Ionospheric Effects on a Wide Bandwidth Chirp Signal

Ionospheric Effects Symposium

May 2017

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Outline

- Examples of wideband channel behavior
  - Collected downlink data from MUOS UHF SATCOM in Sept. 2014 (Synchronous satellite)
  - Characterization of wide bandwidth ionospheric channels
- Brief description of the paper, calculation of wide bandwidth radar signal response to small-scale ionospheric structure
- Examples of disturbed chirp waveforms after propagation through ionospheric structure
- Conclusions

Statistical Parameters that Help Describe ionospheric Propagation Channels

- **S_4 scintillation index**
  - **Quantifies channel amplitude variation with time**

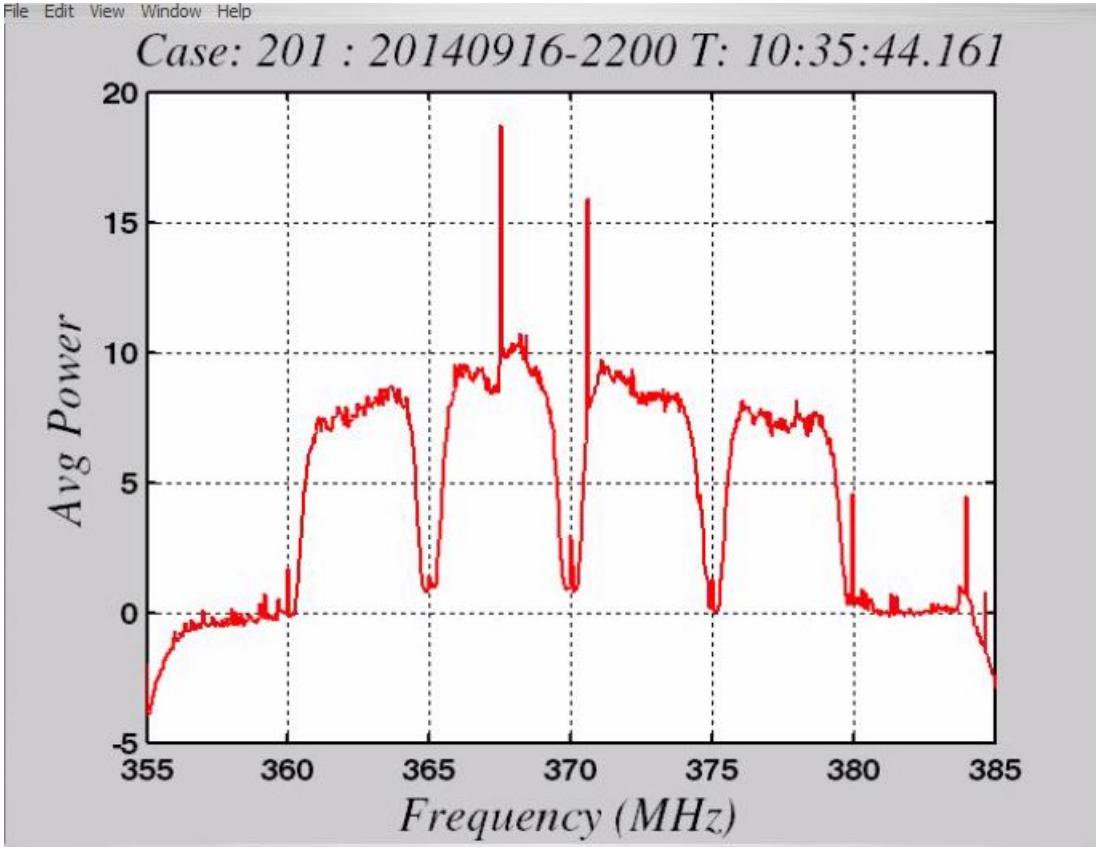
- **Decorrelation time (τ_0)**
  - **Specifies time duration over which the channel is unchanging**

- **Coherence bandwidth (f_{coh})**
  - **Specifies the bandwidth over which the channel spectral components are roughly equal**

Mitigation of ionospheric effects requires knowledge of these channel parameters

MUOS Periodogram Observed with Little or No Scintillation

- MUOS PSD, smoothed in time and frequency. MUOS Pacific satellite, receiver at Kwajalein, Marshall Islands
- MUOS downlink has 4 carriers, each with about 5 MHz bandwidth, centered at 370 MHz
- Large narrow-band tones are most likely local interferers
- MUOS wideband data samples provided by Ron Caton, AFRL (8 hrs of data collected in Sept 2014)



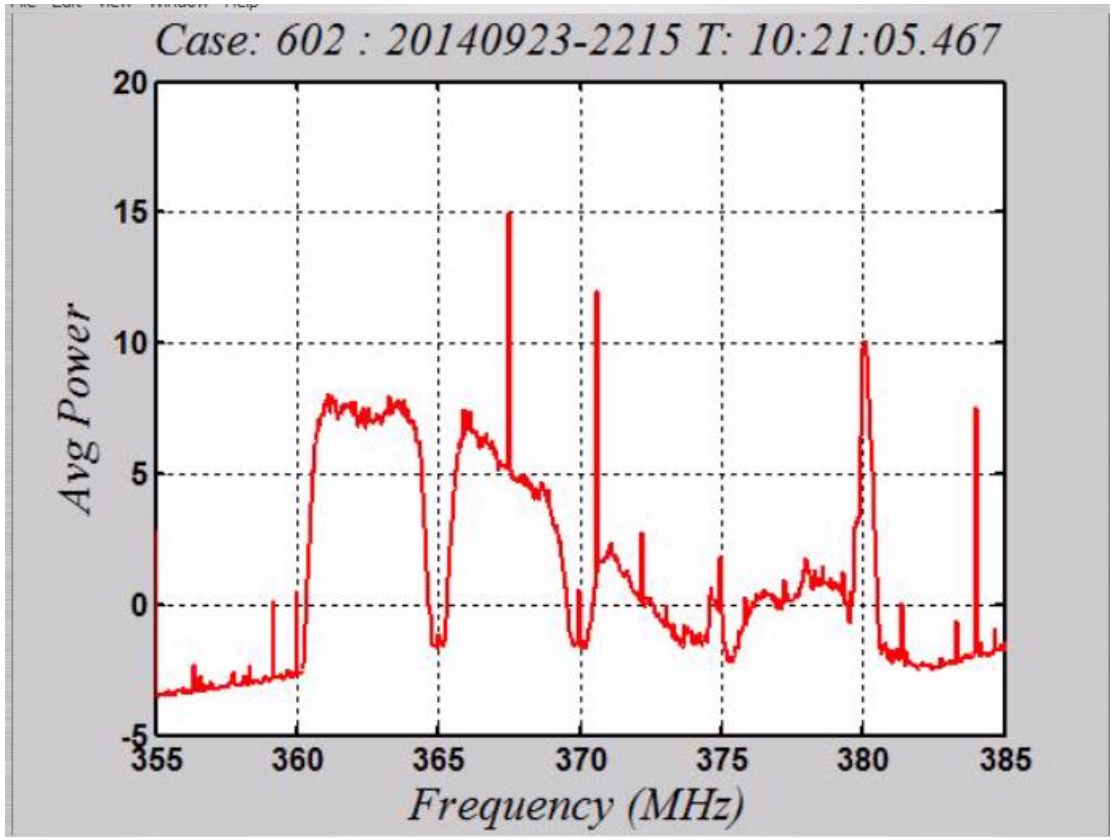
FFTMovieCase201.avi

Collected data with little scintillation

Sept 16, 2014

Wideband MUOS signal observed at Kwajalein, Sept 2014

- MUOS PSD, smoothed in time and frequency. MUOS Pacific satellite
- Large narrow-band tones are most likely local interferers
- MUOS downlink data shows frequency selectivity (decorrelation) across the 20-MHz downlink bandwidth
- But detailed analysis of the impulse response function indicates that the individual 5-Mhz channels are roughly frequency-flat



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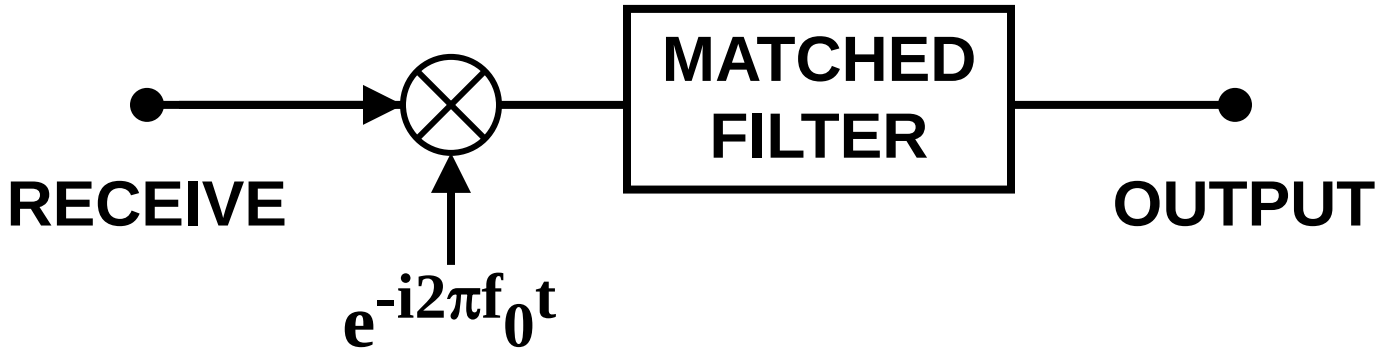
Frequency-selective scintillation across the entire 20-MHZ downlink band, Sept 16, 2014

Highlights of Related Paper

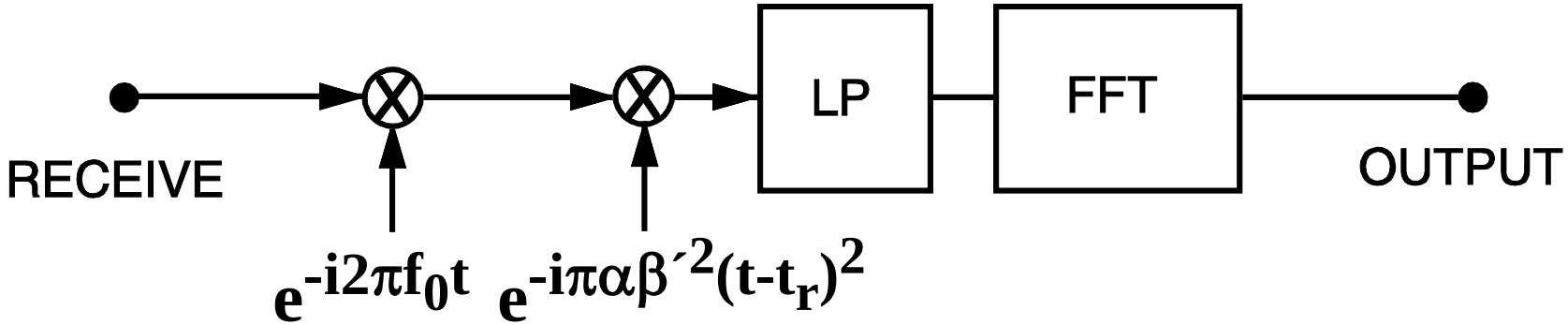
- Consider scalar Helmholtz wave equation for combined mean and random propagating fields
- Write solution in terms of impulse response function for two-way radar propagation
  - Transmitted chirp, moving target, chirp-slope mismatch,etc., all effects on signal processing
- New result: Useful expressions for output of radar signal processor at three important points in the processing chain: (1) after down conversion, (2) after match processing, (3) after stretch processing
- Use multiple-phase screen propagation code to generate realizations of impulse response function
- Generate realizations of matched filter output (compressed pulse) to view propagation effects

Two Alternatives for Processing of Received Chirp Signal

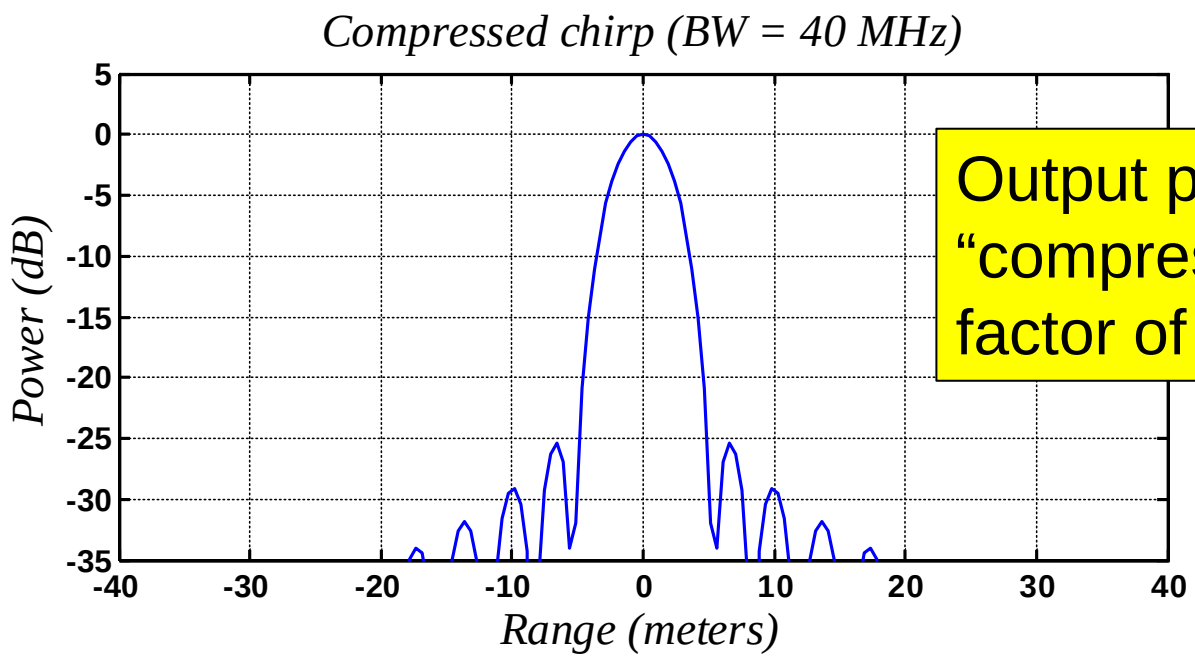
Matched filter or two-pass processing



Stretch or one-pass processing



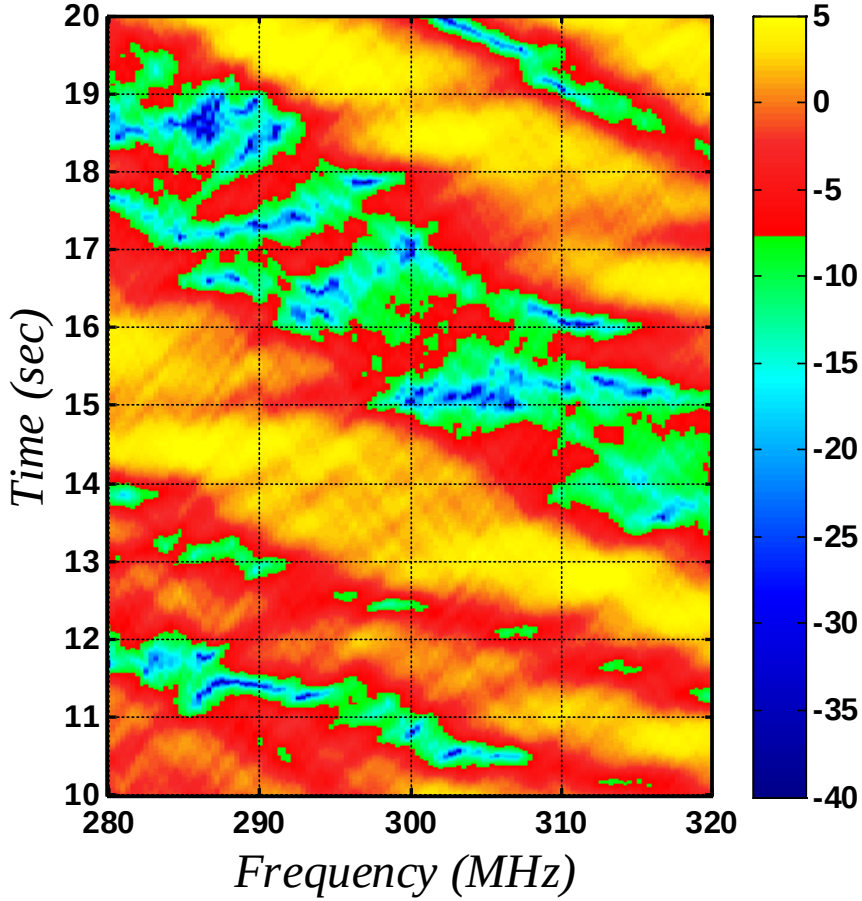
Example of a Compressed Chirp With No Ionospheric Disturbance



Output pulse is "compressed" by a factor of Tc*BW

- **Tc = Time duration = 0.04 sec**
- **BW = Bandwidth = 40 MHz**
- **Range resolution = 3.75 meters**

Amplitude (dB) of Ionospheric Transfer Function Calculated by MPS Code

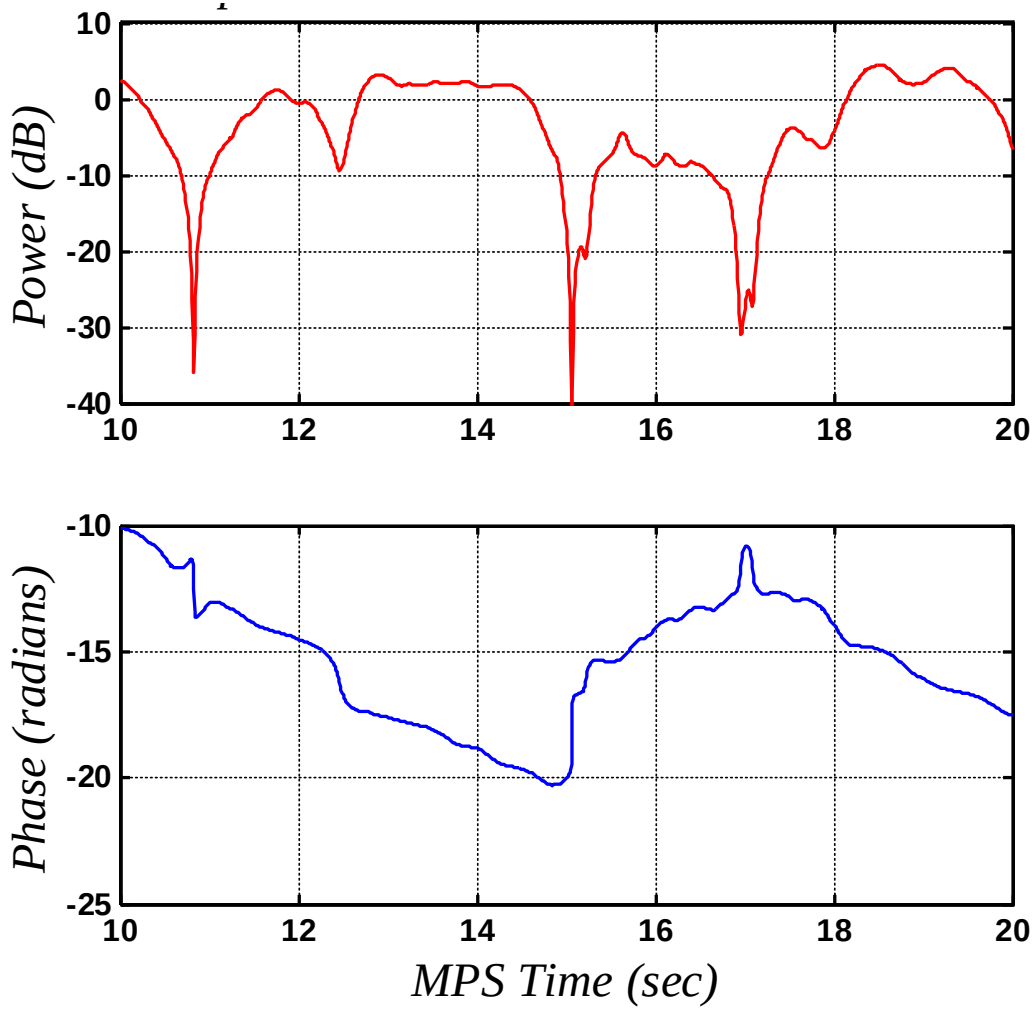


Scintillation severity is similar to that of the earlier MUOS videos

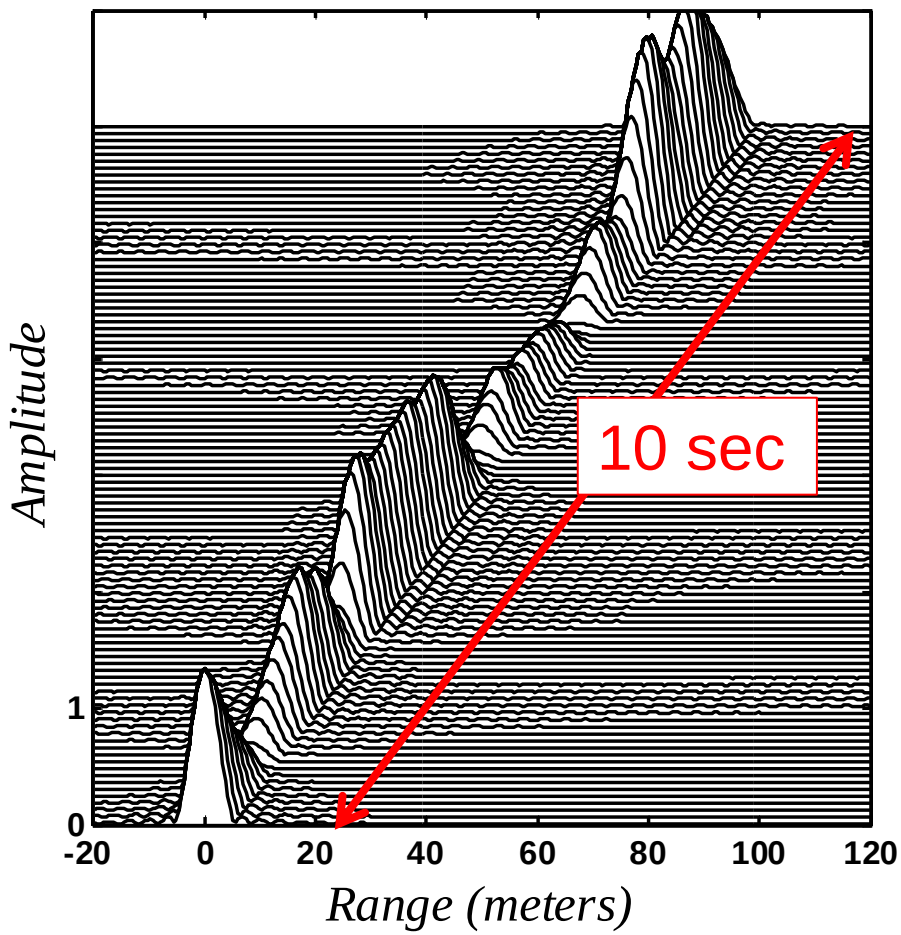
MPS calculation

- 420 km thick ionosphere
- 10 phase screens
- Length = 100 km, 131072 points
- K^{-3} PSD of phase
- Outer scale = 10 km
- Inner scale = 10 m
- 300 MHz carrier
- 128 spectral components over 40 MHz bandwidth
- $S_4 = 1.1$, $f_{coh} = 3.5$ MHz
- Decorrelation distance = 63 meters
- Use velocity = 100m/s to convert distance to time

Ionospheric Transfer Function at the Center Frequency (300 MHz)



Example of Flat Fading



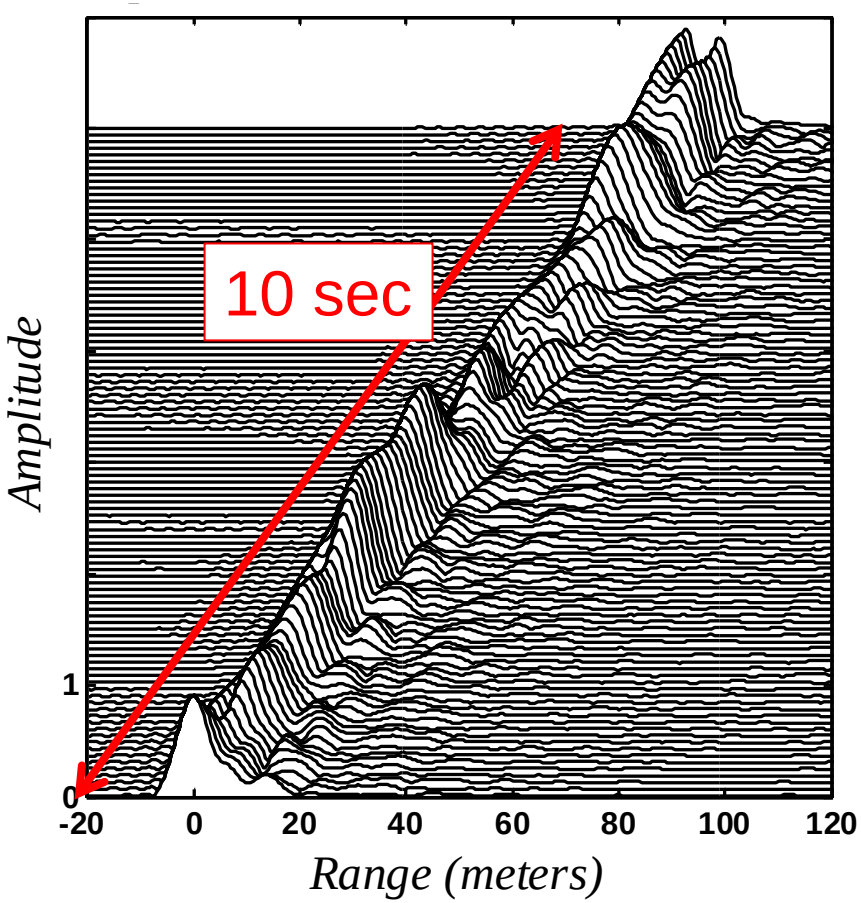
Chirp pulse:
Tc = 0.04 sec
BW = 40 MHz

Ionosphere:
τ_0 = 0.6 sec
f_{coh} = infinity

Small Tc / τ_0
Small BW / f_{coh}

- **Set all spectral components of transfer function equal to that of the center frequency (300 MHz);**
- **Waveform fades but pulse shape is otherwise undisturbed**

Example of Frequency-selective Fading



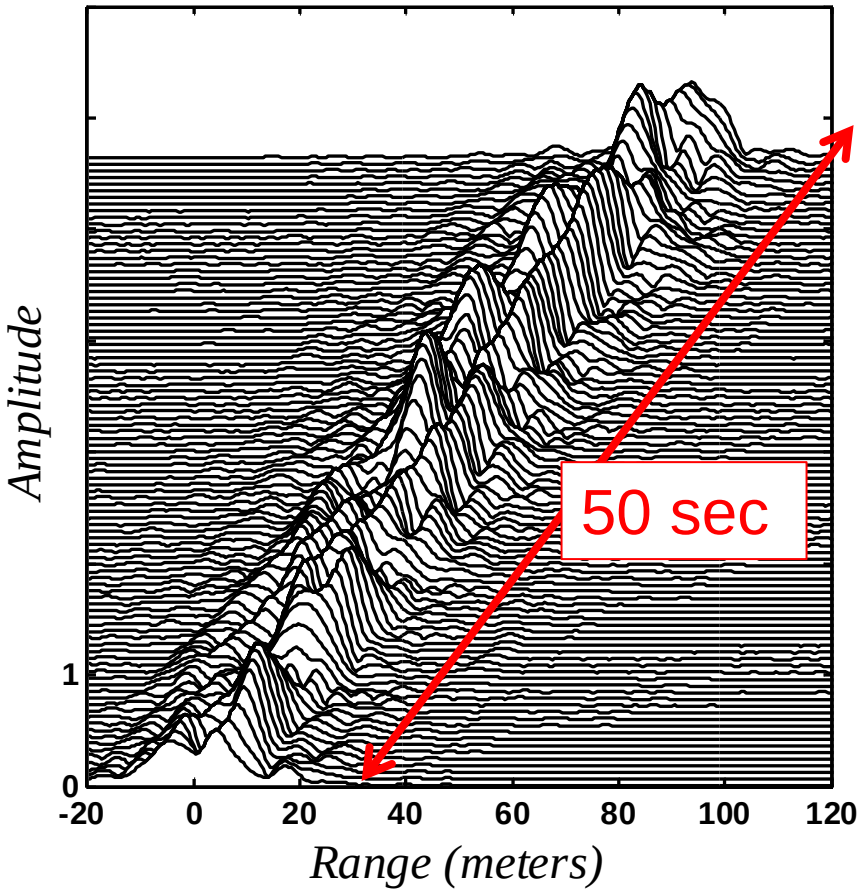
Chirp pulse:
Tc = 0.04 sec
BW = 40 MHz

Ionosphere:
τ_0 = 0.6 sec
f_{coh} = 3.5 MHz

Small Tc / τ_0
Large BW / f_{coh}

- **Radar chirping bandwidth is large with respect to the coherence bandwidth**
- **On-time signal plus interference from delayed versions**

Example of Time-selective Fading



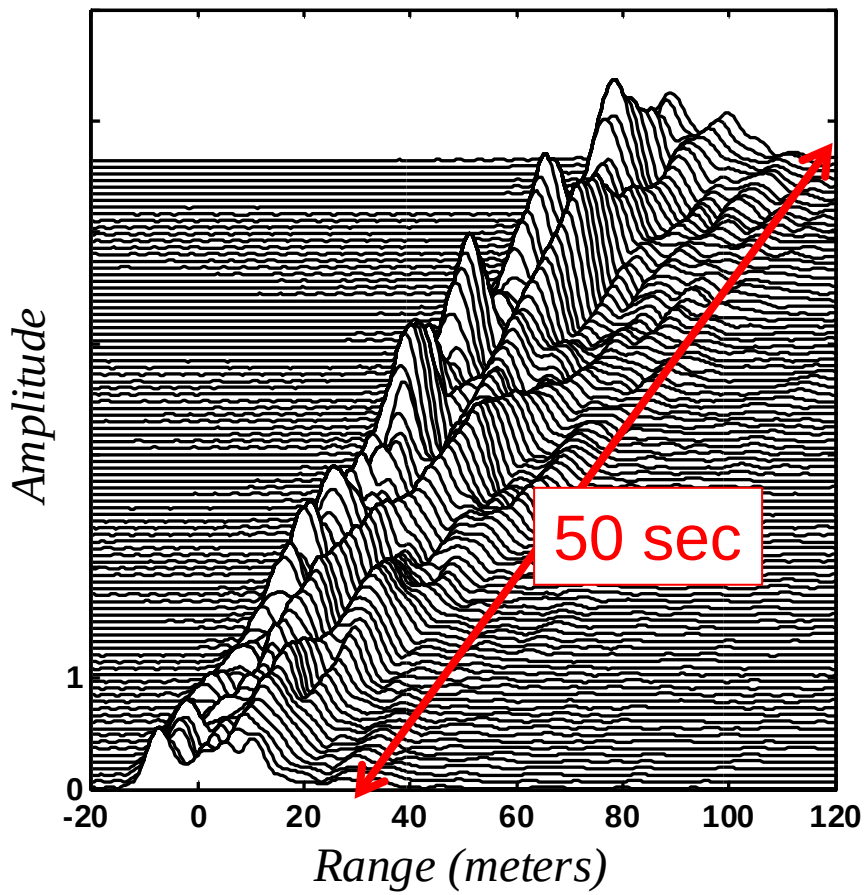
Chirp pulse:
Tc = 5 sec
BW = 40 MHz

Ionosphere:
τ_0 = 0.6 sec
f_{coh} = infinity

Large Tc / τ_0
Small BW / f_{coh}

- **Uncompressed pulse duration is large with respect to ionospheric decorrelation time**
- **Filtering process is disturbed in time domain. Entire compressed chirp is distorted**

Example of Combined Time- and Frequency-selective Fading



Chirp pulse:
Tc = 5 sec
BW = 40 MHz

Ionosphere:
τ_0 = 0.6 sec
f_{coh} = 3.5 MHz

Large Tc / τ_0
Large BW / f_{coh}

- **Large Tc / τ_0 and large BW / f_{coh}**
- **Received, demodulated waveform exhibits both distortion and interference from delayed waveforms**

Wide Bandwidth Systems that may be Impacted by the Ionosphere

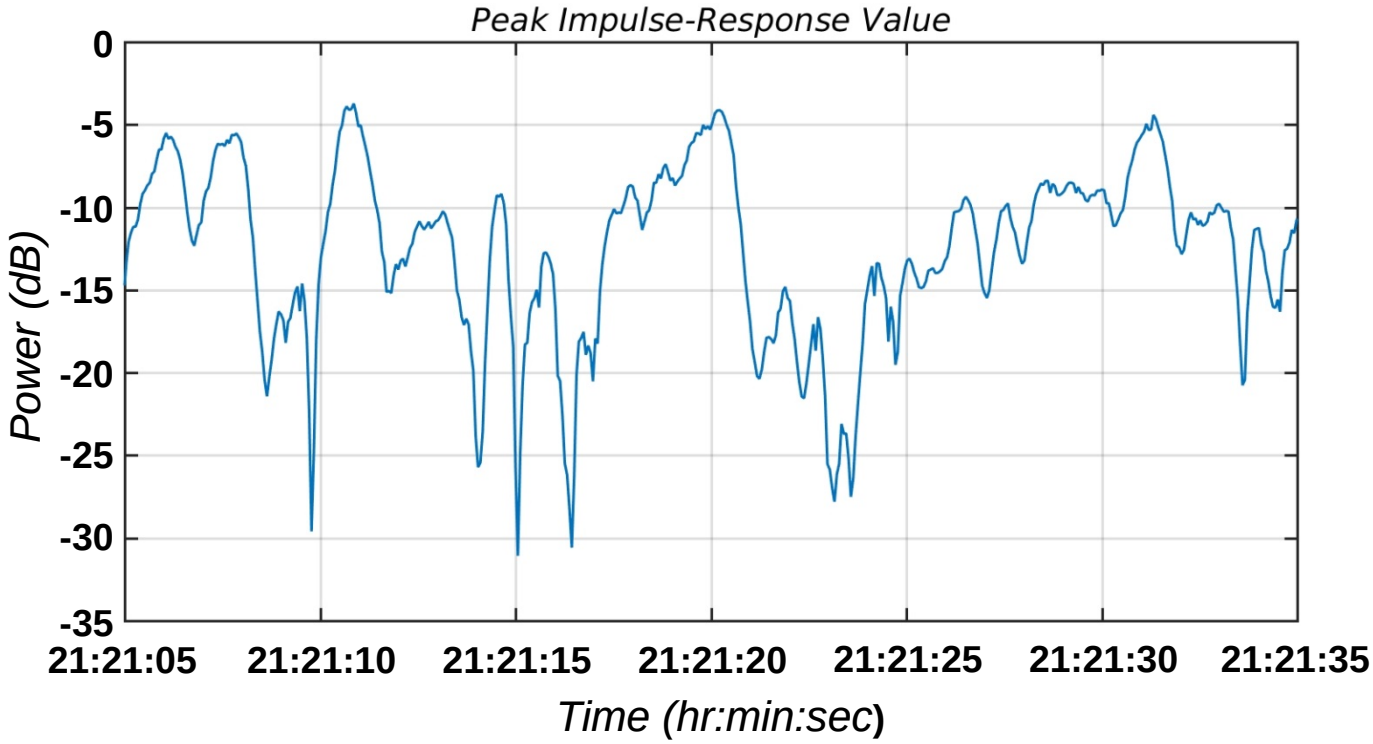
- **MUOS (Mobile User Objective System)**
  - **UHF SATCOM system that is replacing the US Navy UFO system**
  - **Uses a 4.7-MHz waveform at transmission frequencies of 310 MHz (uplink) and 370 MHz (downlink)**
  - **Ionosphere is known to be frequency selective at this frequency & bandwidth**
- **ESA BIOMASS SAR**
  - **Synthetic aperture radar at 435 MHz with 6-MHz bandwidth**
  - **Launch is planned for 2020**
  - **Orbit planned to avoid nighttime ionosphere**
- **VHF/UHF/L-band SAR for foliage penetration**
  - **Hypothetical future system**
  - **Low transmission frequency desired for EM penetration**
  - **High bandwidth required for good range resolution**

Conclusions

- Improving hardware technology is leading to the increased development of wide bandwidth communications and radar systems
- New and planned wide bandwidth systems can benefit from research similar to that presented here to
  - Predict ionospheric effects on signals
  - Quickly generate useful digital realizations of ionospherically corrupted waveforms for both design studies and receiver hardware testing

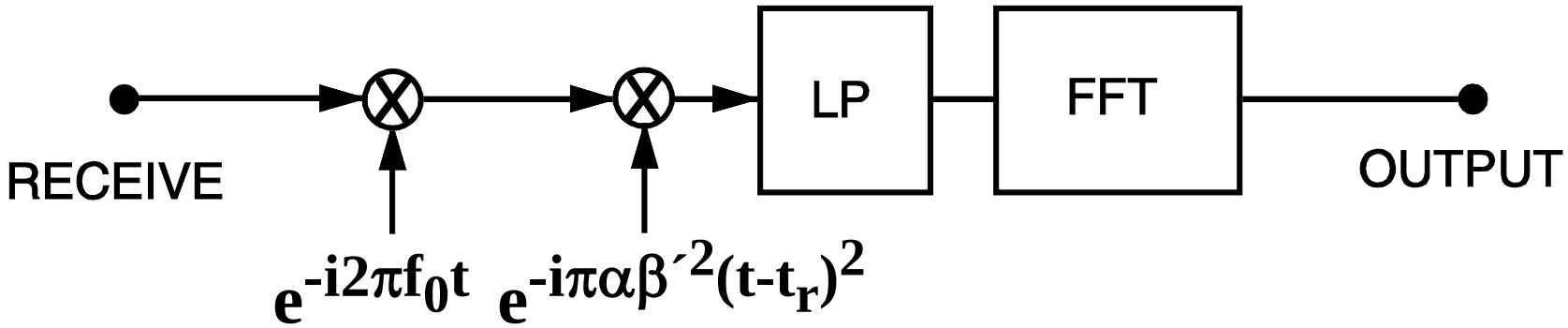
- **BACKUPS**

MUOS data: Peak of the impulse response function, Sept 23, 2014

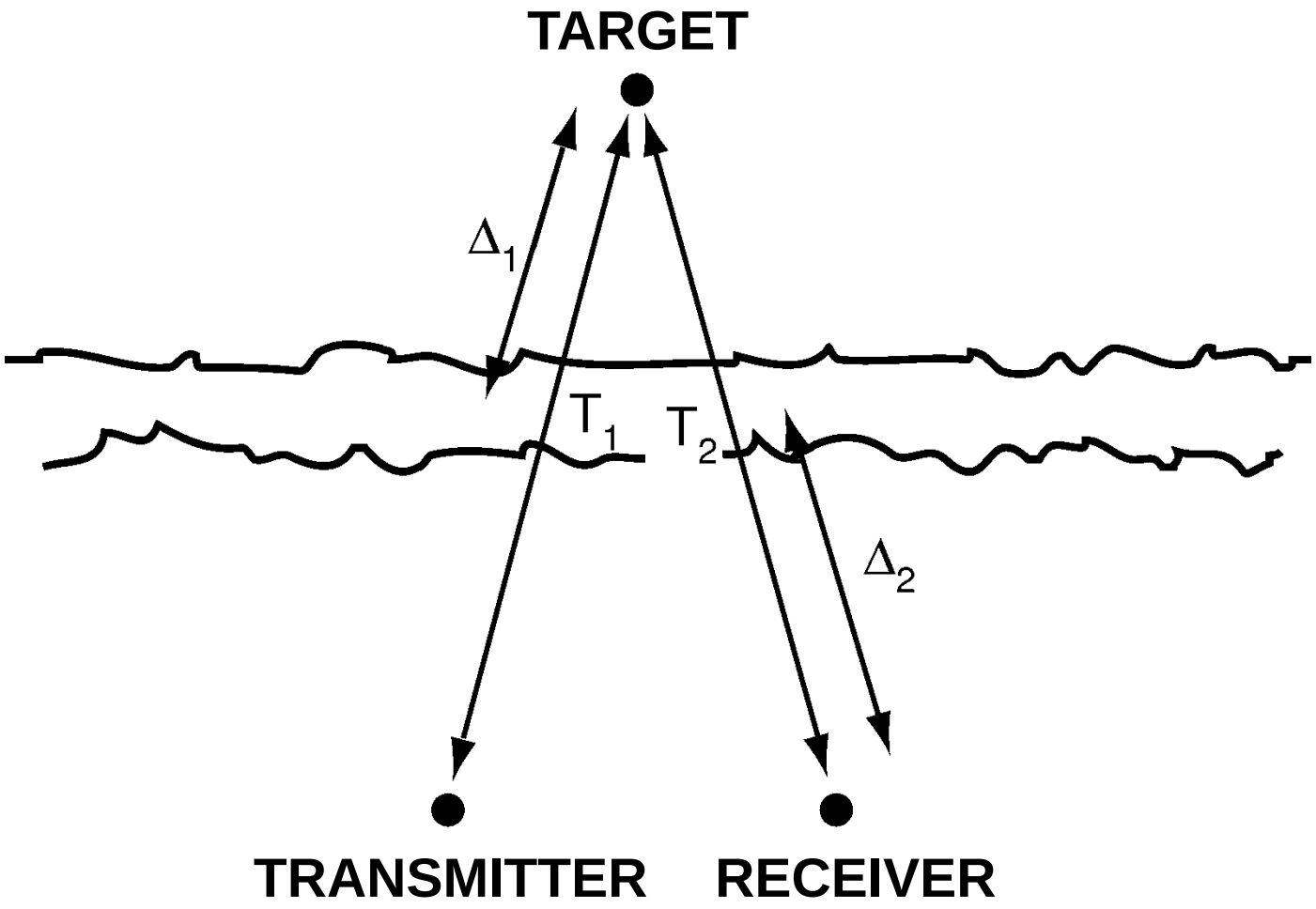


- **Peak power of the time-varying impulse function versus time**
- **We measured S_4 between 0.9 and 1.2 for the entire 11 minutes of this data segment. Only 30 seconds of data is shown.**

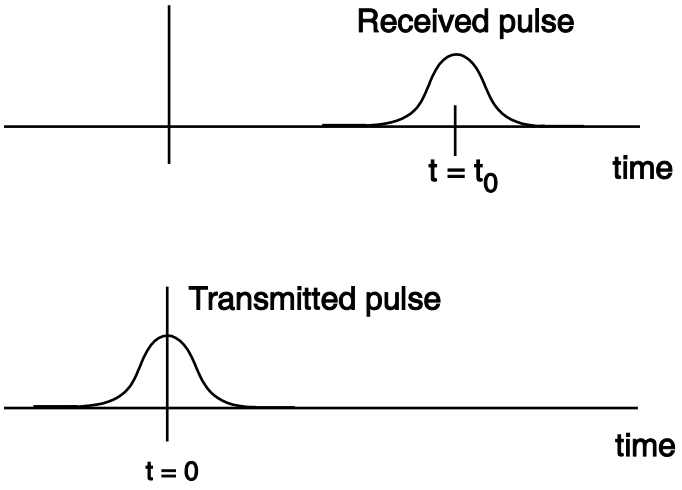
Stretch.eps



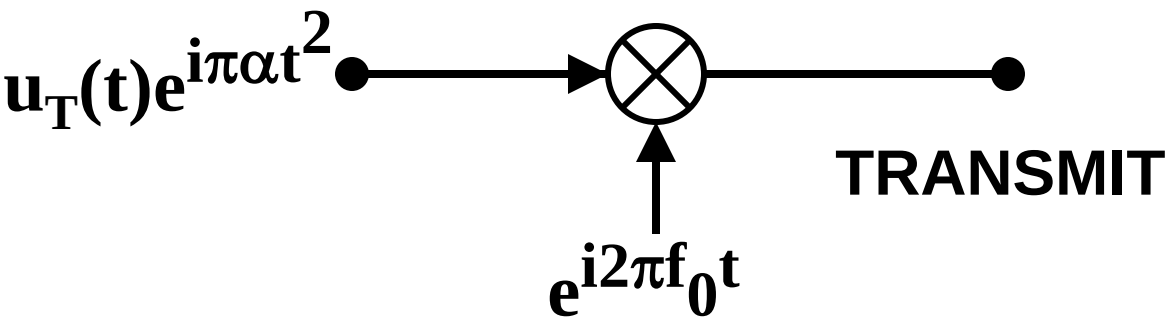
Time_delay.eps



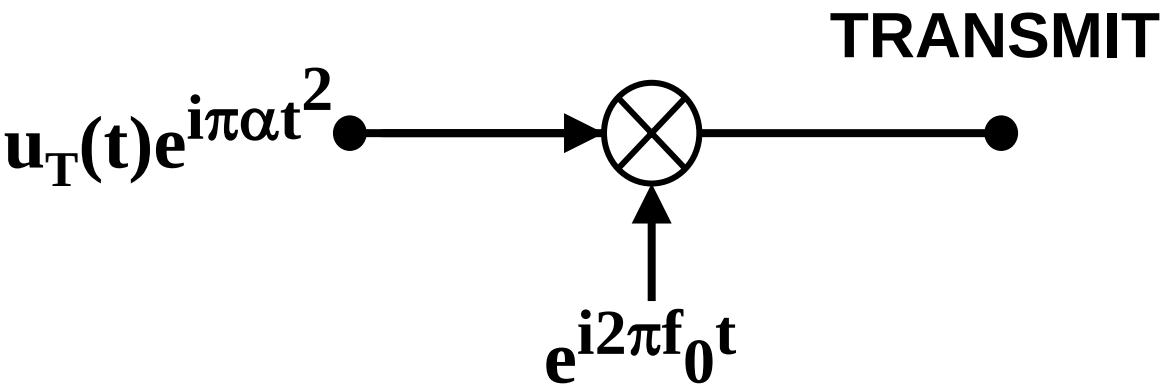
Signal.eps



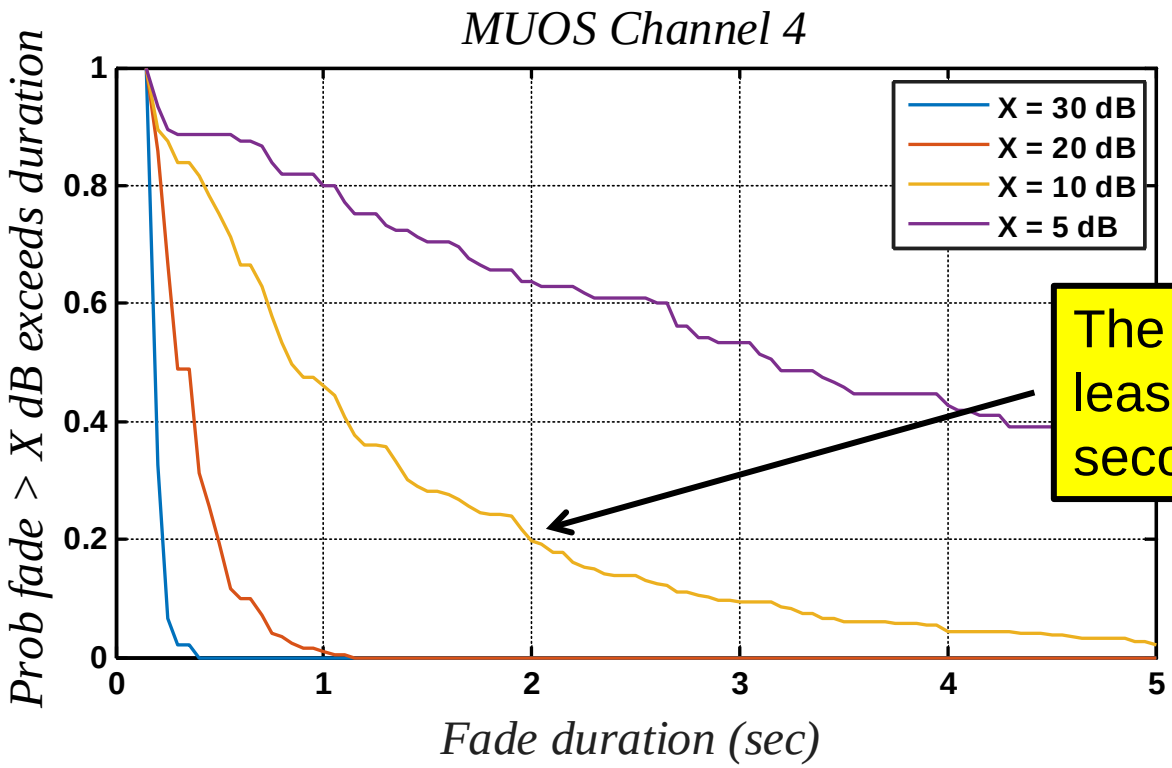
Transmit.eps



Transmission of a Modulated Chirp



Fade duration from 8 hours of AFRL MUOS data taken at Kwajalein



The probability of a fade of at least 10 dB lasting at least 2 seconds is 20 percent

- **Channel fade duration is important for the design and operation of COMM links**
- **Slow, deep fading is a difficult channel phenomenon that is hard to design against**

SRI probe: *Simulated* time-varying transfer function and impulse response function

- **Channel is intended to be a severe ionospheric disturbance, similar in severity to those measured previously at Ascension Island**
- **Channel parameters are consistent with WBMOD, Keith Groves measurement of τ_0 ; f_0 from Knepp et al. (1991, 2002) & Cannon et al. (2006)**

Measurement parameters:

M = 8, K = 32

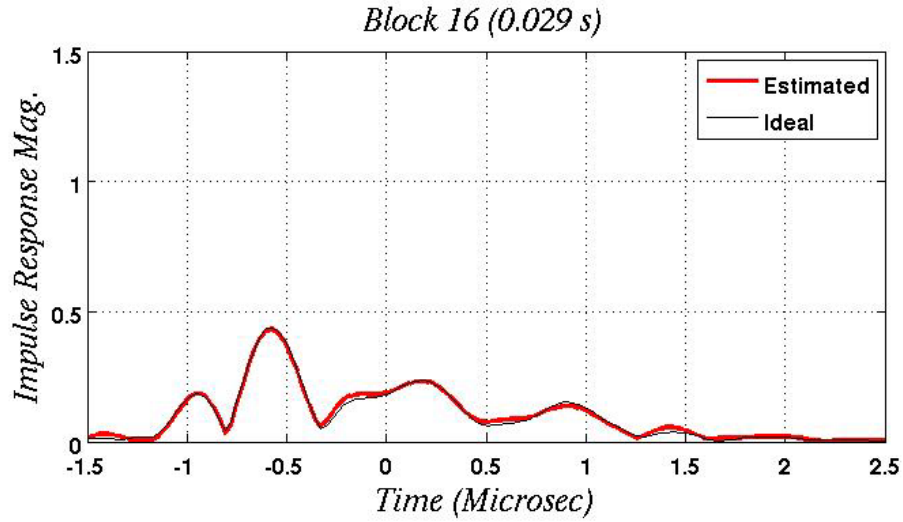
T_{Block} = 2 msec

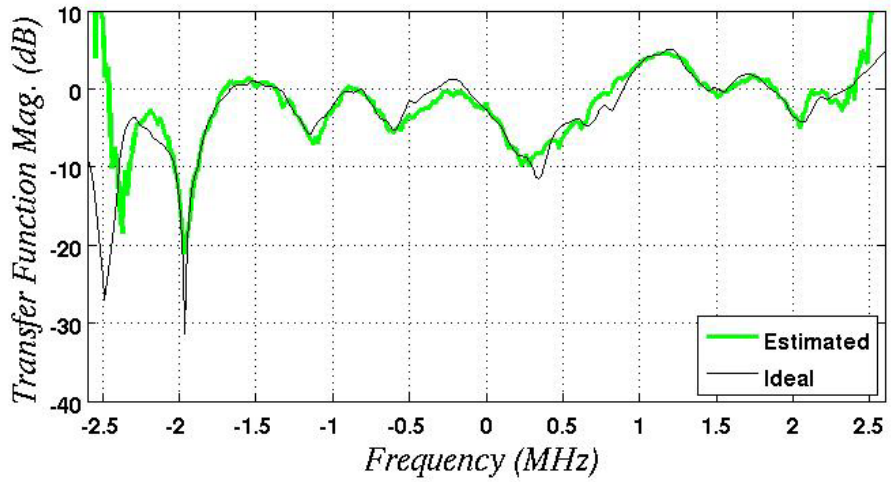
Channel params:

f_0 = 250 kHz

τ_0 = 25 msec

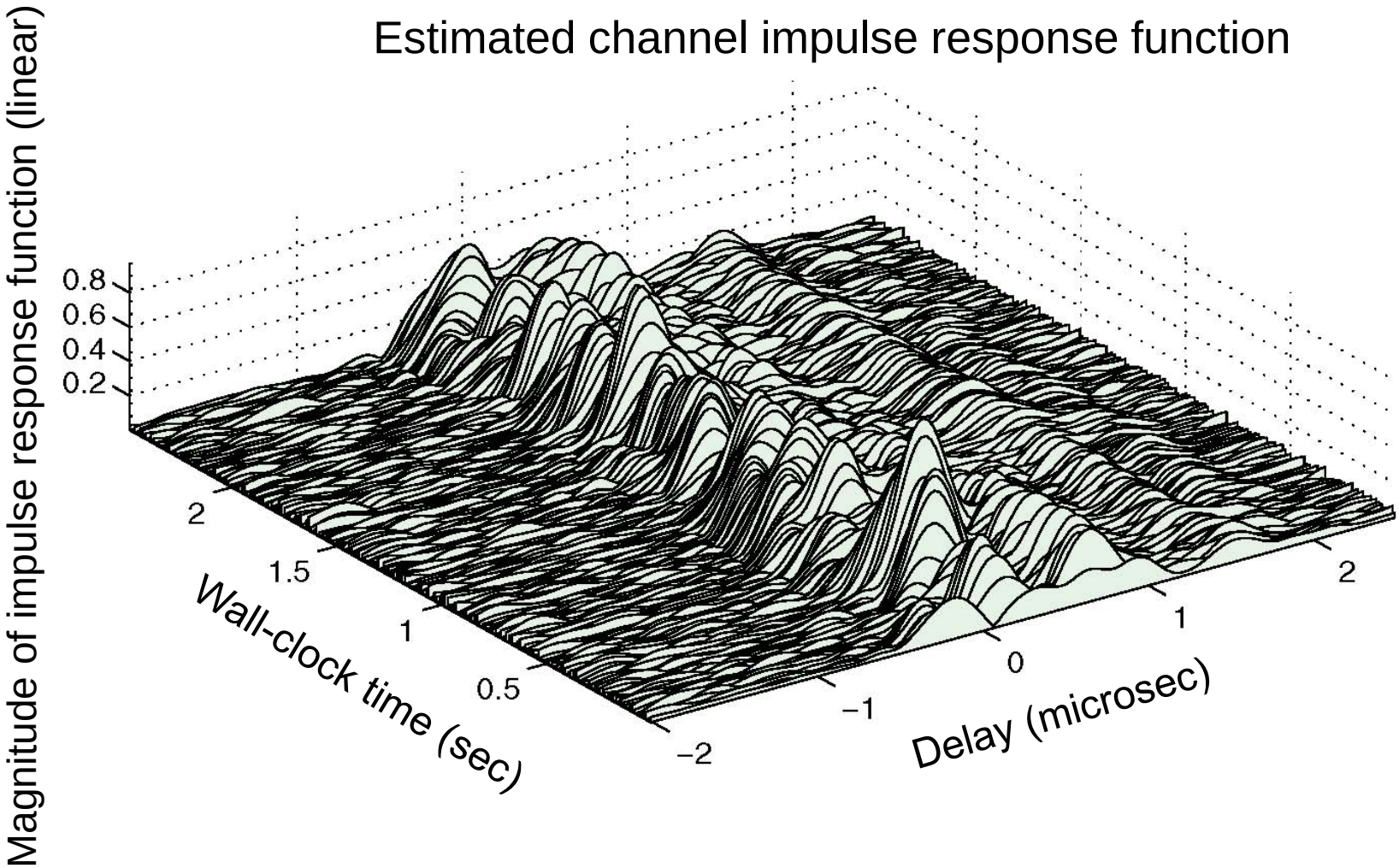
SNR = -8 dB





wbp_M8_SNR_-8_K32_f0_250_t0_25.avi

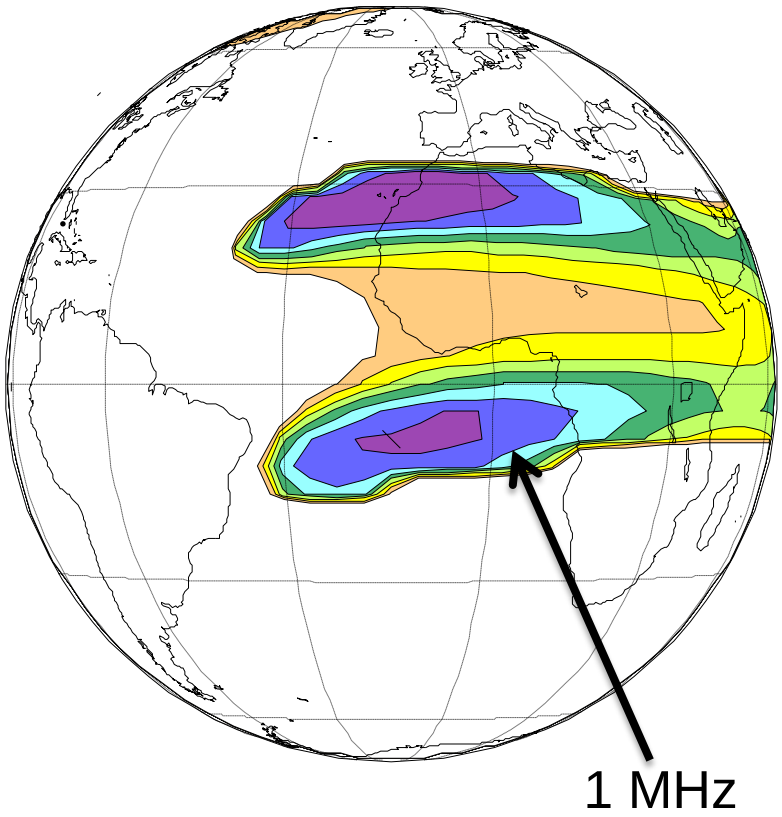
Sequence of impulse responses from simulated data



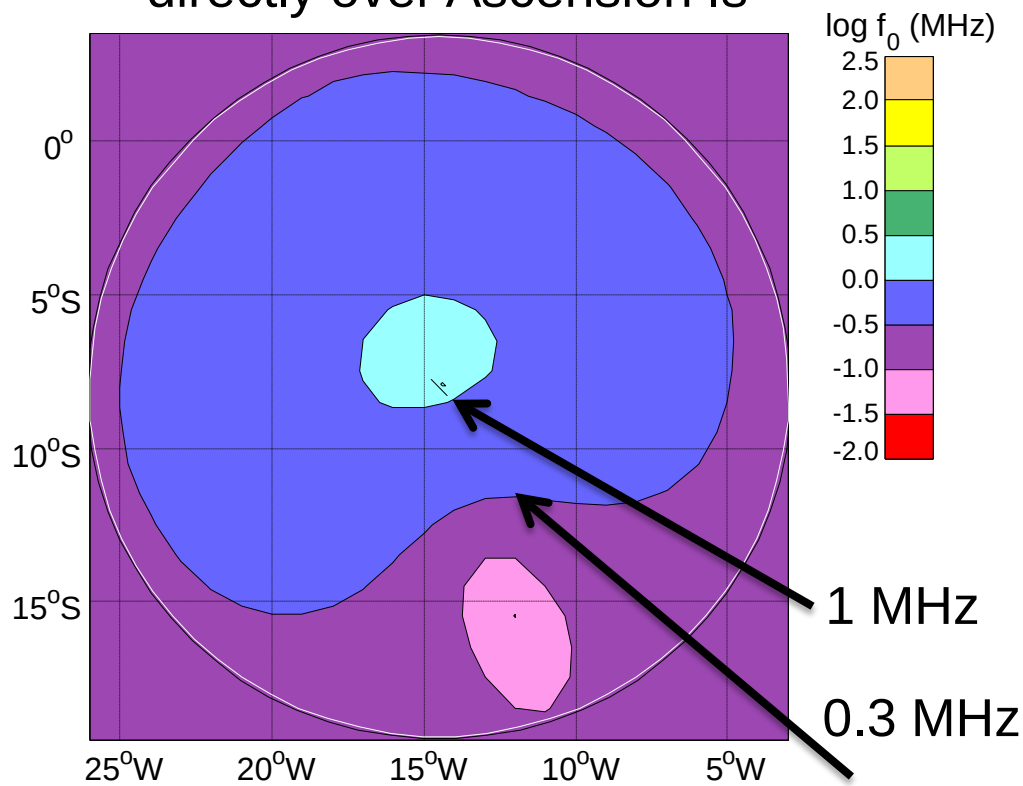
M = 9, K = 8, f_0 = 250 kHz, τ_0 = 25 msec, SNR = -8 dB

PROPMOD prediction of coherence bandwidth at 383 MHz at the 95th percentile

Snychronous satellite



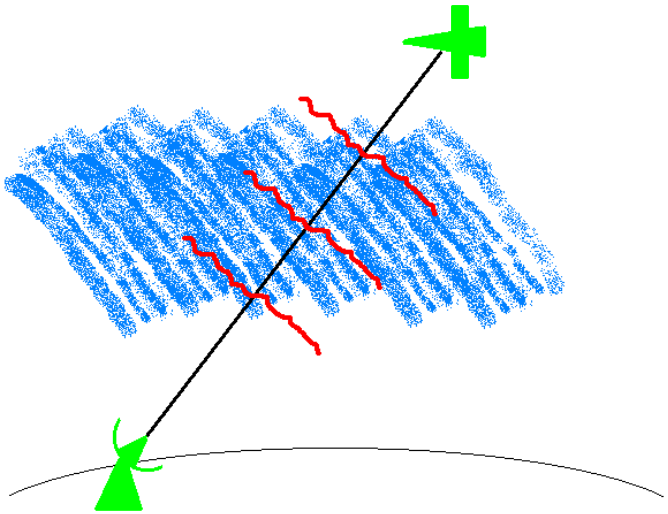
Satellite at 650 km altitude directly over Ascension Is



- **We choose f_0 values of 0.32 and 0.39 MHz for testing of probe signal processing**

Severe scintillation: 22:00 UT, March 15, SSN = 150, most severe day of year

Multiple Phase Screen Signal Generation



- **Parabolic Wave Equation for E-field**

$$-2ik\frac{\partial U(\vec{r})}{\partial x} = \nabla_{\perp}^{2}U(\vec{r}) + k^{2}\varepsilon_{1}(\vec{r})U(\vec{r})$$

Diffraction term

Source term

Solution Method:

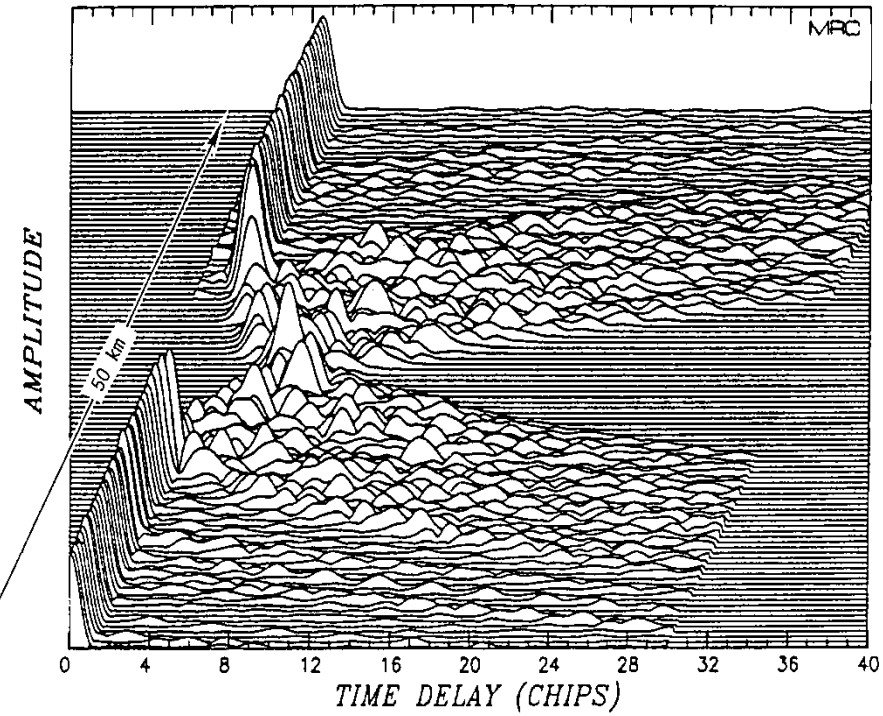
- Collapse ionospheric structure to multiple thin phase-changing screens with free space between
- At phase screen, neglect diffraction term
- Between screens, the parabolic wave equation is source free, so can solve by Fourier Transform method
- MPS technique generates realizations of the spatially-varying transfer function for all levels of scintillation severity

MPS/PROPMOD code legacy

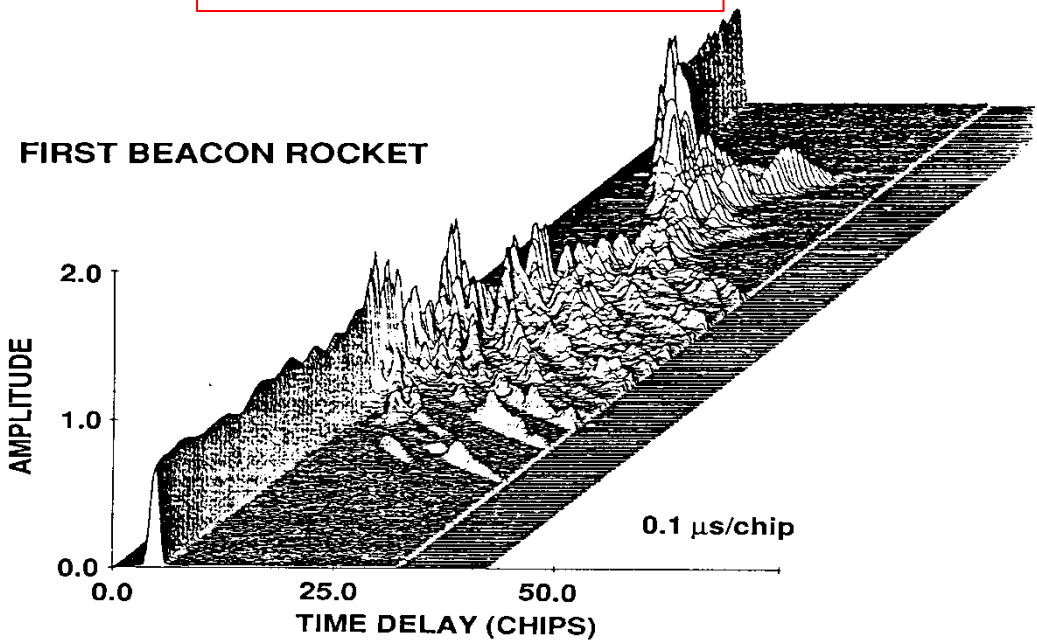
- **MPS code and PROPMOD were used by MUOS to successfully predict March 2001 experimental results**

- **MPS code used to predict received signal from a GPS-like transmitter on a rocket beacon shot behind a barium cloud**

MPS prediction

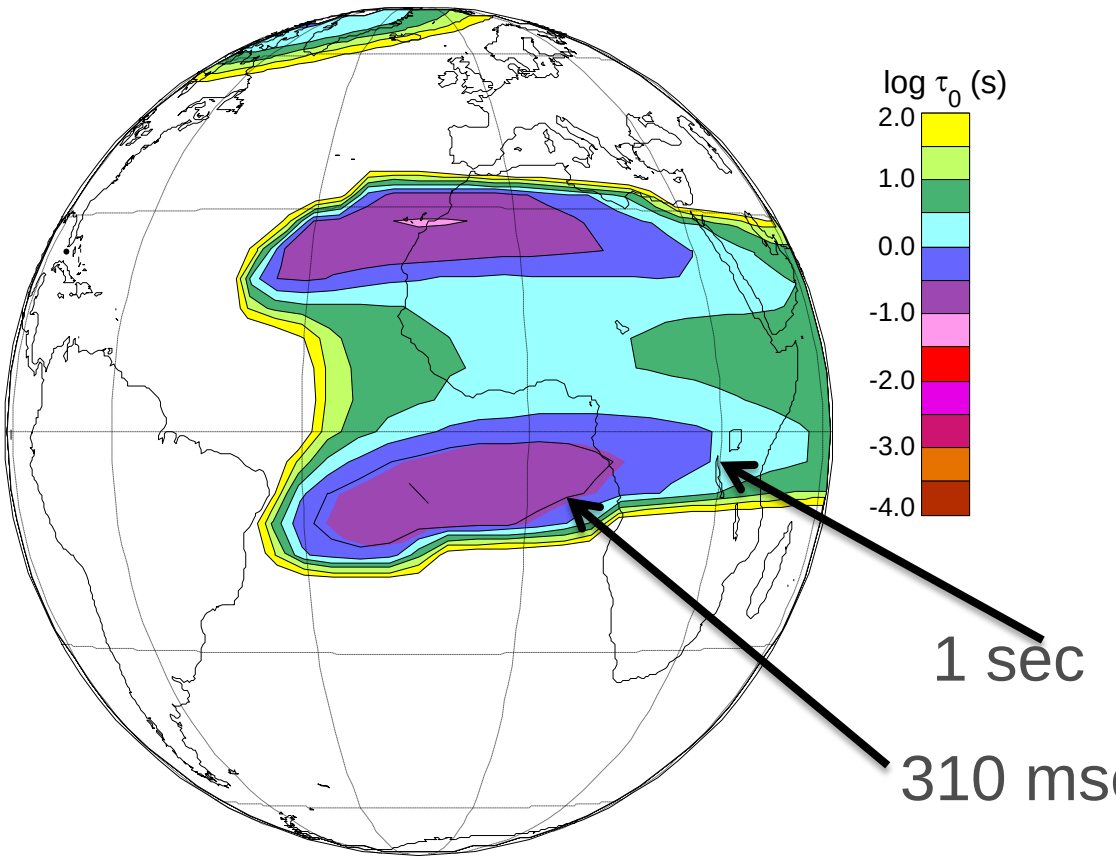


Experimental results



PROPMOD prediction of decorrelation time at 383 MHz at the 95th percentile

- PROPMOD combines WBMOD with PROP code
- Calculates propagation parameters
- PROPMOD Is consistent with Groves' measurements of τ_I at 250 MHz (30-50 msec)
- Groves has 64-107 msec for τ_0 after converting and scaling to 383 MHz



Channel probe measures the impulse response function of the ionosphere

- **The time-varying (t=time) impulse response function h(t,τ) *completely* describes the propagation channel over the bandwidth of the probe. Its Fourier transform H(t,f) is called the transfer function**
- **Convolution of the impulse response with any actual transmitted waveform gives the received waveform, including ionospheric effects**
- **Wideband channel probes are useful to determine the effects of scintillation for systems whose bandwidth exceeds the coherence bandwidth (f_0) of the ionosphere**
- **Isolated narrow-band beacons (tones) can measure many parameters that describe ionospheric scintillation, but *not* the coherence bandwidth**