First Order Scintillation Characterization of Natural and Artificial Disturbances on V/W band signals in the Ionosphere Using the Multiple Phase Screen Technique

Andrew J. Knisely, IEEE USA
Andrew J. Terzuoli, IEEE USA

Overview

- Background
- Ionospheric Modeling
- Numerical Techniques
- Multiple Phase Screen Theory
- Results
- Conclusions

Background

- The V/W frequency band (75GHz to 110 GHz) is becoming more attractive for SATCOM systems used in many commercial applications.
  - 5G networks that will rely on the SATCOM infrastructure to support long range mobile communications.

- In particular Ionospheric disturbances caused by Geomagnetic storms and High Altitude Nuclear Explosions (HANES) is the primary focus.

- The HANE experiment conducted with a computational plasma physics model demonstrates significant signal disturbance in the initial 45 seconds of the blast, assuming the blast is directly over the transmitter.

Nuclear Detonation and Ionosphere Process

- During a nuclear explosion, the air inside the fireball is at a temperature of many thousands of degrees.
- Electron density and collision frequency are high in addition to absorption of electromagnetic waves.
- The regions around the fireball is ionized in varying degrees by the initial thermal and nuclear radiations and by the delayed particles from the radioactive debris.
- As the detonation altitude increases, the radiation can escape at greater distances and the electron density will reach values at which electromagnetic signal propagation can be affected.
- In the D region of the Ionosphere, the most persistent absorption of electromagnetic waves will take place. In the E and F regions, the frequency of particle collisions is low, and refraction is the predominant effect.

Parabolic Wave Equation

$$\left(\frac{\partial^2}{\partial x^2} - 2\underline{\gamma}\frac{\partial}{\partial z}\right)\underline{\overline{U}}\left(x, z\right) = 0$$

- Where U represents the complex waveform in the frequency domain whose field vector points in the *x* direction and propagates in the *z* direction.

- This equation is derived from the scalar Helmholtz equation by assuming a slow varying envelope on the wavefront propagation given by the substitution

Numerical Techniques
Spectral Method

The derivative is approximated by the sequence of Fourier modes in the following manner:

$$\frac{d^k U_N}{dx^k}(x_j) = \sum_{|n|\le N} (in)^k a_n e^{i\left[\frac{2\pi i}{L}\right] n(x_j)}$$

The Fast Fourier transform is taken to acquire the Fourier *U* coefficients:

$$a_n = fft(U) = \frac{1}{N}\sum_{j=0}^{N-1} U(x_j) e^{inx_j}$$

The second order spatial derivative is approximated with the square of the Fourier mode sequence and formulated into a square diagonal matrix where each dimensional length is equal to the length of the input vector:

$$U_{xx} = -n^2 a_n$$

$$n = 1i * [-N/2 + 1, 0, N/2 - 1]$$

Integrate to Spatial Frequency Domain:

$$\int_{-\infty}^{\infty}\left[\frac{\partial^2 \underline{\bar{U}}(x,z)}{\partial x^2}\right] e^{-\beta x} dx = 2\underline{\gamma}\int_{-\infty}^{\infty}\left[\frac{\partial \underline{\bar{U}}(x,z)}{\partial z}\right] e^{-\beta x} dx$$

This forms an Ordinary Differential Equation in the spatial frequency domain:

$$-K^2 \underline{U}(K,z) = 2\underline{\gamma}\frac{\partial \underline{U}(K,z)}{\partial z}$$

Solution to the ODE is integrated back into the spatial position domain:

$$\underline{U}(\mathrm{K}, z_2) = \underline{U}(\mathrm{K}, z_1) e^{-\left(\frac{K^2}{2\underline{\gamma}}\right)\Delta z}$$

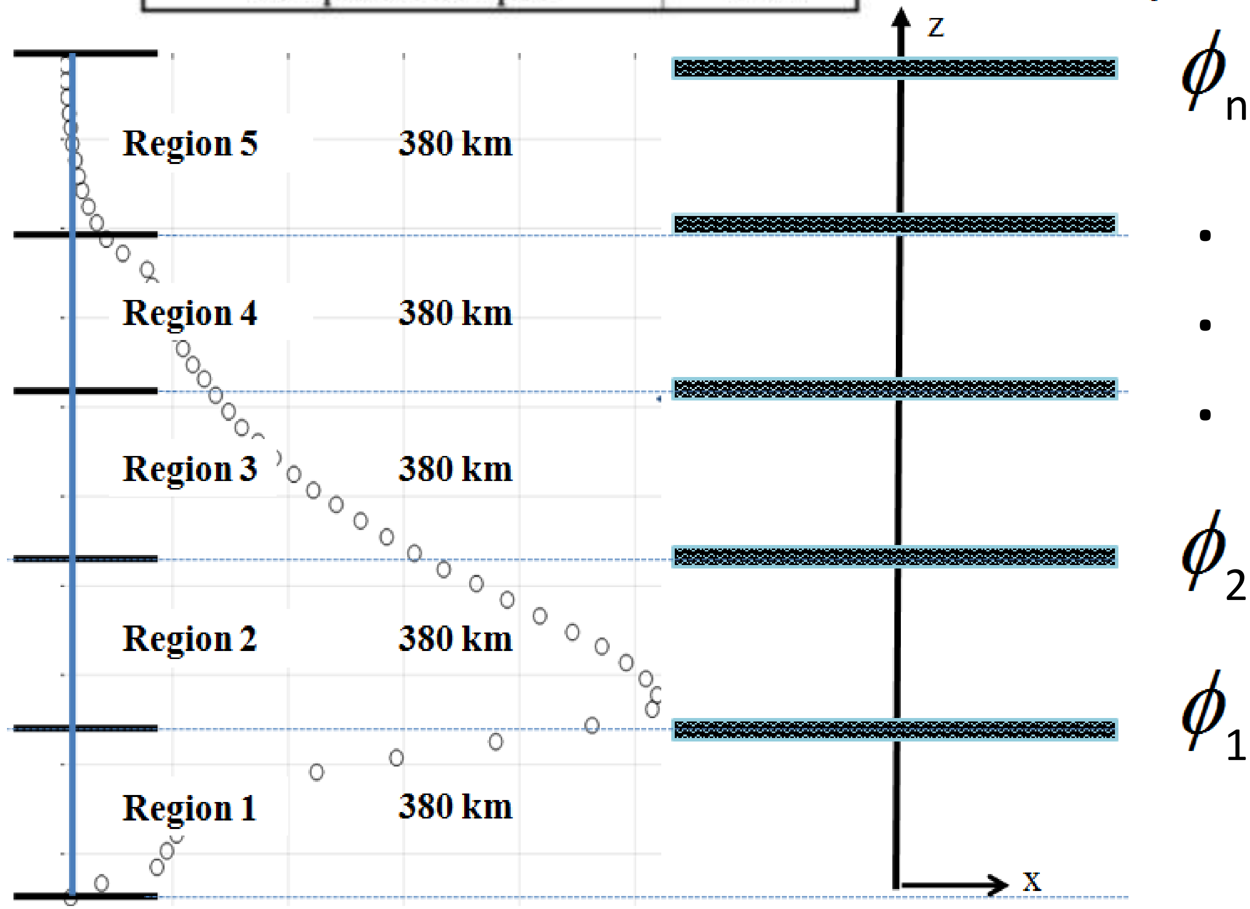
$$\underline{U}(x, z_2) = ifft\left(\underline{U}(x, z_1)\right)$$

Multiple Phase Screen Model

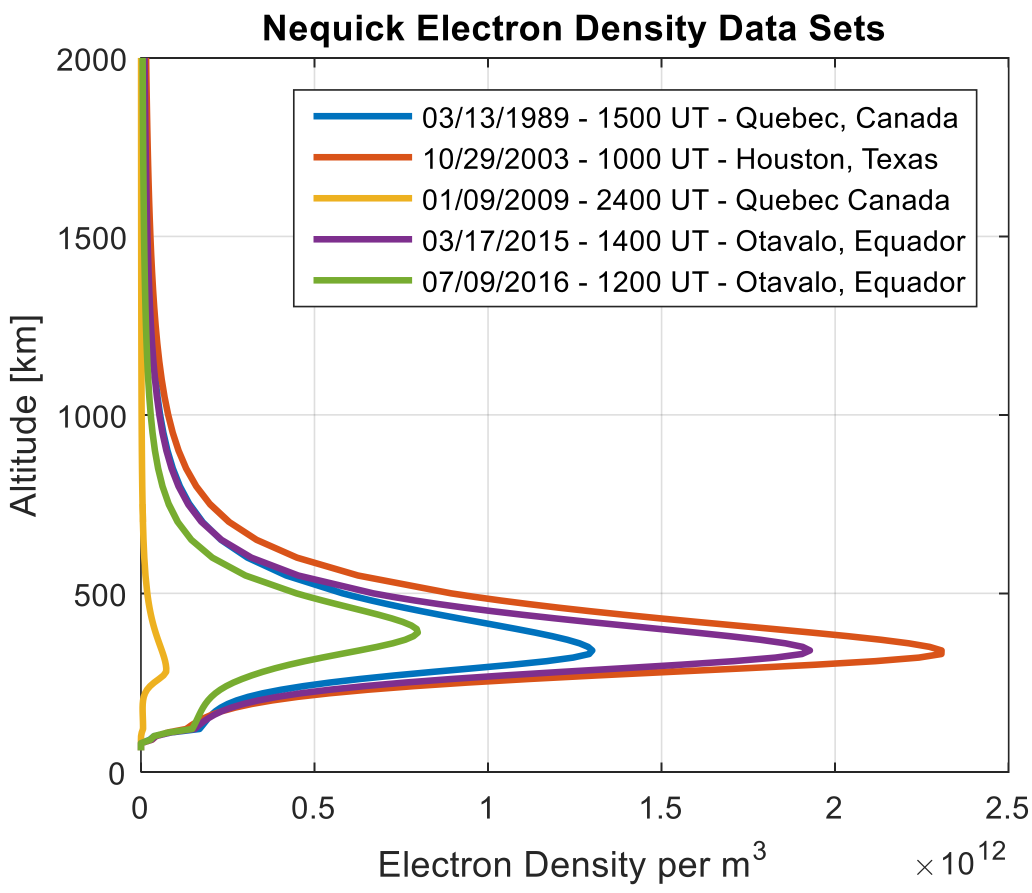
Parameter:	Value
L: Grid Length [km]	10 L_o
L_o : Outer Scale [km]	3
l_i : Inner Scale [meters]	150
N: Spatial Samples	4096

Phasor Series:

$$U_f = U_i e^{\phi}$$

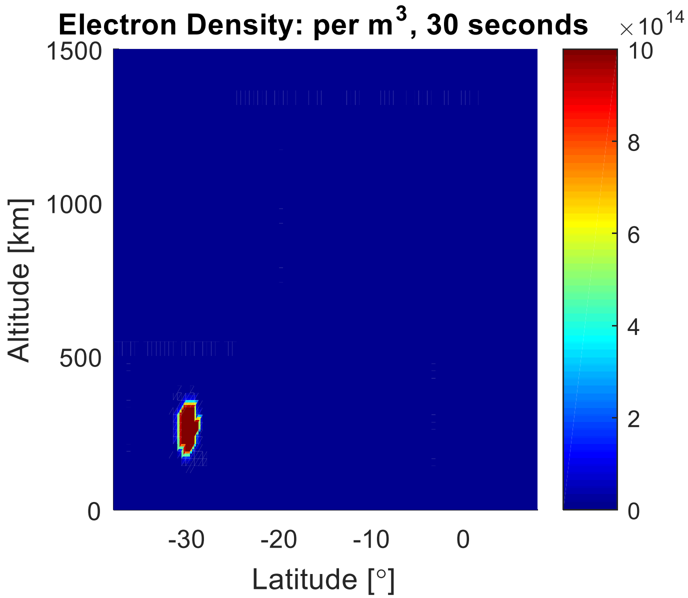


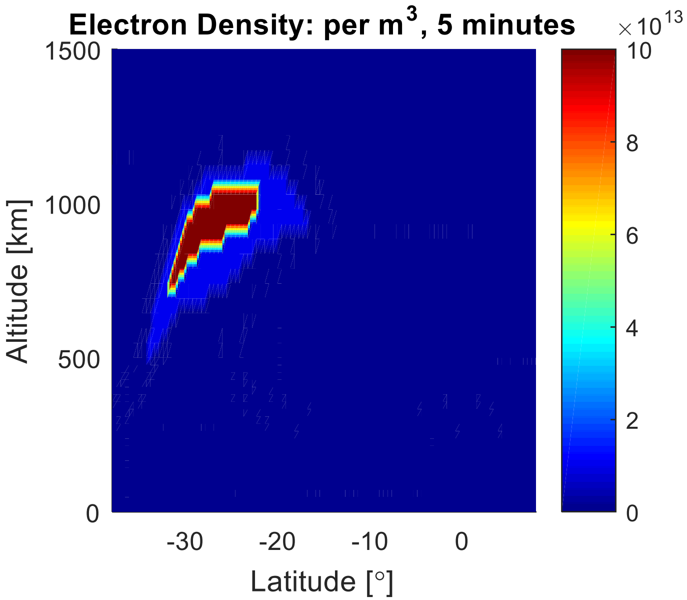
Geomagnetic Storm Data



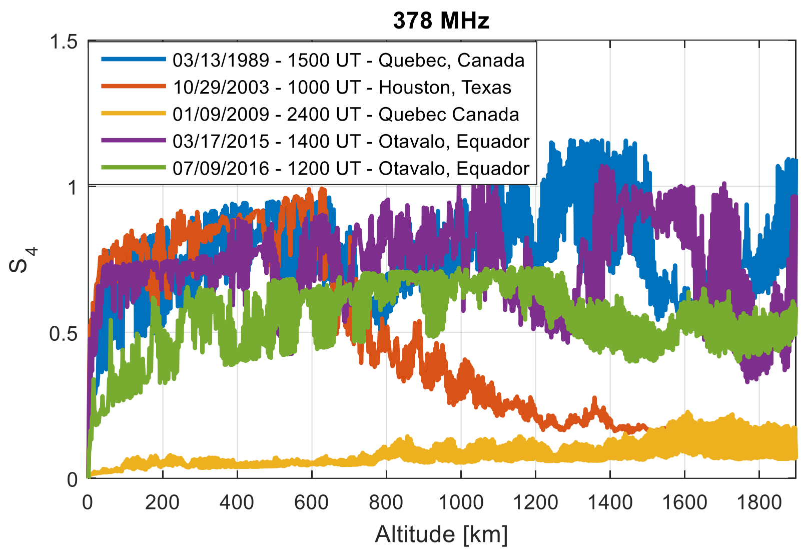
HANE Burst Sequence

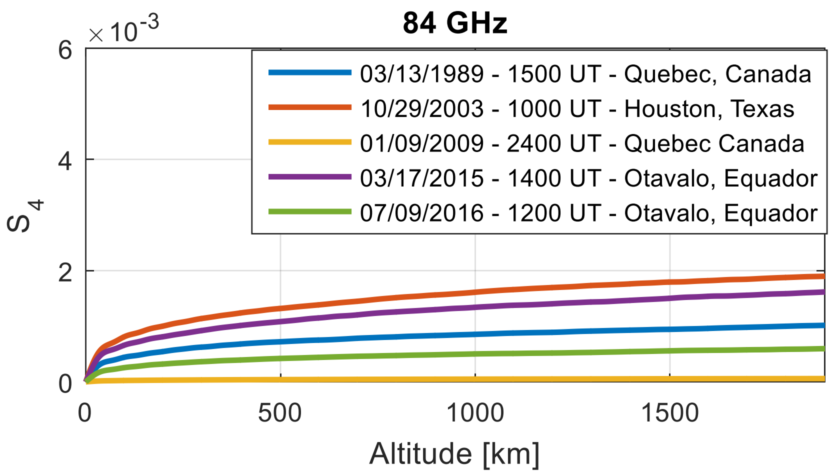
1 MT HANE and
100km altitude

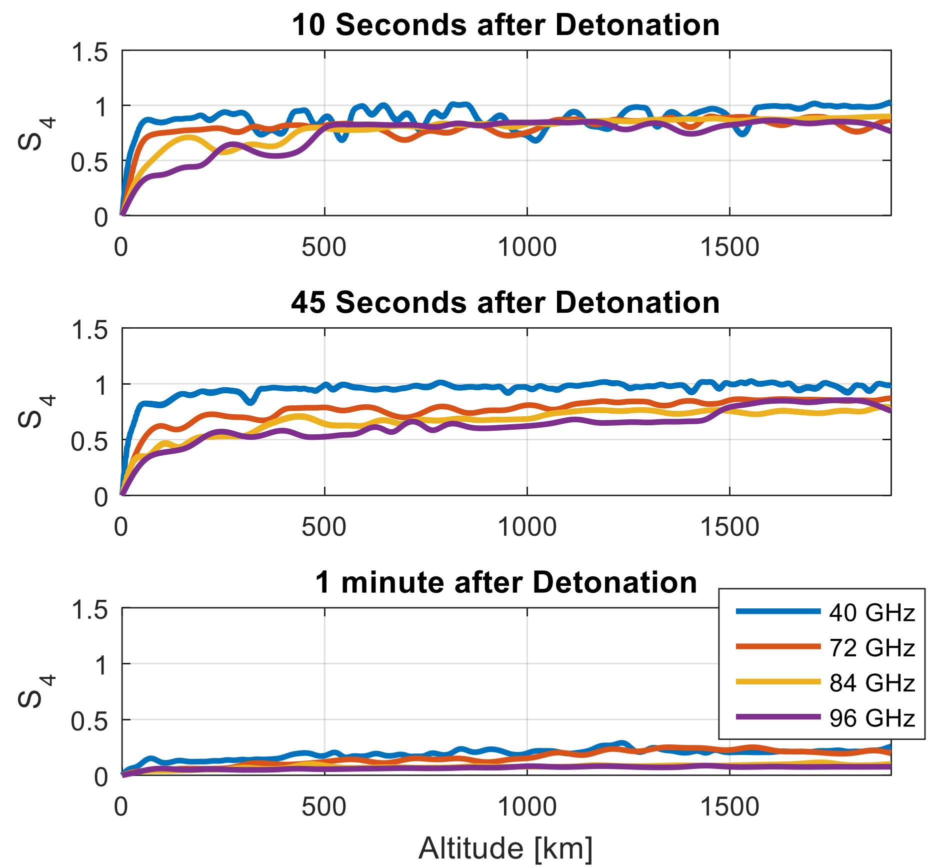




Results


378 MHz
03/13/1989 - 1500 UT - Quebec, Canada
10/29/2003 - 1000 UT - Houston, Texas
01/09/2009 - 2400 UT - Quebec Canada
03/17/2015 - 1400 UT - Otavalo, Equador
07/09/2016 - 1200 UT - Otavalo, Equador
S4
Altitude [km]


84 GHz
×10-3
03/13/1989 - 1500 UT - Quebec, Canada
10/29/2003 - 1000 UT - Houston, Texas
01/09/2009 - 2400 UT - Quebec Canada
03/17/2015 - 1400 UT - Otavalo, Equador
07/09/2016 - 1200 UT - Otavalo, Equador
S4
Altitude [km]


10 Seconds after Detonation
45 Seconds after Detonation
1 minute after Detonation
40 GHz
72 GHz
84 GHz
96 GHz
S4
Altitude [km]

Conclusion

- The results demonstrate that the environmental factors in the Ionosphere must be taken into account in extreme cases of electron density fluctuations depending on the transmit signal frequency.

- Even though the geomagnetic storms yielded little impact on a V/W band signal, a HANE event has significant impact.

- Future research will demonstrate the temporal impact of such events on a wideband signal that incorporate the multiple phase screen techniques to simulate ionic effects.

- The correlation between phase change and time delay must be understood for HANE events. The significance of these results will lead to a model that can assist with the design of assured communication systems

References

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[3] R.0. Dendy, "Plasma Dynamics", Oxford Science Publications, Clarendon Press, 1990.

[4] Dennis L Knepp, "Propagation of Wide Bandwidth Signals Through Strongly Turbulent Ionized Media", electronic file available at: https://apps.dtic.mil/dtic/tr/fulltext/u2/a131355.pdf, 1982.