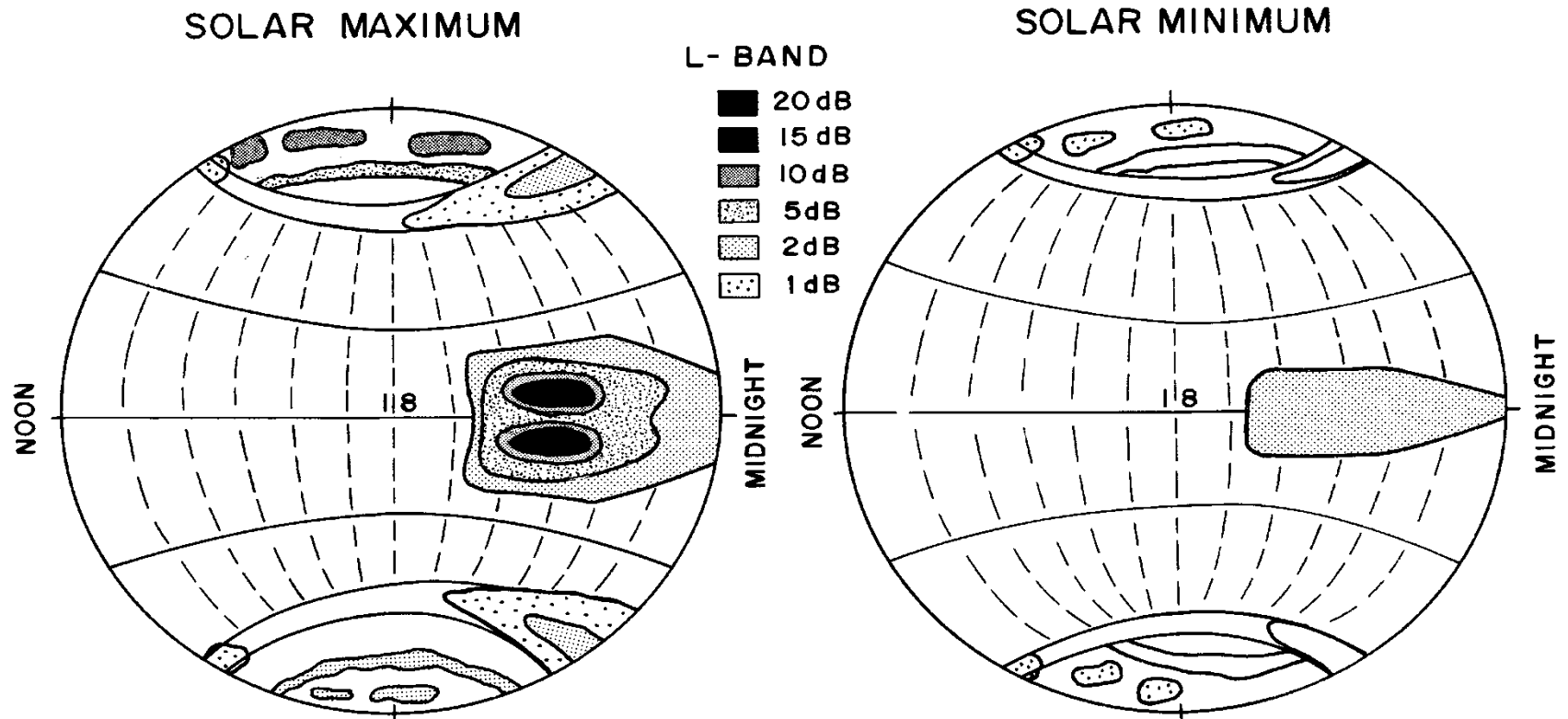


Global Satcom Outage Regions



Global Morphology of Scintillations

"WORST CASE" FADING DEPTHS AT L-BAND



(Basu et al., Radio Sci., 1988)

Controlled Excitation of Plasma Processes in the Middle Latitude Ionosphere by High Power HF Radio Waves

In March 1980, we used the Platteville High Power (1.5 MW) High Frequency facility and detected satellite scintillations from ground stations in Wyoming and from aircraft for underdense and overdense heating in connection with the then proposed Solar Power Satellite.

In September 1981, we used the Arecibo heating facility at Islote and detected radio star scintillations at 430 MHz, Plasma Line enhancement and 50 MHz radar backscatter from Guadeloupe over the heated volume.

In March 1984 and October 1992 we used the EISCAT, Norway, HF transmitters with ERP of 250 MW and studied the evolution of scintillations and irregularity structures from Tromso, Sorkjosen, and Grunnfjord, Norway.

(Publications: Basu et al., GRL, 1980, Basu et al., JGR, 1983, 1987, 1997; Costa, Basu et al., Radio Sci., 1997)

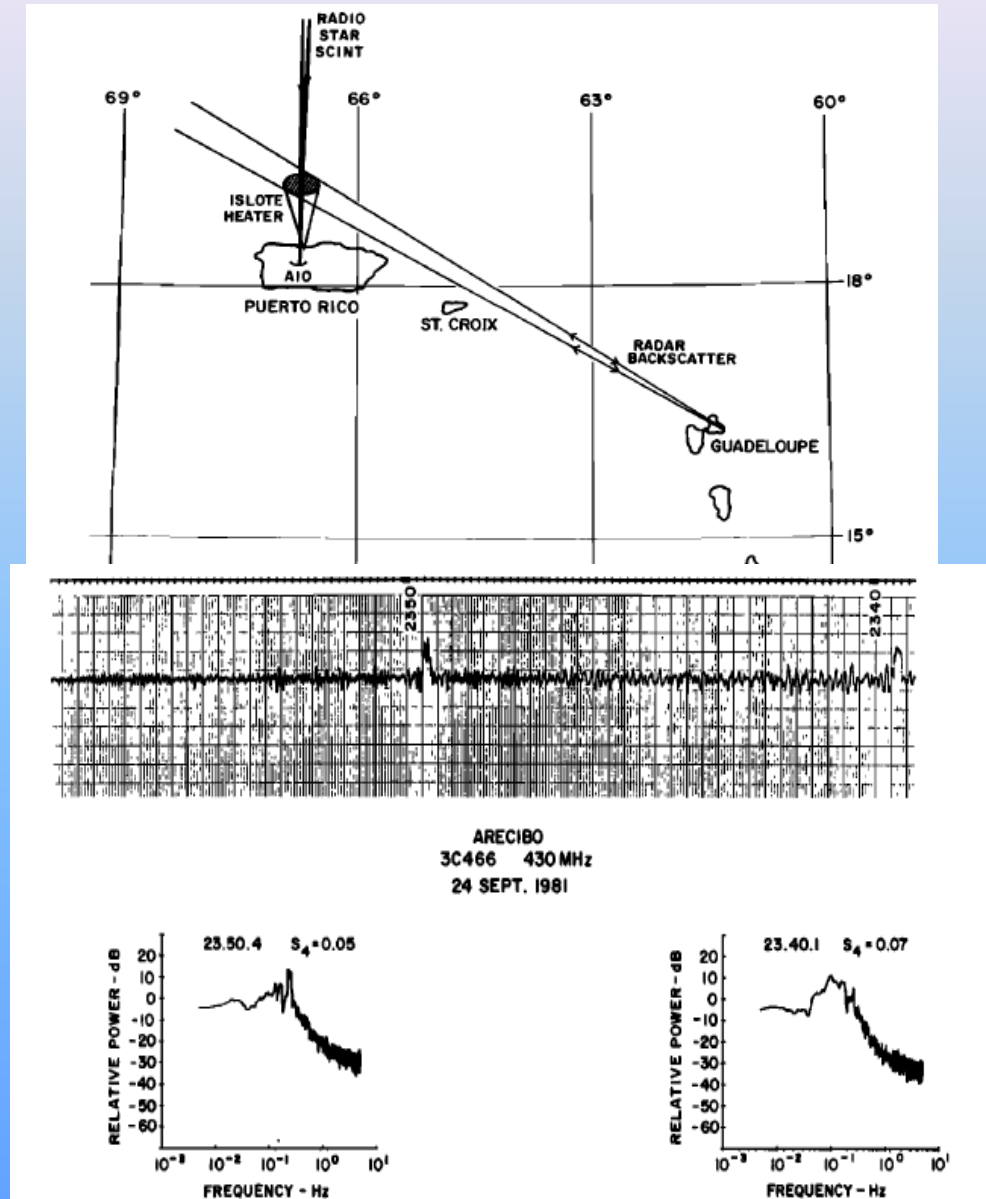


Fig. 4. Heater-induced 430-MHz intensity scintillation data using 3C466 and corresponding spectra for two levels of heater power.

Ionospheric Modification Experiment at Grunnfjord, Norway with EISCAT Heater

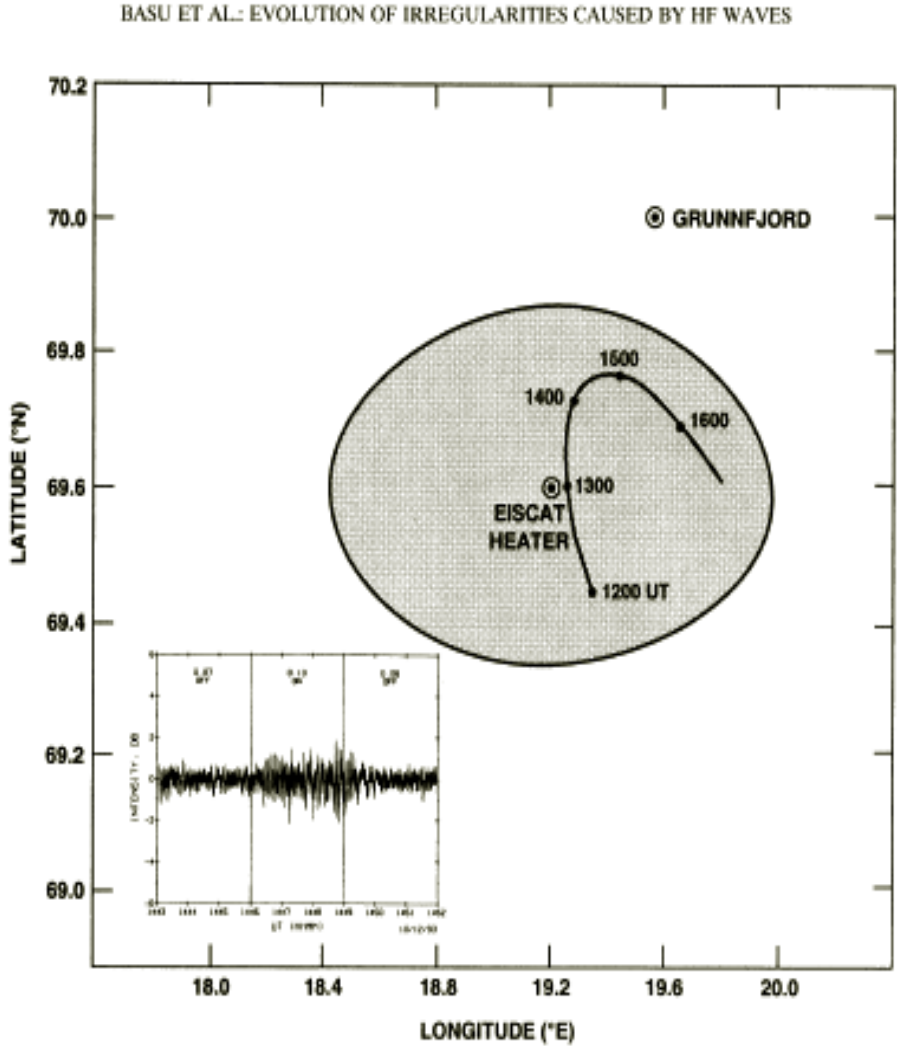
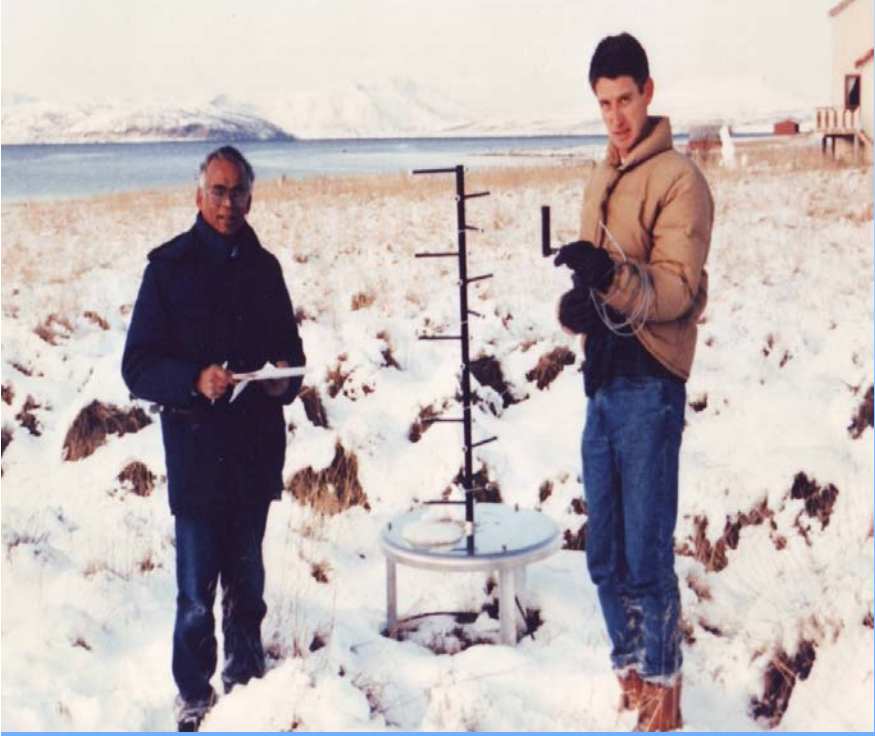


Figure 1. Illustrates the geometry of the observations using the EISCAT heater. The shaded region indicates the half power beam circle of the heater along with the locus of the intersection of the propagation path from the polar beacon satellite to the receiver at Grunnfjord with the HF reflection altitude of 250 km. The inset diagram shows the growth and decay of scintillations at 250 MHz during the heater "on" and "off" cycles.

(Basu et al., JGR, 1997)



S. Basu and R. Livingston at an improvised Field Site at a small fishing village!

Desert Storm and AFRL (PL) Support to the Mission

Prior to 1990, the Air Force was focused on communication and radar observations in the polar and auroral regions.

During the Desert Shield phase before the Desert Storm Operation, we alerted the Strategic Air Command that Equatorial Scintillations will impact theater communication. We provided information on the time of occurrence of scintillation and the extent of their effect on VHF, UHF, L-band and S-band communication. This information helped the Air Force to efficiently prioritize the satellite communication links during scintillation events.



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What led to Sunanda considering a position at NSF?

- Membership in Advisory Committee for Atmospheric Sciences, 1988-1992
- Leading the CEDAR/High Latitude Plasma Structure Group Workshops for many years
- Organizing the HLPS/GAPS Peaceful Valley Workshop in Lyons, CO in June 1992
- Challenge of becoming the first woman to direct the Aeronomy Program
- Sunanda was Aeronomy Program Dir. 1992-2002
- As luck would have it Bob Robinson and I joined together!



FY 94 CEDAR Research Competition

Below is a list of CEDAR awards granted with FY 94 funds. This CEDAR competition was restricted to instrumentation development and upgrades. Nine awards were made with an average grant size of about \$120K. Results of the FY 95 CEDAR competition will be announced at the next CEDAR Workshop in June, 1995.

Proposals recommended for funding:

Ben Balsley - University of Colorado

Modification of Jicamarca for Continuous, Low-Power Operation: The JULIA System

Timothy Killeen - University of Michigan

A Complement of Optical Instruments for the Polar Cap Observatory

Michael Mendillo - Boston University

Optical Tomographic Imaging Facility

Hans Moosmuller - University of Nevada

Approaching "Ultimate" Lidar for Temperature and Wind Measurements in the Mesopause Region

Chiao-Yao She - Colorado State University

Approaching "Ultimate" Lidar for Temperature and Wind Measurements in the Mesopause Region

Gulamabas Sivjee - Embry-Riddle University

Class I Imaging Spectroscopic Facility for Optical Remote Sensing of Airglow and Auroral Processes in the Polar Middle Atmosphere and Thermosphere

FY94 CEDAR Competition Results (New Technology Initiative)

Number of proposals submitted: 33
Total requested for FY94: \$6M
Total funds available: \$1.1M
Number of proposals recommended: 9

Michael Taylor - Utah State University

A Two-Dimensional Temperature Mapper for Short Period Mesospheric Gravity Wave Measurements

Vincent Wickwar - Utah State University

Resonance Lidar to Study the Upper Mesosphere and Lower Thermosphere

Supplements to existing awards

Craig Tepley - *Resonance Lidar Studies at the Arecibo Observatory*

(Supplement to Cooperative Agreement to National Astronomy and Ionosphere Center, Cornell University, PI: Paul Goldsmith)

Bob Robinson, NSF

**Gerhard Haerendel, Director, Max Planck Institute in Garching, Germany, Santi and Michael Mendillo at the ISEA-9 Meeting in Bali Indonesia, 1995.
(I could not attend because of major surgery)**



Don Farley and me at the URSI General Assembly in Lille, France in 1996. As USNC/URSI Chair of Commission G, I nominated Don for the Appleton Prize which he won and I wrote an article on this in the CEDAR Post

Scientific Initiatives at NSF

AER/CEDAR Programs (1992-2002)

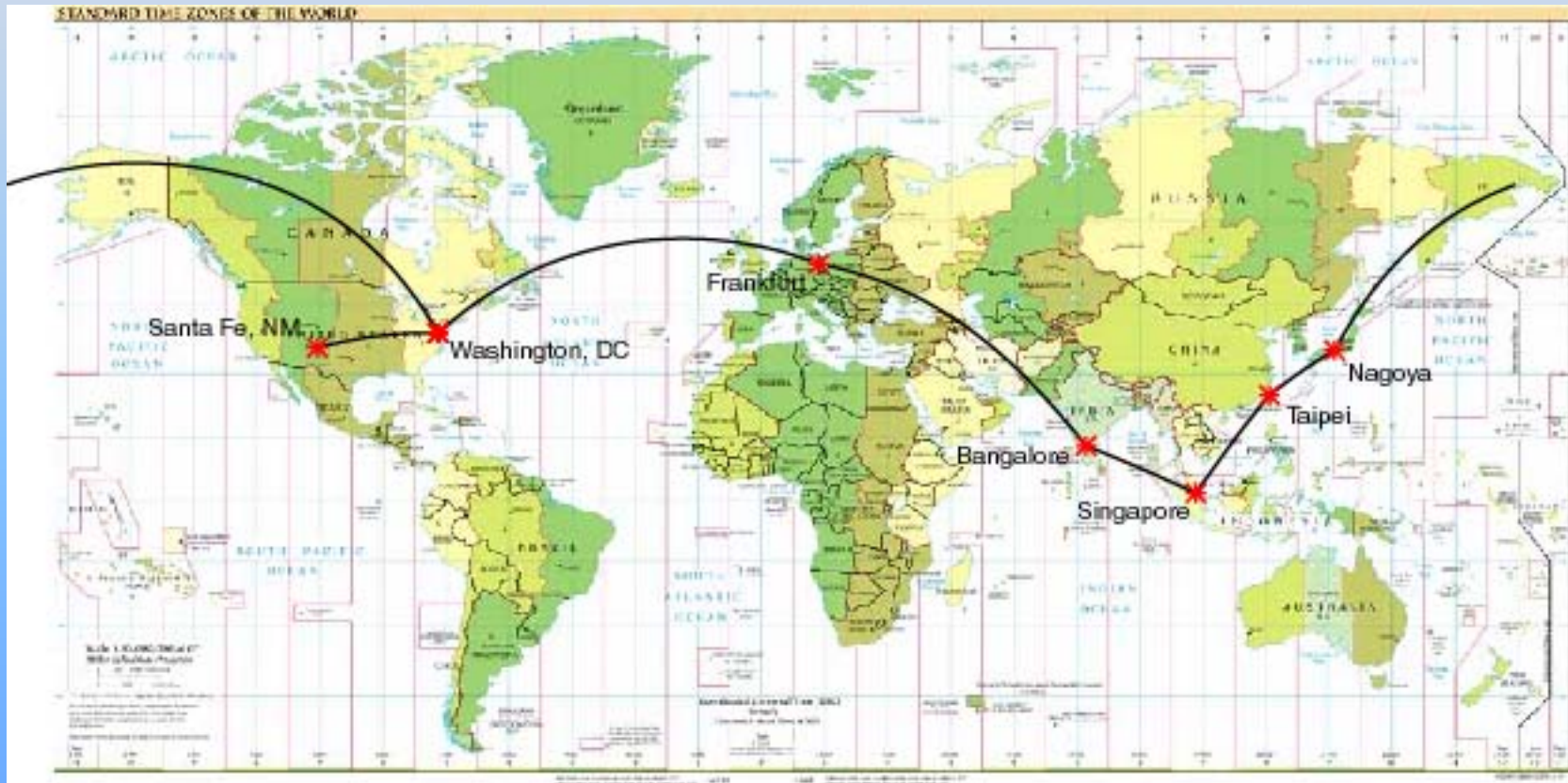
- **Comet SL 9-Jupiter-NSF AER/AST/NASA, 1996**
- **Ionospheric Interaction - NSF/ONR/AFOSR, 1997**
- **CEDAR-TIMED - NSF/NASA(prior to launch), 1998**
- **Maui-MALT – NSF/AFOSR(Haleakala site), 2000**
- **CEDAR-GEM – NSF (M/I Coupling)**
- **Space Weather –NSF/NASA/DOC/DOD/FAA**

Immediately after leaving NSF, Chaired SCOSTEP CAWSES Program 2002-2005 – Presented the IAGA Association and URSI General Lectures in Toulouse, France and New Delhi, India respectively both in 2005

Germany, India and Japan had national CAWSES Programs

Around the World for CAWSES

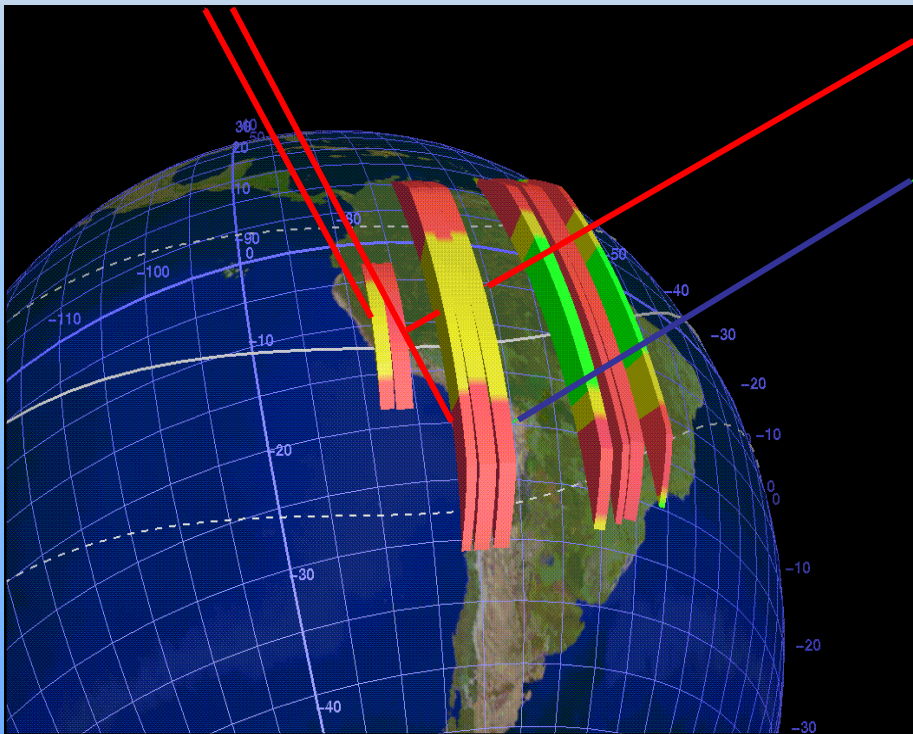
(In 15 days in June 2004)



38,365 kilometers traveled!

SCINTILLATION NETWORK DECISION AID (SCINDA)

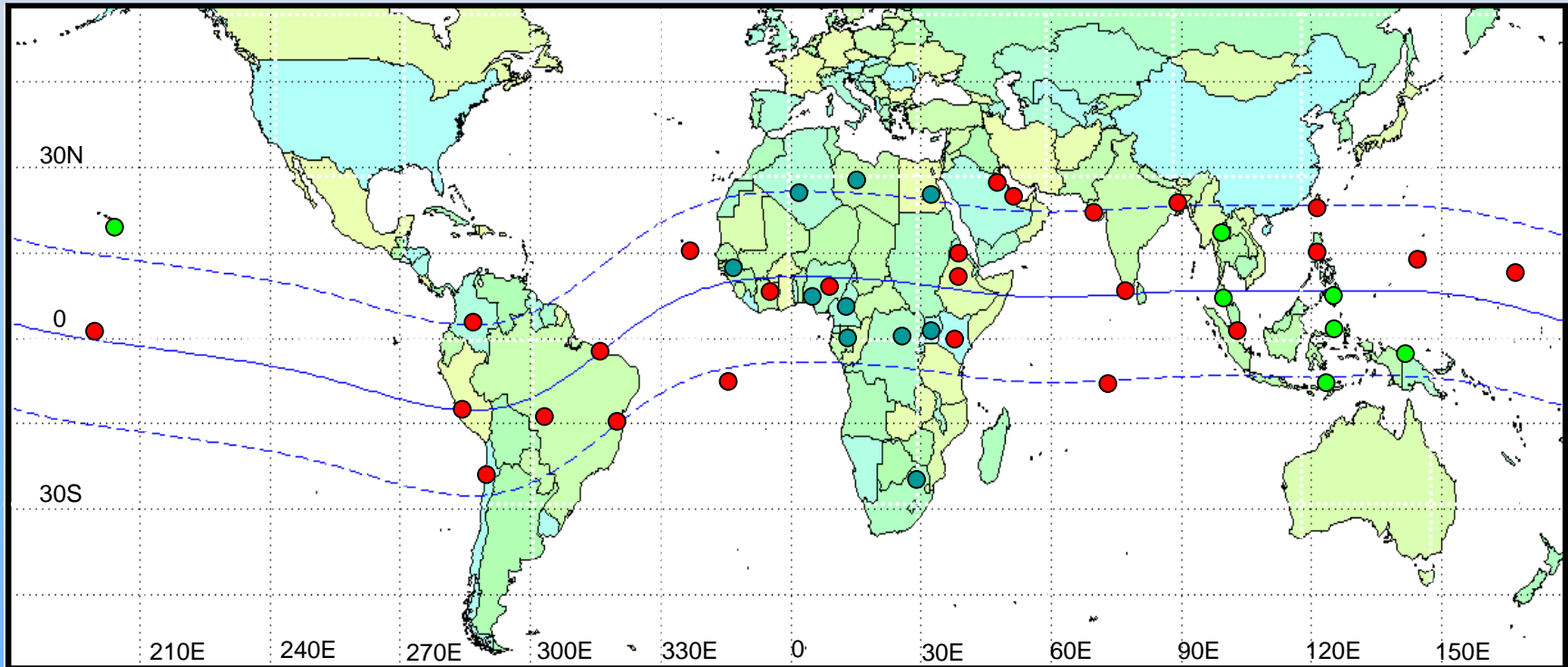
A REGIONAL NOWCASTING SYSTEM



- **Ground-based sensor network**
 - Passive UHF / L-band /GPS scintillation receivers
 - Measures scintillation intensity and eastward drift velocity
 - Automated real-time data retrieval via internet
- **Data drives equatorial scintillation model providing simplified visualizations for UHF SATCOM users**
- **Model produces tailored products distributed on Air Force Weather Agency web site**

SCINDA Ground Stations

Present and anticipated thru 2008



● Existing Sites

● UN IHY Sites

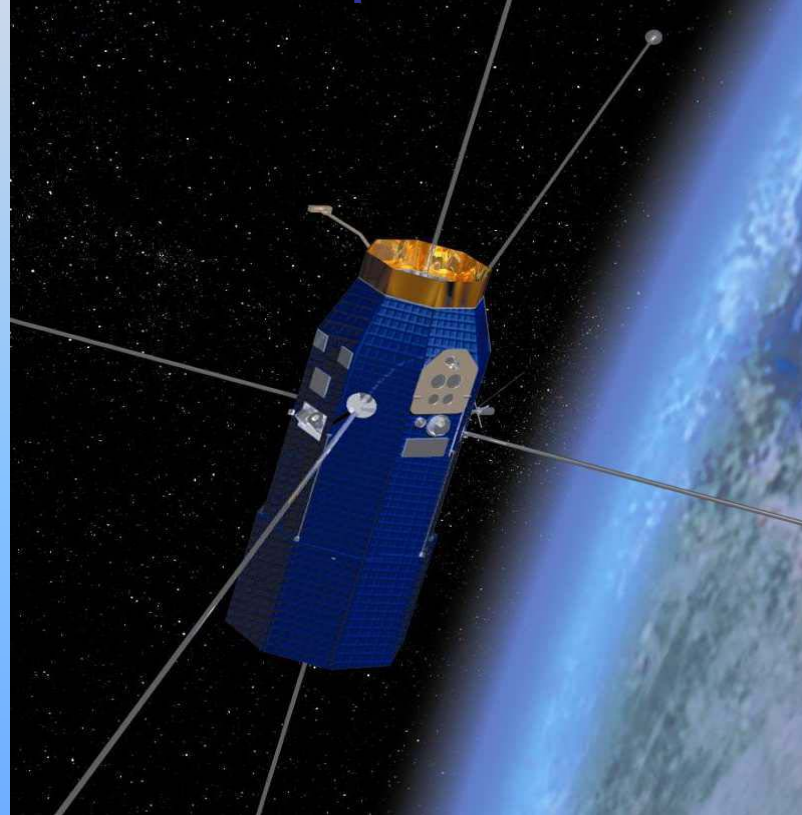
● Other/collaboration

Sensor network provides regional and global context for ionospheric disturbances
Groves, 2008

C/NOFS:

Communication Navigation Outage Forecasting System

Santi and Ed Weber (deceased 2000) gave numerous briefings to the Air Force Space Command on C/NOFS Mission Concept



C/NOFS is a joint STP/AFRL, NRL, NASA Program

- 400 km x 850 km; 13° Orbital inclination
- Original launch date ~2003; Actual launch on April 16, 2008
- C/NOFS will Specify and Forecast Equatorial Scintillations from Satellite In-situ Measurements of
 - Electron Density,
 - Ion Density,
 - Ion Drift
 - Electric Field,
 - Neutral Wind
 - GPS Occultation Sensor
 - Tri-Band Radio Beacon

Physics-Based Data Assimilative Model will Specify and Forecast Ionospheric Scintillation

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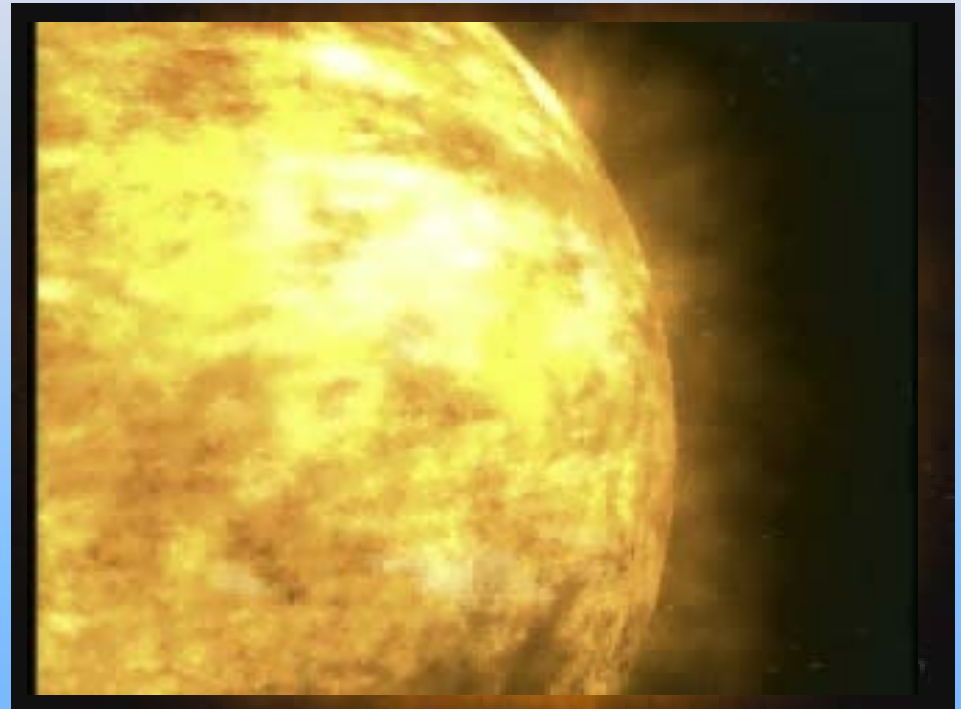
Solar Storms Disturb the Magnetosphere, Ionosphere and Thermosphere

... *and interrupt
civilian and military operations*

During the main phase of large magnetic storms an eastward electric field penetrates from high latitudes through mid-latitudes to the equator over the dayside to the evening period.

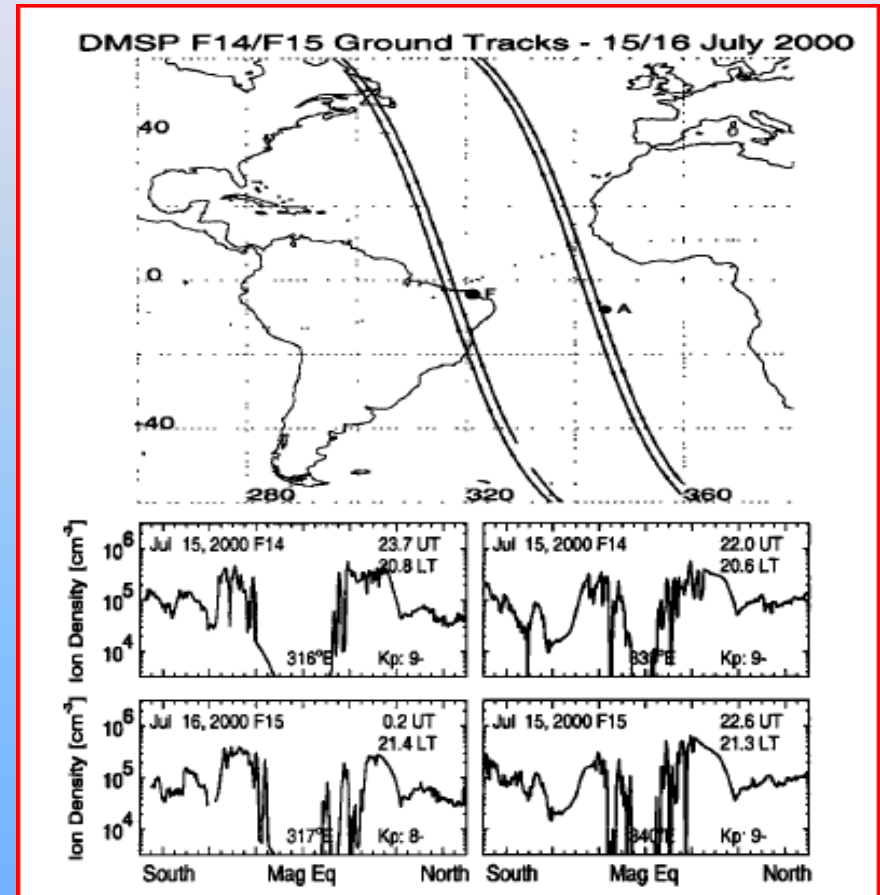
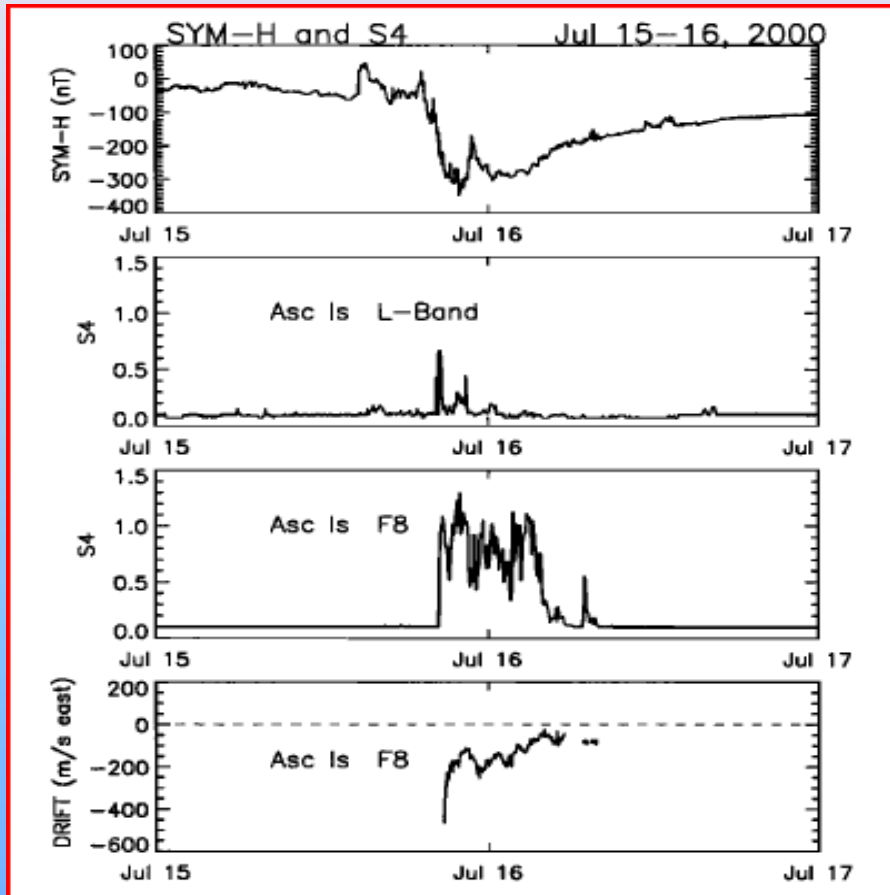
At normally benign mid-latitudes, storm enhanced density, associated with steep density gradients and electron density irregularities, is encountered in the early afternoon period. WAAS system providing guidance to aircraft is disabled owing to increased GPS navigation errors. If the penetration occurs in the evening hours, large plasma flows introduce strong phase scintillations and outages in GPS receivers.

At the magnetic equator, the eastward electric field at dusk causes deep plasma bubbles & severe scintillations,



NASA Simulation

First Study of the Ionospheric Impacts of the Bastille Day Storm (Basu et al., GRL, 2001)



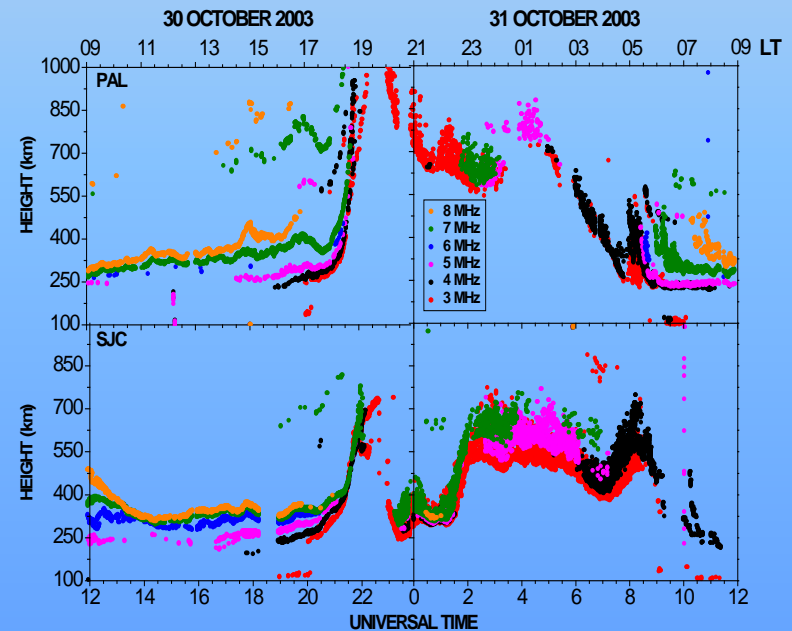
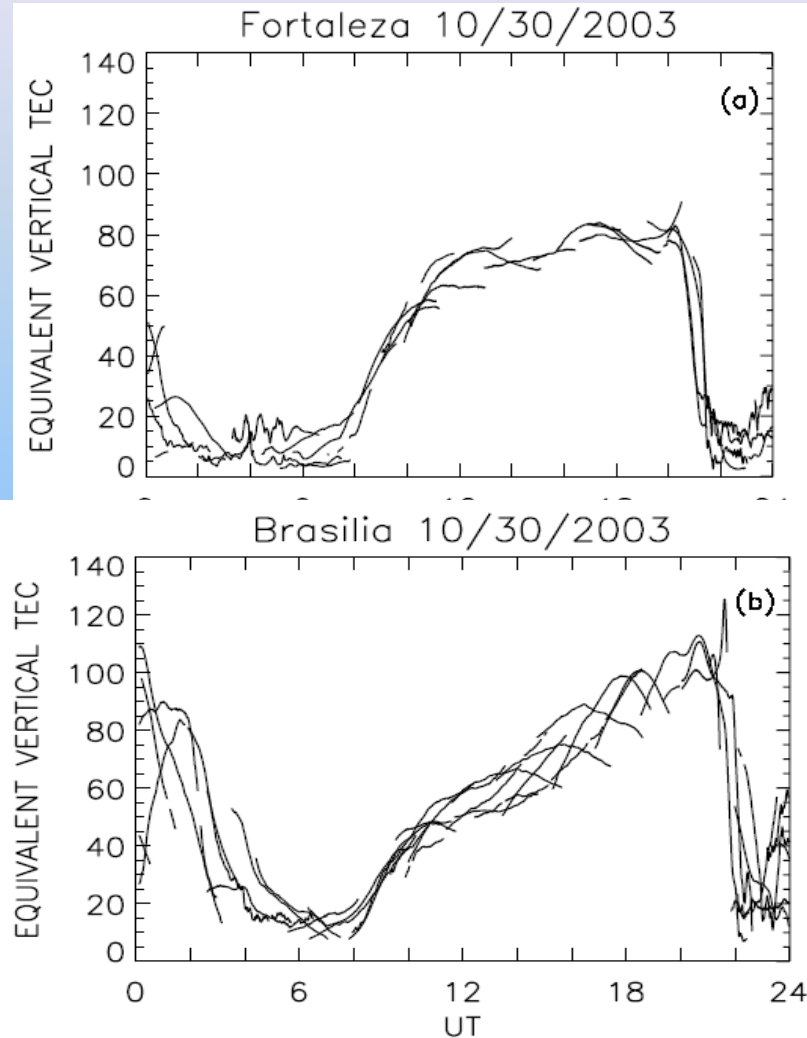
The rapid time rate of change of Dst is associated with PPE, raising F-layer, generating bubbles & scint.

As a consequence of the PPE, the F-region rises above DMSP. Point A denotes location of scintillation station at Ascension Island

Equatorial Ionosphere Severely Impacted During Halloween Storms in October 2003

During the Halloween Day storm of October 30, 2003, ground stations encountered intense TEC gradients and ionosondes observed spectacular height rise in the Brazilian sector

Spectacular Height Rise of F-region



(Basu et al., JGR, 2007)

WAAS – A GPS-based Navigation System

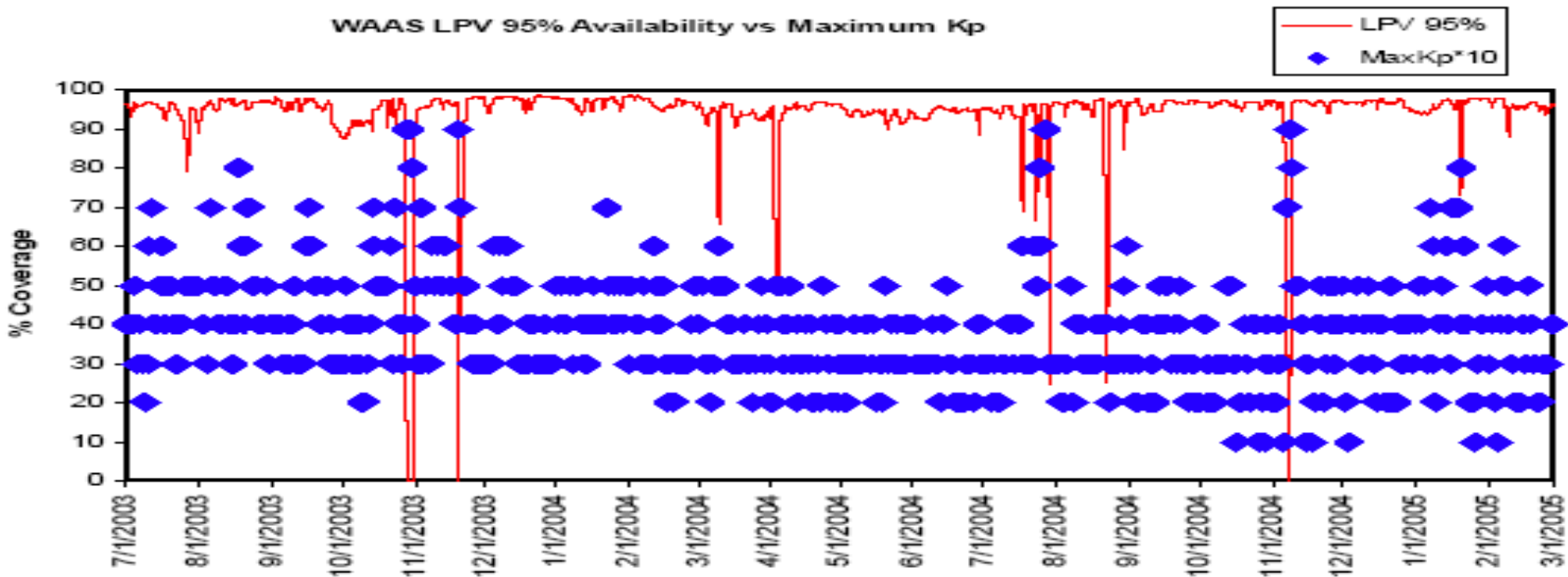


- It is used for navigation and precision approach to airports in US & parts of Canada & Mexico
- WAAS is based on ~30 GPS reference stations
- These stations are linked to form WAAS network
- Each precisely surveyed station receives GPS signals and determines if any errors exist and relays the data to a Master Station
- Master station computes correction information
- Master station prepares correction algorithm & uplinks to a GEO satellite
- GEO satellite broadcasts message on GPS L1 to receivers on aircraft flying within WAAS area
- WAAS improves basic GPS accuracy to ~7m vertically and horizontally

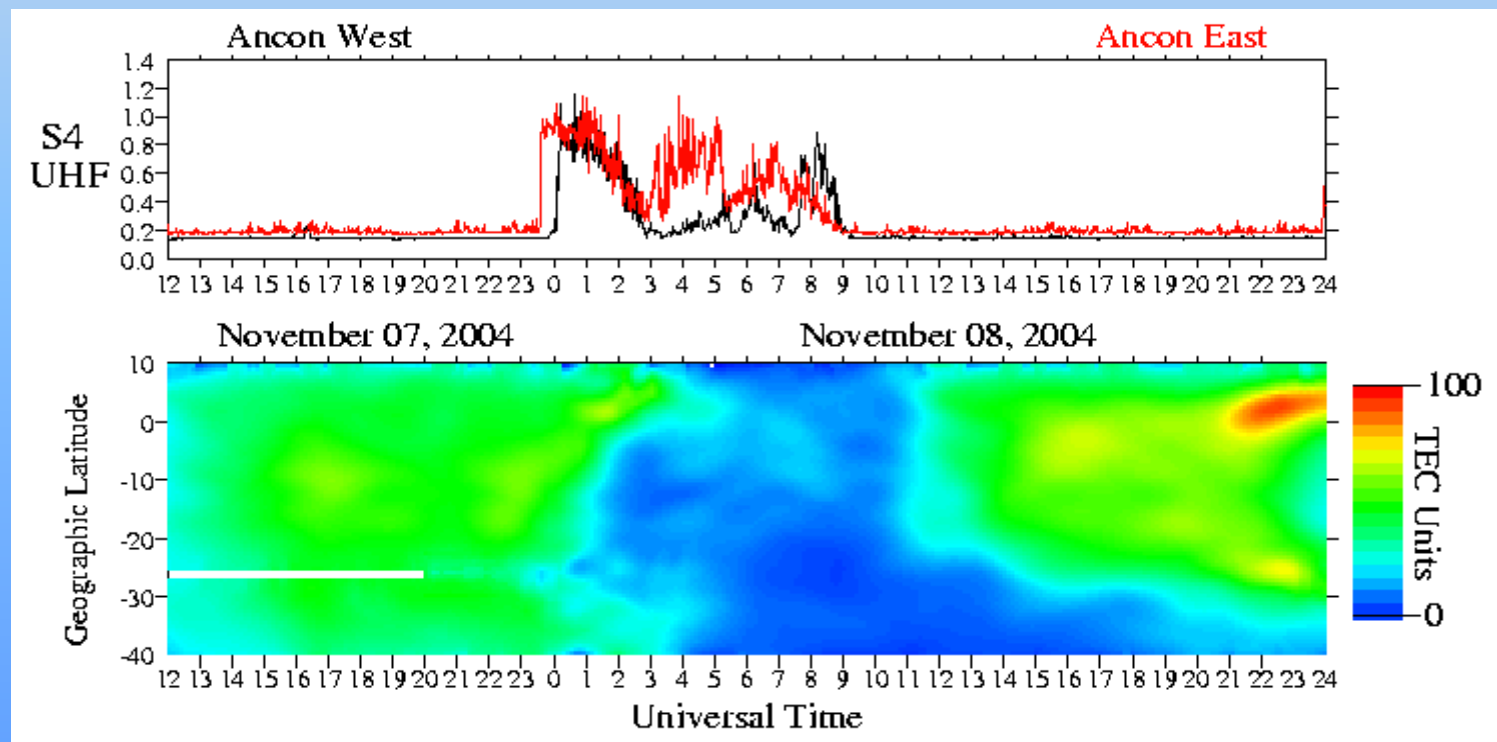
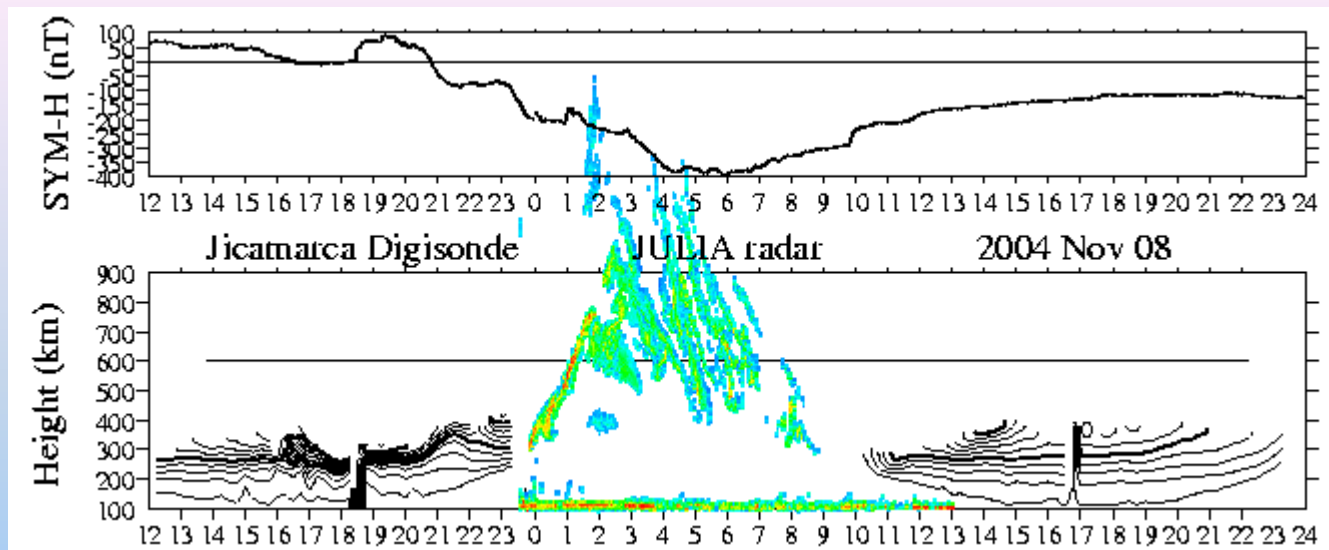
Three Superstorms Considered:

Oct 29-31, 2003; Nov 20, 2003 and Nov 8, 2004

WAAS was unavailable within CONUS for more than 10 hours on each of the above dates

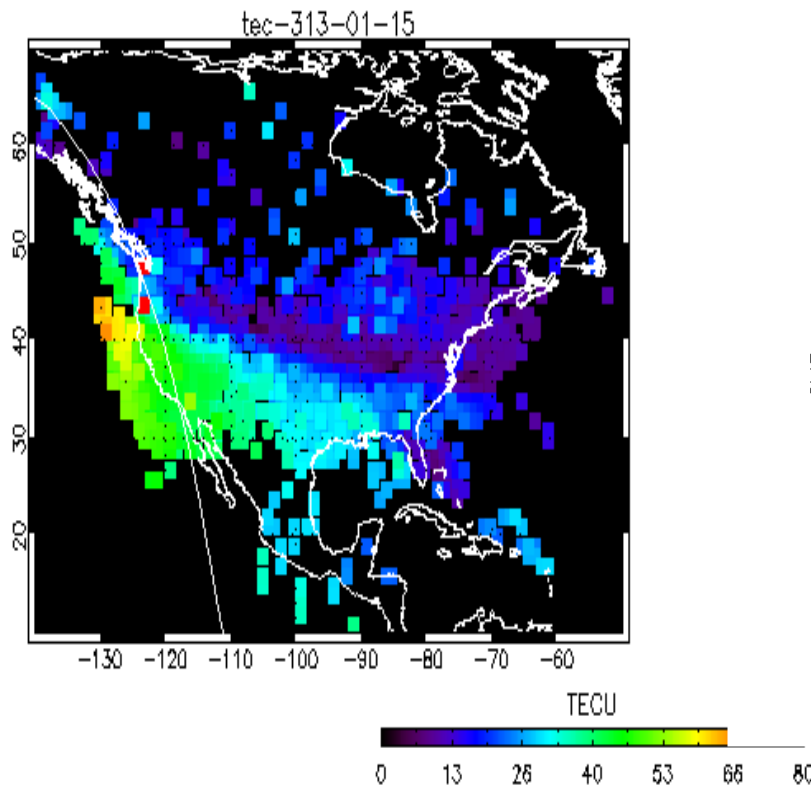


WAAS Minimum Requirement for LPV is Availability > 95% of time over 75% of CONUS

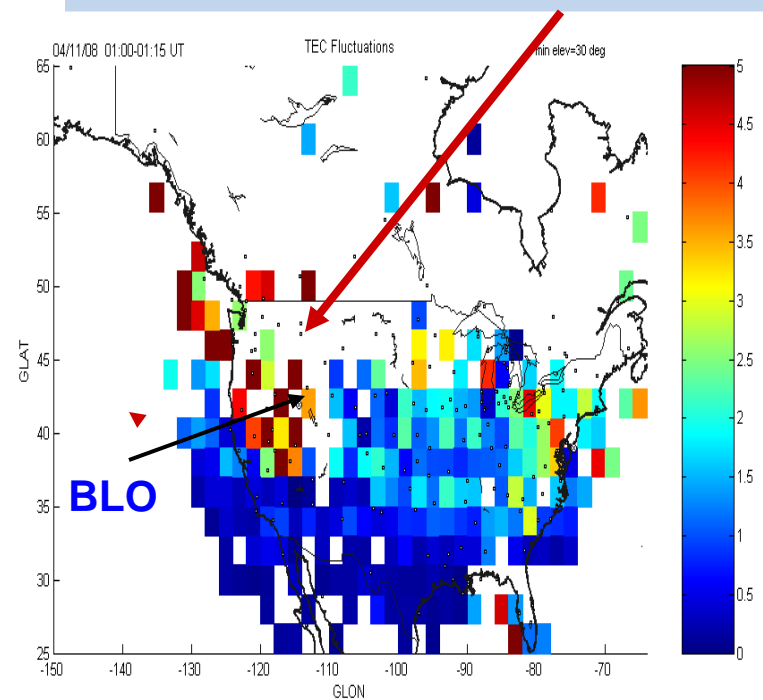


(Basu et al., RadioSc.2010)

TEC & GPS Phase Fluctuation Maps within CONUS during the Nov 8, 2004 Magnetic Storm

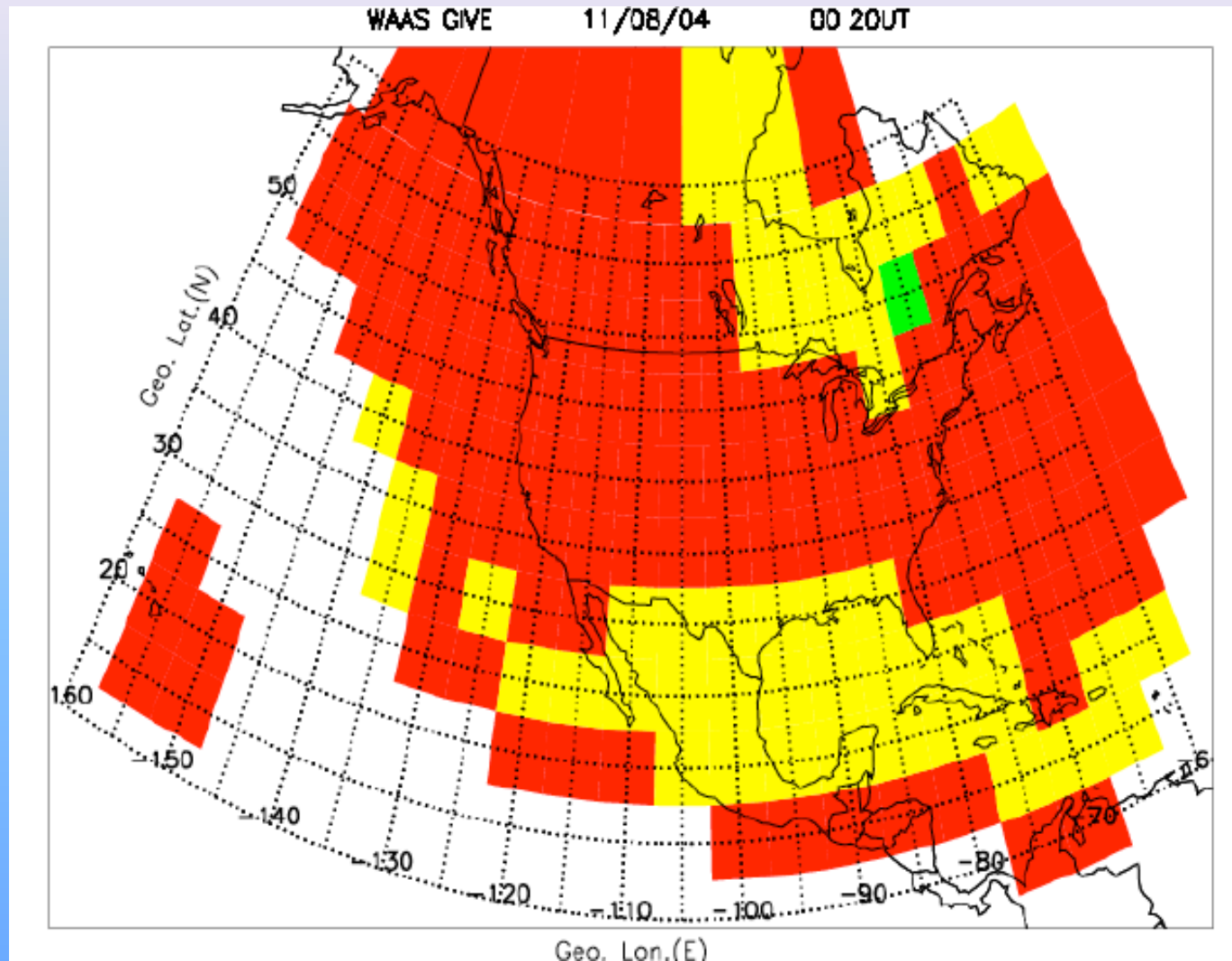


GPS Outage Region



Intense GPS Phase Fluctuations (Delta TEC/MIN) Occur Primarily in the Auroral Region at ~ 0100 UT. **GPS outage caused WAAS to be non-operational for approximately 12 hours** (Su. Basu et al., GRL, 2005)

Impact of High Storm-time Ionospheric Velocities on the WAAS System



GIVE Values

Green < 6 m

6 < Yellow < 45 m

Red > 45 m

6.13 TEC U = 1m delay

(Su. Basu et al., JGR, 2008)

Scope of Presentation

- ✓ **Sunanda's Grad Student Years**
 - Master's in US – awesome discovery!
 - Ph.D. in India (a son in between)
- ✓ **Santi's Beacon Receiver Building Phase**
 - In India with his grad students
- ✓ **Sunanda's Exciting NRC Post-doc Research**
- ✓ **Sunanda and Santi Partnership Phase 1**
- ✓ **Sunanda's NSF Decade – AER/CEDAR**
- ✓ **Sunanda and Santi Partnership Phase 2**

Lessons Learned

- Have no regrets – do the right thing by your family at the cost of career
- Follow your passion in the choice of your career
- Not everyone gets things handed on a platter – working through challenges strengthens your character. The guidance of mentors is essential
- High personal ethics is incredibly important
- Volunteerism is the backbone of our community
- Our science is so critically important to the environment around us that we have a special role to play in working on policy issues affecting it

