RF Channel Simulators Assure Communication System Success through Hardware-in-the-Loop Testing

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The Radio Frequency (RF) Channel Simulator is rapidly emerging as a standard test and measurement instrument for RF communication systems, because it is capable of easily generating RF signals that precisely duplicate those between transmitters and receivers that when deployed, are in motion with respect to one another. The hardware-in-the-loop Channel Simulator adds dynamic and fully physics-compliant RF effects, such as carrier and signal Doppler shift, delay, attenuation, noise, and interference to tested signals. This provides realism to RF test activities without requiring actual relative motion or separation distance, thereby supporting flight and ground system tests without requiring actual flights.

Nominal and worst-case RF conditions and flight profiles can be easily and inexpensively constructed in the laboratory or with on-orbit assets, for inter-satellite link testing, satellite system tests, ground system verification, and similar applications. Using a Channel Simulator enhances system quality and decreases overall costs through broader and deeper test coverage, faster test development and execution, and test equipment cost savings. As well, since the RF Channel Simulator produces signals that are indistinguishable from those that will occur in nature, system over-design or under-design due to unrealistic test signals is minimized.

With advanced visualization and a true physics-obedient implementation, RF Channel Simulators increase efficiency by letting the user focus on the task at hand, rather than the intricacies of instrument control and operation.

I. Introduction

COMMUNICATION systems used in space operations, whether for command and control, data exchange, or human communications, involve transmitter and receiver systems in motion with respect to one another, and are often separated by great distances. Absolutely mission-critical, yet not easily modified or serviced once deployed, these systems must be thoroughly designed and rigorously tested against a vast set of nominal and worst-case mission requirements. Central to testing is precision emulation of RF propagation effects on the communication signals. These RF effects include carrier and signal Doppler shift, range delay, range attenuation, noise, and interference, both accidental and intentional. These signal effects vary with distance, velocity, frequency, medium, location, and proximity to other RF sources.

In-depth device and full-loop system tests must account for each of these RF propagation effects, singly and in combination, for full assurance. Tests and designs failing to properly consider these key signal effects do not represent real-world conditions and result in inferior end systems. Device and system design costs may be higher than necessary if tests impose conditions and parameters that cannot occur in nature. In the limit, insufficient verification can easily result in partial or complete mission failure or communication system-imposed mission restrictions.

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This paper discusses typical test architectures and several critical RF signal impairments, presenting RF Channel Simulators as a powerful, necessary, and economical instrument that positively influence RF communication system design and quality.

II. Applications

Channel Simulators add RF realism to practically any RF link design and test situation where receivers and transmitters are moving with respect to each other. With respect to space operations, Channel Simulators are used to emulate links between fixed or moving terrestrial assets and space vehicles (satellites, manned vehicles, rockets, etc.), inter-linkages between space vehicles, and links between space platforms and atmospheric assets such as UAVs, missiles, aircraft, etc.).

In each case, the RF link is subject to the laws of physics that imply carrier and signal Doppler shift, delay, path loss and noise, as well as intentional and accidental interference. RF link performance also depends heavily on factors such as flight profiles, antenna patterns, modulation types, data rates, transmitter power levels, and receiver Signal to Noise Ratio (SNR) requirements.

Antenna placement is a strong factor whenever antennas cannot be aligned permanently on the corresponding transmitter or receiver antenna. This occurs for example, with spinning or tumbling satellites, or when aircraft turn or bank such that their wings or fuselage come between receiver and transmitter antennas. In these cases, periodic signal attenuation or complete interruption must be accommodated.

When atmospheric or ground assets are part of the link, additional considerations include terrain, as well as atmospheric and weather effects on signals.

Fast amplitude and phase scintillation may characterize signals passing through metallic exhaust plumes, or through an electrically/magnetically disturbed medium. Multipath and statistical models for Rician and Rayleigh fading, as well as user-defined fading, may also apply.

Channel Simulators enable hardware-in-the-loop testing against each of these factors, and more, either singly or in combination. They do so in physics-compliant, phase-continuous fashion, such that their output signals precisely match reality.

III. Channel Simulator Basics

At a high level, Channel Simulators typically contain Analog to Digital (ADC), Digital Signal Processing (DSP), memory, and Digital to Analog (DAC) components, along with a processor and an external control interface at a minimum. These components are usually arranged as shown in Fig. 1.

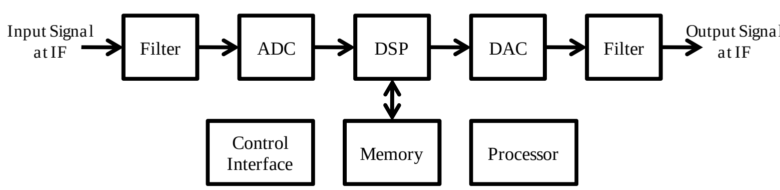

Figure 1. Basic Channel Simulator Block Diagram

The modern Channel Simulator digitizes an Intermediate Frequency (IF) input signal, adds carrier and signal Doppler shift, delay, attenuation and possibly noise through DSP techniques, then converts the modified signal back to IF. Precision Channel Simulators do this in a physics-compliant fashion with high resolution output, in order that Channel Simulator output signals are virtually indistinguishable from real-world signals.

To the basic block diagram of Fig. 1, RF down-converters and up-converters are often added as shown in Fig. 2. These devices convert signals between their native frequencies and the IF used within the Channel Simulator. Frequency up- and down-converters are useful when tests need to be run at RF, and when the IF of the devices to be tested is not accessible, or when it differs from the IF of the Channel Simulator.

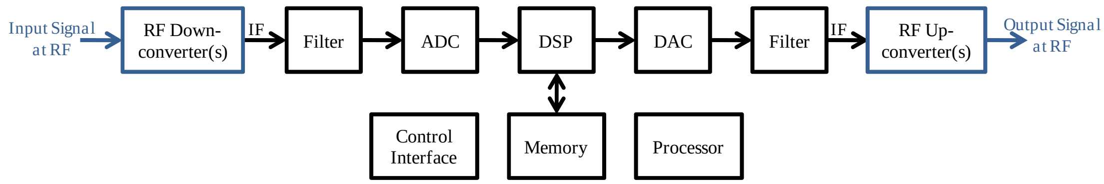

Figure 2. Basic Channel Simulator Block Diagram with Frequency Converters

As shown in Fig. 3, Channel Simulators can also include test and/or interference signal generation capability. Such facilities generally offer multiple channels with independent selection of modulation types, data rates, frequency offsets, power levels and pseudo-random number (PRN) sequence specification. Advanced systems allow in-phase and quadrature phase (IQ) signal inputs, clock and data inputs, and can generate modulated signals from data stored in files. Signal sources can be connected pre-DSP, or post-DSP, so they can emulate signals transmitted on an uplink or downlink, or signals received from elsewhere by the uplink or downlink receiver.

Signal analysis capabilities in the frequency and/or time domains are included in some Channel Simulators as well. This provides traditional spectrum analyzer and oscilloscope capabilities, and in some cases, can provide advanced modulation and interference analysis, as well as advanced alarm generation based on amplitude and frequency masks, as well as threshold ranges of Bit Error Rate (BER), C/N_o, E_b/N_o and others.

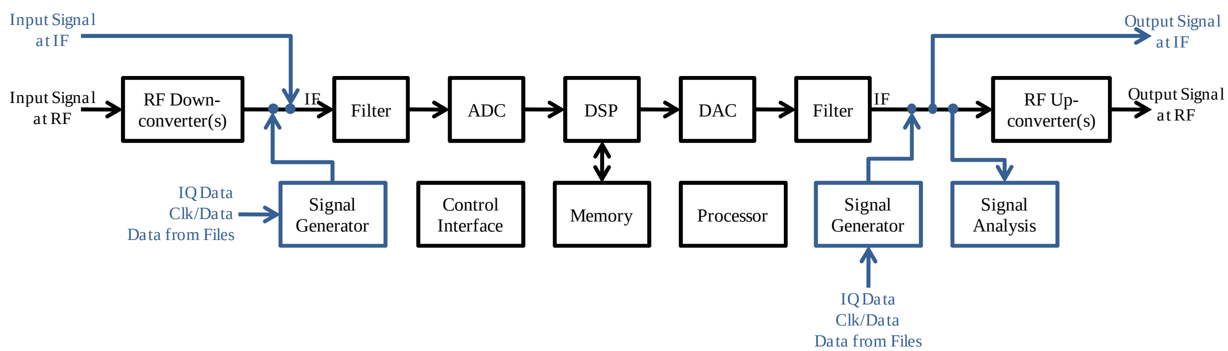

Figure 3. Advanced Channel Simulator Block Diagram

Channel Simulators offer a wide variety of control options, some including the capability to tightly synchronize with external equipment and sensors in real time. Graphical User Interfaces (GUI) and profile file download capabilities are provided, along with ASCII and binary commanding through Ethernet connections for integration with user programs. In some cases, Channel Simulators are equipped with drivers or plug-ins to add hardware-in-the-loop capability to industry standard simulation, visualization and analysis software packages.

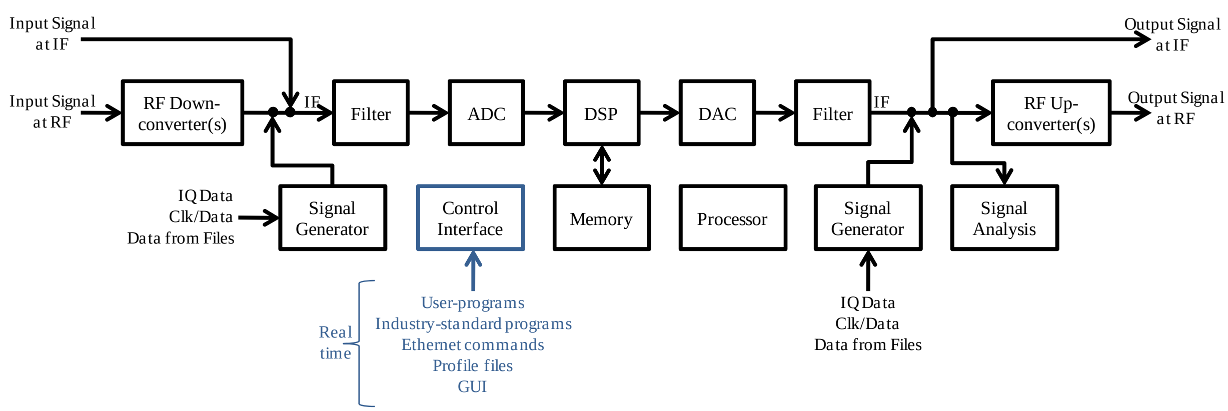

Figure 4. Advanced Channel Simulator Block Diagram

Finally, Channel Simulators are highly configurable for applicability to a variety of test situations over time. Additional channels can be configured, and RF converters can be changed out as applicable uplink and downlink frequency bands vary. Signal generators and signal analyzers can be added, reconfigured, and removed as needed. External signals can be combined into Channel Simulators or split out from them. Amplifiers and antennas can be added to inputs and outputs, for Channel Simulator operation at external test range distances, satellite distances, and even lunar distances.

The major functions of the Channel Simulator will be discussed later in this paper.

IV. Test System Basics

In initial Research and Development (R&D) efforts, transmitter component/system and receiver component/system testing typically involve simple bench setups such as those shown in Figs. 5 and 6, though Test and Measurement (T&M) instrumentation may vary considerably from these examples according to test requirements.

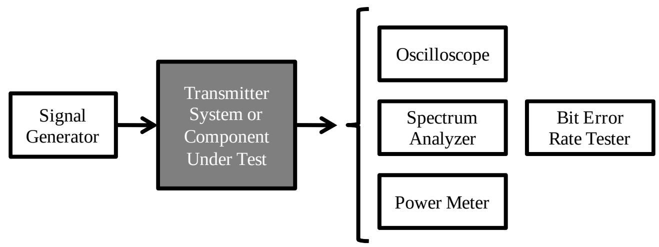

Figure 5. Basic Test Setup for Transmitter Component/System Testing

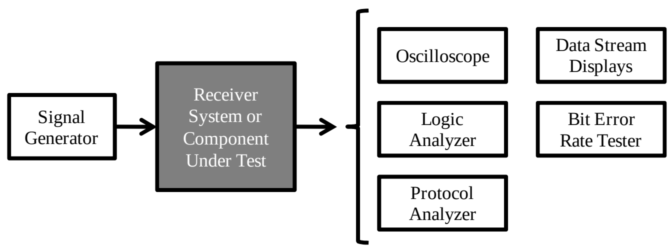

Figure 6. Basic Test Setup for Receiver Component/System Testing

To these basic setups, the RF Channel Simulator can be added as shown in Figs. 7 and 8 in order to provide realistic signals into the test process.

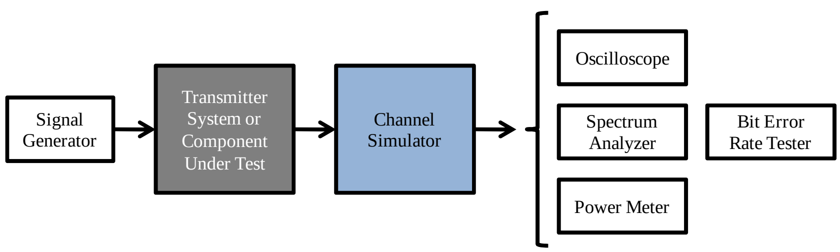

Figure 7. Basic Transmitter Component/System Test Setup Including a Channel Simulator

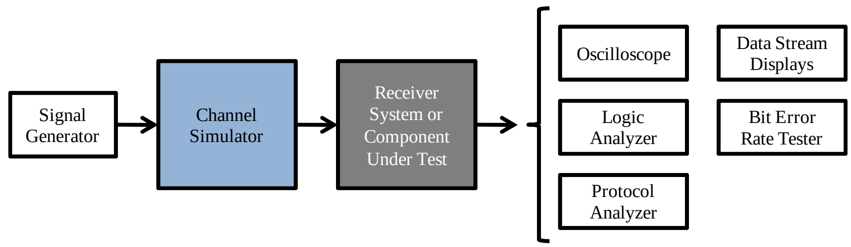

Figure 8. Basic Receiver Component/System Test Setup Including a Channel Simulator

In a Receiver System/Component test, for example, Channel Simulators can assist in answering questions such as these under nominal and worst-case conditions:

1) Can the receiver accommodate the full carrier Doppler shift of the input signal?
2) Can the receiver remain locked across the full carrier Doppler shift <u>rate</u>?
3) Can the receiver's data synchronization mechanisms remain locked as the incoming data rate shifts due to signal Doppler shift?
4) Can the receiver detect signals at tested SNR levels with its Automatic Gain Control (AGC) remaining locked through SNR changes?
5) How well does the receiver perform under RF noise situations and in accidental and intentional interference scenarios?

As systems/components under test mature, test suites evolve as shown in Figs. 9 and 10, with the Channel Simulator inserted at any convenient point in the RF/IF path between the transmitter and the receiver.

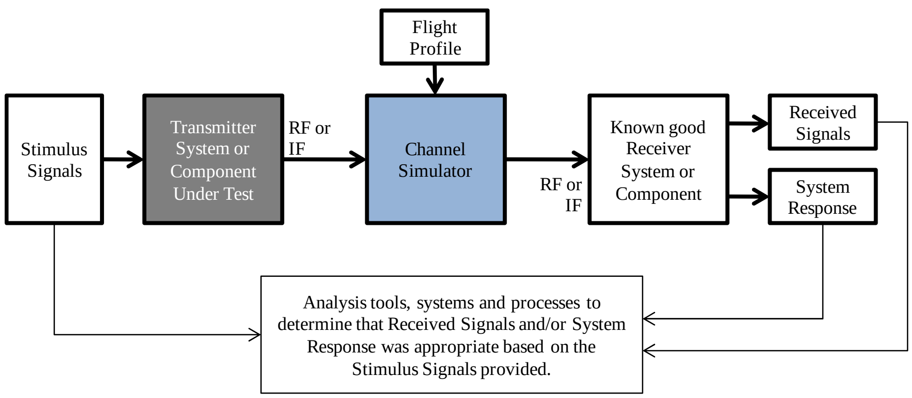

Figure 9. Expanded Test Setup for Transmitter Component/System Testing

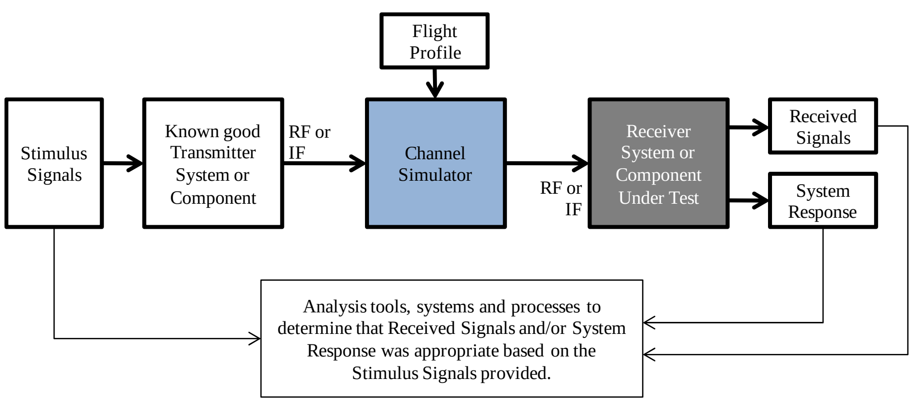

Figure 10. Expanded Test Setup for Receiver Component/System Testing

Although not shown in these diagrams for simplicity, such setups normally include computer control of the devices under test, the known-good components, stimulus and analysis instruments/systems, and signal switching/routing equipment. T&M equipment is usually under computer control, with mission-specific (e.g., Analytical Graphics, Inc.'s STK), general-purpose (e.g., VEE from Agilent Technologies, or LabVIEW from National Instruments), or user-written software functioning as the test executive.

At some point, it may be necessary to test with both a transmitter and a receiver under development. This can be accommodated in a setup as in Fig. 11.

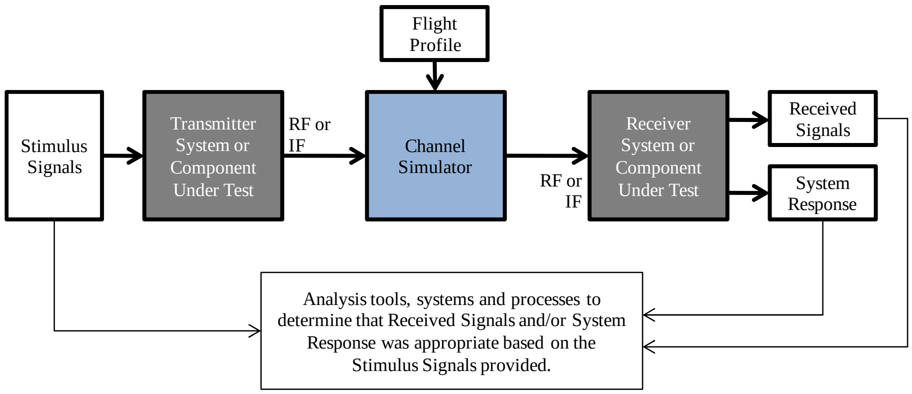

Figure 11. Expanded Test Setup for Full System Testing

An example application of such a test system is shown in Fig. 12. This system is used for testing satellite modems for use with Low Earth Orbit (LEO), Geostationary (GEO), or other satellites. Here, the Channel Simulator applies all the dynamic Doppler shift, delay, attenuation, noise, and interference to the uplinks and downlinks between the two modems. The computer assets on either end of the network are used to verify Quality of Service (QOS) under nominal worst-case situations.

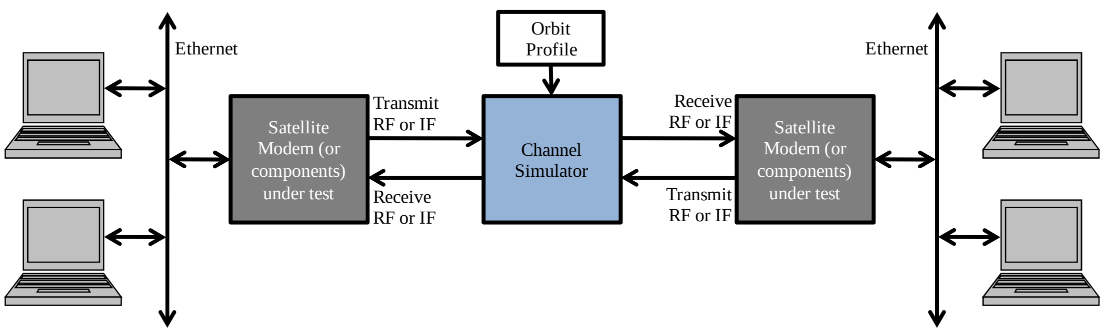

Figure 12. Typical Test setup for Satellite IP Modem Testing

In addition to full modem testing, this setup, or a simplified version of it, is also useful for testing of hardware or firmware modem subcomponents such as modulators, demodulators, encoders, decoders, Forward Error Correction (FEC) behavior, Adaptive Coding and Modulation (ACM) operation, analog system operation, etc. Automated regression tests of these components and systems are also facilitated by the Channel Simulator.

The preceding test setups are mainly small laboratory configurations. Other possibilities exist as well, once amplifiers and antennas are added. For example, to verify that a telemetry receiving station on a large outdoor test range is operating properly, a configuration as in Fig. 13 can be used. This concept can be extended to full test range verification including site-to-site linkage, Range Control Center (RCC), and Best Source Selection (BSS) testing.

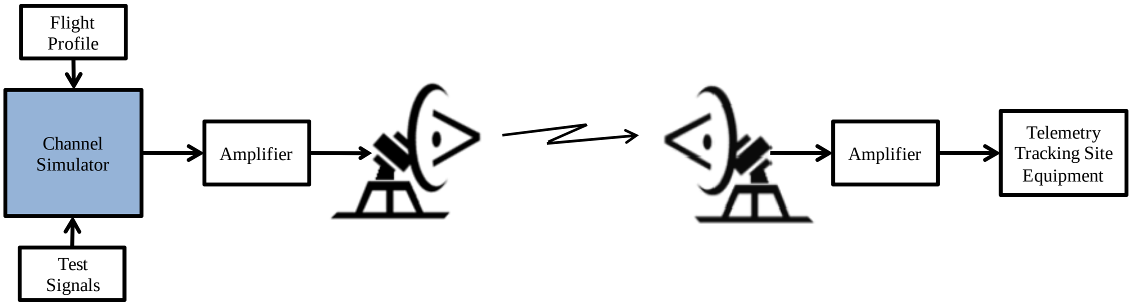

Figure 13. Use of Channel Simulators for Test Range Verification

To verify an inter-satellite link between a to-be-launched LEO satellite and an already-on-orbit GEO satellite, the test configuration of Fig. 14 could apply.

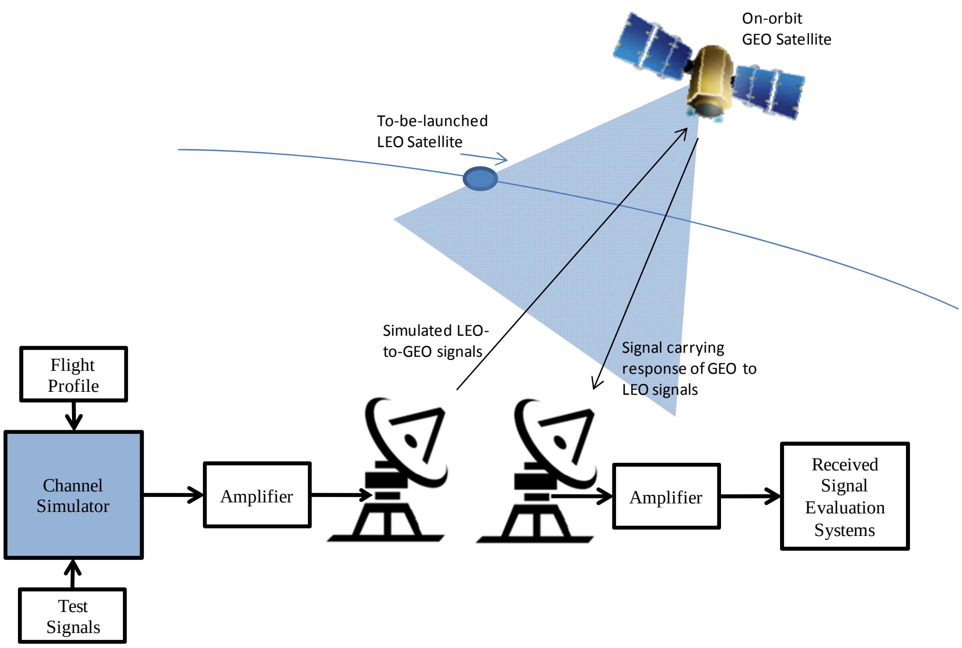

Figure 14. Use of Channel Simulators with On-Orbit Assets

V. Test Systems Must Represent Reality

A key aspect of any test system is the ability of that system to represent reality both from a stimulus perspective and from a measurement viewpoint. Test systems that do not precisely or completely replicate natural RF link propagation dynamics and related phenomena, nominally and at worst-case, result in inadequate and/or unsuitable test.

Systems that do not represent reality can result in designs that problematically perform differently in the test environment versus the real world. Unrealistic test systems can also result in over-design to compensate for testing with signal phenomena that do not occur in nature.

Phase-continuous carrier and signal Doppler shift, range delay and range attenuation in input signals is an absolute requirement when generating RF test signals that precisely mirror nature. Phase-continuity is key, since inadvertent signal phase changes as Doppler shift, delay and/or attenuation are adjusted, can be seen by receivers as erroneous test-system-induced data changes, particularly when the link is using phase-shift keying modulation methods such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 8 Phase Shift Keying (8PSK), etc.

VI. Channel Simulator Characteristics

The Channel Simulator represents reality and produces effects on signals that precisely mirror those that the signal would undergo if it were actually passing through the communications channel. For wireless communications, the channel is actually space and atmosphere, and the needed channel simulation effects include carrier and signal Doppler shift, Doppler shift rate, range delay, range attenuation, and AWGN.

Accurate simulation of these effects is absolutely critical to verification and analysis of space-borne, airborne, and fixed or mobile terrestrial receiver and transmitter systems. In the laboratory, an accurate Channel Simulator can fully replace flying or ground-based receive or transmit systems, and can simulate difficult-to-achieve conditions (e.g., weather extremes, satellite positions/orbits, component degradation/failures, etc.) or dangerous-to-produce scenarios (e.g., atmospheric disturbance, battlefield scenarios, etc.).

Channel Simulators can play a vital role in modeling, predicting, and studying system performance related to satellites not yet launched, or to study the effects of moving satellites to new stations or orbits.

These powerful instruments are also fully capable of precise channel simulation for aircraft, UAVs, Satellite Communications (SATCOM)-on-the-move, and missile applications.

As with all T&M instruments, Channel Simulators are characterized by several key characteristics, capabilities and specifications that make them suitable for their tasks. These include Doppler shift-related capabilities, range delay simulation, range attenuation modeling (including fading), as well as noise and interference generation functions.

Useful channel simulation requires simultaneous and dynamic application of Doppler, range delay, attenuation, as well as noise and interference because signals in nature are affected not by a single effect, but by all effects in combination.

A. Example Scenario

For the remainder of this description of Channel Simulator characteristics, an inter-satellite link is considered between two LEO satellites as shown in Fig. 15. These two satellites are communicating at 14.5 GHz with a 16 Mbps BPSK signal. The transmitter power is 10 mw, and 1-meter dish antennas are pointed at the opposite satellite.

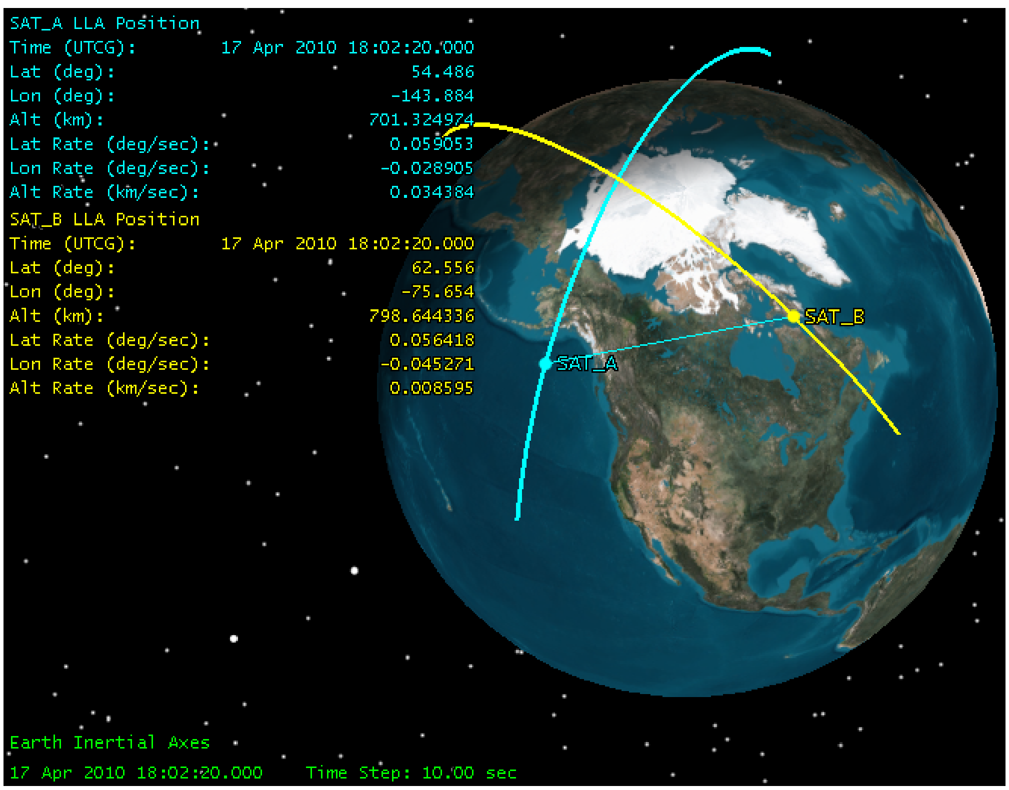

Figure 15. Inter-Satellite Link Simulation Scenario

B. Carrier Doppler Shift

In applications where receivers and transmitters are in motion with respect to one another, carrier Doppler shift is a significant factor in system design and validation.

Receivers must remain locked to a received signal, maintaining proper Bit Error Rate (BER) performance, even as the received signal's frequency shifts over time due to the relative velocity between the transmitter and receiver.

Eq. (1) describes Doppler shift based on the actually transmitted frequency and the relative velocity between the transmitter and the receiver:

$$F_s = F_a(V/c) \tag{1}$$

Where;

F_s Doppler shift (Hz)
F_a Transmitted frequency (Hz)
V Relative velocity between transmitter and receiver (km/s)
c Speed of light (299,792.458 km/s)

Using Eq. (1), Fig. 8 represents the carrier Doppler shift for the example scenario shown in Fig. 15. Channel Simulators apply this frequency shift smoothly, and phase continuously, even during the dramatic Doppler rate change near the center of the plot.

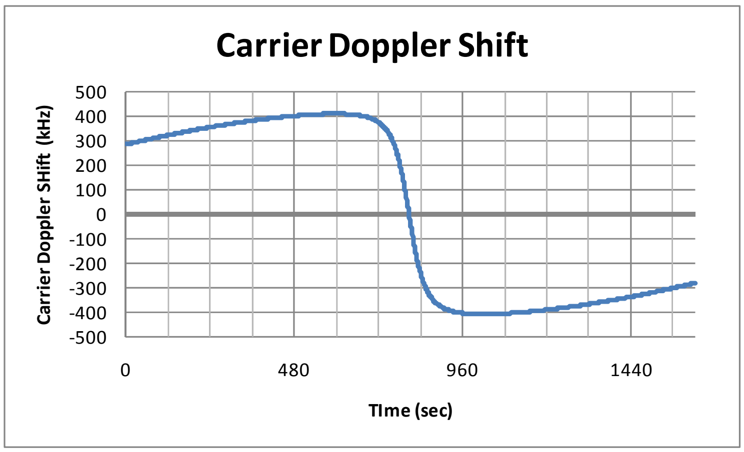

Figure 16. Carrier Doppler Shift for the Example Scenario of Figure 15

As additional examples, Fig. 17 is for a typical LEO satellite pass over an Earth station with a maximum 80° elevation and a minimum range of 715 km. Figure 18 is the same LEO satellite[2] viewed from a different Earth station where the maximum elevation is only 17° with a minimum range of 1700 km. Channel Simulators emulate these scenarios, and far more challenging ones, with strict attention to the laws of physics.

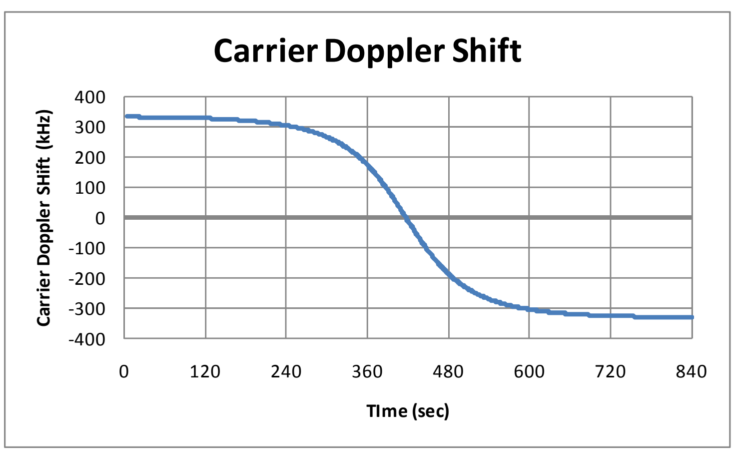

Figure 17. LEO satellite with 80° Maximum Elevation and 715 km Minimum Range

[2] In Fig. 18, the Acquisition of Signal (AOS) to Loss of Signal (LOS) time is shorter than in Fig. 17 even though the same satellite is being plotted. This is due to the difference in maximum elevation between the two plots, and the correspondingly shorter horizon-to-horizon time of the example in Fig. 18.

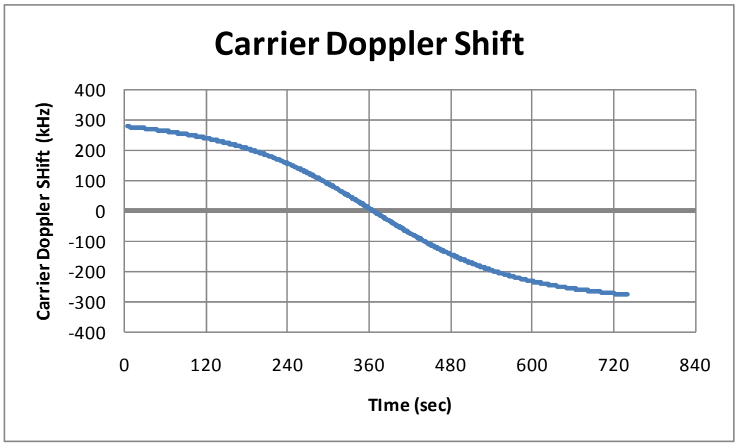

Figure 18. LEO Satellite with 17° Maximum Elevation and 1700 km Minimum Range

Similar plots can be developed, and Channel Simulators controlled, for virtually any communication system where the receiver and transmitter are in motion with respect to each other. Examples include UAV-to-ground, aircraft-to-ship, and satellite-to-aircraft links. In such cases, dramatically different Doppler shift curves exist due to comparatively rapid and sudden changes in the velocity of the transmitter with respect to the receiver.

C. Signal Doppler Shift

Practical communications signals have non-zero bandwidth as can be observed with the 60 kbps BPSK signal in Fig. 19. Since Doppler shift is frequency dependent by Eq. (1), for precise simulation the Channel Simulator must apply appropriate and different Doppler shifts across its bandwidth.

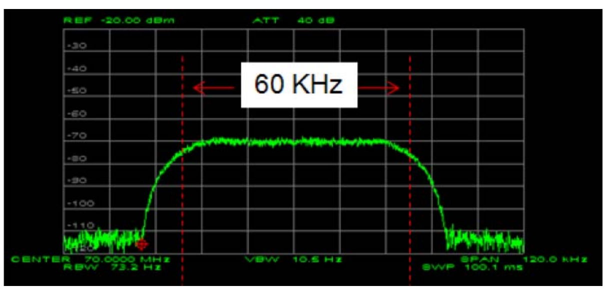

Figure 19. Typical Spectrum of a 60 kbps BPSK with Root Raised-Cosine Filtering

In Fig. 19, the lower frequency edge of the BPSK waveform would receive a slightly smaller Doppler shift than the higher frequency edge, since the left side is at a lower frequency than the right side. This means that the occupied signal bandwidth increases and decreases as a function of the applied Doppler shift, a characteristic that must be duplicated by the Channel Simulator.

This bandwidth expansion and contraction is a result of the Doppler shift contraction and expansion of the BPSK waveform itself, shown in the simplified illustration of Fig. 20. The implication is that data rate changes as a function of Doppler shift, another key characteristic of the Channel Simulator.

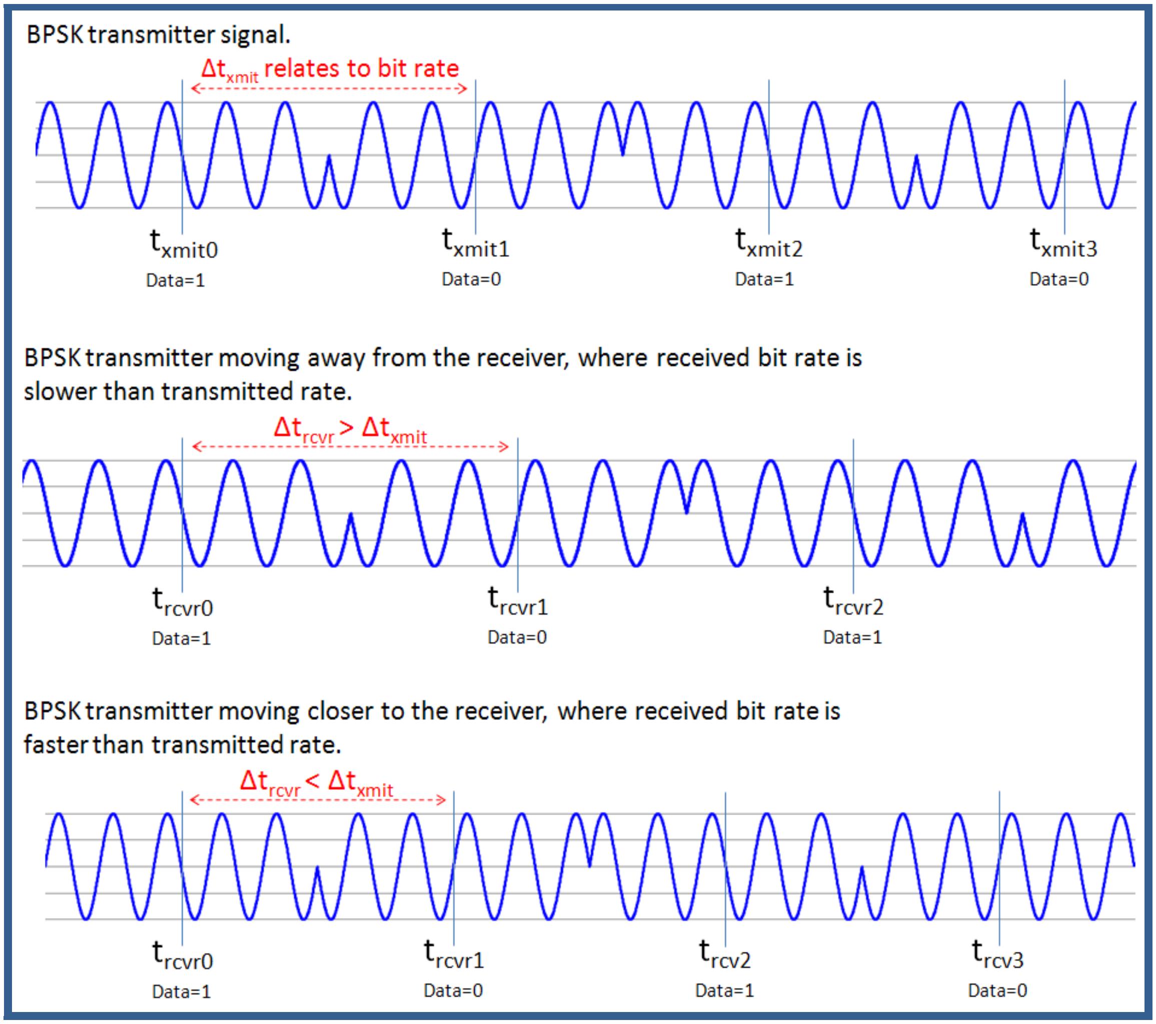

Figure 20. Illustration of Doppler Shift-Related Data Rate Changes in a BPSK Signal

Complete and proper implementation of both carrier and signal Doppler is critically important in a Channel Simulator in order that it fully represent reality.

D. Doppler Shift Rate

Figures 16 through 18 illustrate that Doppler shift rate changes throughout the pass as noted by the various slopes present in the plots. In Figs. 17 and 18, as the satellite rises (the left side of the plot) and sets (the right side of the plot) its motion with respect to the ground station is mostly that which changes its altitude with respect to the ground station, not its line-of-sight range which affects Doppler shift. These are the flatter, more horizontal areas of the plots, where Doppler shift remains relatively constant due to comparatively small changes in the closing velocity between the transmitter and receiver. In these flat areas, the Doppler shift rate is relatively small.

The steeper portions of the curves are where the transmitter distance from the receiver is changing more rapidly due to closer proximity of the transmitter and receiver. At the point where the transmitter and receiver are closest, the Doppler shift curve crosses the X axis, and the velocity changes sign from positive values (transmitter approaching receiver) to negative values (transmitter moving away from the receiver). As can be observed by contrasting the slope at the X-axis crossing in Fig. 17 with that of Fig. 18, closer approaches indeed result in more dramatic Doppler shift rate changes.

Channel Simulators must apply Doppler shift rates both within and beyond the anticipated ranges for verification of appropriate receiver system margin.

E. Propagation Delay

All communication systems have some form of inherent delay in propagation between transmitter and receiver. This is true for wire-line systems, optical systems, and wireless radio systems. In each case, propagation velocity is related to the dielectric constant of the medium through which the signal passes.

Propagation velocity is expressed as a percentage of the speed of light, and in vacuums (dielectric constant = 1) and in air (dielectric constant = 1.00054) propagation velocity can be considered to be 100% of the speed of light for most practical purposes.

Therefore, in wireless communication systems the propagation delay between a transmitter and receiver can be calculated by dividing the straight line distance between the transmitter and the receiver, by the speed of light.

$$D = R / c \tag{2}$$

Where;
- D Delay (sec)
- R Range (km)
- c Speed of light (299,792.458 km/s)

For the example scenario shown in Fig. 15, the propagation delay profile of Fig. 21 can be expected.

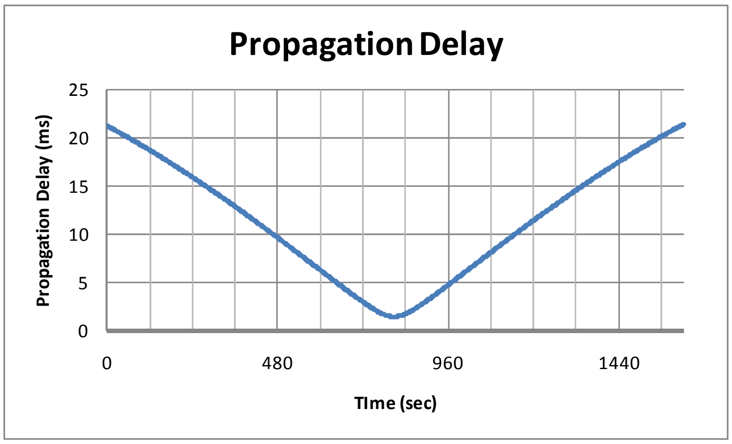

Figure 21. Propagation Delay for the Example Scenario of Figure 15

When performing one-way tests, where a receiver or transmitter is being tested, the Channel Simulator must be capable of signal delay ranges dictated by both the closest and farthest separation between transmitter and receiver. Depending on orbital characteristics and ground station locations, minimum and maximum separation relates to the satellite's apogee (farthest point from the Earth) and perigee (nearest point to the Earth).

When performing simulations of bent pipe uplink and downlink communications scenarios, Channel Simulators apply smooth and phase-continuous delay for the total of the uplink delay plus the downlink delay.

Communications systems testing between atmospheric vehicles (aircraft, UAVs, and missiles) and between such vehicles and ground stations or satellites follow the same considerations, except that minimum and maximum delays are much smaller due to the relatively close proximity between transmitters and receivers.

F. Range Attenuation

Receiver system performance also depends on the power level of the received signal. Satellite-borne transmitters are typically low-power systems at great distances from receiver systems. Modeling dynamic signal power levels, and validating operation under worst-case conditions are key receiver system tests.

The power level of a received signal is primarily affected by free-space path loss, which can be calculated from Eq. (3):

$$L = 32.4 + 20 \log F + 20 \log R \tag{3}$$

Where;
- L Free-space path loss (dB)
- F Frequency (MHz)
- R Range (km)

For the example scenario shown in Fig. 15, the range delay profile of Fig. 22 can be expected.

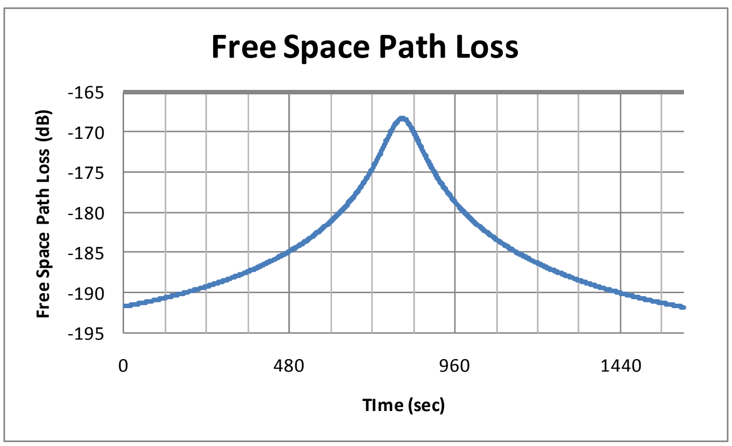

Figure 22. Path Loss for the Example Scenario of Figure 15

A Channel Simulator must accept a low-level input signal then further attenuate it according to the attenuation profile of the communications system being tested. To properly simulate the LEO of Figure 11, the Channel Simulator would require a dynamic, phase-continuous attenuation capacity of at least 25 dB.

Additional path loss occurs when antenna patterns, weather, cable lengths, user-defined losses, and other similar factors are included. Channel Simulators typically have sufficient dynamic attenuation capability, still with phase continuous performance, to accommodate these additional and often dynamic losses.

G. Phase Continuity and High Resolution Interpolation

As noted several times in this paper, Channel Simulators must perform their operations in a fully phase-continuous manner, with absolute and strict attention to applicable physics laws and principals. This ensures that throughout the instrument's capabilities, and as highly dynamic scenarios are run, no data errors are introduced as a result of waveform discontinuities, inappropriate transitions, or glitches.

The Channel Simulator must faithfully model nature in this regard, so that the instrument can be confidently substituted into the communications system for accurate and dependable results. This implies sophisticated high-resolution interpolation between commanded Doppler, delay, or attenuation points.

VII. Conclusion

Realistic and comprehensive RF testing can significantly enhance communication system quality and decrease costs. The RF Channel Simulator is a vital tool for generating realistic test signals with appropriate carrier and signal Doppler shift, delay, attenuation, noise and interference.

These signal perturbations are phase-continuous in nature, and vary smoothly and dynamically based on the relative motion between transmitters and receivers. Channel Simulators recreate such perturbations with extreme attention to their physics and nature.

The unique architecture of the RF Channel Simulator allows engineers a comprehensive and flexible test capability unlike any other. From simply passing test signals through nominal RF paths, to worst-case paths with the harshest RF conditions applied, no other piece of test equipment can provide the range of testing afforded by emulating the true physics of the RF propagation channel.

Since receiver and transmitter relative motion is generally complex, Channel Simulators must be controlled in a visual and intuitive manner so that users can focus on the problems they are trying to solve and the tests they are attempting, rather than on the details of how to make the Channel Simulator work in the scenarios of interest.

As engineers continue to squeeze every possible performance improvement and function into their systems, and as they seek solid margin on their system's technical specifications, they naturally approach the limits of design. While early simulation can help assure functioning designs, there is no substitute for deep hardware-in-the-loop testing under realistic environmental conditions for full final product assurance. The RF Channel Simulator is a vital and unique element in this process, not only from a performance and functional verification viewpoint, but from an efficiency and cost effectiveness perspective as well.