A Channel Probe for Space Situational Awareness

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Outline

- Value of a channel probe
  - What it does
- Examples of wideband channel behavior
  - Collected downlink data from MUOS UHF SATCOM in Sept. 2014
  - Simulated processing from SRI channel probe
    - from LEO satellite (for COSMIC-2)
- Systems that could benefit
- Key channel parameters that affect probe design
  - How we estimate these for the LEO satellite
- SRI probe waveform and processing
- Summary

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**

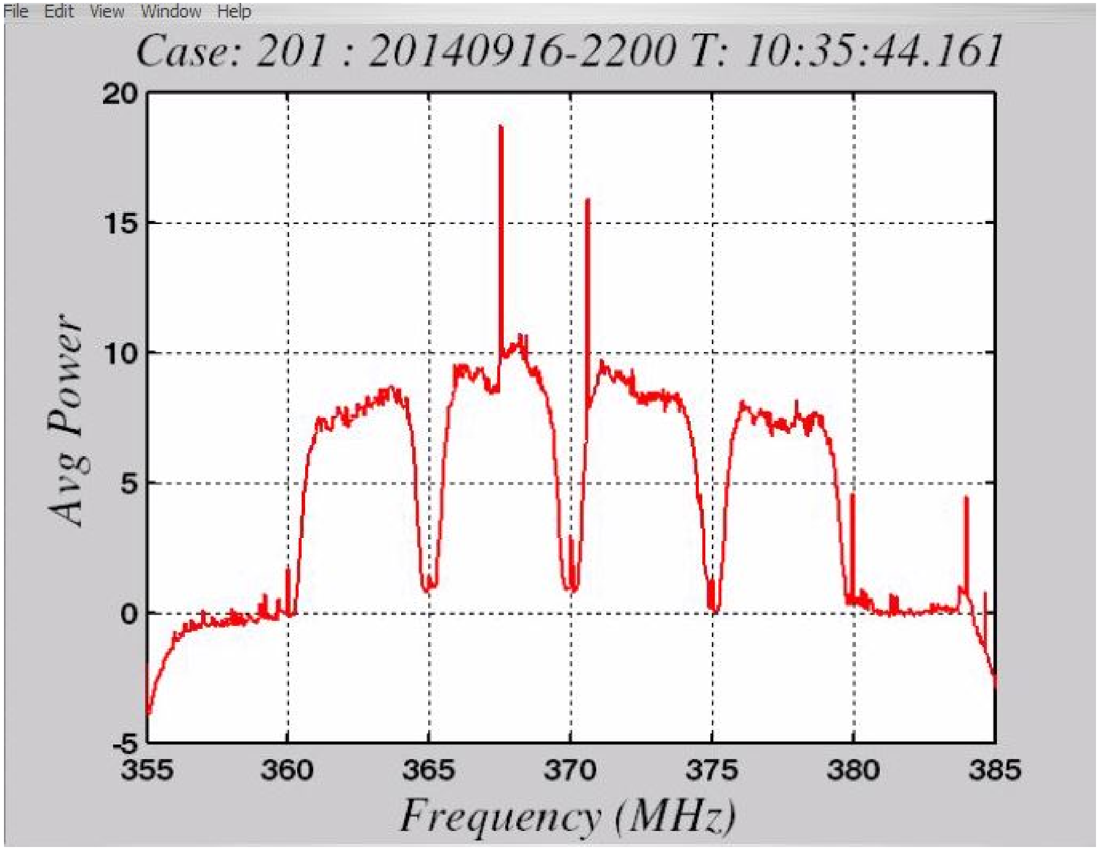
- **Isolated narrow-band beacons (tones) can measure many parameters that describe ionospheric scintillation, but *not* the coherence bandwidth**

Statistical parameters that 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_0)
  - Specifies the bandwidth over which the channel spectral components are roughly equal

MUOS power spectral density observed with very little 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)



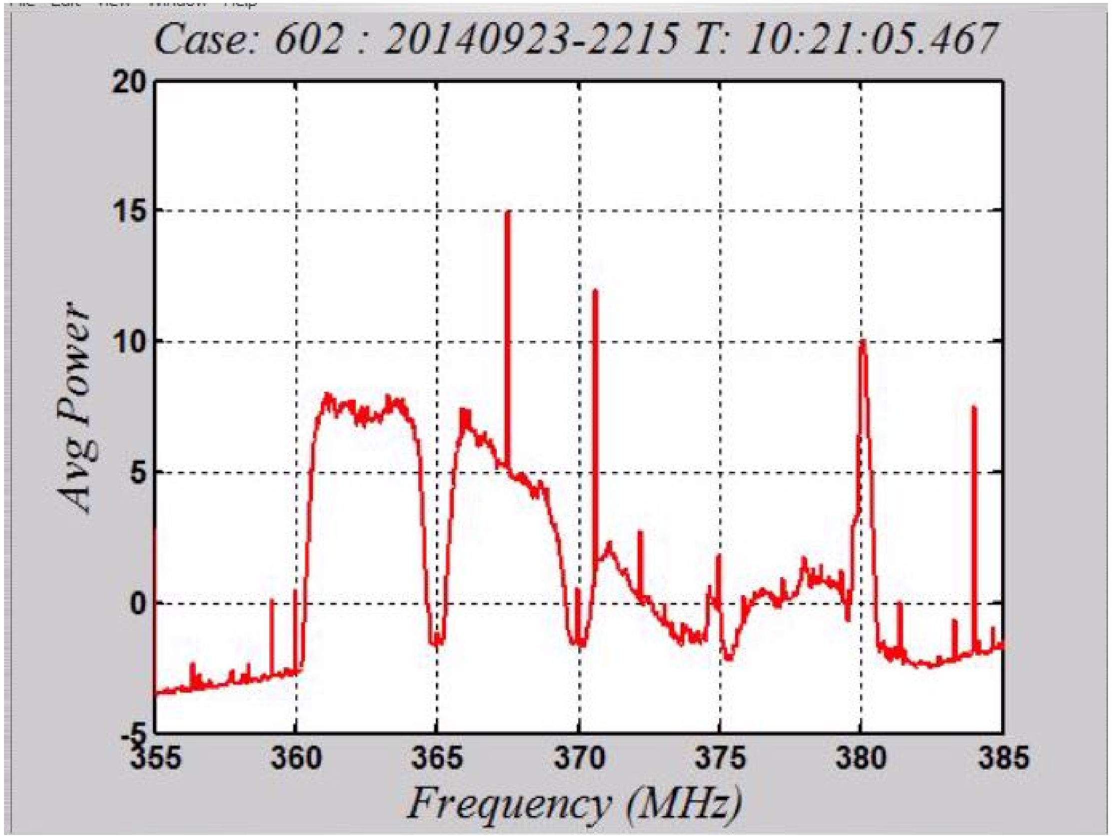
FFTMovieCase201.avi

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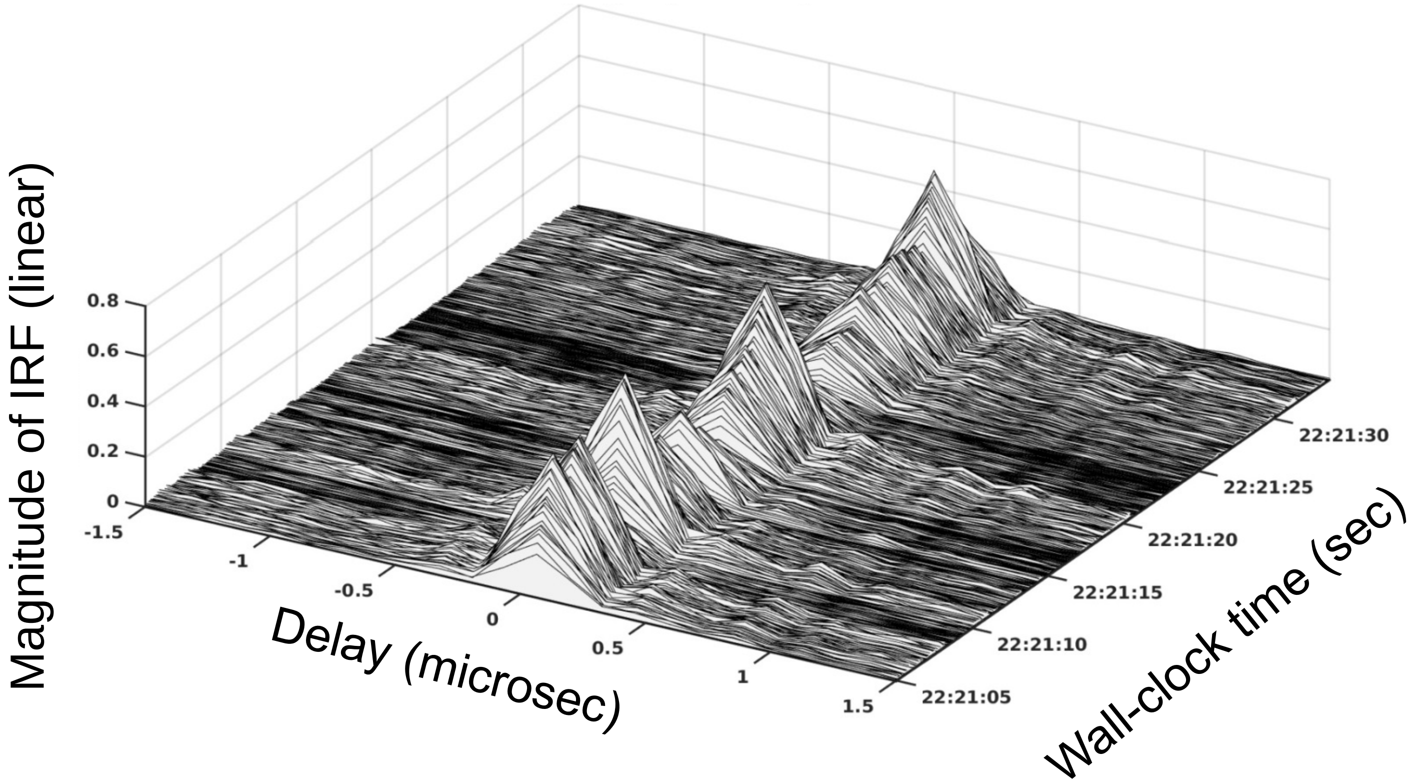
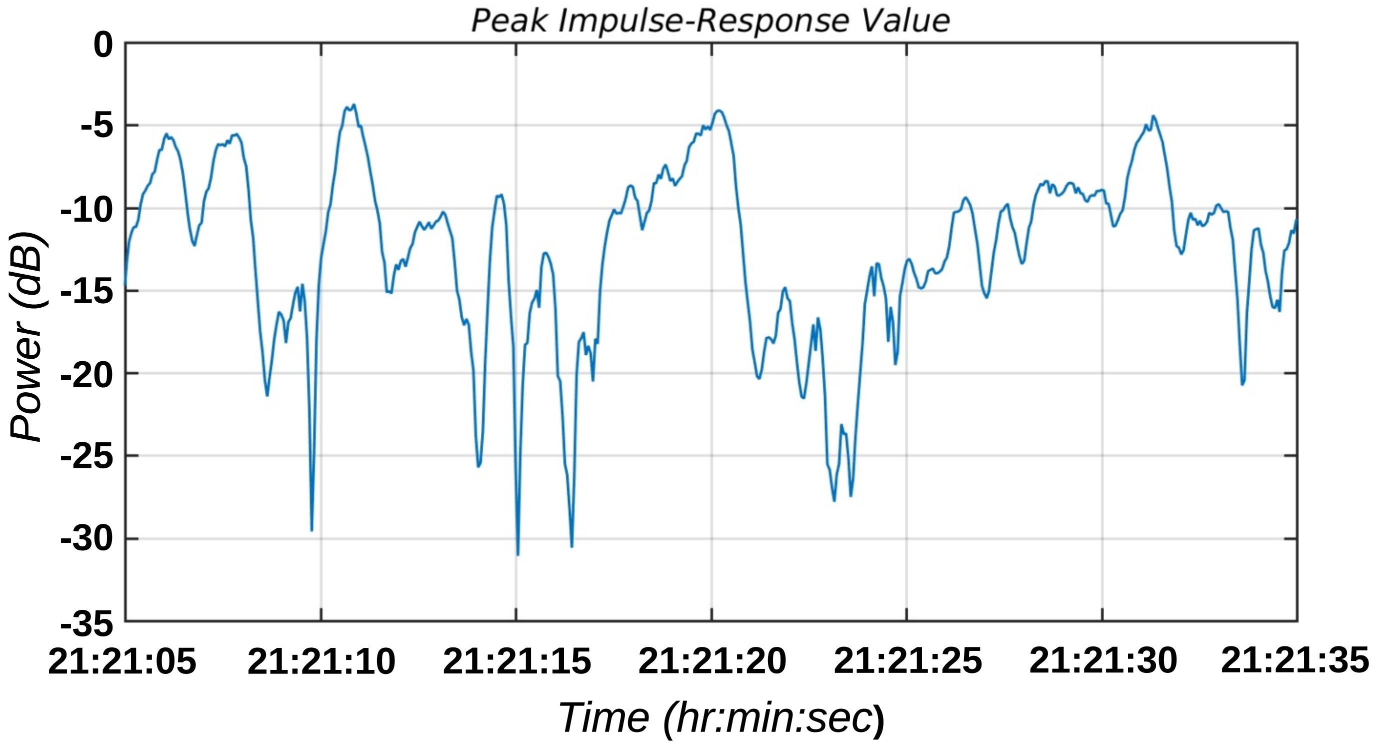
Frequency-selective scintillation across the entire 20-MHZ downlink band, Sept 16, 2014

Time varying impulse response function, Sept 23, 2014



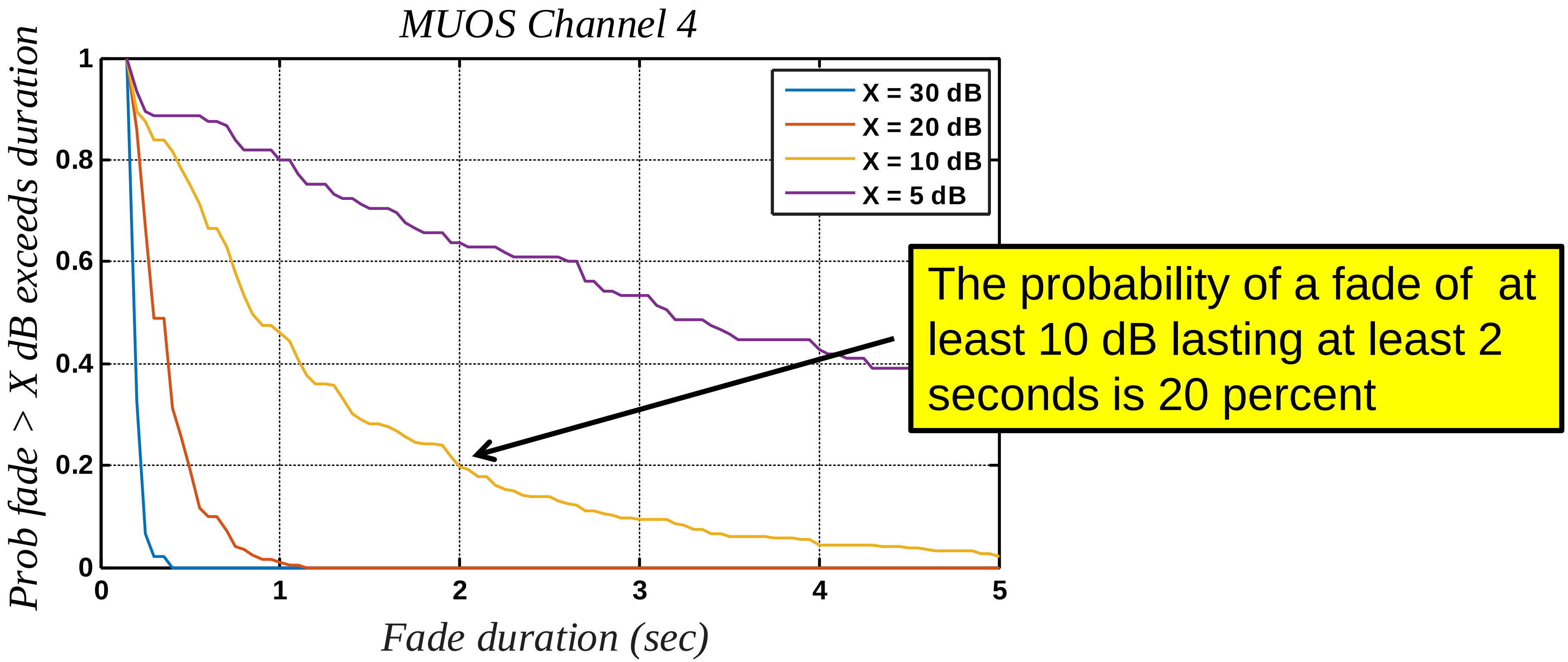
- **The impulse response function is obtained by analyzing the common pilot channel (CPICH) signal in each MUOS 5-MHz band**
- **The figure is a 30-second snapshot of the magnitude of the MUOS impulse response function of one of the 4 downlink channels**
- **We processed all the data obtained from AFRL and found mostly time-varying flat fading in the individual 5-MHz MUOS bands**

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.**

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



- **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

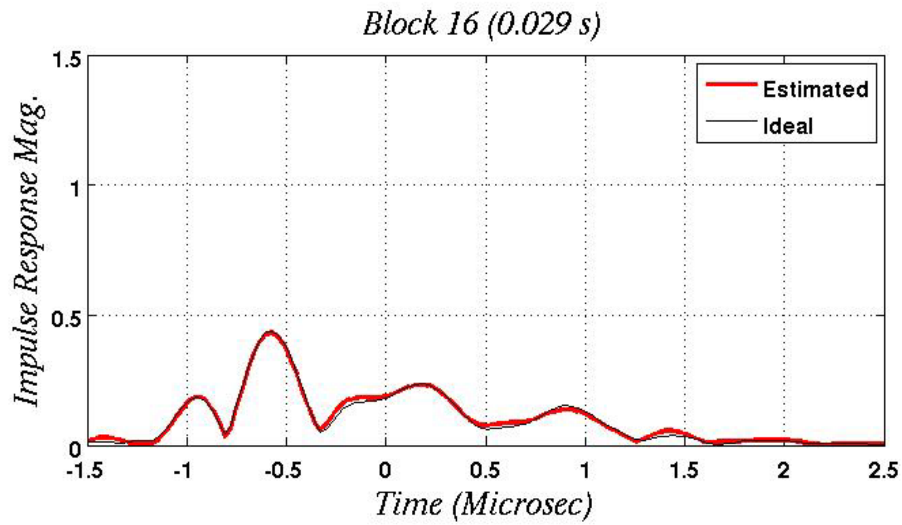
T_{Block} = 2 msec

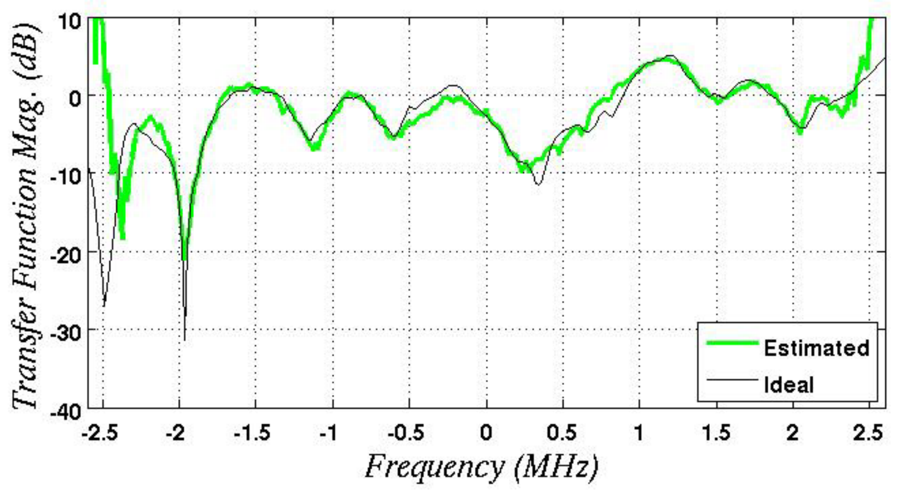
Channel params:

f_0 = 250 kHz

τ_0 = 25 msec

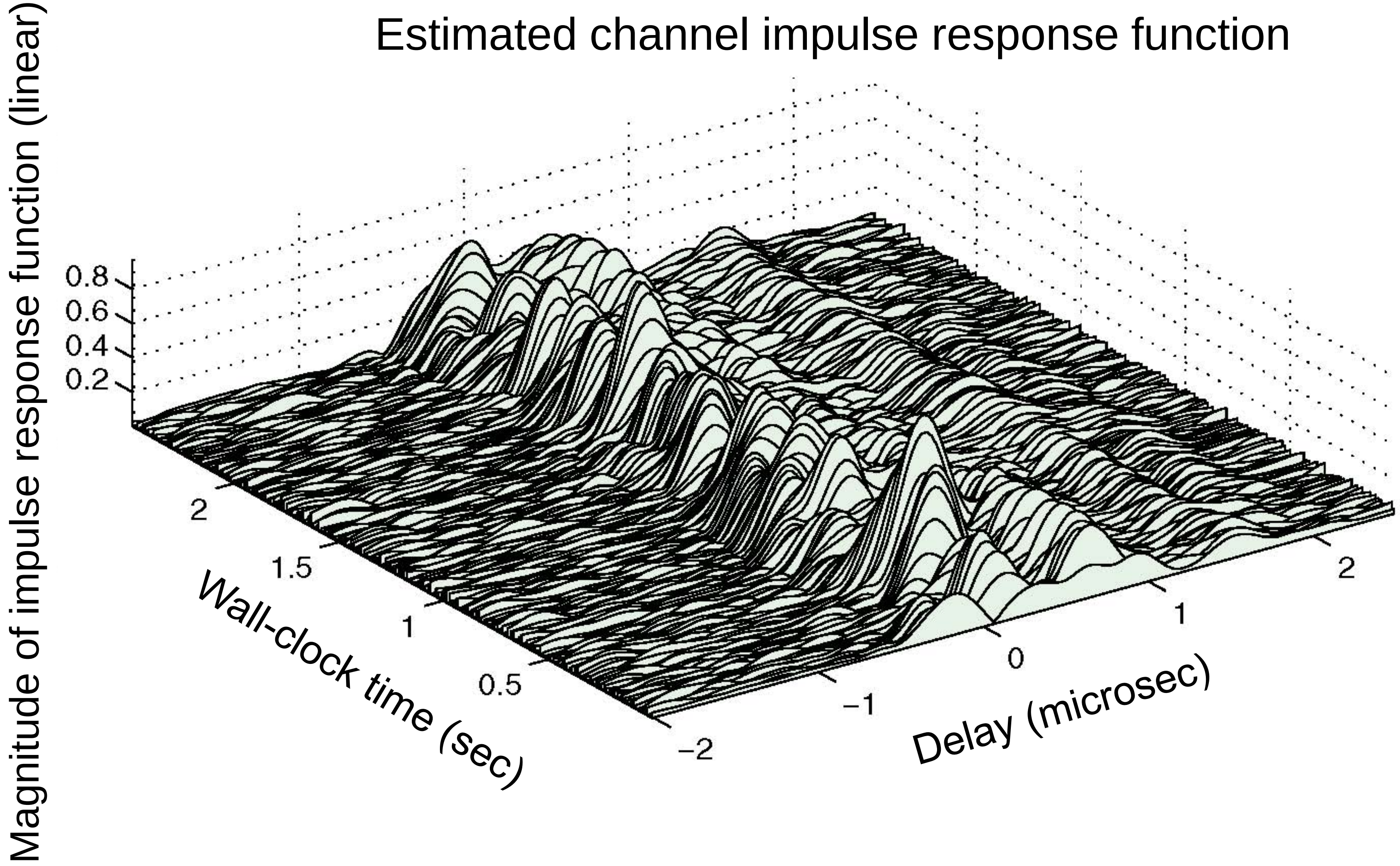
SNR = -8 dB





wbp_M8_SNR_-8_K32_f0_250_t0_25.avi

Sequence of impulse responses from simulated data



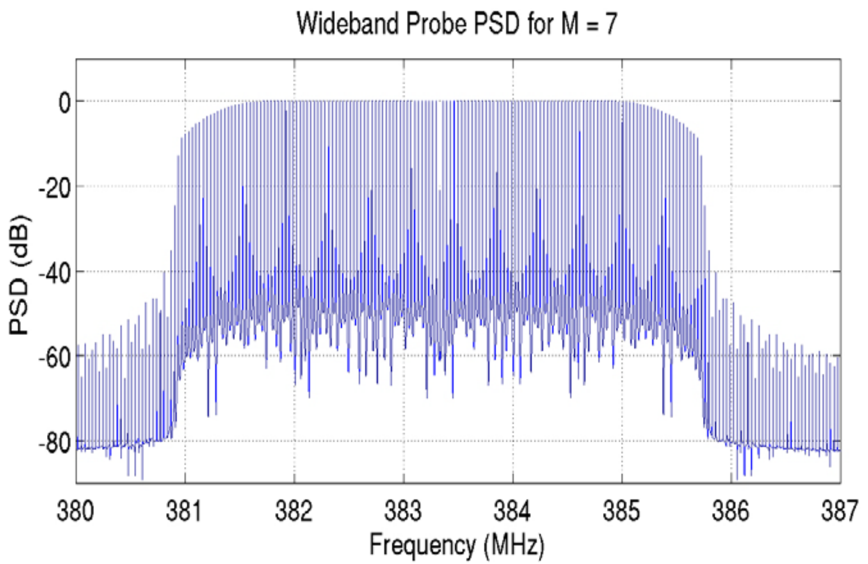
$M = 9$, $K = 8$, $f_0 = 250$ kHz, $\tau_0 = 25$ msec, SNR = -8 dB

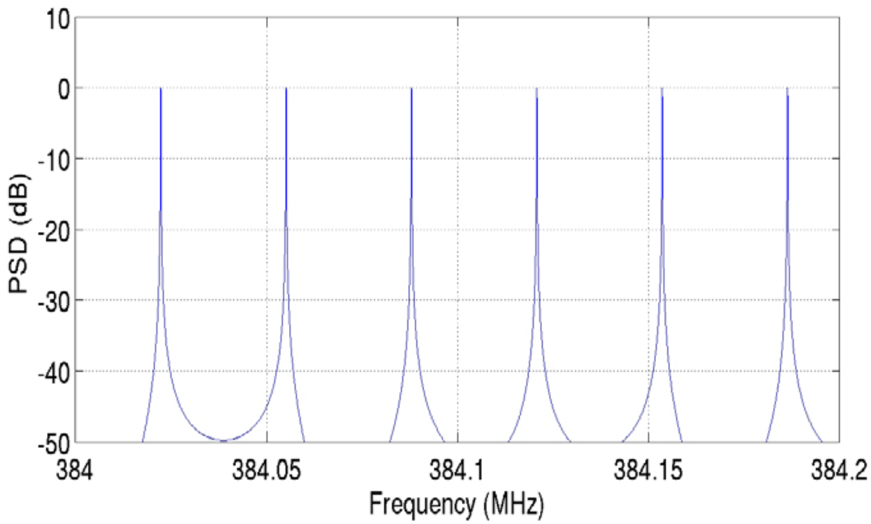
Systems that would benefit from a wideband channel probe

- **MUOS (Mobile User Objective System)**
  - UHF SATCOM system to replace the present 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
- **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

SRI wideband probe waveforms

- **Periodic waveform**
- **5 MHz bandwidth**
- **A single period:**
  - **Bi-phase-modulated maximal-length shift-register sequence**
  - **Shift-register lengths of M=7-10**
  - **Square-root raised-cosine filtering**
- **M determines tone separation**
- **Equal-strength tones throughout most of signal bandwidth**
- **The probe waveform is much more flexible than the MUOS CPICH waveform**





Channel estimation core concept

- For linear time-invariant systems, the input $x(t)$ and output $z(t)$ are related by the impulse-response function $h(t)$: $z(t) = h(t) \otimes x(t)$.
- In the frequency domain, this becomes $Z(f) = H(f)X(f)$.
- We receive a noisy version of the distorted signal $y(t) = h(t) \otimes x(t) + n(t) + i(t)$.
- Form the estimate $\frac{Y(f)}{X(f)}$:

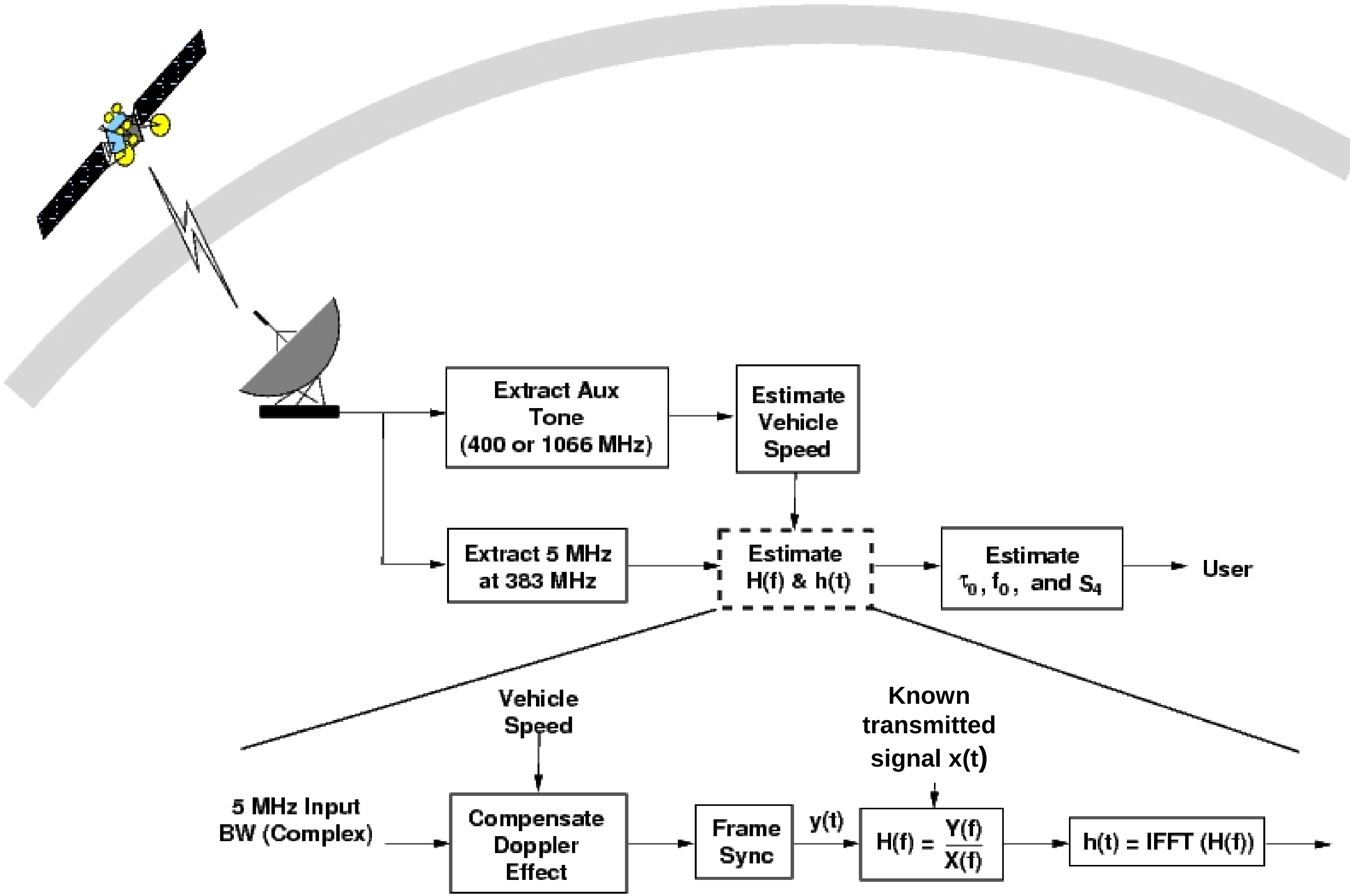
$$\hat{H}(f) = \frac{H(f)X(f) + N(f) + I(f)}{X(f)}$$

- Suppose $X(f)$ is zero except at $f = f_k$. (i.e., x(t) is periodic).
- If $N(f_k) + I(f_k)$ is negligible, then $\hat{H}(f_k) \approx H(f_k)$.
- The periodicity of $x(t)$ guarantees this outcome provided the noise and interference is not also periodic with Fourier frequencies f_k.
- We end up with a sampled version of $H(f)$.
- The density of sampling is controlled by the tone spacing in $x(t)$.

Design of the channel probe

- The channel probe must be designed to operate during ionospheric scintillation
- Decorrelation time (τ_0) and coherence bandwidth (f_0) drive the design of the ionospheric probe
  - Must integrate long enough to accommodate noise and interference
  - Cannot integrate for a time that greatly exceeds τ_0
  - The smaller the f_0, the more tones are needed for frequency resolution
- We consulted with Keith Groves and also used PROPMOD to estimate the reasonable worst case value of τ_0 (4-6 msec)
- The NWRA PROPMOD code estimates the range of f_0 for severe scintillation conditions (0.3-1 MHz). The only measurements:
  - Knepp et al. (IEEE Trans A&P, 1991), Knepp et al. (MILCOM, 2002), Cannon et al. (Radio Sci, 2006)

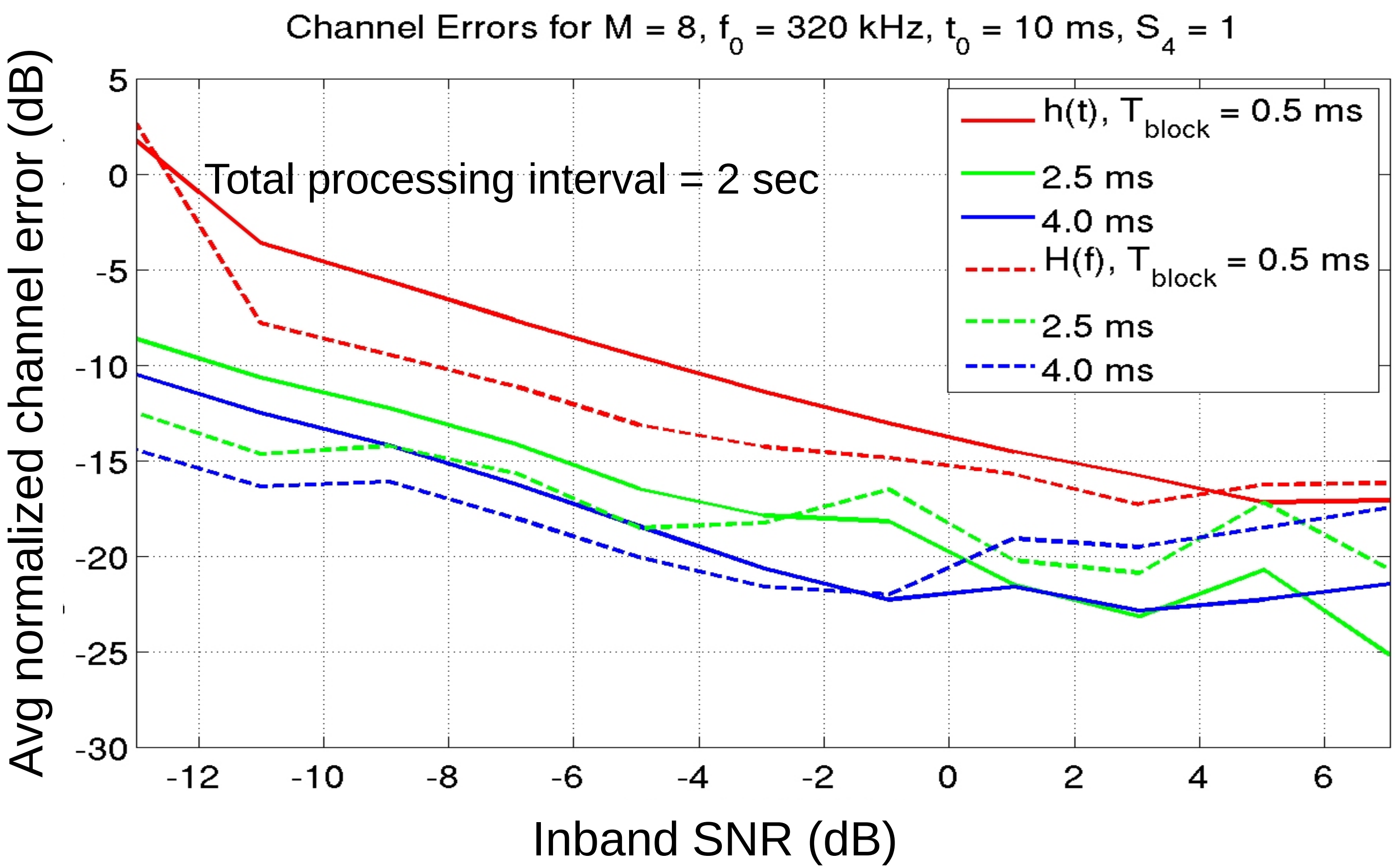
SRI probe signal processing for channel estimation



Receiver signal processing

- The NWRA multiple phase screen propagation simulation (Knepp, Proc IEEE, 1983) is used to generate realizations of h(t, τ) and H(t, f)
- Simulations to date: S_4 = 1; Coherence bandwidth f_0 : 320 & 400 kHz; Decorrelation time τ_0: 10, 25, 50 msec
- Range of M: 7-10; Wide range of T_{block}
- Our link budget analysis is based on SRI antenna patterns
  - Predicted SNR (in 5-MHz band) range is -11 to -5 dB
  - Range of SNR used in simulation is -18 to 7 dB
- Receiver processing uses higher freq tone and/or satellite ephemeris info to estimate range rate, corrects for Doppler across the band (i.e., time dilation), performs time sync, takes the FFT and estimates h(t, τ), H(t, f), S_4, f_0 and τ_0

Performance example: Channel estimation errors



As expected, performance improves for higher SNR and longer processing time (T_{block})

Status of SRI wideband probes

- SRI International has delivered 6 ionospheric probes to AFRL/SMC
- Each probe transmits S-band, L-band, and UHF tones as well as the wideband periodic waveform described in this talk
- The wideband waveform will be available for transmission, but is not yet a part of the planned ground-station operation
- Receivers for the tones and for the wideband waveform are not yet fully developed
- Future funding for the probe development and processing is not planned

Conclusions

- The SRI channel probe is extremely useful to support new wide bandwidth SATCOM and radar systems
- Our analysis of collected MUOS data indicates the usefulness of the channel probe
- We have implemented in Matlab and C a signal processing model that represents the SRI wideband channel probe and software to process the collected data after transionospheric propagation
- Good measurement accuracy is observed in our simulations over the expected range of SNR and channel conditions