Advanced Hardware-In-the-Loop RF Testing Assures Communication System Mission Success

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ABSTRACT

Robust Radio Frequency (RF) Communication Systems (COMMS) are vital to the success of every satellite mission. But, most RF COMMS links are subject to a wide variety of signal impairments, many of which are particularly acute with small satellites. Powerful RF COMMS modeling and simulation techniques have emerged to assure the performance of these vital communications systems. Even greater assurance is possible when real-world RF signals are directly generated by the same modeling and simulation systems, and are liberally used for component-level and full-system test.

For effective and full-coverage flight COMMS and/or ground COMMS testing, RF Channel Simulators must augment traditional Test & Measurement gear such as signal generators, spectrum analyzers and oscilloscopes. RF Channel Simulators enhance flight COMMS and ground COMMS tests with signal and carrier Doppler effects, as well as range attenuation, range delay, Additive White Gaussian Noise (AWGN) and interference.

Inserted in the lab within Intermediate Frequency (IF) or RF signal paths, RF Channel Simulators create signal impairments that precisely match the RF path perturbations that will be experienced when the communications devices are actually deployed. Use of RF Channel Simulators increases mission confidence through deeper testing, minimizes design and test time, and reduces system over-design that can occur when low-fidelity simulations are employed.

TEST EQUIPMENT

Robust COMMS testing includes traditional Test & Measurement (T&M) equipment for stimulus and analysis. Such equipment includes spectrum analyzers, signal generators, oscilloscopes, data generators, bit error testers and other instruments specific to the mission and to the Device Under Test (DUT).

The RF/IF Channel Simulator, a relatively new T&M instrument for COMMS engineering, is also required for thorough test.

The necessary T&M equipment is connected to the DUT in a manner that allows for hands-off test operation. In R&D applications, full automation may not be required, thus simplifying the instrumentation setup, but in Quality Assurance (QA), production, environmental or stress-testing situations, full automation is desired, so electronic switching may be necessary in order to apply test signals to various DUT inputs, to connect analysis instruments to a different DUT outputs as the test proceeds, and to control the DUT.

COMMS test scenarios involving satellites are complex from a relative motion and COMMS link modeling perspective. As a result, 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.

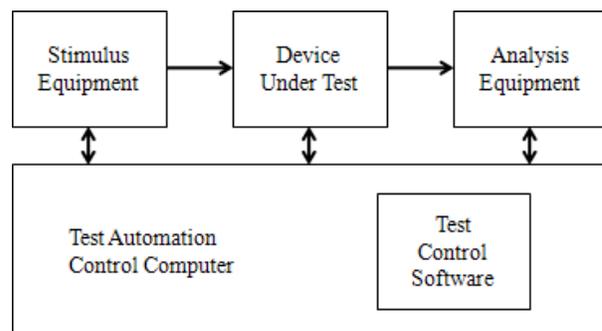A basic automated test setup is shown in Figure 1 below.

Figure 1. Basic automated test setup.

With appropriate scaling to this basic test setup, the DUT may range from a ready-to-launch satellite, or ready-to-deploy ground station, all the way down to a purchased module, developed component or aggregated subassembly on an engineering bench.

Tests may be conducted at Intermediate Frequency (IF) or RF using cable interconnection, as in Figure 1. More realistic RF tests can be conducted on-air within a lab or test facility as depicted in Figure 2.
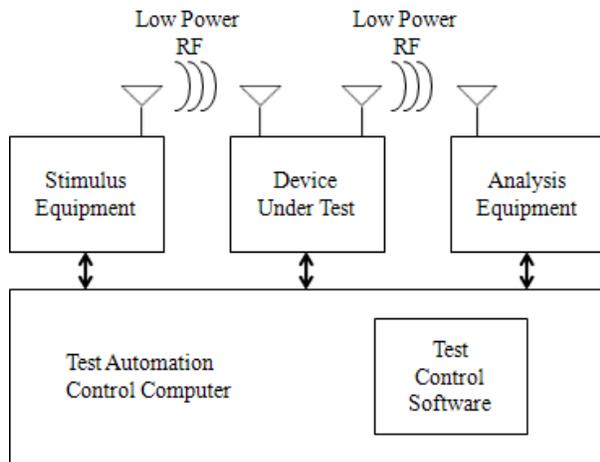

Figure 2. Basic automated test setup with low power RF links.

As shown in Figure 3, when higher power RF links are utilized, on-orbit and distant assets may become part of the test system or these assets may act as surrogates for test or proof-of-concept activities.
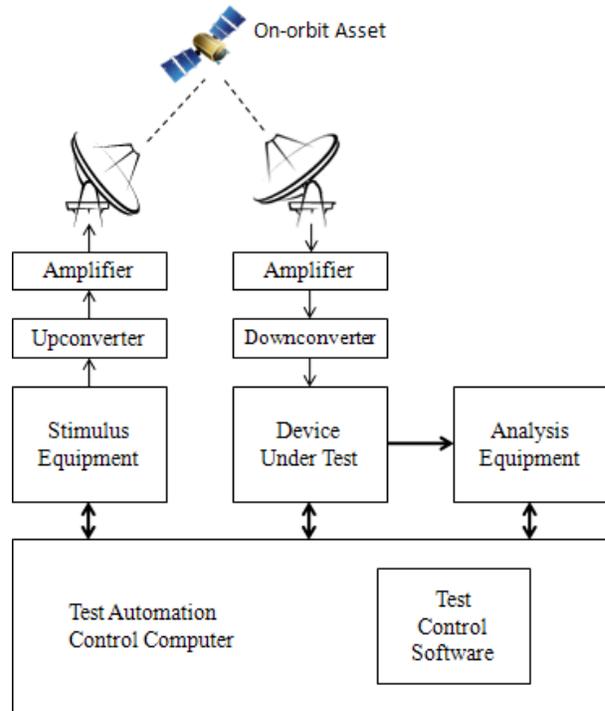

Figure 3. Use of on-orbit assets for test and proof-of-concept activities.

Sophisticated, yet easy-to-construct test setups such as in Figure 3 are useful for extremely realistic testing of flight or ground COMMS hardware, firmware, software or algorithms. One example would be the high fidelity simulation of an Inter-Satellite Link (ISL) between a not-yet-launched Low Earth Orbit (LEO) satellite and an on-orbit Geostationary (GEO) satellite. In this example, the Stimulus Equipment supplies the simulated LEO signal to the GEO, and the simulation would allow high accuracy test of ground COMMS systems and components.

Numerous test equipment configurations are possible if test equipment is modular and easily user-reconfigurable.

Such testing is useful in R&D activities, production work, quality assurance efforts and pre-launch verification. These tests are also used heavily in regression testing and compliance testing, where new or modified hardware, software or firmware is to be validated prior to installation into a COMMS system.

TEST SYSTEMS MUST REPRESENT REALITY

A key aspect of any COMMS 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 replicate natural RF link propagation dynamics and related phenomena result in

inadequate and/or unsuitable test. As well, test systems must be capable of both nominal-case and worst-cast testing.

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

Phase-continuous Doppler shift, range delay and range attenuation in DUT input signals is an **absolute requirement** when generating COMMS signals that precisely mirror nature. Inadvertent signal phase changes as Doppler shift, delay and attenuation are adjusted to simulate a satellite pass, for example, can be seen by receivers as erroneous test-system-induced data bit or data symbol changes, particularly when the COMMS link is utilizing phase-shift keying modulation methods such as Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 8PSK, etc.

CHANNEL SIMULATOR

At the heart of a COMMS test system, the Channel Simulator adds dynamic Doppler shift, delay, attenuation, AWGN and interference to an input signal before the signal is input to the DUT, or after the signal is output from the DUT.

When testing a DUT that normally **receives** signals from a satellite, or that receives signals on a satellite, the **Stimulus Equipment** block of Figures 1, 2 and 3 look like Figure 4.
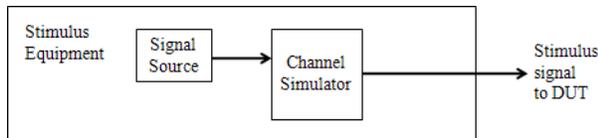

Figure 4. Stimulus equipment with Channel Simulator.

In this configuration, the Channel Simulator receives a signal from the Signal Source, applies Doppler shift, delay, attenuation and AWGN, and presents the resulting signal to the DUT at IF or RF. The Channel Simulator is then dynamically controlled via the appropriate orbital mechanics, resulting in stimulus signals to the receiver DUT that are indistinguishable from those that would occur with an actual flight.

Interference sources can be included to simulate accidental or intentional interference at the transmitter and/or at the receiver as shown in Figure 5.
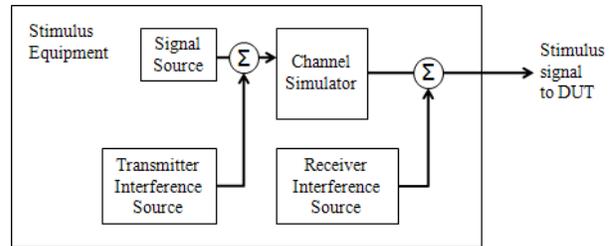

Figure 5. Stimulus equipment with Channel Simulator and Interference Sources.

Similarly, when testing a DUT that normally **transmits** signals to or from a satellite, the **Analysis Equipment** block of Figures 1, 2 and 3 look like Figure 6.
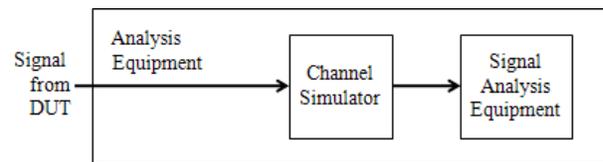

Figure 6. Analysis Equipment with Channel Simulator.

Here, the Channel Simulator receives a signal from the DUT, applies Doppler shift, delay, attenuation and AWGN, and presents the resulting signal to the Signal Analysis Equipment (e.g. Spectrum Analyzer, BERT, etc.) at IF or RF. As in the receiver DUT case, the Channel Simulator is then dynamically controlled via the appropriate orbital mechanics, resulting in signals from the transmitter DUT that are indistinguishable from those that would occur with an actual flight.

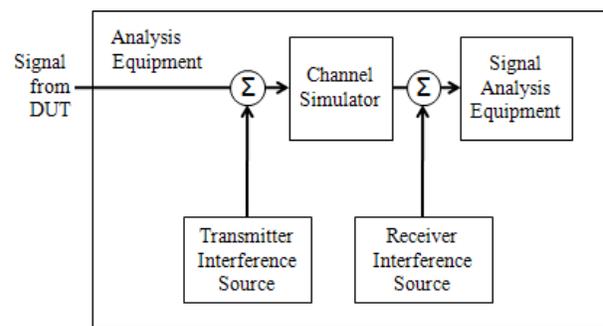Transmitter and/or receiver interference sources can be included as shown in Figure 7.

Figure 7. Analysis Equipment with Channel Simulator and Interference Sources.

With these basic configurations, thorough receiver DUT and transmitter DUT testing can be conducted.

CHANNEL SIMULATOR CHARACTERISTICS[1]

The Channel Simulator 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 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 lab, 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., nuclear disturbance, battlefield scenarios, etc.).

Channel Simulators can play a vital role in the modeling, prediction and study of 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.

Doppler shift

In wireless COMMS applications where receivers and transmitters are in motion with respect to one another, 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 motion of the transmitter and the receiver.

Equation 1 describes Doppler shift based on the actually transmitted frequency and the relative velocity between the transmitter and the receiver:

$$Fs = Fa * V/c \qquad (1)$$

where Fs = Doppler shift in Hz; Fa = actually transmitted frequency in Hz; V = relative velocity between transmitter and receiver in km/s; and c = speed of light (~300,000 km/s).

Figure 8 illustrates Equation 1 for a LEO satellite orbiting circularly at 800 km. As its 1.5 GHz signal is encountered at the Acquisition of Signal (AOS) point, and as it moves toward a fixed receiving station, the received signal is at a higher frequency than is actually being transmitted. When the satellite is at its minimum range from the receiving station, the received signal is at the actual frequency, and as the satellite sets toward the Loss of Signal (LOS) point, the received signal is lower than its actual frequency.
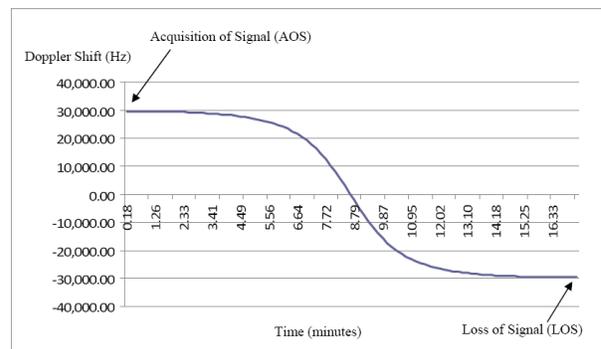

Figure 8. Doppler Shift Versus Time for a 1.5 GHz Signal from a LEO Observed at a Fixed Ground Station.

For this satellite, the following Doppler shift ranges would be observed at a fixed ground station.

Table 1. Doppler Shift Versus Time for a 1.5 GHz Signal from a LEO Observed at a Fixed Ground Station.

Original Frequency (F$_O$)	Observed Doppler (F$_S$)
435 MHz (UHF-band)	± 8.6 kHz
1.2 GHz (L-band)	± 23.7 kHz
2.4 GHz (S-band)	± 47.4 kHz
5.7 GHz (C-band)	± 112 kHz
10.5 GHz (X-band)	± 207 kHz
24.0 GHz (Ku-band)	± 474 kHz

As Equation 1 describes, Doppler shift is frequency dependent. Because data signals have non-zero

bandwidth, various portions of the signal are at different frequencies as can be observed with the 120 kbit/sec QPSK signal in Figure 9.
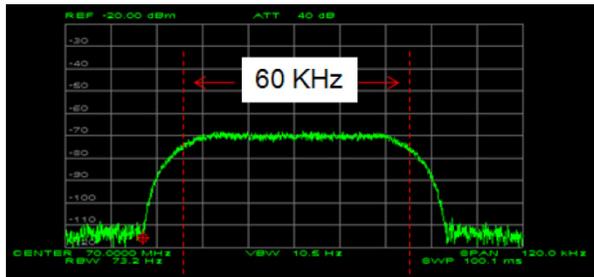

Figure 9. Typical 60 kHz Bandwidth of a 120 kbit/sec (60 kSymbols/sec) QPSK Signal.

For precise simulation, the Doppler shift capacity of the Channel Simulator must apply appropriate and different Doppler shifts across its bandwidth. For example, in Figure 9 the left side of the waveform would receive a slightly lower Doppler shift than the right side, because the left side is at a lower frequency than the right side.

Proper Doppler shift implementation is critically important, particularly at high carrier frequencies associated with satellite COMMS channels, and at high data rates that result in wide bandwidth data signals. Failure of the Channel Simulator to properly implement both carrier **and** signal Doppler shift, can introduce bit errors, can lead to DUT over-design, and can lead to false conclusions that DUT operation is correct.

Doppler Shift Rate

Figure 8 also shows that the Doppler shift rate changes throughout the pass. The flatter, more horizontal areas of the S-curve are where the Doppler shift remains relatively constant due to comparatively small changes in the closing velocity between the satellite and the ground station. As the satellite rises (the left 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.

The steeper portion of the curve is where the satellite's range from the ground station is changing more rapidly, and as the S-curve crosses the X axis, the velocity changes sign from positive values (satellite approaching receiver) to negative values (satellite moving away from the receiver).

The X axis is crossed more steeply when the mid-point of the satellite's over-flight is closer to the ground station. Maximum Doppler shift rate occurs when the satellite passes directly overhead, and lower rates are observed for lower elevation angle passes.

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

Range 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 where 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.

$$D = R / c \qquad\qquad (2)$$

where D = delay in s; R = range in km; and c = speed of light (~300,000 km/s).

For the LEO satellite discussed earlier, the range delay profile of Figure 10 can be expected. Elliptical and higher orbits produce dramatically different results.
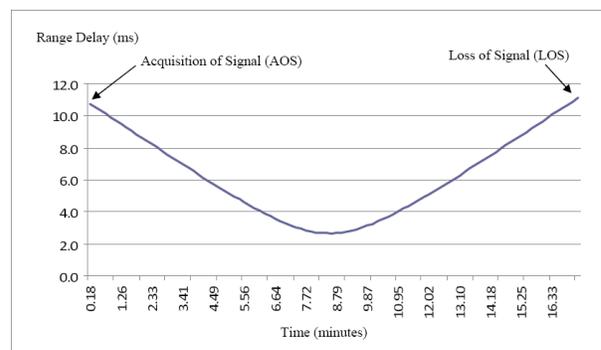

Figure 10. Range Delay Versus Time for a Signal from a LEO Observed at a Ground Station.

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 an uplink and downlink communications scenario, the Channel Simulator must be capable of delaying for the uplink plus the downlink paths.

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.

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 affected by free-space path loss, which can be calculated from Equation 3:

$$L = 32.4 + 20 \log F + 20 \log R \qquad (3)$$

where L = free-space path loss in dB; F = frequency in MHz; and R = range in km.

For the LEO satellite discussed earlier, the path loss profile in Figure 11 could be expected.
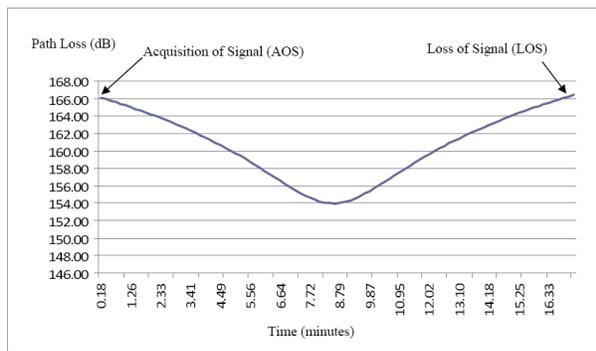

Figure 11. Path Loss of a Signal from a LEO Observed at a Ground Station.

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 an attenuation capacity of at least 12 dB to13 dB.

With MEO and HEO satellites having highly elliptical orbits, or where atmospheric, Rician, Rayleigh, or Nakagami fading is to be modeled, the needed attenuation range is on the order of 50-60 dB.

Phase Continuity and High Resolution Interpolation

Channel Simulators must perform their operations in a fully phase-continuous manner. This ensures that throughout the instrument's capabilities, 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.

CHANNEL SIMULATOR CONTROL

Channel Simulators must be computer controllable, as are most modern T&M instruments. Generally, this is implemented by a client/server control model within the Channel Simulator as in Figure 12.
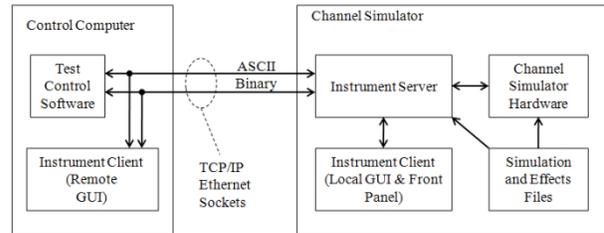

Figure 12. Channel Simulator client/server control model.

This control model allows the Channel Simulator to be flexibly controlled by industry standard applications, user-written programs, simulation files, and Channel Simulator-supplied GUIs.

Creation of simulation files requires detailed user knowledge of the Doppler shift, delay, attenuation and AWGN parameters per unit time. When constructing simple test cases, such as linear ramp-up and ramp-down of such parameters, simulation files can be easily constructed using spreadsheet tools such as Microsoft Excel, various mathematics packages or user-written programs.

In many Channel Simulator applications, Doppler shift, delay, attenuation and AWGN parameters are a

function of the distance/time relationship of an orbiting spacecraft and a fixed or mobile ground station. In ISL applications, multiple flight paths may be involved in determining the Channel Simulator parameters.

While it is certainly possible to create simulation files for these more complex cases, the client/server model of the Channel Simulator allows it to be controlled by industry standard physics-based and highly visual modeling and simulator software packages. One such package is Analytical Graphics, Inc.'s STK software which controls the Channel Simulator as shown in Figure 13. This diagram is a specific instance of the more general diagram of Figure 12.
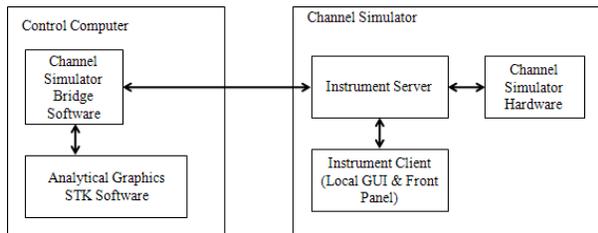

Figure 13. STK control of the Channel Simulator.

Use of visualization and modeling software such as STK allows the user to intuitively select or create satellites and orbits, as well as ground stations or terrestrial ground tracks for receiver and or transmitter sites. Once specified, STK provides thorough animation along with high-accuracy calculations of the receiver-transmitter range and range rate and RF link characteristics which are then used in the Channel Simulator Bridge Software to control the Channel Simulator.

In Figure 14 below, STK has been used to create a simulation that allows testing of a receiver DUT. The test conditions include signals from two satellites (TestSatA and TestSatB) in different orbits being simultaneously received by the receiver DUT.
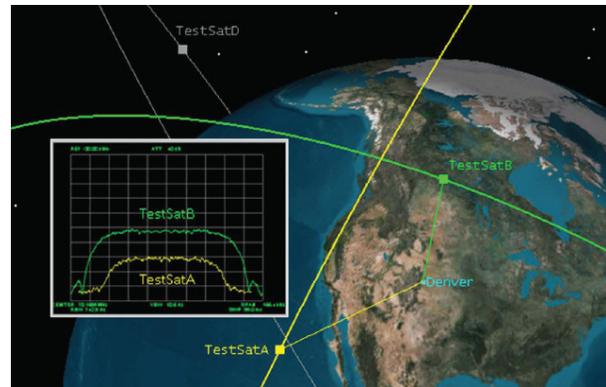

Figure 14. STK visualization and channel simulator control.

In this case, STK is controlling two Channel Simulators simultaneously, one that simulates the TestSatA-Denver COMMS channel, and another that simulates the TestSatB-Denver channel. The outputs of the two Channel Simulators are combined before being fed to the receiver DUT as shown in Figure 15 (an extension of Figure 13).
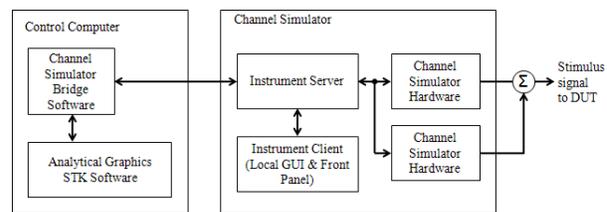

Figure 15. STK control of multiple channel simulators.

The spectrum analyzer inset in Figure 15 shows the combined output of the two channel simulators utilizing the carrier-under-carrier interference analysis mode of a spectrum analyzer module that can be configured into the Channel Simulator.

In general, multiple Channel Simulators operate from the same reference signal, and have the ability to be armed, and triggered synchronously with other Channel Simulators and other T&M instruments. This allows multiple COMMS channels to be simultaneously simulated, as depicted in Figure 16.
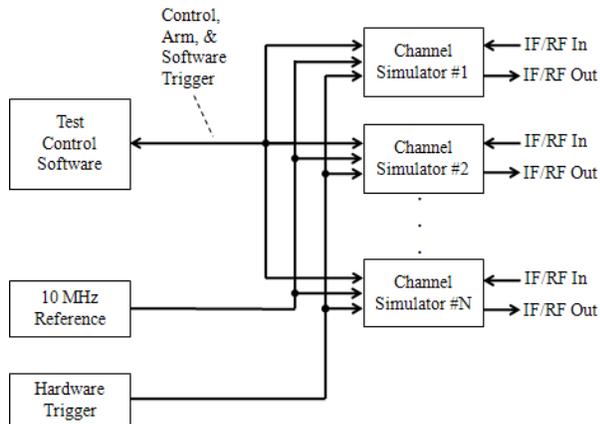
Figure 16. Control of multiple channel simultaneous channel simulators.

STK scenarios can be much more complex than in this simple example, and can include spin and tumble models as well as antenna geometries and beam patterns, transmitter and receiver characteristics, and COMMS link parameters such as power levels, frequencies, modulation types, data rates, etc. The Channel Simulator follows these settings, resulting in a sophisticated modeling and simulation system that also produces real-world test signals for DUT verification and assurance activities.

Simple construction of sophisticated scenarios, accurate generation of resulting signals, and visualization of running scenarios and created signals, gives the Channel Simulator an important role in training and education activities.

SUMMARY

Hardware-in-the-loop testing at RF and IF contributes significantly to Communication System Mission Success. Modeling and simulation is an important step in the process, but these activities must result in real-world signals that precisely mirror those that would be received in an actual flight scenario.

The Channel Simulator is a vital tool for generating realistic test signals, as it dynamically and phase-continuously applies Doppler shift, delay, attenuation and AWGN.

Creation of such real-world signals must be intuitive, yet effective, with the creation process greatly enhanced by a seamless coupling between industry standard modeling and simulation tools and Channel Simulation instruments.

References

1. Williams, S.R., "Cost-Effective, Focused Instrumentation for TT&C and COMMS Engineering," Proceedings of the 45th Annual International Telemetering Conference, San Diego, CA, October 2008. Some portions of this paper are used with permission, and are Copyright © 2008, International Foundation for Telemetering.

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