IONOSPHERIC SCINTILLATION: A TUTORIAL

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IONOSPHERIC SCINTILLATION
Introduction

- Electromagnetic Wave Propagation through Random Medium
  - Tropospheric Scintillation / Neutral Turbulence/ Twinkling of Stars
  - Ionospheric Scintillation/ Ionospheric Irregularities of Electron Density/ Fluctuations of Phase and Amplitude of Signals Received from Satellites
  - Interplanetary Scintillation/ Inhomogeneities in the Solar Wind/ Fluctuations of the Intensity of Radio Stars

- Scintillation Studies for Remote Sensing of the Turbulent Medium
  - Spectrum of Neutral Turbulence from Tropospheric Scintillation
  - Solar Wind Velocity from IPS
  - Ionospheric Irregularity Spectrum/ Irregularity Drifts

- Ionospheric Scintillation Studies to Assess Impact on Satellite Communication and Navigation (GPS) Systems, Determine their Global Variation and Design Robust Comm/Nav Systems

Incident Plane Wave
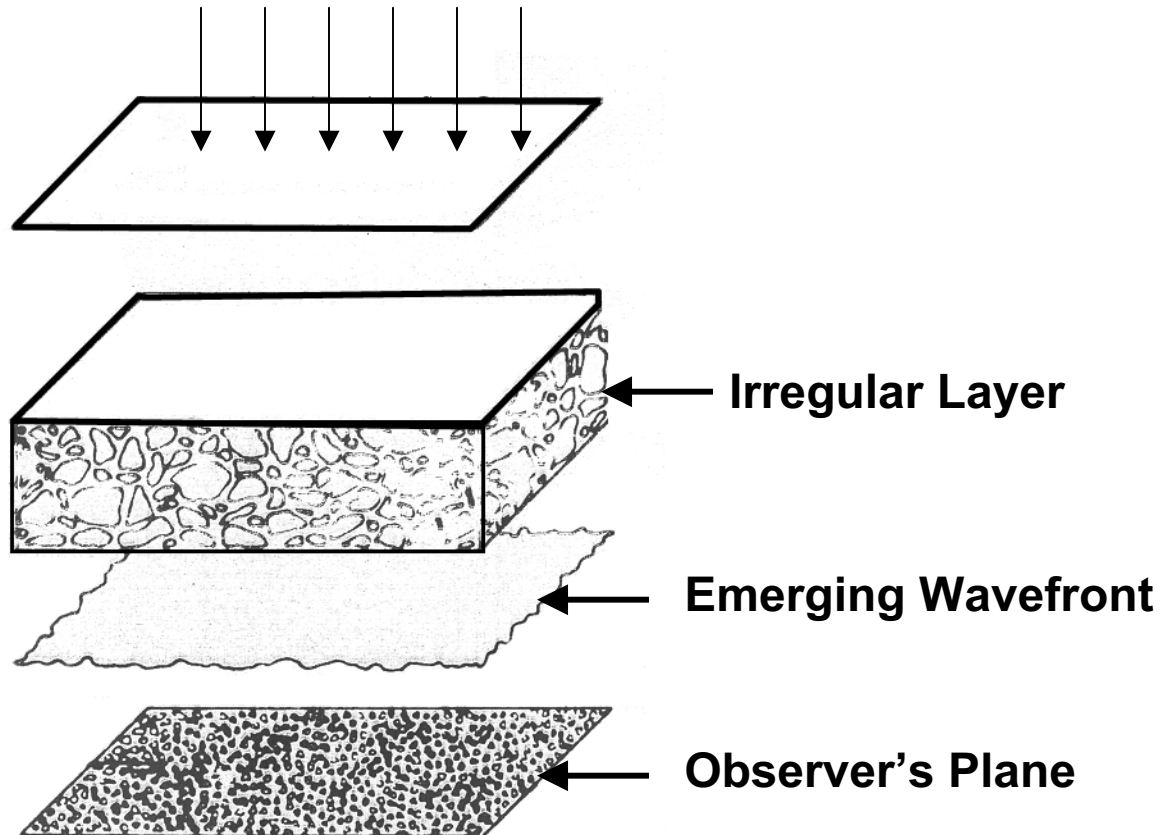
Pictorial illustration of the phase fluctuations Imposed on a wavefront traveling away from an Irregular layer for a vertical radio path.

Scintillation Theory/Radio Wave Propagation in Random Media

When the radio wave frequency $f \ll f_p$, the plasma frequency, the dielectric fluctuations are very small compared to unity, and the temporal variations of N are very slow, the vector wave equation reduces to the scalar wave equation

$$\nabla^2 E + k^2 \left[1 + \epsilon_1 (r, t) \right] E = 0$$

where E is a component of the electric field vector.

For forward scatter with propagation in the z direction, we define the complex amplitude as

$$E = u(r, t) e^{ikz}$$

Combining the two equations and assuming that the wavelength is small compared with the irregularity scale-lengths, so that $2k \left| \partial u / \partial z \right| \gg \left| \partial^2 u / \partial z^2 \right|$, we get the parabolic equation

$$2ik \, \partial u / \partial z + \nabla_\perp^2 u = -k^2 \epsilon_1 (r, t) u$$

Let us consider that k/L >> $1/r_0^2$, where L is the thickness
of the irregularity layer thickness and r_0 is outer scale of the
irregularities, i.e., $\sqrt{\lambda L} \ll r_0$. It signifies that the Fresnel
scale for propagation within the irregularity layer is very
small compared to the outer scale and therefore there is no
diffraction i.e.,

$$2ik \frac{\partial u}{\partial z} = -k^2 \epsilon_1 (r, t) u$$

We get

$$u(\rho, z, t) = A_0 e^{i\phi(\rho, z, t)}$$

where

$$\phi(\rho, z, t) = \frac{k}{2} \int_{-L}^{z} \epsilon (r, t) \, dz$$

$$\phi(\rho, 0) = -\lambda r_e \, \delta N_T (\rho)$$

where $\phi(\rho, 0)$ is the phase at the exit plane or at the phase
screen, $r_e = e^2 \mu_0/4\pi m$, is the classical electron radius (=2.8
x 10^{-15} m), and $\delta N_T(\rho)$ is the fluctuation of the electron
density integrated through the irregularity layer of
thickness L.

When ta plane wave propagates along the z axis, with normal incidence on the phase screen located at z=0, the complex amplitude u (ρ, z_R) of the wave in the reception plane at a distance z_R from the phase screen may be obtained from the Fresnel diffraction formula (*Ratcliffe, Reports of Progress in Physics, 19, 90, 1956*) as,

$$ u\left(\rho, z_R\right) = \sqrt{\frac{i}{\lambda z_R}} \int_{-\infty}^{+\infty} u\left(\rho', 0\right) \exp\left[\frac{i\pi\left(\rho-\rho'\right)^2}{\lambda z_R}\right]^2 d\rho' $$

For a shallow phase screen where $\varphi \ll 1$, the spectrum of the logarithmic amplitude χ and the phase deviation S can be obtained as,

$$ F_\chi\left(\kappa, z\right) = F_\varphi\left(\kappa\right) \sin^2\left(\kappa^2 z/2k\right) $$

$$ F_S\left(\kappa, z\right) = F_\varphi\left(\kappa\right) \cos^2\left(\kappa^2 z/2k\right) $$

Where κ is the transverse spectral wave vector and F_φ is the spectrum of the phase at the screen. It illustrates that the diffraction process introduces a spatial filtering of the phase spectrum. The trigonometric filtering functions are known as the Fresnel filtering functions.

The intensity scintillation index S_4, the normalized second central moment of signal intensity fluctuations is defined as,

$$S_4^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$

For weak scintillation S_4 has been obtained (*Rino, Radio Sci., 14, 1147, 1979*) for a power law irregularity environment as,

$$S_4^2 = 4\sqrt{\pi} \, r_e^2 \lambda^2 (L \sec\theta)\langle\delta N^2\rangle \kappa_0^{p-3} \, \Gamma\left(\frac{p/2+1}{2}\right) \times$$

$$\cdot \, \Gamma\left(\frac{3-p/2}{2}\right) \cdot Z^{p/2-1} \, g/(p/2-1)$$

where θ is the incident angle of the wave, $\langle\delta N^2\rangle$ is the variance of electron density fluctuations, $Z=\lambda z_R \sec\theta/2\pi$, g is the geometric factor depending on the anisotropy of irregularities (g=1 for isotropic irregularities), p is the 3-dimensional irregularity spectral index, $\kappa_0 = 2\pi/r_0$ is the outer scale wave number.

It is important to note that the frequency dependence of $S_4 \propto f^{-n}$, where $n = (p+2)/4$. For p=4, $S_4 \propto f^{-1.5}$.

It should be noted that the above expression is for weak scattering and is valid when $S_4 < 0.5$.

For strong scattering, S_4 does not exceed unity for $p < 5$ and the frequency dependence is weak.

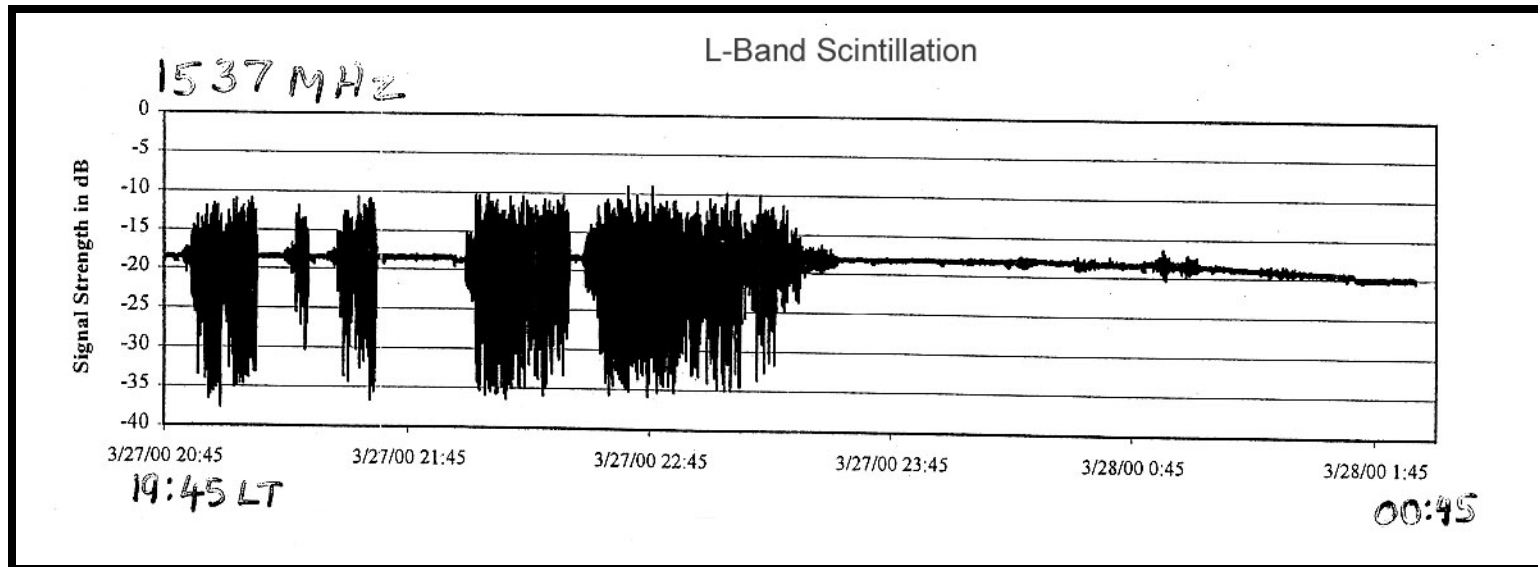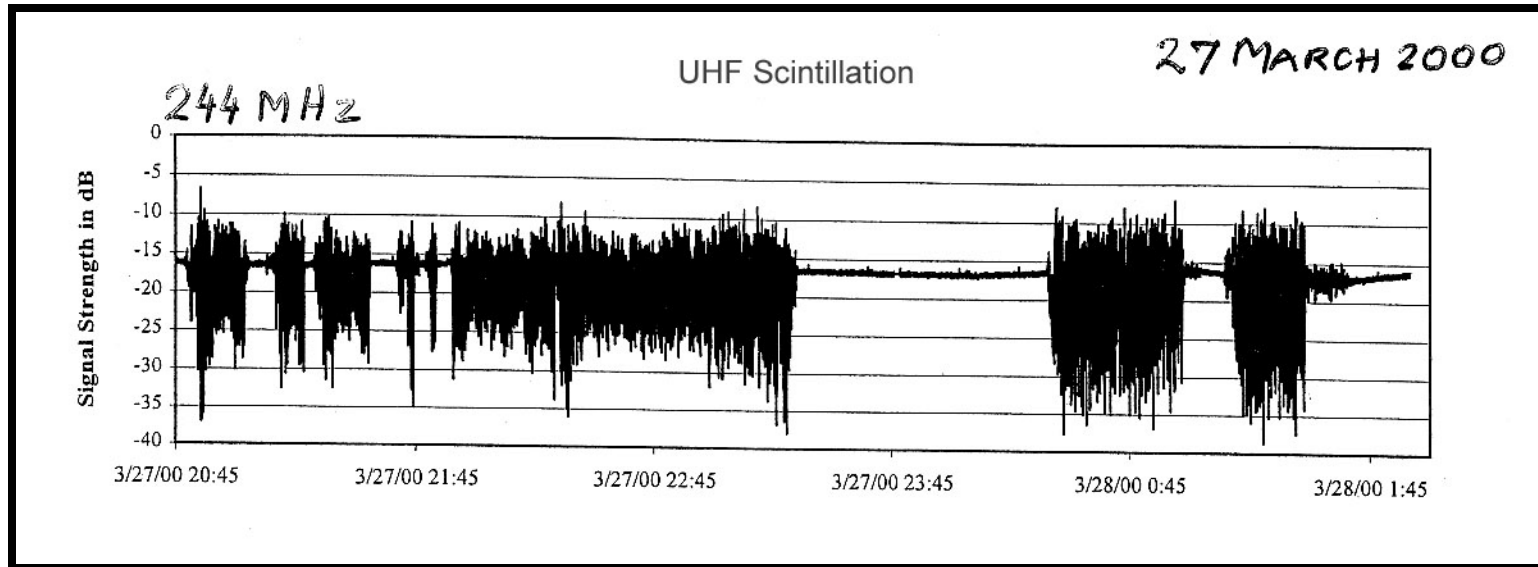For strong scattering and $p > 5$, S_4 may exceed unity but eventually saturates at unity.

The phase scintillation index or the standard deviation of phase fluctuations, σ_φ can be obtained from

$$\sigma_\varphi^2 \propto \langle \delta N^2 \rangle \cdot \left(v_{eff} \, \tau_c \right)^{p-1}$$
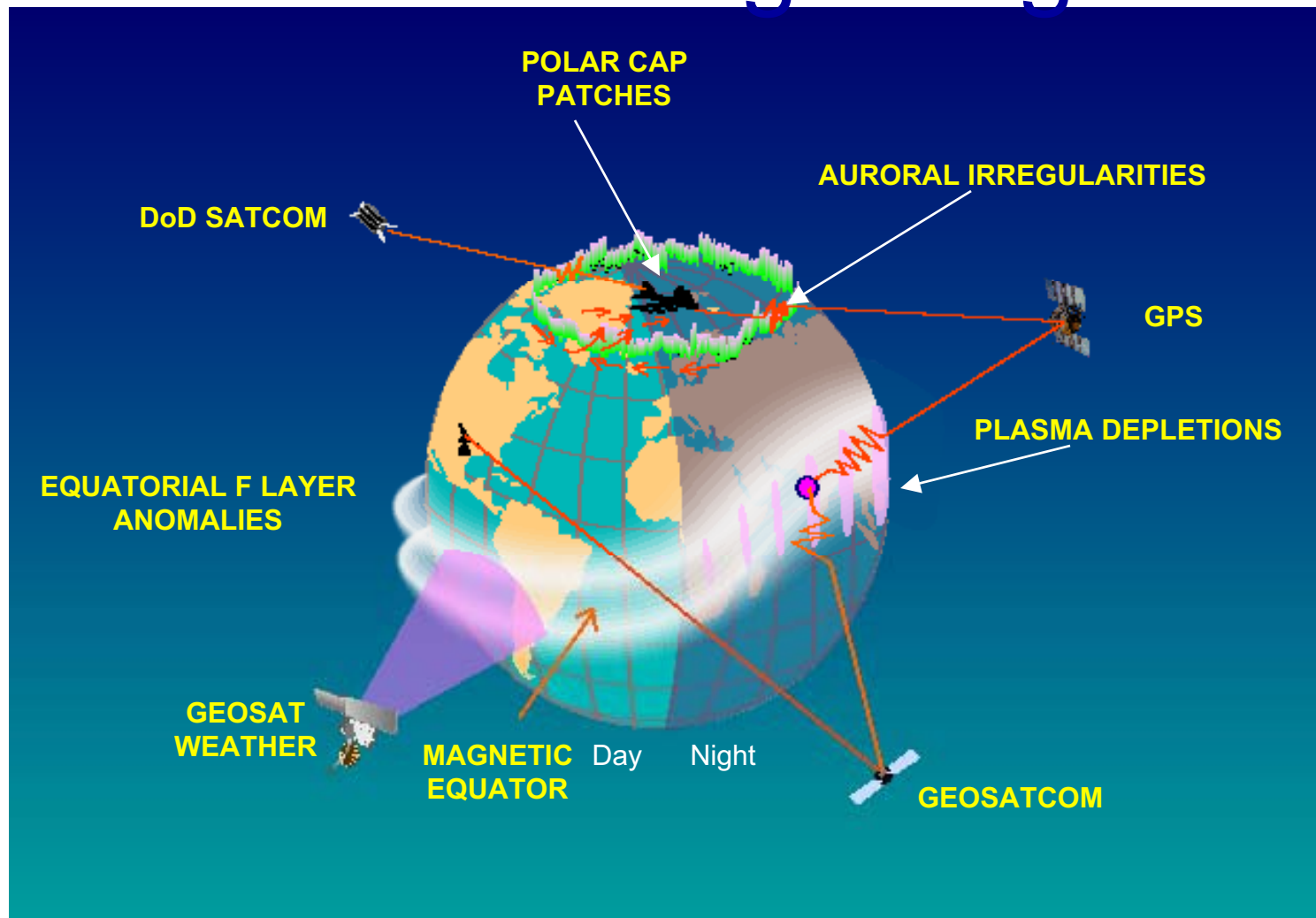
where v_{eff} is the effective scan velocity of the propagation path through the irregularities and τ_c is the data interval that corresponds to $1/f_c$, where f_c is the low frequency cut off of the detrend filter.

(Rino, C.L., *Radio Sci., 15, 41, 1980*; Yeh, K.C. and Liu, C.H., *Proc. IEEE, 70*, 324, 1982; Yeh, K.C. and Wernik, A., *in Wave Propagation in Random Media (Scintillation)* edited by Tatarskii, Ishimaru, Zavrotny, published by SPIE and Institute of Physics Publishing, 1992)
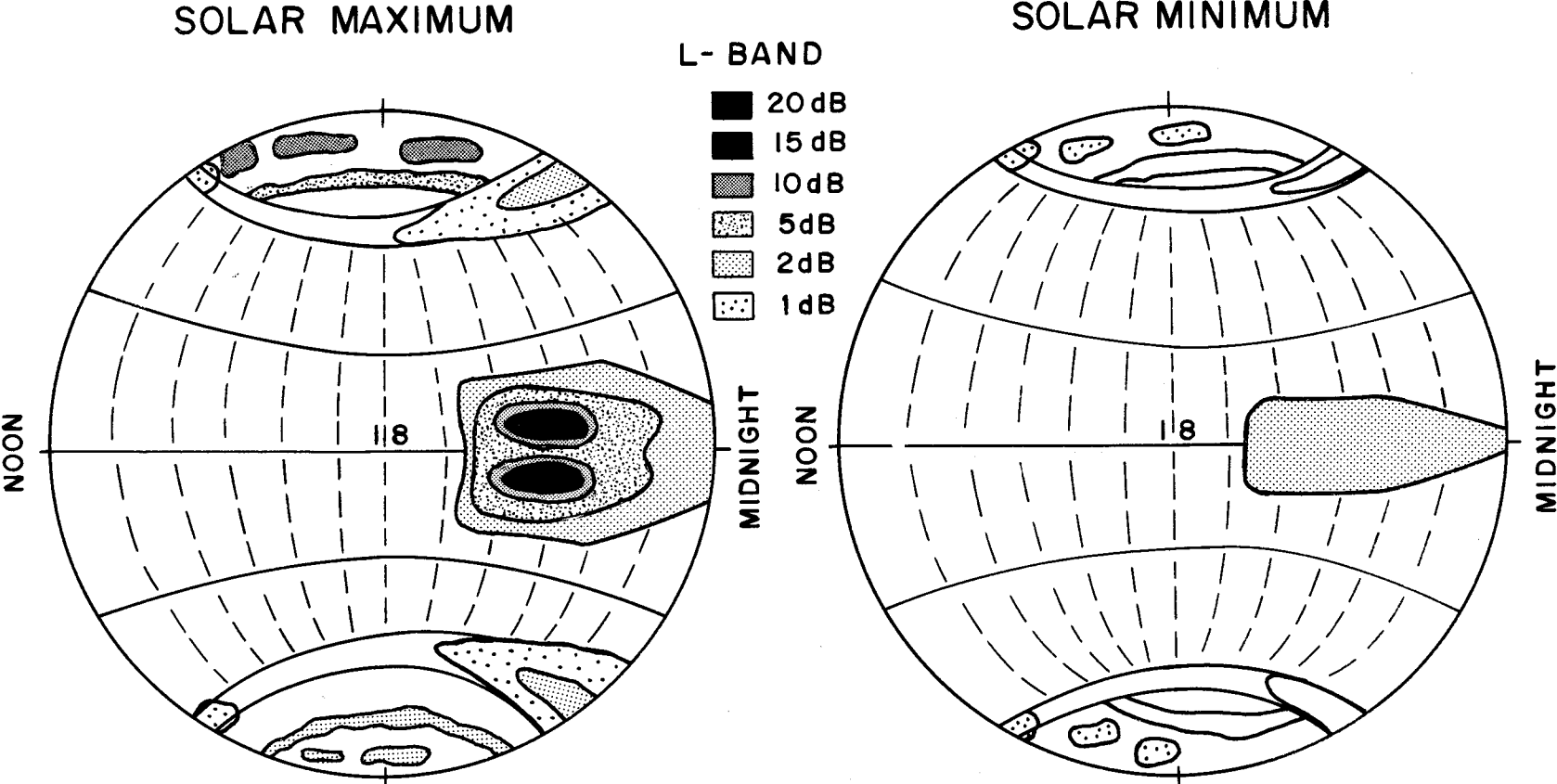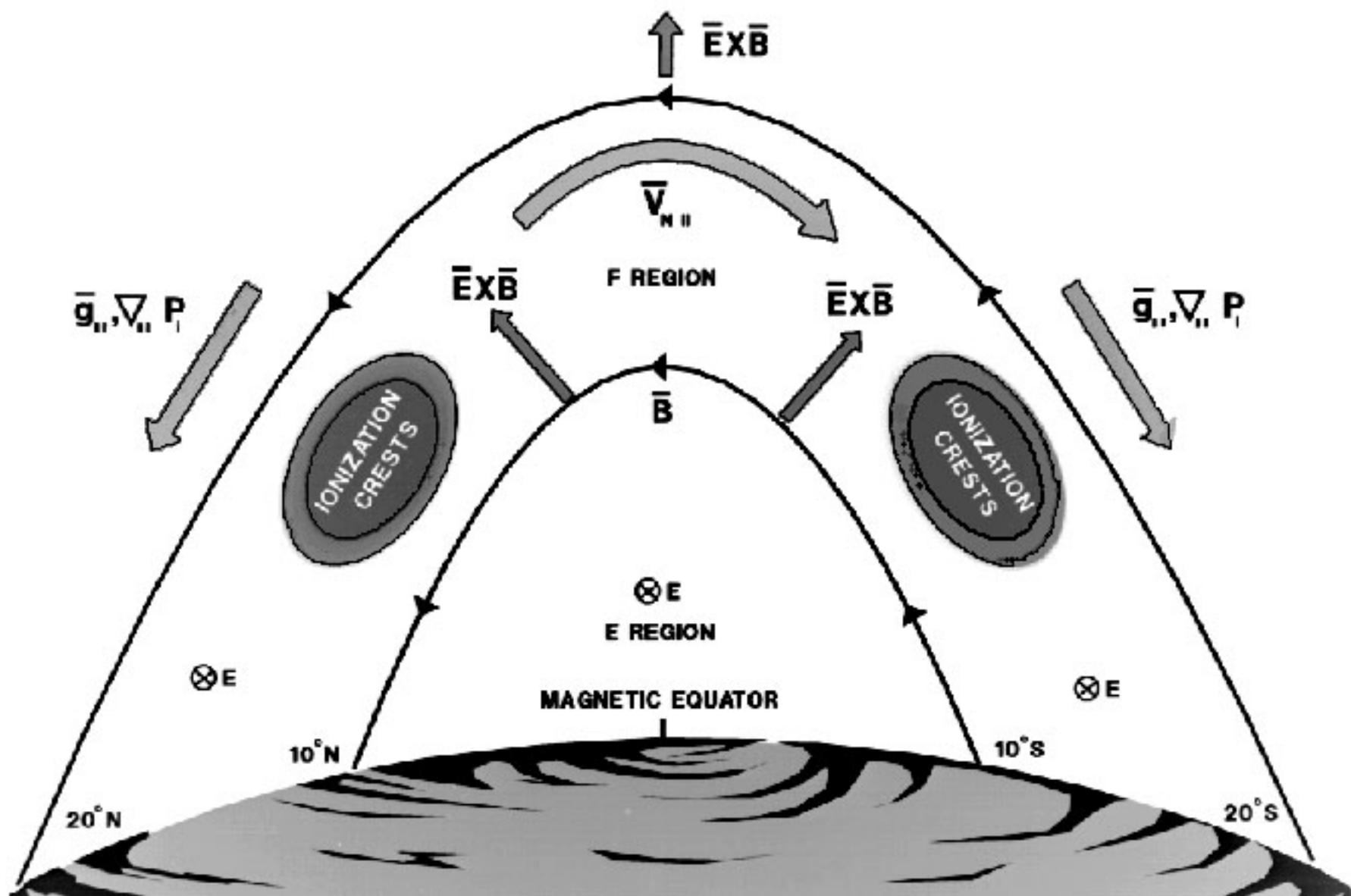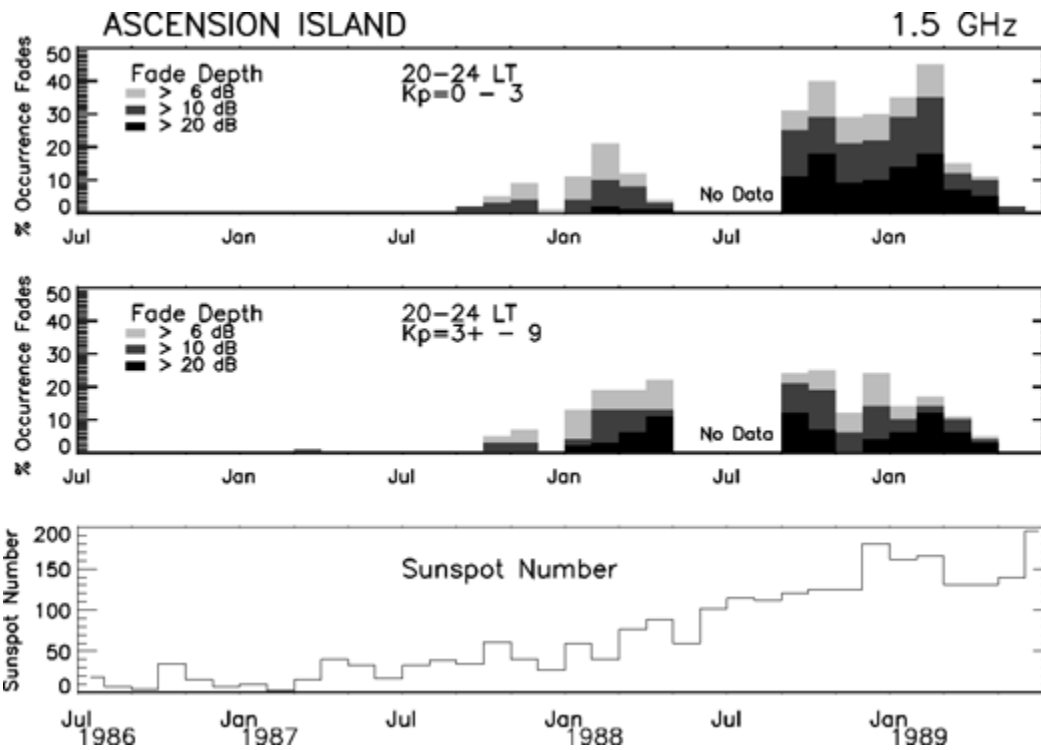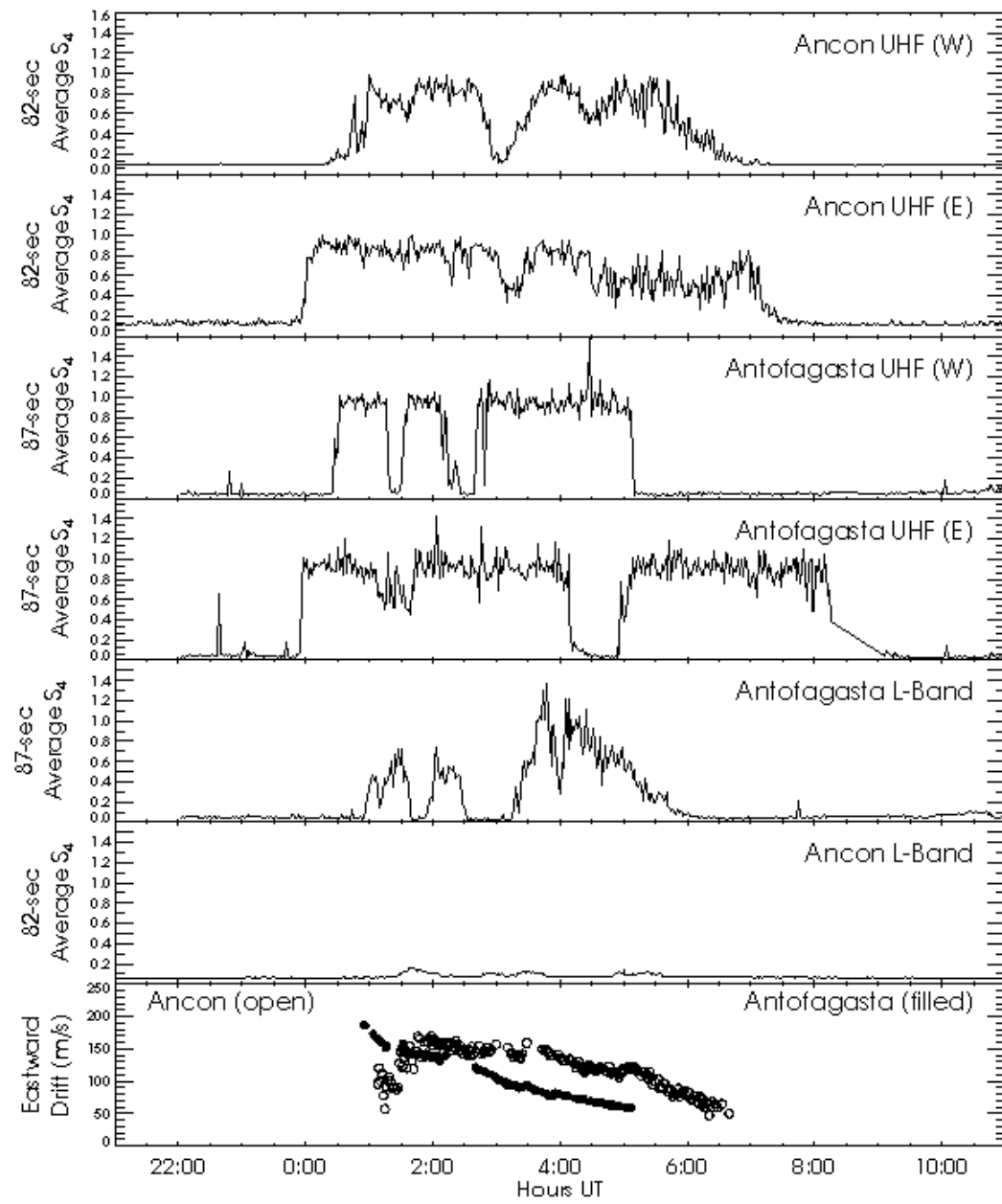
ASCENSION ISLAND

Global C³I Outage Regions

"WORST CASE" FADING DEPTHS AT L-BAND

SOLAR MAXIMUM

SOLAR MINIMUM

L- BAND

20 dB
15 dB
10 dB
5 dB
2 dB
1 dB

NOON

MIDNIGHT

18

NOON

MIDNIGHT

18

$\bar{E}\times\bar{B}$

$\bar{V}_{N\parallel}$

F REGION

$\bar{E}\times\bar{B}$

$\bar{E}\times\bar{B}$

$\bar{g}_{\parallel}, \nabla_{\parallel} P_i$

$\bar{g}_{\parallel}, \nabla_{\parallel} P_i$

IONIZATION CRESTS

IONIZATION CRESTS

$\bar{B}$

$\otimes E$

E REGION

$\otimes E$

$\otimes E$

MAGNETIC EQUATOR

10°N

10°S

20°N

20°S

ASCENSION ISLAND 1.5 GHz

Fade Depth
> 6 dB
> 10 dB
> 20 dB

20-24 LT
Kp=0 - 3

No Data

Fade Depth
> 6 dB
> 10 dB
> 20 dB

20-24 LT
Kp=3+ - 9

No Data

Sunspot Number

Jul   Jan   Jul   Jan   Jul   Jan
1986   1987   1988   1989

AFRL-SCINDA Scintillation Data
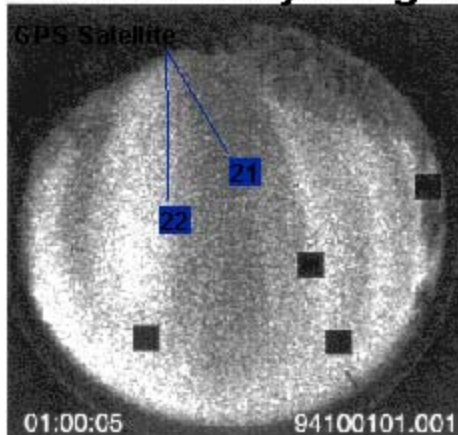99299 -- 10/26/1999

GLOBAL POSITIONING SYSTEM (GPS)

- **24 Satellites in 6 Orbital Planes, Inclination 55^0 , Period 12 Sidereal Hours**

- **Satellites Broadcast Ranging Codes and Navigation Data on Two Frequencies**
  - **L1 = 154 x 10.23 MHz = 1575.42 MHz**
  - **L2 = 120 x 10.23 MHz = 1227.60 MHz**

- **L1 Carrier Modulated by C/A Code (1.023×10^6 chips/sec, msec sequence) plus 50 Hz Navigation Data as well as P(Y) Code (10.23×10^6 chips/sec, 7 day sequence)**

- **L2 Carrier Modulated by P(Y) Code**

- **For Scintillation Studies:**
  - **Carrier phase and amplitude at L1 are used**

- **For TEC Studies:**
  - **Differential (L1/L2) carrier phase and differential (L1/L2) group delay are Used**

Equatorial Ionosphere Plasma Depletions
Scintillation of GPS Signals
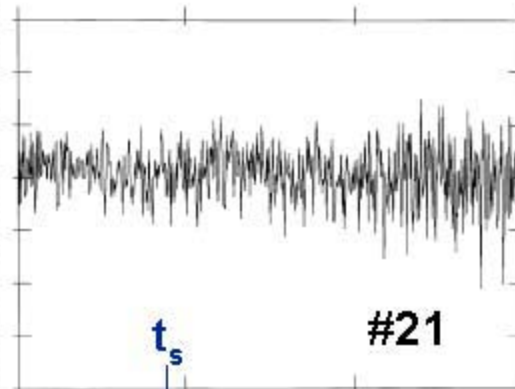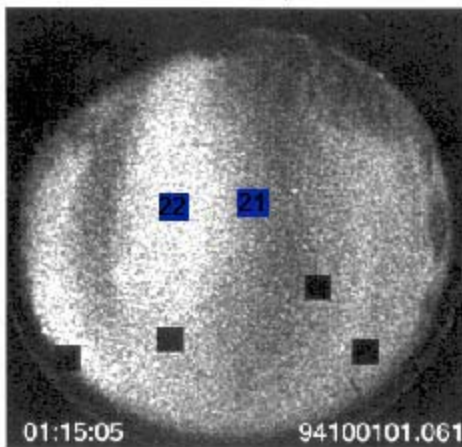# TEC Variations

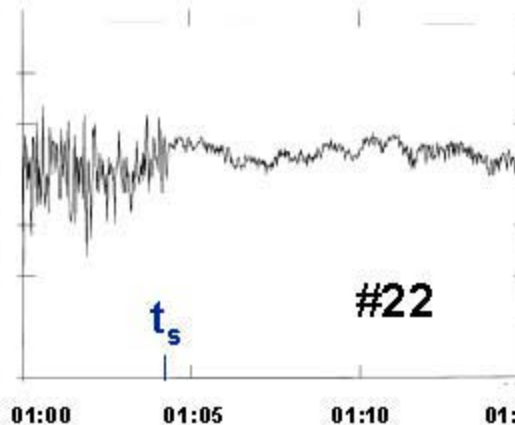Equatorial Ionosphere Scintillation Effects on GPS

Chile: 1 October 1994

6300A All Sky Images

GPS Satellite

21

22

01:00:05   94100101.001

Plasma Depletions

22   21

01:15:05   94100101.061

Scintillation for GPS Satellite #21

TEC t_s

t_s #21

Scintillation of GPS Signals

Relative TEC Changes Over Two Hour Period 0000-0200 UT

Scintillation for GPS Satellite #22

TEC t_s

t_s #22

01:00   01:05   01:10   01:15
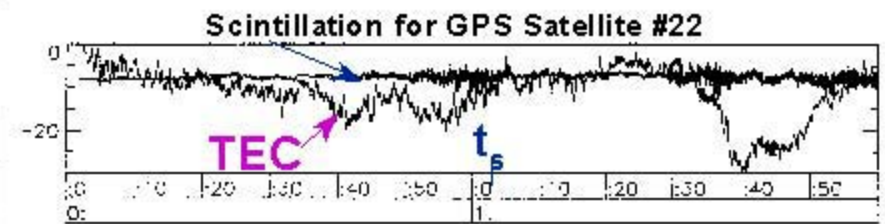
Antofagasta - 27 October 1999

Ancon   250 MHz
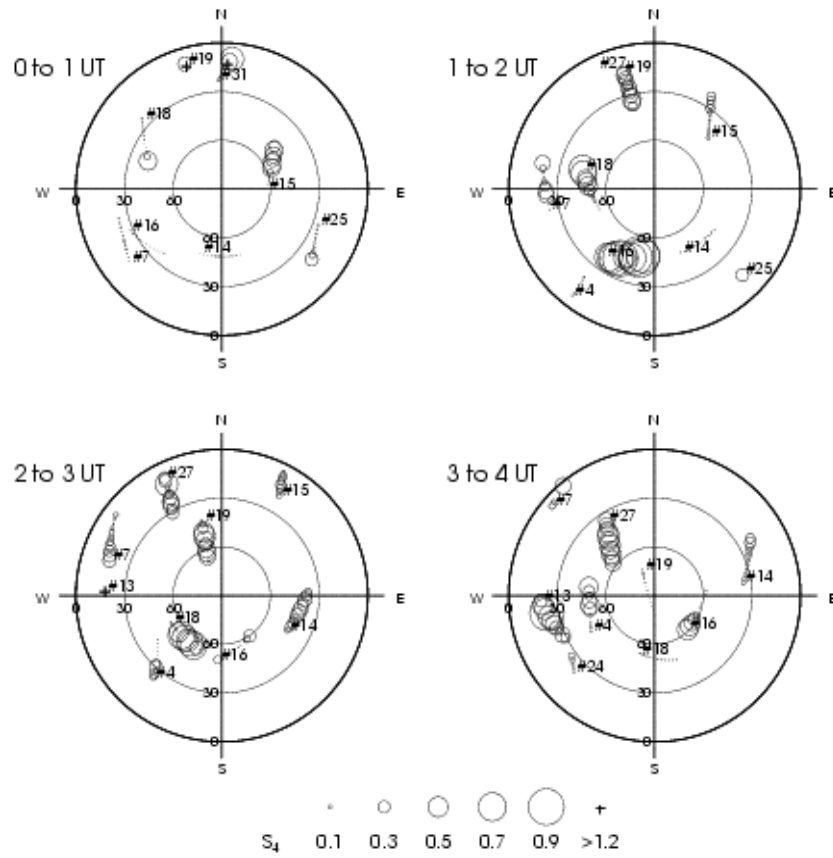
# PHASE AND AMPLITUDE SCINTILLATION FROM SATELLITE IN-SITU MEASUREMENTS

- Apply Huygens-Fresnel Diffraction Theory to Irregular Ionosphere Represented by a Phase Screen

- Phase Screen Model 1
  - Phase Fluctuations Proportional to Electron Density Fluctuations Obtained From Satellite In-situ Measurements

- Phase Screen Model 2
  - Phase Fluctuations Obtained From Irregularity PSD and Phase Spectra Represented by Analytical Functions

- Compare Phase and Amplitude Scintillation Results for Frequencies Ranging From low-UHF to L-band
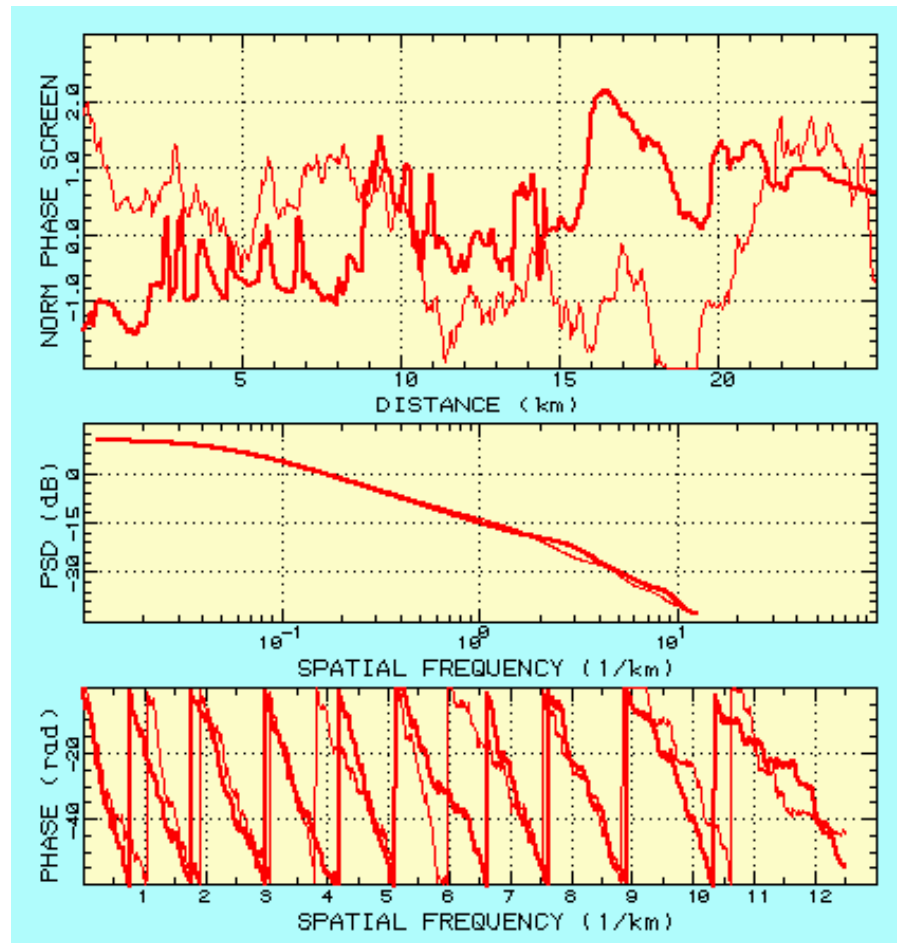
Top: normalized phase fluctuations $\varphi(x)$ resulting from the first model (thick line, *in situ* data reproduced from McClure et al. [1977]) and the second model (thin line, assuming $f_o = 0.04\ km^{-1}$, $f_b = 2.50\ km^{-1}$, $p = 1.86$ and $q = 3.00$). Center: corresponding MEM power spectral densities (same line code). Bottom: corresponding phases of the FFT components after the original $\pm\ \pi$ discontinuities have been eliminated and the resulting line has been artificially broken into sections, to allow the phase curve to be displayed within the selected vertical scale (same line code).
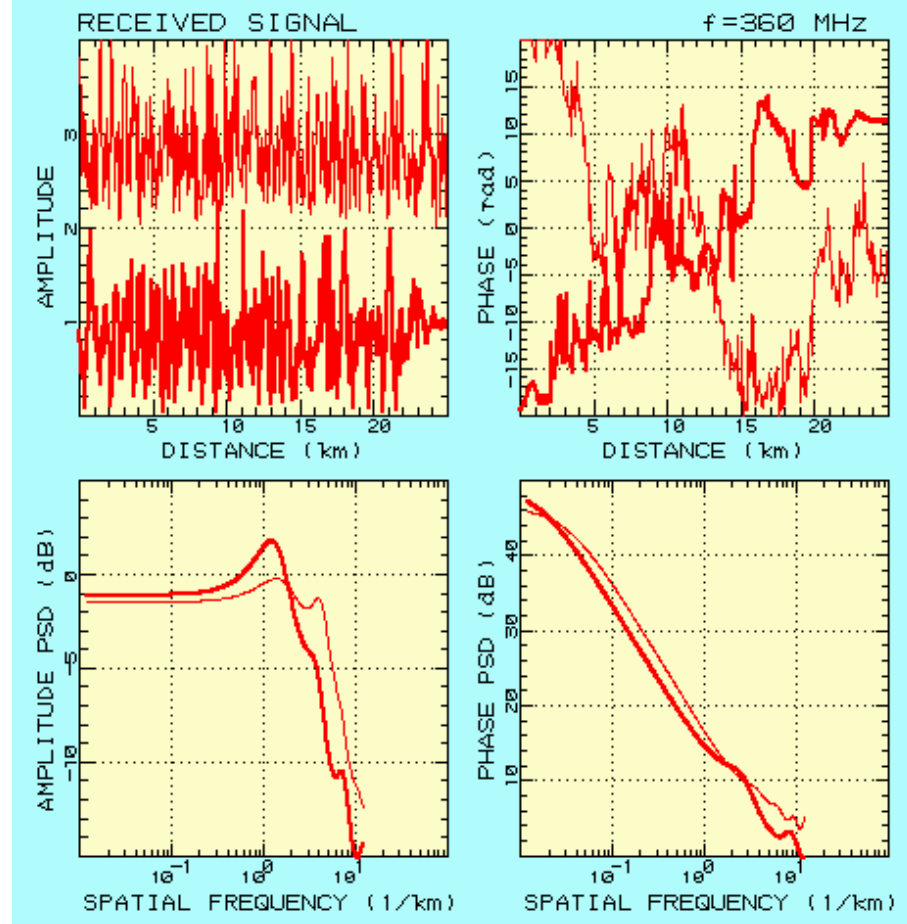
Amplitude and phase of the received signals at *360 MHz*, as well the respective MEM power spectral densities (*PSD*s), for the two phase screen models of Figure 1, assuming $N_o =$
2.5 · 10^{11} el/m³, *L = 100 km, h= 400 km, δx = 40 m, θ = 0°, G = 1*, and fractional rms electron density fluctuation of *5 %*. Thick and thin lines have been used to display the results from the first and the second models, respectively. Two amplitude units have been added to the second amplitude signal, for displaying purposes only.
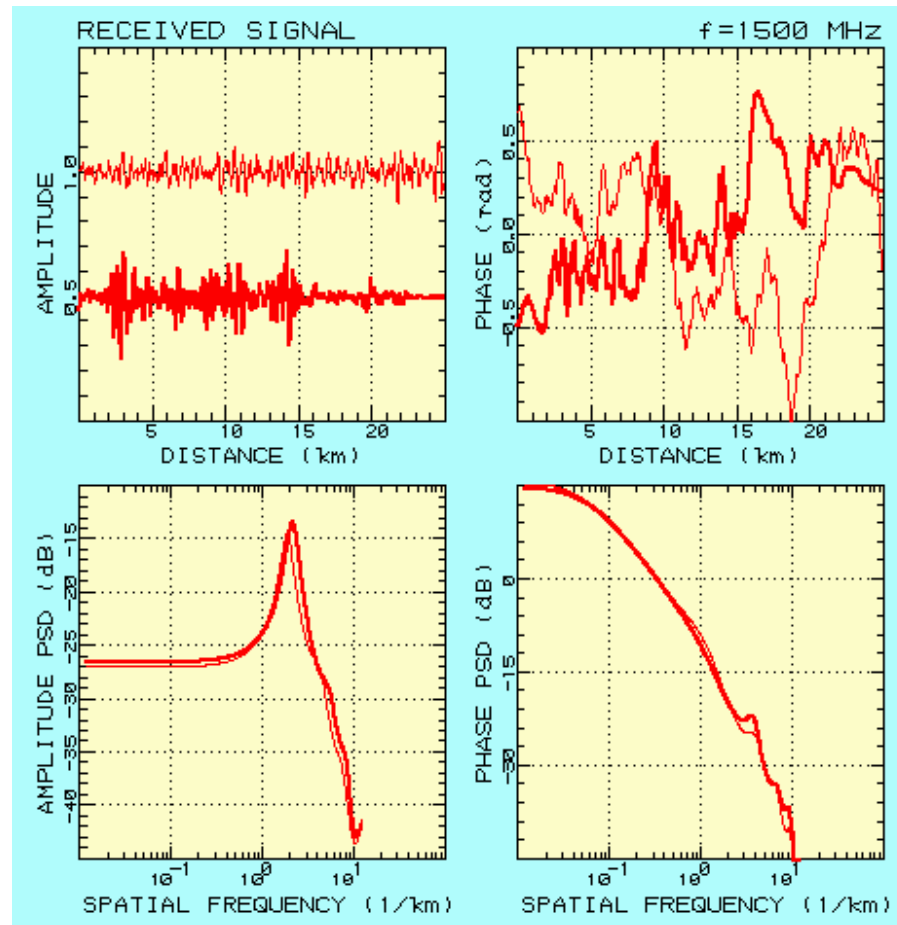
Amplitude and phase of the received signals at *1500 MHz*, as well the respective MEM power spectral densities (*PSD*s), for the two phase screen models of Figure 1, assuming $N_o =$ *2.5 · 10¹¹ el/m³*, L = *100 km*, h= *400 km*, δx = *40 m*, θ = *0°*, G = *1*, and fractional rms electron density fluctuation of *5 %*. Thick and thin lines have been used to display the results from the first and the second models, respectively. A constant value (*-0.5*) has been added to the first amplitude signal, for displaying purposes only.

EQUATORIAL SCINTILLATION DISTURBANCE STRUCTURE
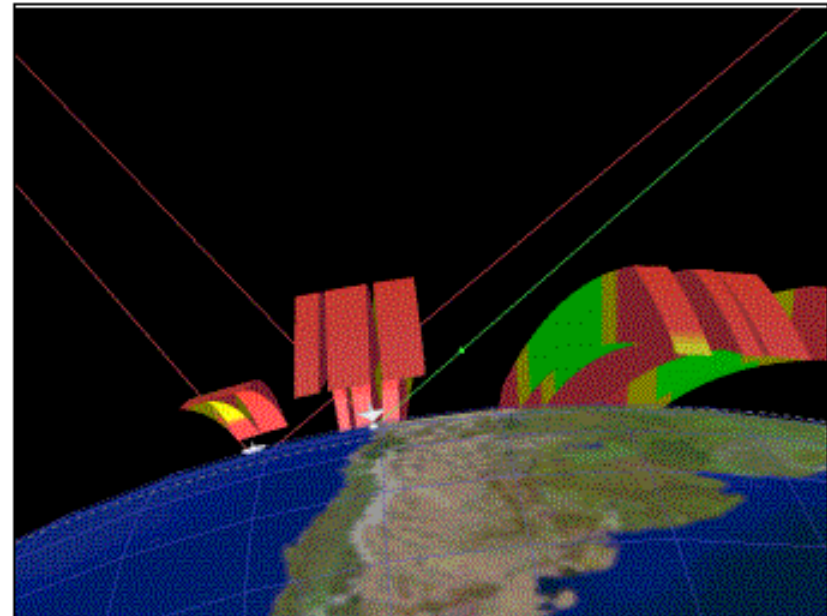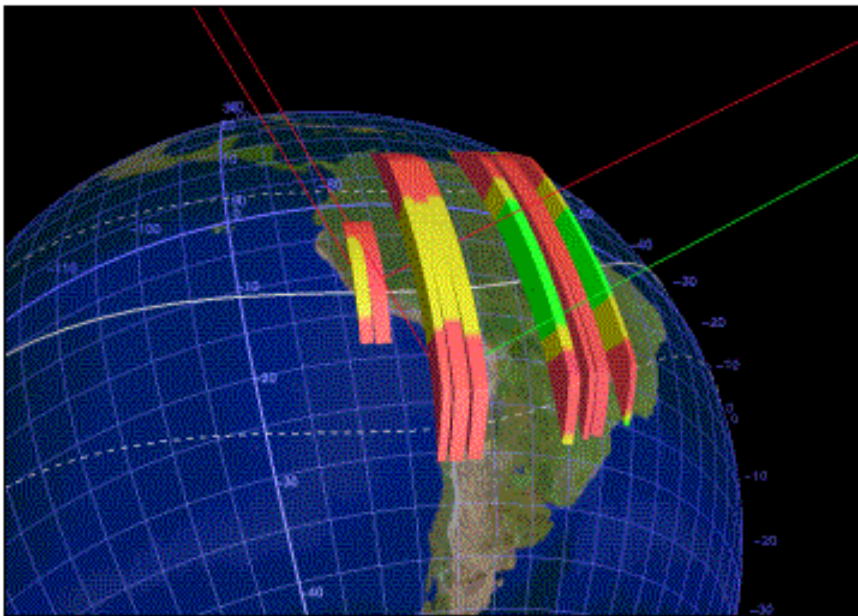
SEVERE   MODERATE   WEAK

Actual Display of Ionospheric Disturbances Measured by AFRL Scintillation Network Decision Aid (SCINDA)

C/NOFS Satellite

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

- 400 x 710 km; 13° Orbit
- Launch on January 24, 2004
- C/NOFS to Specify and Forecast Equatorial Scintillation From Satellite In-situ Measurements of Plasma Instability Drivers (E field, Ion Velocity, Neutral wind), Plasma Density Fluctuations, GPS Occultation Sensor and Radio Beacon Transmissions for Scintillation and TEC Measurements

What Are C/NOFS Payload Elements?

Challenge: Effectively Integrate Proven Sensors into
Scintillation Forecasts and Nowcasts

Name	Description	Instrument PI
VEFI	Vector Electric Fields	NASA/GSFC (Code 690)
PLP	Planar Langmuir Probe	AFRL/VSBX
NWM	Vector Neutral Winds	U Texas-Dallas
IVM	Ion Velocity Meter	U Texas-Dallas
CORISS	GPS Occultation	Aerospace Corp.
CERTO	Multi-Frequency Beacon	NRL (Code 6794)

Payload Represents Extensive Space Flight Heritage

References

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CONCLUSIONS

- Theory of EM Wave Propagation Through Ionospheric Irregularities is Mature and Tools are Readily Available

- Ionospheric Scintillation Measurements - A Powerful Tool for Probing the Characteristics of Ionospheric Irregularities of Electron Density and their motion

- GPS Provides Multi-point Measurements of Ionospheric Irregularities and Elicits Space/Time Variation of Ionospheric Turbulence

- Day to Day Variability of Equatorial Scintillation Remains an Outstanding Problem

- Scintillation Network Decision Aid (SCINDA) Very Successful for the Specification and Short Term Forecast of Equatorial Scintillation

- Communication Navigation Outage Forecasting System (C/NOFS) will for the First Time Measure the Characteristics of Ionospheric Irregularities as well as the Drivers of the Equatorial Spread-F
  - Will Specify Equatorial Scintillation from Space
  - Will Attempt to Forecast Scintillation by Using In-situ Measurements of Plasma Instability Drivers, Models and Ionospheric Irregularities