Scintillation Simulator Test Results

Hardware-In-The-Loop Emulation of Ionospheric Scintillation

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***Abstract*—Ionospheric scintillation induces distortion onto RF communication and radar signals that propagate through the ionospheric medium. Unless properly accounted for, this scintillation may greatly impact the performance of military and commercial satellite signals. Accurate verification of satellite systems and associated ground equipment is achievable through the use of hardware-in-the-loop (HWIL) scintillation simulators. Test results of a scintillation simulator are presented and compared with theoretical performance of Rayleigh, Rician, and Nakagami-*m* fading.**

Keywords—scintillation; fading; satellite; communications; radar; hardware in the loop testing; simulator; ionosphere; MASS

I. Ionospheric Scintillation

The natural ionosphere may produce a variety of disturbances to radio frequency (RF) communication signals propagating through the ionosphere. Disturbances due to large-scale (or mean) ionization include attenuation, time delay, Faraday rotation, and Doppler shift. Relatively small-scale ionospheric structures may also result in scintillation of signals propagating through it. Scintillation effects include random fluctuations in phase, amplitude, and angle-of-arrival. Fig. 1 depicts the multipath nature of the scintillation phenomenon where a large number of random propagation paths exist.

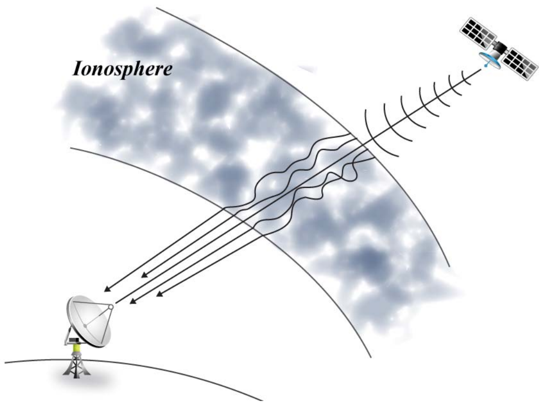

Fig. 1. Scintillation-induced multipath propagation through ionosphere.

Scintillation effects may be intensified after a high altitude nuclear weapon detonation due to an increase in the electron density and structure irregularities in the ionosphere. For signals at a given carrier frequency, the observed propagation effects are likely to be significantly worse after a high altitude detonation. Carrier frequencies that are generally unaffected by the natural ionosphere may suddenly be significantly impacted after a nuclear event [1].

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II. Scintillation Characteristics

A. Scintillation Statistics

With strong scattering from a disturbed ionosphere, the in-phase (I) and quadrature (Q) components of the signal electric field are each zero-mean Gaussian random variables. The I and Q components are statistically independent with each having variances equal to one-half of the total signal power. In this situation, the amplitude distribution is Rayleigh, and the phase is uniformly distributed over 360 degrees.

Amplitude scintillation intensity is quantified by the scintillation index, S_4. The scintillation index ranges from zero to one, and Rayleigh fading occurs when $S_4 = 1.0$. When the scintillation index decreases below 1.0, the amplitude distribution becomes Rician. Fig. 2 illustrates a typical amplitude and phase response over time with Rayleigh fading (left) and Rician fading with $S_4 = 0.6$ (right). Fade depths greater than 20 dB are highlighted in red. Signal enhancements (increases in received power) occur as well as fades (reductions in received power), and the average, long-term gain is 0 dB.

The Nakagami-*m* distribution is often preferred to the Rician distribution as it has the advantage of providing a better fit to measured amplitude statistics in the natural ionosphere for both weak and strong scattering conditions [2]. However, the Nakagami-*m* distribution alone, unlike the Rayleigh and Rician fading models, has the disadvantage of being an amplitude-only description of fading. The shape parameter, *m*, is related to the scintillation index as $m = 1 / (S_4)^2$ [3].

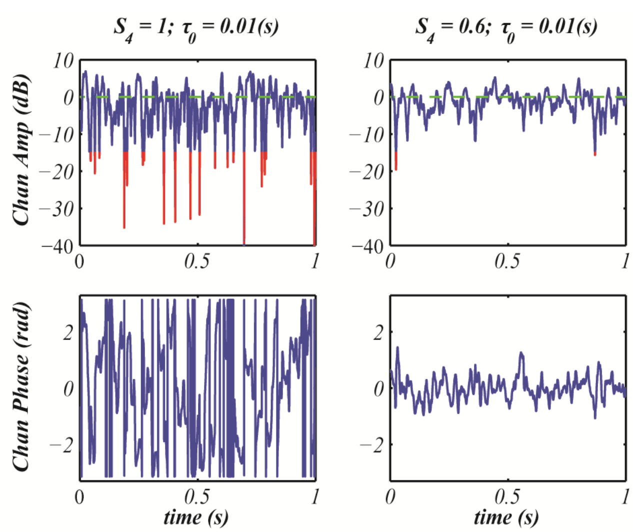

Fig. 2. Rayleigh fading (left) and Rician fading with $S_4 = 0.6$ (right).

B. Frequency Selective and Flat Fading

Ionospheric scintillation may be categorized as frequency selective or flat fading. The frequency selective bandwidth, f_0, is a measure of decorrelation in the channel frequency response. For communication signals, the frequency selective bandwidth, f_0, may be viewed as a maximum channel carrier-bandwidth available for communication relatively free of channel-induced intersymbol interference. While f_0 limits the useable carrier-bandwidth, frequency-agile signals may take advantage of frequency selective conditions by using hop separations that are on average larger than f_0 to achieve an effective gain via frequency diversity. Frequency decorrelation effects may be ignored for communication systems with operational bandwidth, B, when B is significantly less than f_0. Such a channel is referred to as a "flat fading" channel. Otherwise the channel is referred to as "frequency selective". Depending upon the details of the communication link (e.g., modulation, frequency hopping, coding, etc.), flat Rayleigh fading may represent the worst-case fading environment in terms of bit error rate (BER) degradation.

C. Decorrelation Time

The signal decorrelation time, τ_0, provides a measure of the fading rate and is defined as the 1/e magnitude point in the time domain autocorrelation function of the complex received signal [4]. The fading rate is commonly defined as $1/\tau_0$, and slow fading corresponds to large values of τ_0 while fast fading occurs with small τ_0 values. Fig. 3 compares Rayleigh fading with $\tau_0 = 10$ *msec* (left) and $\tau_0 = 100$ *msec* (right).

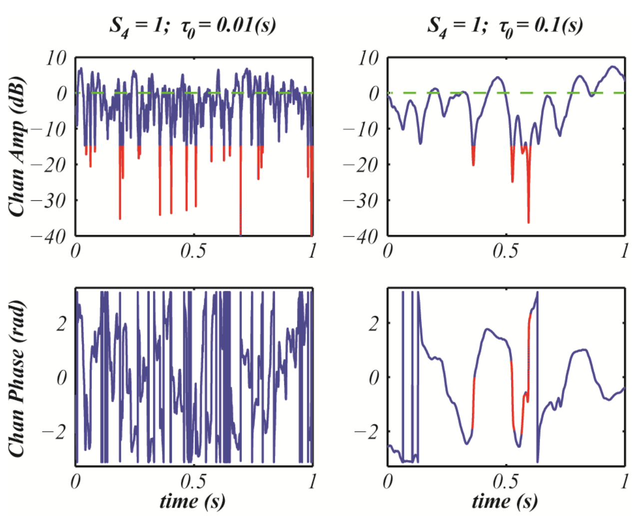

Fig. 3. Decorrelation times of 10 msec (left) and 100 msec (right).

D. Doppler Spread

The time variation of the undesired modulation from scintillation induces spectral spreading on the signal, and the more rapid the scintillation, the greater the spectral spreading. This frequency domain spreading is known as Doppler spread and is characterized by the spectral shape and bandwidth. The shape of the Doppler power spectrum has been described as an f^{-4} power law dependence in slow fading conditions. In fast fading, a Gaussian shaped spectrum is typically observed [4]. Occasionally an f^{-6} power law shape is used as a compromise between the f^{-4} and Gaussian shapes. Fig. 4 illustrates the differences between these spectral shapes with $\tau_0 = 10$ *msec*. From zero to -10 dBc, the shapes are virtually identical but diverge at lower amplitudes and greater offset frequencies.

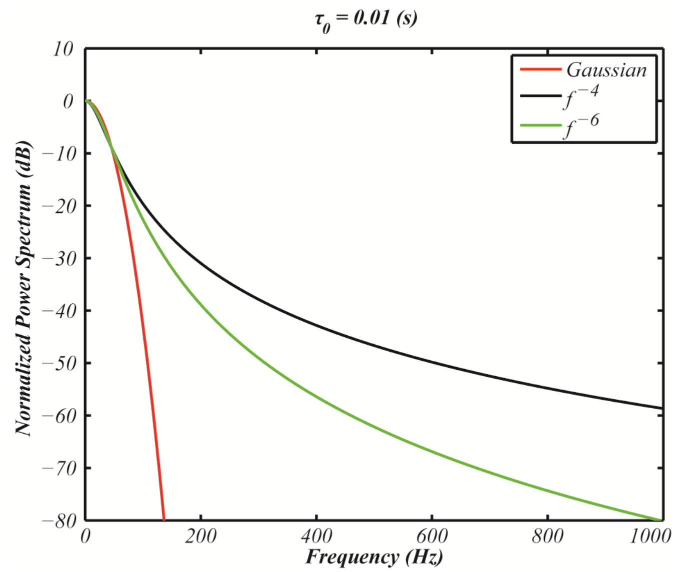

Fig. 4. Comparison of Doppler spectrum shapes with $\tau_0 = 10$ *msec*.

E. Stationary & Non-Stationary Statistics

The statistical channel characteristics (e.g., S_4, τ_0, and f_0) may change over time (Fig. 5) either due to changes in the ionization structure or electron density levels along the propagation line-of-sight. Nonstationary behavior is important to model for adequate testing of dynamic processes (e.g., platform motion, automatic gain control, antenna tracking, etc.). With time-varying statistics, there are often undesirable interactions between Doppler/delay due to platform motion, receiver control loops, and the channel characteristics, particularly when the loop bandwidths are within an order of magnitude of the rate of change of the channel characteristics.

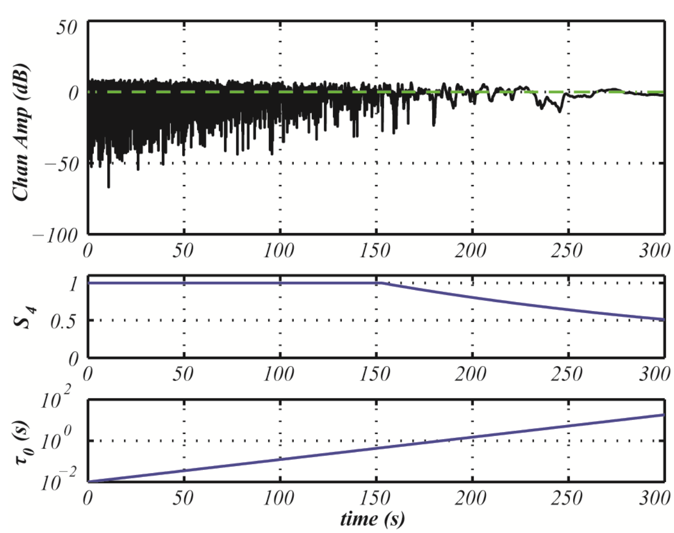

Fig. 5. Nonstationary statistics; S_4 constant then decreasing, τ_0 increasing.

F. In-Phase/Quadrature Demodulation

The receiver must faithfully demodulate the distorted signal to recover the underlying information. Fig. 6 provides a view (in the I/Q plane) of the significant distortion with a Rayleigh-faded signal. In this figure, the unit circle is depicted with a dashed green line, and fade depths greater than 20 dB are highlighted in red. In this example, the transmitted signal is an unmodulated signal with constant amplitude and phase, which would, therefore, be a single point on the unit circle. The channel's Rayleigh fading response imparts both amplitude and phase distortion, which moves the received signal dramatically around the I/Q plane.

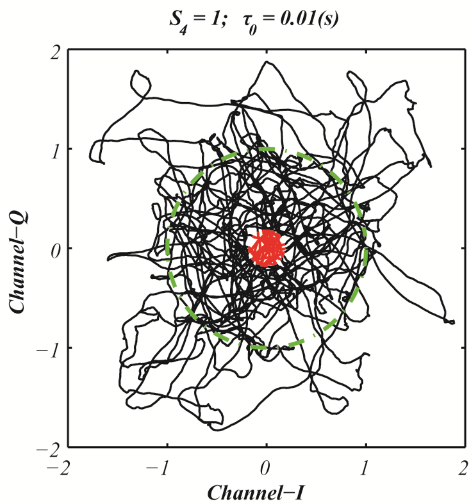

Fig. 6. Rayleigh fading in the I/Q plane with τ_0 = *10 msec*.

For this reason, scintillation-hardened waveforms are designed to mitigate the degradation introduced by fading. Often, noncoherent modulations with interleaving and coding are used to mitigate the effects of scintillation [5]. Noncoherent or differentially coherent modulation reduces vulnerability to rapid phase fluctuations. The use of forward error correction (FEC) coding allows the demodulator to operate at a relatively high average error rate using redundancy to correct errors and achieve acceptable performance. Many FEC techniques assume a random distribution of errors, due solely to additive white Gaussian noise (AWGN), rather than bursts of errors due to fades. Interleaving is a time diversity technique that spreads out bursts of errors into a more uniformly random error pattern such that the FEC process can effectively correct errors [4].

III. HWIL Scintillation Simulators

While analysis and computer simulations are beneficial tools during the design process, hardware-in-the-loop (HWIL) testing is typically the best approach for performance verification, since stand-alone computer simulations often leave potentially vulnerable system components either insufficiently modeled (e.g., by assuming floating-point instead of fixed-point arithmetic) or not modeled at all (e.g., interactions between gain control loops, antenna tracking loops, and frequency tracking mechanisms). For example, antenna tracking loops using lobing or conical scan techniques may degrade when the received signal power scintillates. The degradation varies as the scintillation bandwidth fluctuates greater than and/or less than the antenna tracking bandwidth. When ionospheric-effect testing is included in the initial performance verification plan for a communication system, the verification cost to the program is often significantly reduced.

A. MILSATCOM Atmospheric Scintillation Simulator

The Air Force's Arnold Engineering Development Complex (AEDC) sponsored the development of the Military Satellite Communications (MILSATCOM) Atmospheric Scintillation Simulator (MASS). The MASS is a wideband flat fading HWIL simulator implemented with a modular architecture as shown in Fig. 7. The MASS is the first HWIL scintillation simulator to be used successfully for scintillation testing of both live satellite uplinks and downlinks. Historically, ground terminal transmitter non-linearities have precluded generation of scintillating uplink signals with the proper fading statistics at the output of the ground antenna.

Fig. 7. MILSATCOM Atmospheric Scintillation Simulator (MASS).

The following table summarizes the MASS capabilities.

TABLE I. MASS Scintillation Capabilities

Parameter	Capability
Channels	Two (with independent scintillation)
Interfaces	L-band through Ku-band
Bandwidth	Up to 2 GHz
Signal & noise levels	Compatible with terminal under test
Distributions	Rayleigh, Rician, Nakagami-*m*
Amplitude scintillation	-52 dB to +8 dB
Phase scintillation	Yes, phase continuous
τ_0	100 µsec to 30 sec
S_4	0.0 to 1.0
Doppler spectrum	Gaussian, f^{-4} power law, f^{-6} power law
Modes	Benign, parametric, scripted
Attenuation	0 to 52 dB (static or slowly varying)
TEC Doppler	-1.0 to 1.0 MHz
Spurious	45 dBc
Uplink pre-distortion	Linearizes AM-AM & AM-PM distortion[1]
Downlink noise	Broadband AWGN with user-defined amplitude

[1] Amplitude Modulation (AM), Phase Modulation (PM); AM-AM and AM-PM are the undesirable amplitude and phase modulation distortion in the terminal's transmitter caused by varying input power due to fading at the IF.

The modular nature of the MASS facilitates customization of the interfaces between the terminal and the MASS. Specifically, the top module shown in Fig. 7 is denoted the MASS Interface Module (MIM), which contains the interface hardware specific to the terminal of interest. During integration of the MASS with the terminal under test, the MASS is commanded to Benign Mode and BER performance of the terminal is verified such that no degradation is introduced with the inclusion of the MASS in the signal paths (that is, when fading is not present).

B. *Parametric and Scripted Operation*

The MASS operator may select between parametric testing (scintillation with stationary statistics) and scripted testing (scintillation with non-stationary statistics). The script capability allows specific scenarios with time-varying values of S_4, τ_0, total electron content (TEC) Doppler, and attenuation.

A user-controllable random seed value provides the ability to re-create identical scintillation profiles in either the parametric or scripted modes. This capability is imperative for repeatable testing. Additionally, instrumentation and recording features of the MASS aid post-test analysis.

C. *Integration at Intermediate Frequencies*

The MASS has been integrated within the intermediate frequency (IF) paths of Satellite Communications (SATCOM) terminals to conduct tests with satellite simulators and on-orbit satellites, as depicted in Fig. 8. This test configuration utilizes all equipment in the link providing a truly comprehensive verification of link performance in scintillation.

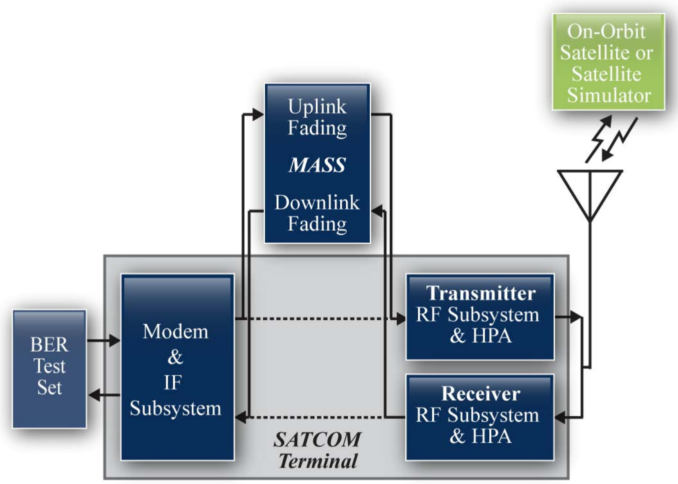

Fig. 8. MASS integrated with terminal at IF interfaces.

Using any HWIL scintillation simulator within the transmit and receive IF paths requires careful consideration to ensure the scintillation characteristics are properly imparted on the communication link.

1) Uplink Considerations: Non-linearities in the terminal's high power amplifier (HPA) must be addressed to ensure that the transmitted waveform is properly scintillated when radiating from the terminal's antenna. These non-linearities include AM to AM distortion as well as AM to PM distortion. Additionally, non-linearities over frequency must be considered, particularly for frequency-hopped waveforms. The MASS includes pre-distortion capabilities to ensure the transmitted uplink signal has the proper scintillation statistics for transmission to the satellite. Non-linearities in the terminal's transmit path require careful measurement and characterization such that the pre-distortion technique is effective over time, temperature, frequency, and amplitude.

Often the terminal HPAs operate in a saturated mode with fixed output power. In such instances, the drive power to the HPA must be reduced such that the HPA is operating in a linear (or pseudo-linear) region of the AM-AM power curve. A necessary consequence, however, is that the terminal's nominal transmit power is reduced in comparison with normal operation. Further, since scintillation imparts signal enhancements as well as fades (see section. II.A), additional headroom must be allocated to allow enhancements, if required. Accordingly, the uplink may need to be operated with a lower effective isotropic radiated power (EIRP) and proper consideration given to the link budget and test data.

2) Downlink Considerations: The downlink BER performance is partially dependent upon the received G/T of the terminal[2]. The low noise amplifier (LNA) in the terminal's receive path typically dominates the receiver noise floor seen by the demodulator. However, since the downlink fading is imparted after the LNA, the LNA noise and the signal are both faded, as compared with a realistic scenario where the signal is faded but the LNA noise is not. The MASS includes a noise source to add noise back into the receive path to compensate for the faded LNA noise, thus emulating the realistic noise environment that exists in the presence of scintillation.

D. *Comparison with Previous HWIL Scintillation Simulators*

The MASS is the fourth-generation HWIL scintillation simulator and provides significant capabilities beyond previous simulators. The Advanced Channel Simulator (ACS) program included the development of two HWIL scintillation simulators, (1) the ACS-FF for flat fading and (2) the ACS-FS for frequency selective fading. The second-generation simulator was the frequency selective Wideband Channel Simulator (WCS), which increased the instantaneous bandwidth to 100 MHz. Mission Research Corporation (MRC) developed the ACS and WCS in the mid- and late 1990s, respectively. The Configurable Link Test Set (CoLTS) was the third-generation simulator developed in the early 2000s by Welkin Sciences, LLC (the HWIL simulator successor of MRC). The CoLTS-LJ, currently in development, continues the evolution with the addition of L-band interfaces, jamming emulation, and channel-configuration flexibility. The following table summarizes the evolution of capabilities in these five generations of scintillation simulators.

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[2] G/T is a figure of merit for terminal receive performance with G being the receive antenna gain and T the receive noise temperature.

TABLE II. COMPARISON OF PREVIOUS SCINTILLATION SIMLULATORS

Parameter	ACS - FF	ACS - FS	WCS	CoLTS	MASS	CoLTS-LJ
Fading	Flat	Frequency selective	Frequency selective	Frequency selective	Flat	Frequency selective
Channels	1	1	2	4	2	1, 2, or 4+
Interfaces	700 MHz, X-band	700 MHz	700 MHz	700 MHz	Application specific	L-band
Bandwidth	60 MHz	40 MHz	100 MHz	125 MHz	2 GHz	125 MHz +
TEC Delay & Doppler	-	Delay, Doppler	Delay, Doppler	Delay, Doppler	Doppler	Delay, Doppler
GEO Delay	No	No	Yes	Yes	No	Optional
Distributions	Rayleigh, Rician	Rayleigh, Rician	Rayleigh, Rician	Rayleigh, Rician	Rayleigh, Rician, Nakagami-*m*	Rayleigh, Rician, Nakagami-*m*
Modes	Parametric	Scripted	Scripted	Scripted	Parametric, Scripted	Parametric, Scripted
DTRA Certified	Yes	Yes	Yes	Yes	Yes	-

IV. TEST RESULTS

Extensive testing has been performed on the MASS unit to ensure the scintillation statistics and other characteristics accurately emulate real-world scintillation. The test configuration for these measurements is shown in Fig. 9. A continuous wave (CW) signal is used as the input, and a spectrum analyzer is used to periodically record the output power from the MASS after scintillation is applied. The recorded measurements are analyzed and compared with theoretical curves for the scintillation parameters used.

Due to the constraints in minimum resolution bandwidth and sweep times, the verification tests are partitioned into slow and fast fading categories. For slow fading tests, the faded amplitude is measured, recorded, and analyzed. With fast fading tests, the spectral width of the faded signal is measured.

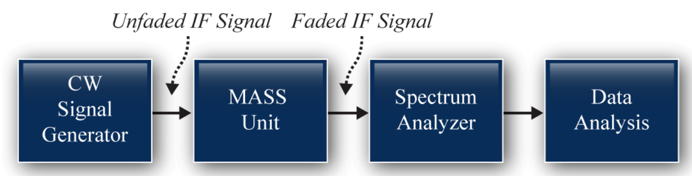

Fig. 9. Test Configuration for verifying MASS scintillation performance.

A. Slow Fading Tests

Tests often use relatively slow fading (large τ_0) to optimize measurement accuracy for several statistical verifications including the cumulative distribution function (CDF) of fade amplitudes, fade durations, and the time separation of fades.

A plot of the CDF (Fig. 10) illustrates the probability of a fade of certain depths (or enhancements) with Rayleigh fading. The theoretical CDF for Rayleigh fading is the black line, and the measured performance of the MASS is the red line. The theoretical curve represents an infinitely long and perfect Rayleigh fading realization with no implementation loss or measurement errors. Given the statistical nature of the fading and the necessity for finite length tests, the measured data will deviate slightly from theory, and each finite length fading realization (with a different random seed) will exhibit slightly different statistics. To enable quantitative comparisons between measured data and the theoretical performance, 95 percent confidence intervals (CI) are used as upper and lower bounds around the theoretical curve within which the measured fade amplitudes are expected to lie. Stated another way, it is expected that 95 percent of all measurements will fall within these 95 percent confidence interval bounds.

For a given fading realization sequence, there are a larger quantity of shallow fades than deep fades. Hence, in the CDF plot, there are numerous measurements in the upper portion of the curve and relatively few near the bottom. Consequently, the measured curve (red line) is smooth for shallow fades, becoming noisier as the fades are deeper. Also, the confidence intervals become wider for deeper fade amplitudes, since there are fewer fades at these lower levels.

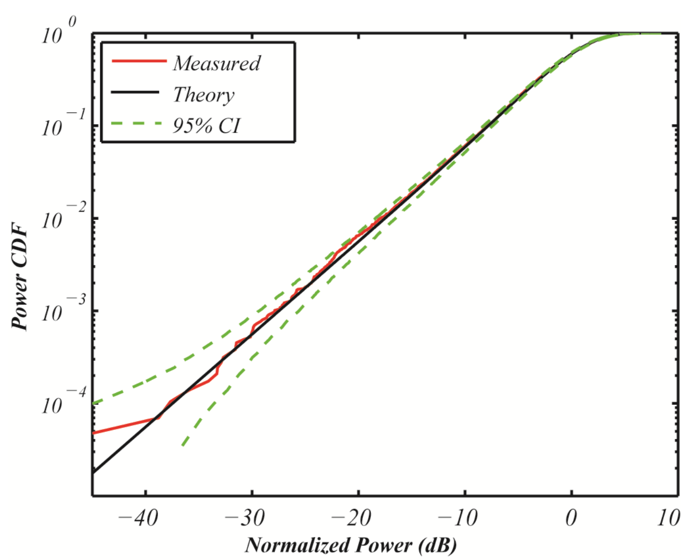

Fig. 10. Cumulative Distribution Function (CDF) for Rayleigh fading.

Another statistical verification conducted with relatively slow fading is the measurement of fade durations (i.e., the time duration of a fade greater than a certain depth). When the fade depth is near the link margin, bit errors will increase for fades equal to or greater than these depths. Fig. 11 shows the theoretical time durations for fades of specific depths (in Rayleigh fading) along with the measured performance data from the MASS Unit. In addition to fade duration, the time separation between fades is often used to characterize the second order statistical properties of the fading.

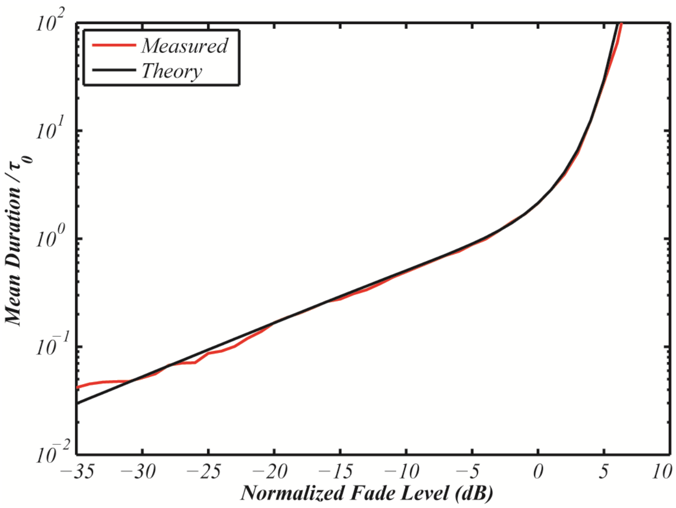

Fig. 11. Fade duration vs. fade depth for Rayleigh fading.

B. Fast Fading Tests

The time varying amplitude and phase modulation induced by scintillation causes spectral spreading of the transmitted signal. An unmodulated CW signal ideally occupies a single frequency and has no spectral spread (width). When such a CW signal is passed through a scintillating channel, the output signal exhibits spectral spreading due to the amplitude and phase scintillation. Fig. 12 depicts the measured and theoretical spectral shapes of a CW signal affected by scintillation.

In Fig. 12, a Gaussian spectrum shape was utilized in a flat Rayleigh fading channel. Both the measured and theoretical shapes are shown. The agreement between theory and the measured data is very close. A decorrelation time of 0.1 msec was used for the spectrum shown in Fig. 12. The f^{-4} and f^{-6} power law shapes exhibit similar agreement between measured spectral shapes and theory.

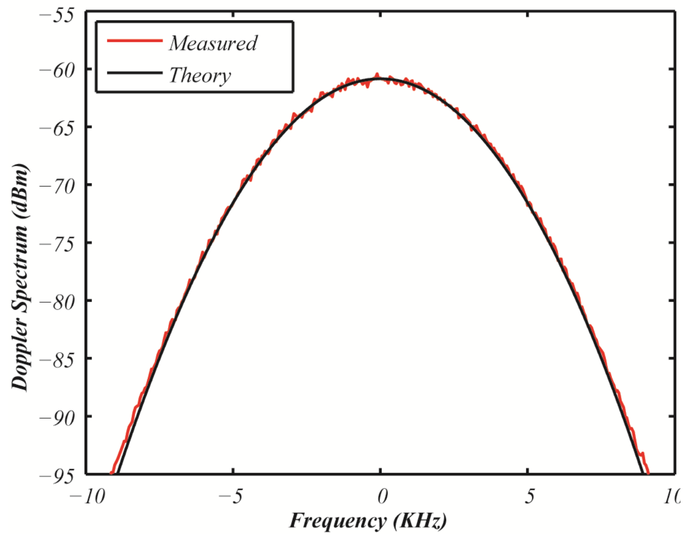

Fig. 12. Measured and theoretical Gaussian Doppler spectrum shapes.

C. Large-Scale Attenuation

In addition to the small-scale multipath fading induced by ionospheric irregularities, slower large-scale attenuation may be present as depicted in the example of Fig. 13. The MASS provides the capability to impart both small-scale and large-scale fading on different and independent time scales. This capability enables both large-scale attenuation, such as rain fading and shadowing, as well as small-scale rapid fading due to multipath.

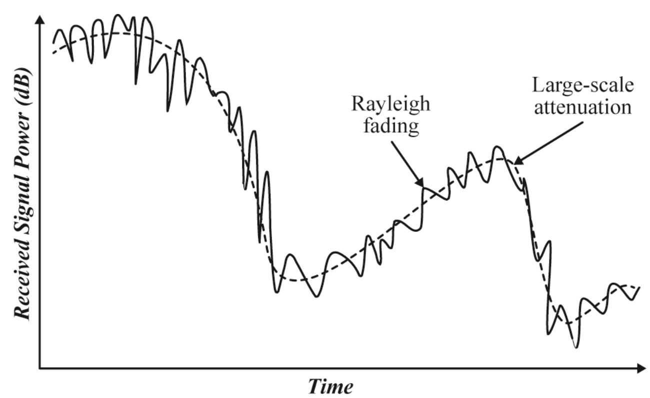

Fig. 13. Small-scale Rayleigh fading and large-scale, time varying attenuation.

D. TEC Doppler

The total electron content (TEC) is a function of the electron density in the ionosphere and the RF propagation path through the ionosphere. Time variation of TEC and movement of the electrons induce a Doppler frequency offset on RF signals propagating through it [6], [7]. This is typically a slowly varying Doppler shift and is not to be confused with the Doppler spread due to scintillation (see section II.D).

E. Independent Validation

The Defense Threat Reduction Agency (DTRA) has certified the MASS Unit to ensure compliance with government-certified nuclear scintillation models. DTRA and its predecessor agency, the Defense Nuclear Agency (DNA), developed sophisticated physics-based models of nuclear scintillation effects [8]. DTRA certification provides Department of Defense (DoD) MASS customers with the confidence that scintillation performance is consistent with validated models and verified by an independent DoD agency.

V. Applications

HWIL scintillation simulators such as the MASS may be used to accurately emulate ionospheric scintillation effects due to natural and/or nuclear disturbances. Current military satellite communications include the Wideband Global SATCOM (WGS) constellation, the Mobile User Objective System (MUOS), and the Advanced Extremely High Frequency (AEHF) satellites. There are also the older generation of military communication satellites such as the Defense Satellite Communication System (DSCS), the predecessor to WGS and the Milstar constellation, which AEHF will succeed. Future MILSATCOM systems include the Enhanced Polar System (EPS). Additionally, non-communication satellites, such as the Global Positioning System (GPS) and space-based radar, may be susceptible to natural or nuclear ionospheric scintillation.

Commercial satellite systems such as DirectTV®, DigitalGlobe™, SiriusXM™, Globalstar™, Viasat®, etc., all utilize RF links that encounter natural ionospheric RF propagation effects.

Rayleigh and Rician fading models are often used to describe the multipath characteristics of mobile communication systems (military or commercial), including satellite communications on-the-move (SOTM) [9], [10]. Further, models for multipath fading in terrestrial mobile communications typically employ Rayleigh and Rician fading statistics [11].

The test flexibility provided by the MASS (various statistical distributions, scintillation parameters, stationary/non-stationary statistics, large and small scale fading) enable its application to a wide variety of HWIL scintillation test purposes both military and commercial for natural or nuclear scintillation.

VI. Summary

Ionospheric scintillation due to natural or nuclear disturbances introduces fading distortion to RF signals propagating through it. MILSATCOM and commercial satellite systems are often designed to operate effectively in the presence of such fading. To determine and quantify the effects of this fading, it is beneficial to perform hardware-in-the-loop testing and verification of transionospheric RF signals

The MASS Unit is a HWIL scintillation simulator used for accurate emulation of flat fading. Other scintillation simulators, such as the Configurable Link Simulator (CoLTS), provide HWIL test capability for frequency selective fading.

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