Application Note

GROUND STATION TESTING ON SATELLITES IN ORBIT

Products:

- R&S®FSW
- R&S®SMW
- R&S®NRP
- R&S®ZVA

M.Naseef, R. Minihold | 1MA263 | Version 4e | 10.2021

Note:

Please find up to date document on our homepage
http://www.rohde-schwarz.com/appnote/1MA263

Application Note: DVB-S2 & DVB-S2X Signal Generation in K-Band and Analysis
http://www.rohde-schwarz.com/appnote/1MA273

Contents

1 Overview

After a communications satellite is on its target orbit, several routines need to be performed in order to ensure proper performance from the transponders in the payload. The on-orbit measurements are a vital part of the maintenance of a live satellite as well.

Operating a satellite channel for an on-orbit measurement rather than the intended application comes with significant opportunity cost and hence test duration needs to be minimized as much as possible.

Rohde & Schwarz test and measurement equipment recommended in this paper is market leading not only in terms of measurement accuracy but also offers unparalleled speed of measurement.

This application note focuses on satellite post-launch or on-orbit measurement and monitoring strategies used for satellite functionality checks when running maintenance routines. A complementary paper treats pre-launch payload measurements.

2 Abstract

As of June 2016, there are 1419 operational satellites in space [1]. More than half are communications satellites and more than a third of these are commercial communications satellites. After a satellite arrives on its target orbit, it is activated and test routines need to be performed in order to verify proper performance of transponders in the payload. *On-orbit* or in-orbit measurements also form a vital part of the maintenance of a live satellite [2].

This application note is focused on particular measurements required to characterize the proper functionality of a satellite in orbit. The complexity of on-orbit measurements makes it desirable to understand the theory as well as practical challenges. Physical side conditions and solutions to overcome the related difficulties are explained. For example, the theoretical link budget calculation and measured link budget value are never the same. Using the Rohde & Schwarz solution of referencing the measurement to the best-in-class NRP-series power sensors for EIRP measurement helps to minimize the difference between these two link budget values. NRP-series also allows automatic internal correction of load matching of the source.

For long-distance group delay test, the ZVA-series network analyzer offers built-in measurement uncertainty calculation as a unique aid in choosing the best-suited aperture value. Gain Transfer (or Conversion Loss) measurement is treated in the same section.

Real-time Spectrum Analysis greatly helps with monitoring against double illumination, while the generic vector signal analysis aids in monitoring satellite carriers.

A major driver in test cost is the time a satellite radio channel is out of service for the measurements. When a satellite payload is first being tested on-orbit, it is advantageous to complete the tests as quickly as possible so the satellite can be put into service and start earning revenue. Time taken for on-orbit measurement needs to be minimized without sacrificing reliability. R&S equipment recommended in this application note is industry leading in both, measurement accuracy and speed of measurement. All over this application note, speed of measurement is stated with the intention to give the reader a rough estimate of measurement time and hence test cost that can be saved while performing the measurements using Rohde & Schwarz solutions.

This application note focuses on a few important post-launch measurement setups where Rohde & Schwarz offers unique solutions used for satellite functionality checks and running maintenance routines. Also possible with the same R&S equipment, but not addressed here are IPFD, G/T, Gain Flatness, Power backoff and Frequency Conversion Error measurements.

The parallel paper 1MA273 concentrates test and measurement possibilities for DVB-S2 and DVB-S2X signals in the Ku & Ka -band.

Abbreviations

The following abbreviations are used in this application note for Rohde & Schwarz products:

- The R&S®SMW200A vector signal generator is referred to as **SMW**
- The R&S®SMF100A vector signal generator is referred to as **SMF**
- The R&S®SMZ Frequency Multiplier is referred to as **SMZ**
- The R&S®FSW signal and spectrum analyzer is referred to as **FSW**
- The R&S®ZNBT vector network analyzer is referred to as **ZNBT**
- The R&S®ZVT vector network analyzer is referred to as **ZVT**
- The R&S®ZVA vector network analyzer is referred to as **ZVA**
- The R&S®RTO digital oscilloscope is referred to as **RTO**
- The R&S®AFQ100B UWB Signal and I/Q Modulation Generator is referred to as **AFQ**
- The R&S®NRPxxS/SN Three-Path Diode Power Sensor is referred to as **NRPxxS/SN**
- The R&S®NRP2 Power Meter is referred to as **NRP2**
- The R&S®FSUP Signal Source Analyzer is referred to as **FSUP**
- The R&S®FSL Spectrum Analyzer is referred to as **FSL**
- The R&S®SMBV100A Vector Signal Generator is referred to as **SMBV**
- The R&S®SMB100A RF and Microwave Signal Generator is referred to as **SMB**

3 Theoretical background

3.1 Equivalent Isotropic Radiated Power (EIRP)

Measurement of EIRP helps to verify the satellite antenna to be properly directed at the ground station during antenna pattern mapping. The antenna patterns tests are used to ensure the beam patterns are oriented correctly on the earth. It also identifies problems earlier in the antenna feed system of a satellite, once the antenna orientation has been found or corrected.

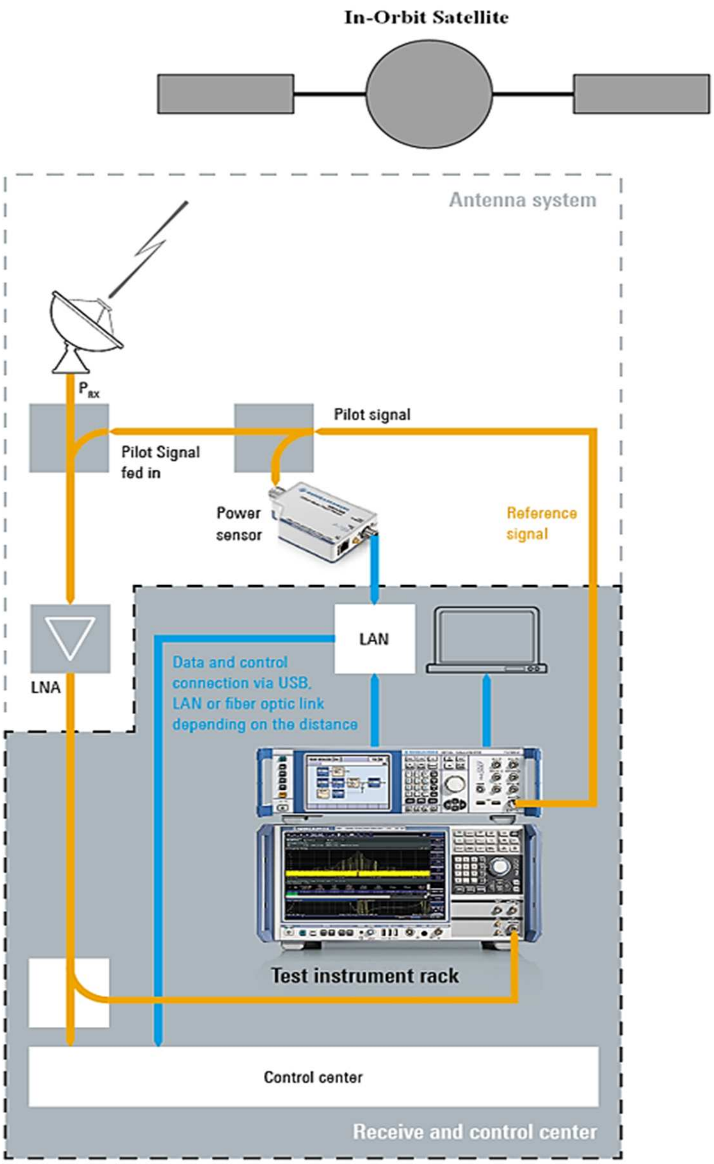


Figure 1: The earth station setup for EIRP test when the satellite in on its target orbit

Once the performance of a satellite transmit chain is established, it can serve as an indicator to quality of the radio path (attenuation along the downlink).

To define the value of this parameter, we need to refer to the Friis transmission equation. EIRP is the product of gain of the transmit antenna G_T in the direction of maximum gain and Input Transmitted Power (P_T) at the satellite

$$EIRP = P_T G_T$$

Measurement of EIRP from ground station requires derivation for the receive side

$$EIRP = \left(\frac{4\,\pi\,R}{\lambda}\right)^2 \left(\frac{P_R}{G_R}\right)$$

where,

P_R = power received at the receive antenna

G_R = gain of the receive antenna

R = distance between the satellite and ground station

λ = (median) wavelength of the radiated signal

EIRP typically is expressed in dBW.

3.2 Group Delay

The measurement of on-orbit group delay is not usually concerned with the absolute time delay of a filter or a frequency converter. The major concern here is whether each of the signal's frequency components experience the same delay so that their phase relative to one another is maintained. The relative group delay of the signals is especially important for the digital modulation schemes that are commonly used in modern satellite communications. To put it in better words, the requirement is that the signals maintain their shape as they pass through a RF component.

Group delay measurements are based on phase measurements. The measurement procedure corresponds to the definition of group delay τgr as the negative derivative of the phase φ (in degrees) with respect to frequency f:

$$\tau_{\mathrm{gr}} = -\frac{1}{360^0} \cdot \frac{d\varphi}{df} \qquad (1)$$

For practical reasons, Vector Network Analyzers measure a difference coefficient of the transmission parameter S21 instead of the differential coefficient. This yields a good approximation to the wanted group delay τ_{gr}, if the variation of phase φ is not too non-linear in the observed frequency range Δf, which is called the aperture.

$$\tau_{\mathrm{gr}} = -\frac{1}{360^0} \cdot \frac{\Delta\varphi}{\Delta f} \qquad (2)$$

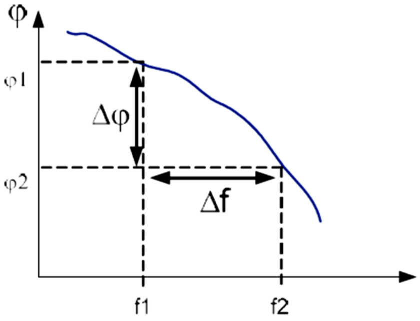


Figure 2: Definition of phase shift Δφ= φ2-φ1 and aperture Δf=f2-f1

Figure 2 shows the terms Δφ= φ_2-φ_1 and Δf=f_2-f_1 for linearly decreasing phase response, e.g. of a delay line.

Commonly used group delay measurements are relative and absolute group delay. Relative group delay measurements ignore the constant delay caused by the DUT. This delay affects all frequency components in the same way and does not lead to a change in the signal shape. However, the absolute group delay is significant in certain cases, e.g. if the signal delays of two transmission channels are to be adjusted. When measuring absolute group delay it is necessary to take into account the movement of the satellite relative to the ground station, which can be even more significant when measuring satellites in non-geostationary orbits.

$$\tau_{\mathrm{rel}} = \tau_{\mathrm{abs}} + min|\tau_{\mathrm{gr}}| \qquad (3)$$

3.3 Double-Illumination

During the operational lifetime of a satellite, one of the common problems encountered in satellite communications is interference or double-illumination.

It occurs when an earth station directs an uplink to the wrong satellite and thus drives the satellite transponder into saturation. There are instances when this not an "accidental" problem.

Preventing such saturation in the congested orbital space requires detecting this harmful interference, ideally by real-time spectrum monitoring. The double-illumination needs to be detected quickly and the faulty carrier ID needs to be automatically detected for fast problem resolution.

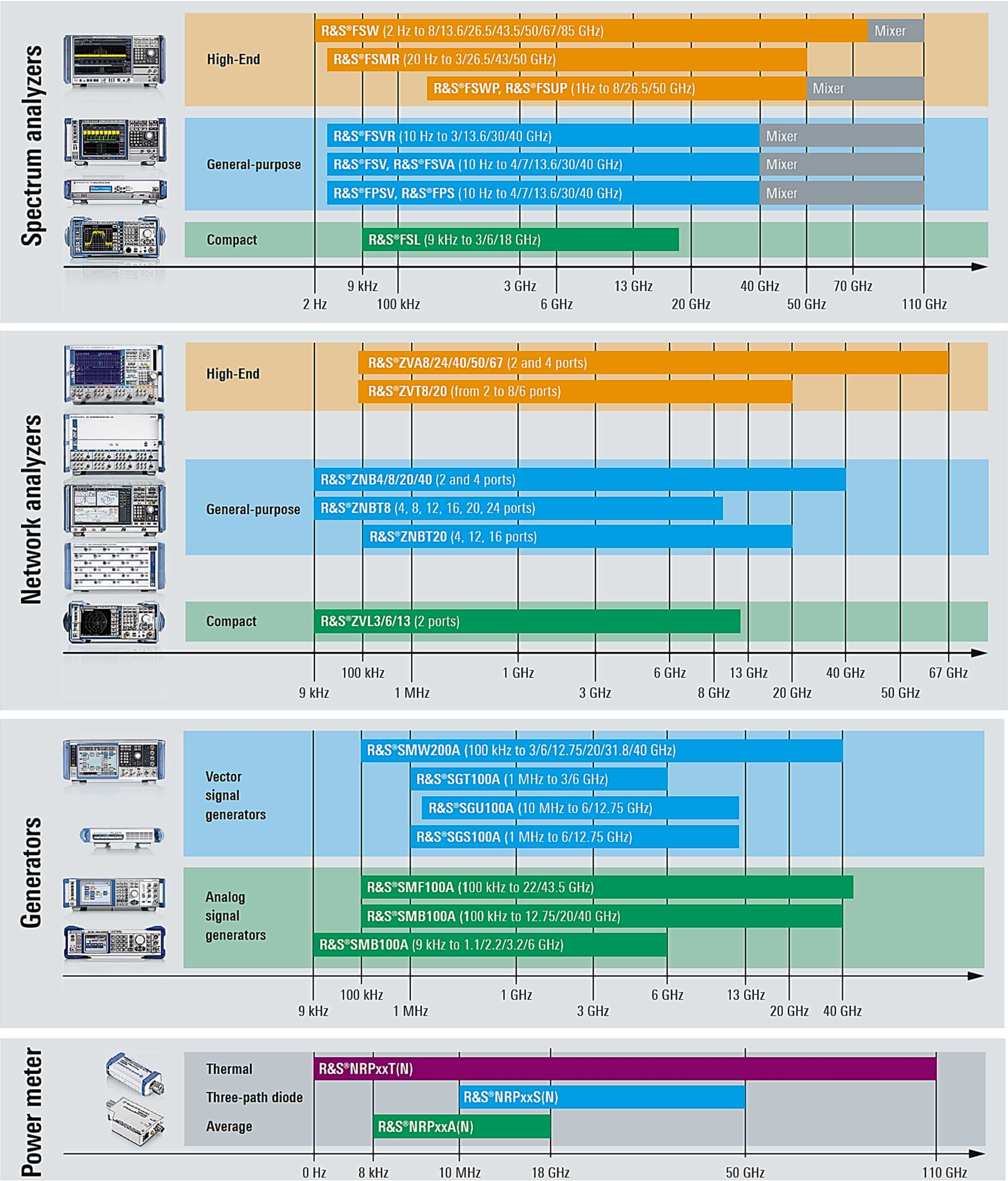
3.4 How Doppler effects On-Orbit Measurements

The Doppler Effect is defined as the variation of the frequency of an electromagnetic (EM) wave as observed by a receiver that is moving relative to its source. A satellite in space, depending on the orbit it is flying in, travels at significant high velocities. As a result, a huge frequency variation is created and this influences the complexity of space communication. Lower orbit satellites are known to be the fastest moving satellites and can have Doppler shifts in the range of hundreds of kilohertz relative to the earth station tracking it. The Doppler shift also changes due to the curvature of the earth. A dynamic Doppler compensation scheme needs to be employed in order to ensure proper communication with a satellite in space.

The frequency of the transmitted signal is adjusted multiple numbers of times so that the satellite receives a constant frequency signal. In addition to the effect on frequency, the power level also changes as the range (distance to the satellite) changes. This form of Doppler shift is because of the vertical motion (earth perpendicular motion) that satellites experience due to the elliptical force acting on them. This effect is not particularly significant for the geostationary orbit, but is significant for low-earth orbiting satellites.

The rate at which the satellite moves has a big impact on the complexity of the measurement setup.

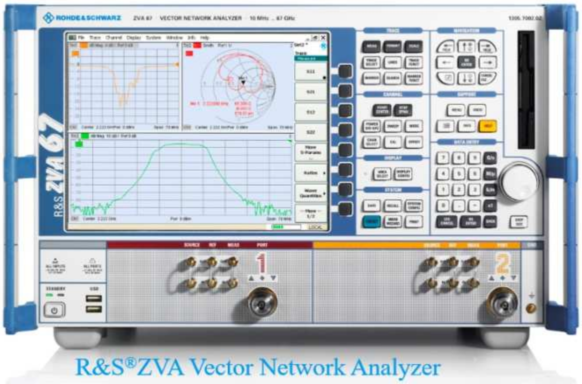
4 R&S Product Portfolio for Satellite Testing



5 R&S Featured Products for On-Orbit Measurements

R&S®SMA100B RF and Microwave Signal Generator

- Max. Frequency range from 8 kHz to 72 GHz
- Excellent SSB phase noise of typ. –132 dBc (at 10 GHz and 10 kHz offset)
- Output power exceeds 30 dBm across wide frequency ranges
- Wideband noise of –162 dBc (meas.) at 10 GHz and 30 MHz offset
- Exceptionally low harmonics
- Versatile Power analysis with additional R&S®NRP-Zxx power sensor



R&S®ZVA Vector Network Analyzer

- Frequency Range 300 kHz to 8 GHz (R&S®ZVA8), 10 MHz to 24/40/50/67/110 GHz (R&S®ZVA24/40/50/67/110)
- Phase and group delay measurements on mixers with and without LO access
- Long Distance Group Delay Measurement
- Linear and nonlinear amplifier and mixer measurements
- Noise figure measurements
- Pulse profile measurements with 12.5 ns resolution
- True differential measurements for reliable characterization of active devices with balanced ports
- Short measurement times due to fast synthesizers, wide IF bandwidths and high dynamic range
- Direct access to the generators and receivers for 30 dBm output power and 150 dB dynamic range
- First VNA with IF bandwidths up to 30 MHz for pulsed measurements on amplifiers and mixers

R&S®FSW Signal and Spectrum Analyzer

- Frequency range from 2 Hz to 8/13.6/26.5/43.5/50/67/85 GHz
- Low phase noise of -137 dBc (1Hz) at 10 kHz offset (1 GHz carrier)
- -88 dBc dynamic range (with noise cancellation)
- Up to 8 GHz analysis bandwidth
- Real-time analysis up to 800 MHz bandwidth
- Multiple measurement applications can be run and displayed in parallel
- Resolution bandwidth from 1 Hz to 10 MHz, 80 MHz

R&S®NRPxxS/SN

- Frequency Range from 10 MHz to 50 GHz
- 10 000 triggered measurements/s
- More than 50 000 readings/s
- Remote monitoring via LAN over any distance
- 93 dB dynamic range
- Built-in trigger I/O port
- Intelligent averaging function minimizes measurement time
- Minimizing measurement uncertainty
- Three-path diode power sensors

6 Test Procedures for On-Orbit Measurements

6.1 On-Orbit EIRP Measurement

Satellite links are indispensable in sound and TV broadcasting and in worldwide communications via telephone, the Internet, or mobile radio. Smooth, round the-clock operation must therefore be ensured in particular for commercial systems.

However, if satellite signals arrive at an earth station with insufficient field strength, this may cause serious problems. The bit error ratio (BER) increases rapidly, to an extent that a communications link may be rendered useless. Such detrimental effects are attributable to a variety of causes. In many cases, atmospheric influences affect wave propagation: fog, clouds, and precipitation attenuate signals and increase noise especially at higher frequency bands like the Ku-band and particularly at Ka-band.

Errors in antenna alignment may result in only part of the available power being picked up. This applies in particular to large, high-directivity parabolic antennas. A close attention must also be paid to the ambient conditions under which receiving systems have to operate: Many satellite antennas are installed in the open, i.e. they have to withstand humidity, extreme temperatures, and mechanical stress caused by wind load. This also has a negative effect on signal quality, which is aggravated by the effects of wear and tear that occur over the course of time.

Although the above effects increase attenuation on the transmission path by a few decibels only, this may easily exceed the capabilities of the background correction algorithms. This is because only relatively low headroom is provided for the carrier-to-noise (C/N) ratio. This is by no means a planning error but the result of economic considerations. If the level of the incoming signal – which arrives at the antenna at approx. –115 dBm – were increased by a mere 3 dB in the interest of higher safety margin, either the satellite transmit power would have to be doubled or the diameter of the receiving antenna enlarged by 50%. The more meaningful approach therefore is to invest in appropriate alternative strategies to make full use of the existing, scarce resources. This includes the continuous monitoring of the receive power in order to prevent creeping degradation of the system.

Figure 3 shows the earth station setup for EIRP test when the satellite is on its target orbit. A reference pilot signal with:

- a known RF level (the power level should be high enough to be measured with a power sensor but at the same time should be low enough, not to drive the LNA in a non-linear region)
- same carrier frequency and signal bandwidth as expected in the satellite downlink is fed in at the measurement point by an SMF signal generator.

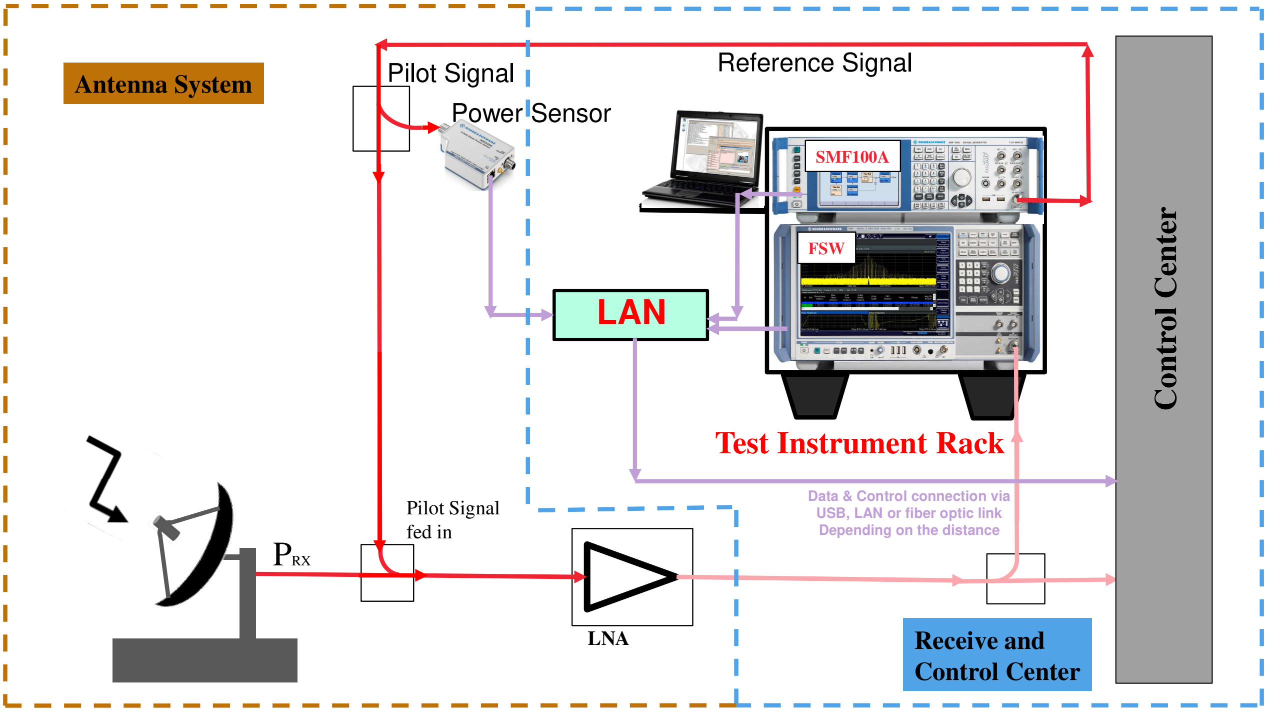


Figure 3: Test Setup for EIRP measurement in the receive path of a satellite-to-earth radio station

Like the signal from the satellite, the pilot RF signal travels through most of the receive transmission path up to Receive and Control Center, where a signal or spectrum analyzer is used to determine the level difference between the two signals. Along the entire transmission path, both signals undergo the same amplification and attenuation, as their carrier frequencies / spectral shapes are almost identical. This means that the level difference measured at the spectrum analyzer mirrors the level difference at the reference point, and thus the RF receive level at the ground station antenna output is known. However, the power sensor does not measure the pilot RF signal level directly at the reference point but some distance ahead where the pilot level is higher.

This level difference is due to the attenuation introduced by the intermediate passive components. Since this attenuation is safely assumed to be stable even long-term, it needs to be measured only from time to time for each expected downlink channel. The resulting channel-specific value is then subtracted from the value returned by the power meter reading.

The new R&S®NRPxxSN power sensors are factory-calibrated to provide highly accurate measurement across their entire level, frequency and temperature range. Failure of the sensors due to overload (in this particular application case) can be ruled out because of the low power levels, that fall within the specified power handling capability of the sensors from -70 dBm to +23 dBm up to 33 GHz.

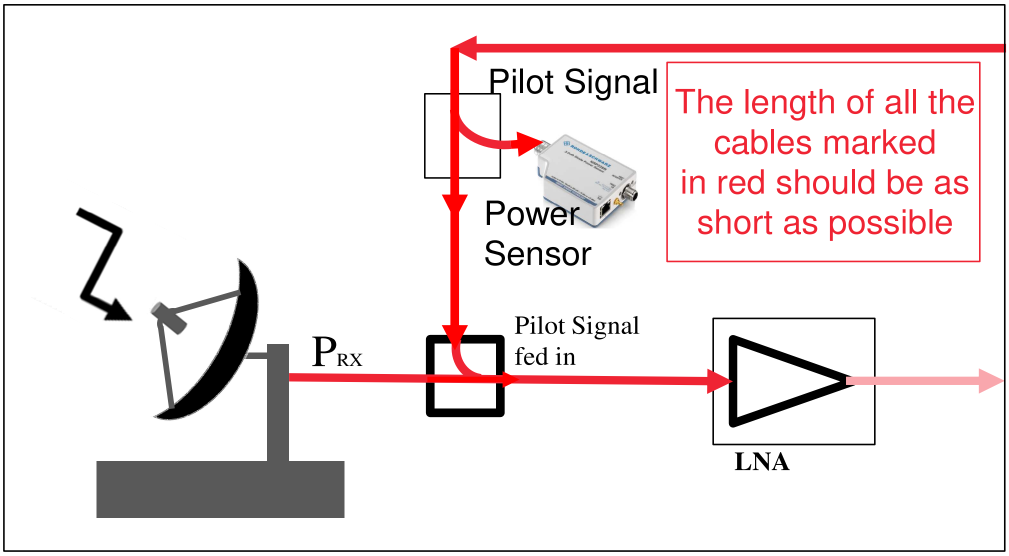


Figure 4: The optimal measurement point for the Antenna System

Figure 4 shows the optimal measurement point of an antenna system, which is located between the antenna output and the input of the first extremely low noise amplifier (LNA), which is typically flange mounted on the antenna. While the RF signal level is lowest at this point, achievable measurement accuracy is highest here. Measuring power later in the chain at the Receive and Control Center would cause uncertainties. This is because of inadequate stability of the gain provided by the LNA and the attenuation introduced by the possibly very long receive feed from the antenna. The RF level at the antenna output is very low, in some cases 50 dB below a diode power sensor's measurement limit. Therefore, it must be measured bandlimited, i.e. with a selective analyzer. While wideband power meters have the best-possible accuracy, an indirect measurement transferring this accuracy to a selective instrument such as a spectrum analyzer is optimum. Hence, a two-step approach is needed.

To obtain comparable results of the receive power independently of the receive antenna characteristics, the equivalent isotropic radiated power (EIRP) of the satellite is calculated from the receive power. The EIRP is the power that the satellite must radiate so that the measured receive power is obtained. For this calculation, it is assumed that an isotropic transmit antenna is used, i.e. an antenna that uniformly radiates in all directions.

$$\frac{EIRP}{dBW} = \frac{P_{RX}}{dBm} + \frac{G_r}{dB} + \frac{a}{dB} - 30$$

where **P_{RX}** is the receive power, **Gr** the gain of the receive antenna, and **a** the nominal path attenuation in the order of 200 dB. Comparing the EIRP values thus obtained with the satellite's specified EIRP will yield a measure of the current quality of the radio link.

Three-path diode power sensors are suitable for numerous applications, including this one, since they support continuous average, burst average, timeslot average, gate average and trace measurements coupled to a very low measurement limit. These power sensors feature outstanding performance and unprecedented measurement speed and accuracy. For detailed analysis, the sensors offer additional measurement functions such as timeslot mode and trace mode with a video bandwidth of 100 kHz.

Offering a frequency range of up to 50 GHz, the NRPxxS/SN power sensors are a perfect choice for installation, maintenance and remote monitoring of ground stations for satellite systems. The NRPxxSN LAN power sensors are ideal for remote monitoring applications, e.g. for satellite systems, where sensors need to be placed at different points in the system. After connecting the sensors to a LAN using power-over-Ethernet (PoE) switches, the system can be remotely monitored from a control center.

Using an Internet connected PC, the NRPxxSN sensors can be conveniently controlled via a web browser, that means no additional software application needs to be installed on the control PC.

6.2 On-Orbit Group Delay Measurement

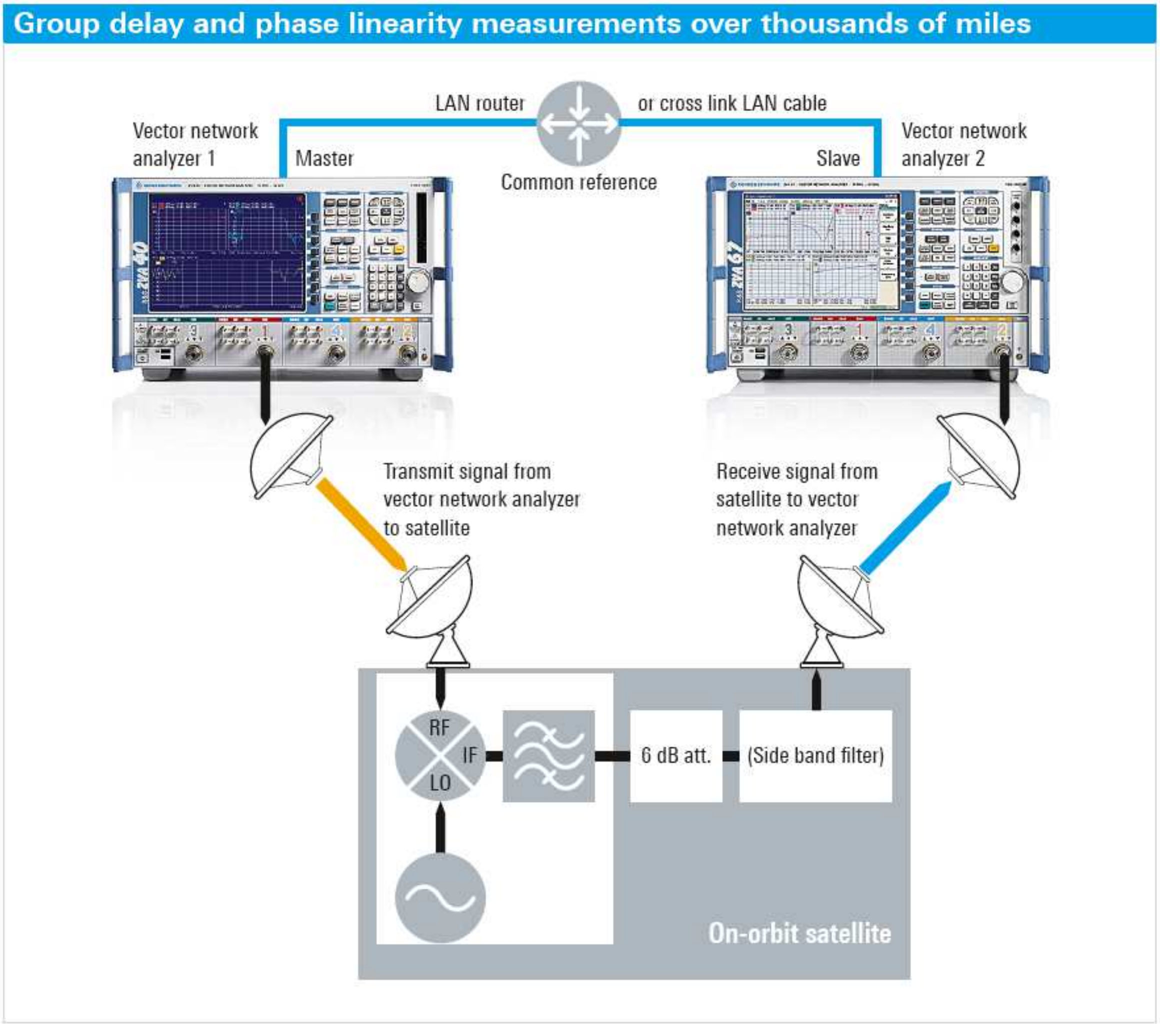


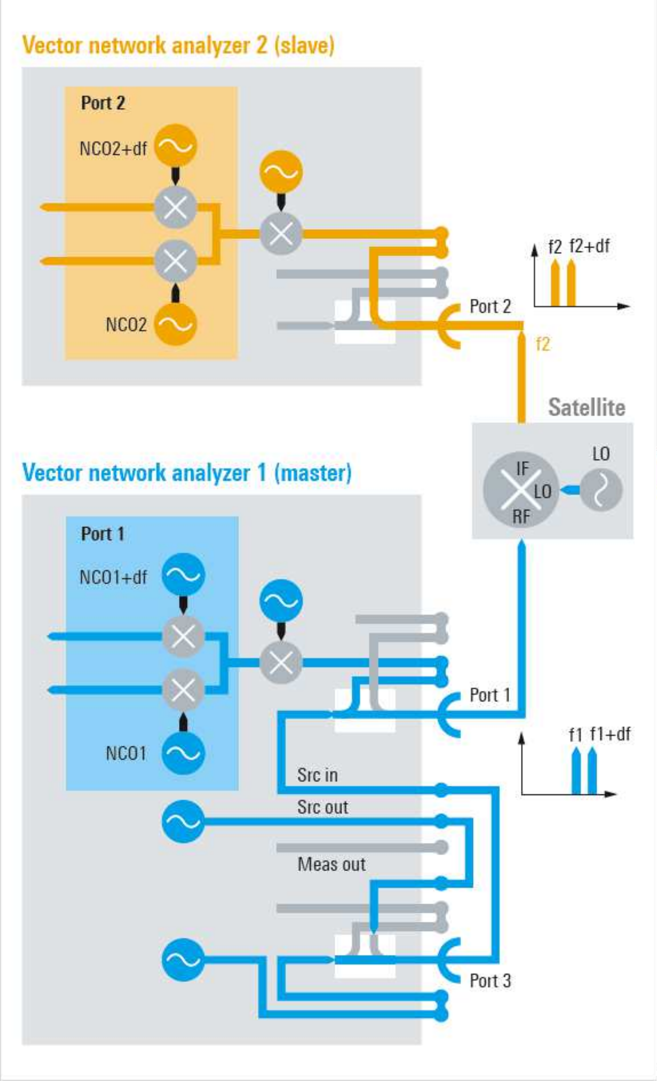
Figure 5: Group Delay measurement setup using two separated ZVA

Measuring group delay over distance between the transmitter and receiver requires synchronization, triggering and transferring results from the two stations. Using the configuration shown in Figure 5, the long distance group delay measurement can be made very easily.

The ZVA-K10 Long Distance Group Delay Measurement is an extension of the existing ZVA-K9 Group Delay Measurement on frequency converting devices with embedded LO. The option ZVA-K10 is designed to measure relative group delay and deviation from linear phase of frequency converting and non-frequency converting DUTs with two separated instruments of the ZVA/T family. The measurement requires no coaxial connection between both instruments. The communication between both instruments is performed via LAN/LXI connection. The two network analyzers communicate with each other and synchronize the test sequence between each other via a LAN connection.

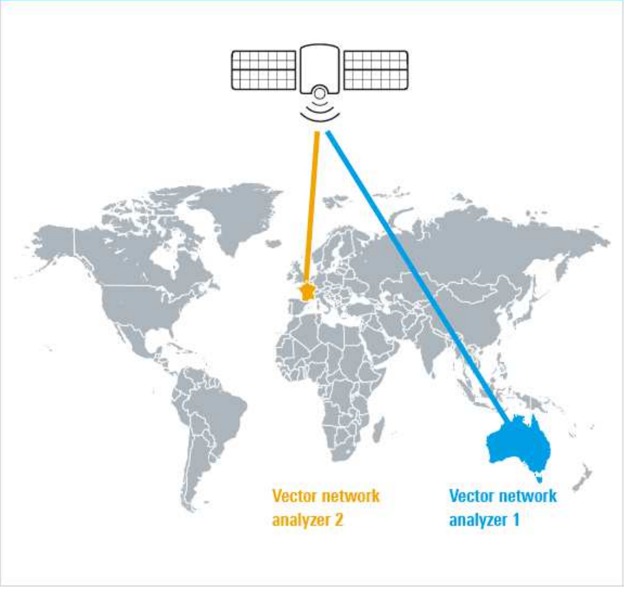
Using the configuration shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**, the long distance group delay measurement can be made very easily. For this measurement setup, two ZVA vector network analyzers are required and are configured as master and slave. The minimum firmware version 2.76 are required on both of the ZVAs. The first ZVA works as a master and controls via a LAN/ LXI connection a second slave ZVA. The master generates the required two-tone signal, controls and synchronizes the receiver of the slave instrument, and displays the measurement result on its screen. Both instruments are connected to a common reference frequency (normally wireless, e.g. GPS reference). A LAN cable directly between the instruments or via a LAN router establishes the connection for synchronization.

Internal block diagram of the group delay measurement setup using two VNAs from Rohde & Schwarz



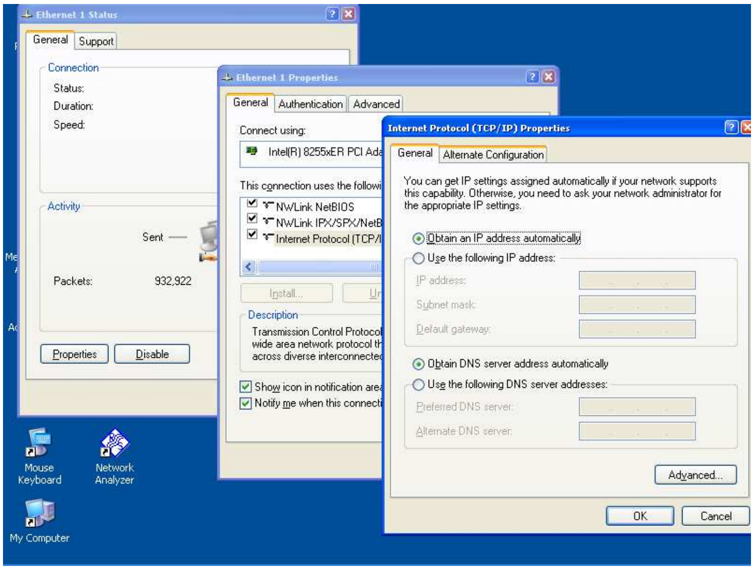
- ► 2 different ZVA:
  NCOs (digital LOs) for reference and receiver channels are separated
  → highly stable time conditions
- ► Common frequency reference is very important

Possible position of the two VNAs



For the LXI instrument setup:

- ► Connect the two ZVA/ZVT via LAN router or a (crosslink) cable
- ► Set both ZVA/ZVT to "Obtain IP address automatically"



Internet Protocol (TCP/IP) Properties

You can get IP settings assigned automatically if your network supports this capability. Otherwise, you need to ask your network administrator for the appropriate IP settings.

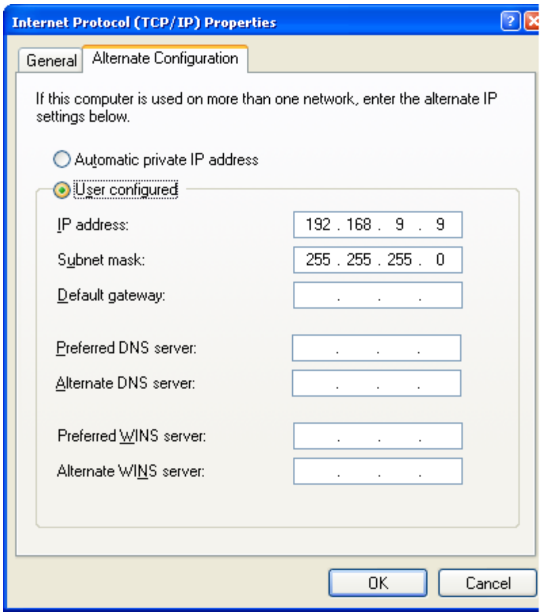
● Obtain an IP address automatically

○ Use the following IP address:

● Obtain DNS server address automatically

○ Use the following DNS server addresses:

- ► Open „Alternate configuration“, enter a „User configured“ IP address (e.g. one digit higher than the slave ZVAT address)



Internet Protocol (TCP/IP) Properties

If this computer is used on more than one network, enter the alternate IP settings below.

○ Automatic private IP address

● User configured

IP address: 192 . 168 . 9 . 9

Subnet mask: 255 . 255 . 255 . 0

Default gateway: . . .

Preferred DNS server: . . .

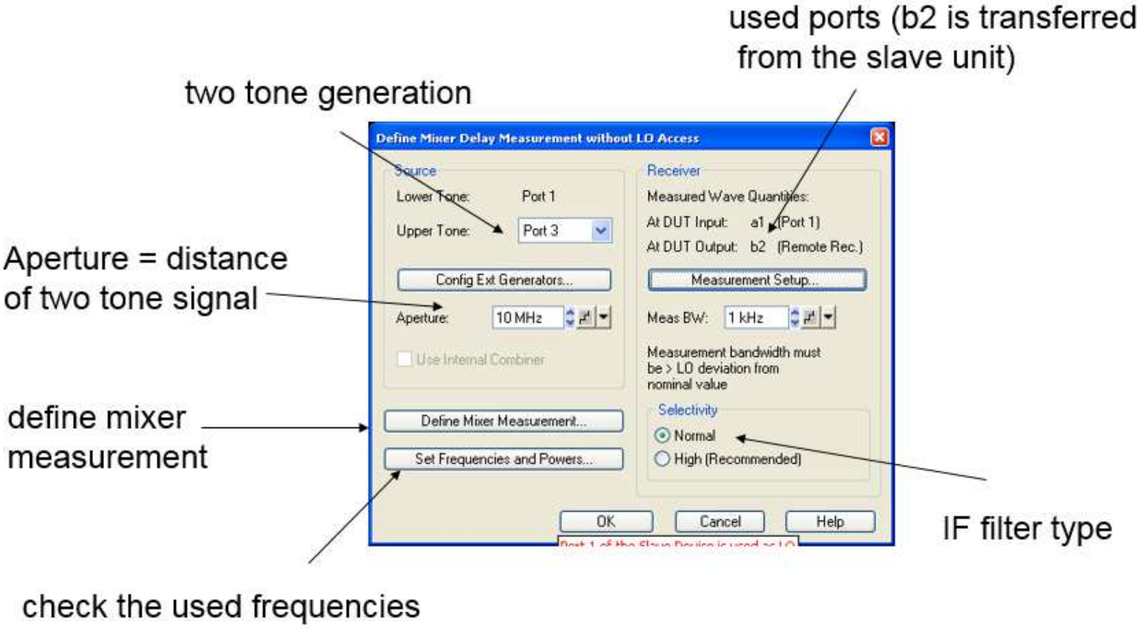
Alternate DNS server: . . .

Preferred WINS server: . . .

Alternate WINS server: . . .

- ► Start the NI "Measurement & Automation Explorer"
- ► Add a new network device
- ► → Enter the IP address manually!

Configuring the User interface on the R&S®ZVA:



used ports (b2 is transferred from the slave unit)

two tone generation

Aperture = distance of two tone signal

define mixer measurement

check the used frequencies

IF filter type

Define Mixer Delay Measurement without LO Access

Source

Lower Tone: Port 1

Upper Tone: Port 3

Aperture: 10 MHz

☐ Use Internal Combiner

Receiver

Measured Wave Quantities:

At DUT Input: a1 (Port 1)

At DUT Output: b2 (Remote Rec.)

Meas BW: 1 kHz

Measurement bandwidth must be > LO deviation from nominal value

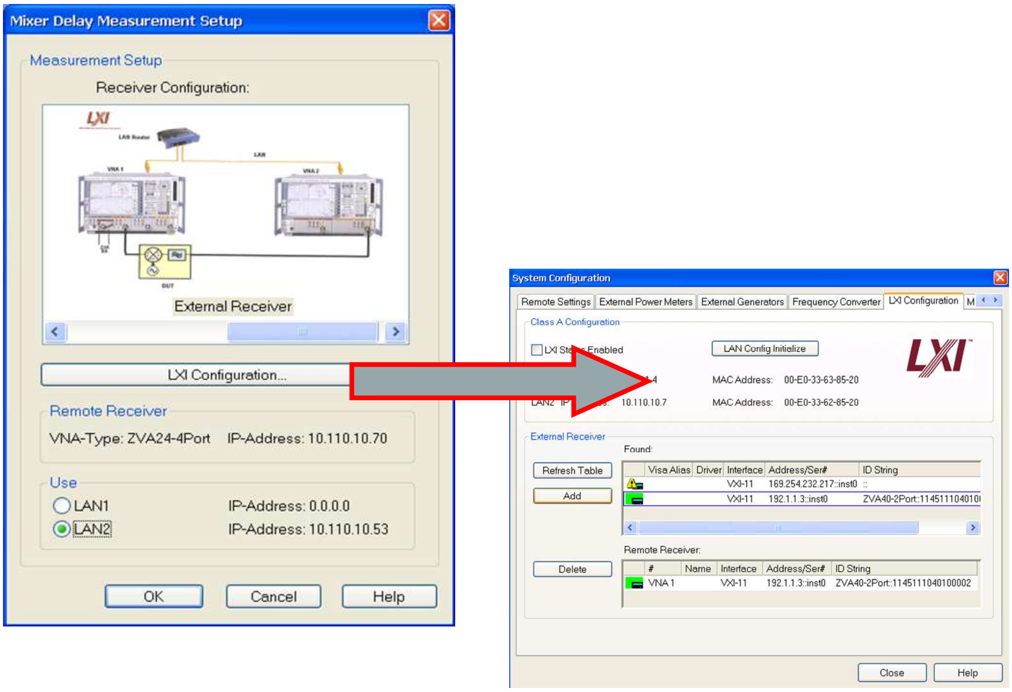
Selectivity

● Normal

○ High (Recommended)

Port 1 of the Slave Device is used as LO

Mixer Delay configuration:



Mixer Delay Measurement Setup

Measurement Setup

Receiver Configuration:

Remote Receiver

VNA-Type: ZVA24-4Port IP-Address: 10.110.10.70

Use

○ LAN1 IP-Address: 0.0.0.0

● LAN2 IP-Address: 10.110.10.53

System Configuration

☐ LXI Sta... Enabled

...4 MAC Address: 00-E0-33-63-85-20

LAN2 IP... 10.110.10.7 MAC Address: 00-E0-33-62-85-20

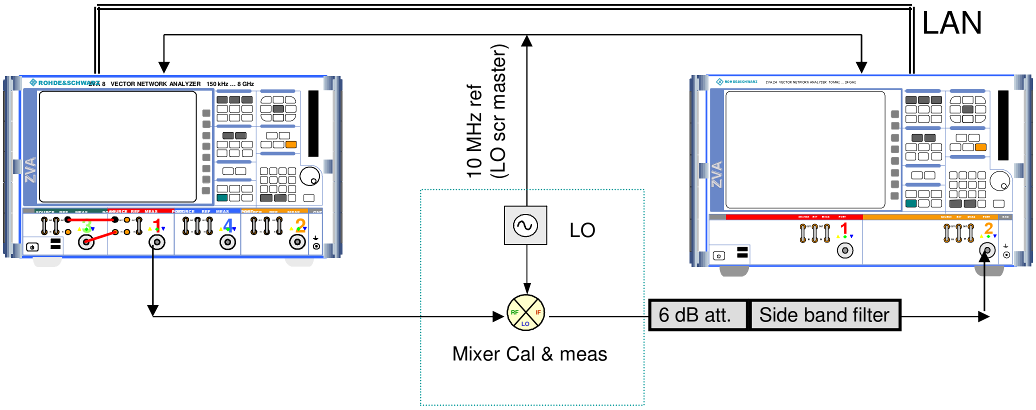
Found:

	Visa Alias	Driver	Interface	Address/Ser#	ID String
⚠			VXI-11	169.254.232.217::inst0	::
🟩			VXI-11	192.1.1.3::inst0	ZVA40-2Port::114511104010

Remote Receiver:

	#	Name	Interface	Address/Ser#	ID String
🟩	VNA 1		VXI-11	192.1.1.3::inst0	ZVA40-2Port::1145111040100002

Calibration and Verification:



Calibration setup:

- Golden or known mixer
- Embedded LO realized by an external source
- 10 MHz reference connected

Measurement setting

- Same mixer setup like calibration

Verification:

- Keep the calibration mixer connected
- Insert a 50 cm cable
- → evaluate ~ 2 ns delay

Typical values for:

- Group delay: ~size of mixer
- Minicircuit: 100 ps or 320 ps
- 50 cm cable: ~2 ns

Group delay (default)

- MEAS :→ :→ : Mixer Meas :
  - Mixer Delay
  - Delay Derivative
  - Mixer Phase (relative)
- Ratio b2/a1

Do's and Don'ts for Long Distance Group Delay Calibration

To keep calibration valid, do not…

- Power down the analyzers.
- Change the aperture.
- Switch to measurement quantities, which are not supported by the option ZVA-K10.

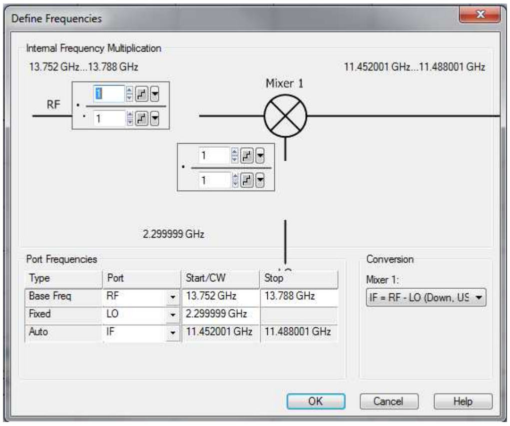
Reason

- The NCOs (internal digital LO) will restart, with arbitrary phase.
  → Arbitrary delay (new calibration required).
- → Absolute GD is possible, when instruments are not switched off after Cal.
  → Otherwise, GD is relative to the calibration mixer.
- Do not disconnect the 10 MHz reference signal for calibration.
- Do not switch to wave quantities:
  a trace is displayed, but mostly no meaningful data are displayed.
- Use the lowest possible frequency range in order to minimize cable loss.
- Use a cable & mixer with defined delay between Tx Port Analyzer 1 and Rx Port Analyzer 2.

Typically, satellite converters are used for up- and down-links of satellites, or inside satellites. The LO is not accessible, and the reference signal is not available. Group delay is the key parameter for low bit error rate of data transmission.

Test conditions for Group Delay Measurements

- Bandwidth 36 MHz
- Pin -25 dBm
- Pout -85 dBm…-45 dBm
- Uplink 13 GHz
- Downlink 11 GHz
- LO 2.3 GHz
- Altitude 39553 km
- Absolute group delay uplink 131.8 ms
- Up+Down link 263.6 ms



Port Frequencies

Type	Port	Start/CW	Stop
Base Freq	RF	13.752 GHz	13.788 GHz
Fixed	LO	2.299999 GHz	
Auto	IF	11.452001 GHz	11.488001 GHz

Conversion

Mixer 1: IF = RF - LO (Down, US

- Phase shift between two adjacent frequency points may not exceed 180°.

- For two-tone technique, phase shift within the aperture may not exceed 180°.

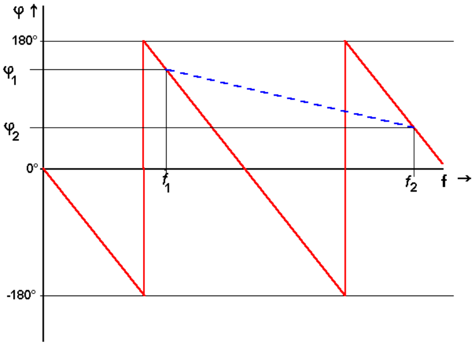


Figure 6: Incorrect phase tracking caused by too large aperture

$$\Delta\varphi(f) = -360 * \Delta f * \tau$$

$$\Delta\varphi_{max} = 180° \qquad => \Delta f_{max} = \frac{0.5}{\tau}$$

$$\tau = 260\,ms$$

$$\Delta f_{max} = \frac{0.5}{260\,ms} = 1.9\,Hz$$

Measurement Uncertainty:

$$\partial\tau = \frac{-1}{360°} * \frac{\partial\varphi}{\Delta f}$$

$$\partial\varphi = 0.1°$$

Aperture	Group delay uncertainty
2 Hz	140 us
10 Hz	28 us
10 kHz	28 ns
100 kHz	2.8 ns
1 MHz	278 ps
2 MHz	140 ps
5 MHz	56 ps

Table 1: Typical Group Delay uncertainty for different aperture

Group Delay τ	Aperture Δf		
	Minimum	Optimum	Maximum
1 ns	300 kHz	300 MHz	500 MHz
10 ns	30 kHz	30 MHz	50 MHz
100 ns	3 kHz	3 MHz	5 MHz
1 us	300 Hz	300 kHz	500 kHz
10 us	30 Hz	30 kHz	50 kHz
100 us	3 Hz	3 kHz	5 kHz
1 ms	0.3 Hz	300 Hz	500 Hz

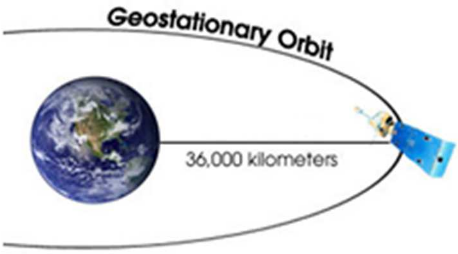
Table 2: Typical Group Delay for different aperture

- Use of wide aperture, e.g. 3 MHz
- Aperture is selected according to group delay variation of the transponder
  - Measurement of relative group delay
  - Shows group delay variation inside the frequency band of the transponder channel (including uplink and downlink amplifier)

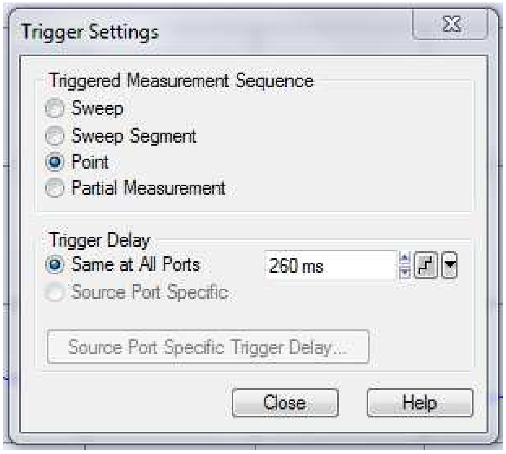
6.2.1 Group Delay Measurement Problems

There are usually two problems with the long distance group delay measurement.

1. Long distance



- ► Transition time of about 130 ms due to distance to earth in case of geostationary satellites (More precise delay values can be computed if the orbital state vectors of the satellite are known)
- ► Delay of 260 ms between measurement of sending two-tone signal and receiving it. The ZVA receiver already switched to next frequency points when former signal arrives
- ► Solution => trigger delay of > 260 ms
- ► Select **Point** trigger delay
- ► Measurement time per point about 260 ms



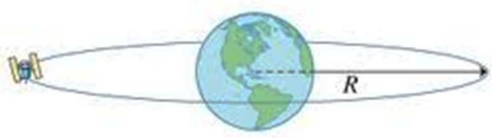
Trigger Settings

Triggered Measurement Sequence
○ Sweep
○ Sweep Segment
● Point
○ Partial Measurement

Trigger Delay
● Same at All Ports 260 ms
○ Source Port Specific

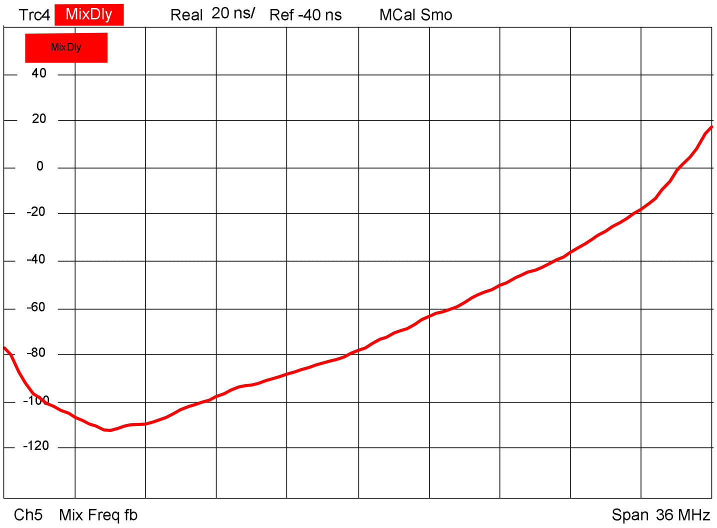
Figure 7: Trigger setting configuration

2. Movement of the satellite



- ► Movement of the satellite in its elliptic orbit
- ► Change of distance e.g. 2230 m/h; this value varies depending on the satellite and its position in the orbit
- ► Measurement time of ZVA:

- 101 points 260 ms -> 26 seconds



- Distance shift during 1 hour
  - = 2230 m
- Distance shift during 1 sec
  - = 2230 m / 3600 = 0.62 m
    => for up and downlink 2 * 0.62 m = 1.24 m
- Distance shift from beginning of sweep to end of sweep
  - Sweep time for 101 points
  - = 101*0.26 = 26.3 s
  - = sweep time (sec) * 1.24 m
  - = 26.3 * 1.24 m = 32.58 m
- Increase of group delay from the beginning of the sweep to end of sweep
  - Dt = Dist / c
  - 32.58 m / 3 exp(8) = 108.6 ns
- Correction by using quasi CW sweep:
  - Additional group delay measurement using narrow span to achieve identical sweep speed
  - Displayed linear variation is due to the satellite movement
  - Subtraction from frequency swept Group Delay via trace math

- Trc4 – Trc 5 (Figure 8**Fehler! Verweisquelle konnte nicht gefunden werden.**)

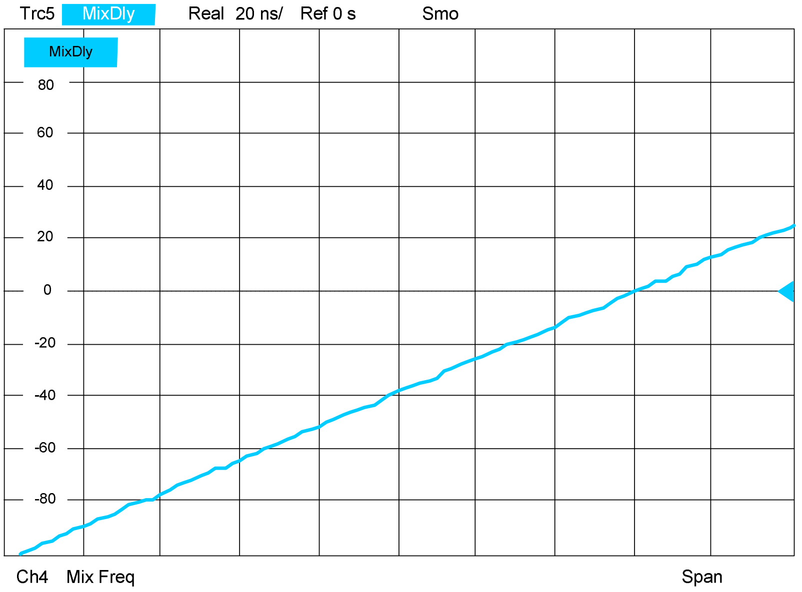


Figure 8: Corrected long distance group delay plot

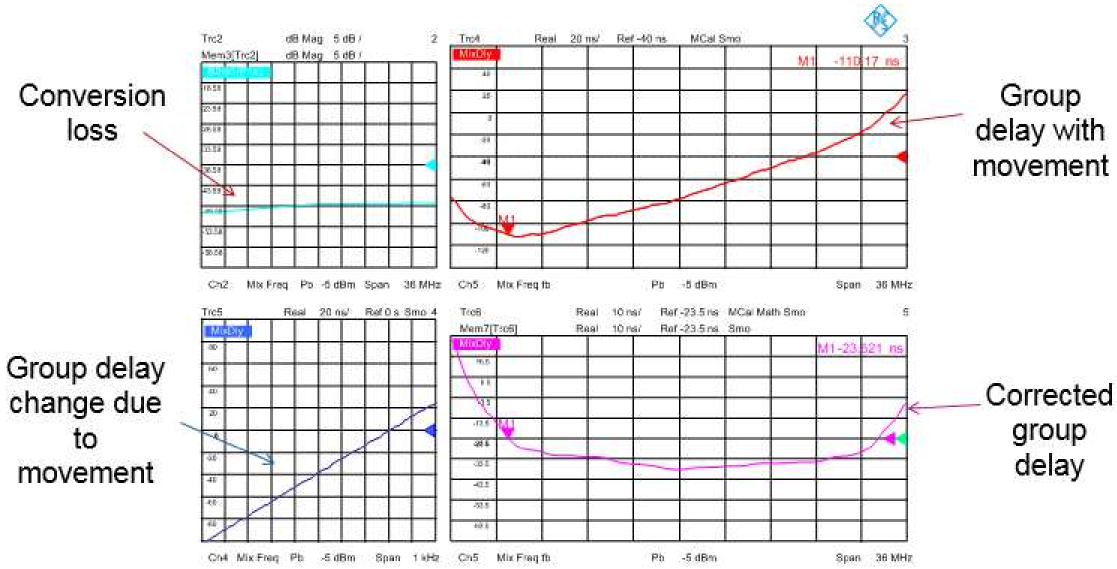


Figure 9: Group delay results before and after correction

Figure 9 shows the group delay measurement on an end-to-end satellite link with and without correction by using quasi CW sweep.

6.3 Double-Illumination Monitoring

Accidental interference results in a satellite link in the worst case, being taken out of operation or degradation in the guaranteed QOS. It is desirable to performing the double-illumination monitoring as fast as possible. The optional real-time measurement application extends the FSW to a full-featured real-time spectrum analyzer. With this, the FSW offers the combination of a high-end signal and spectrum analyzer with excellent RF performance without the drawbacks of traditional real-time analyzers and an outstanding real-time performance in one box.

The FSW-B800R option displays 800 MHz of RF spectrum seamlessly and in real time, nearly 1 200 000 FFTs/s and a 100% Probability of Intercept (POI) for a signal duration down to 0.91µs. In case the assessment bandwidth requirement is less, the B512R or B160R with 512MHz and 160MHz bandwidth, respectively, can also be used for seamless real time spectrum monitoring.

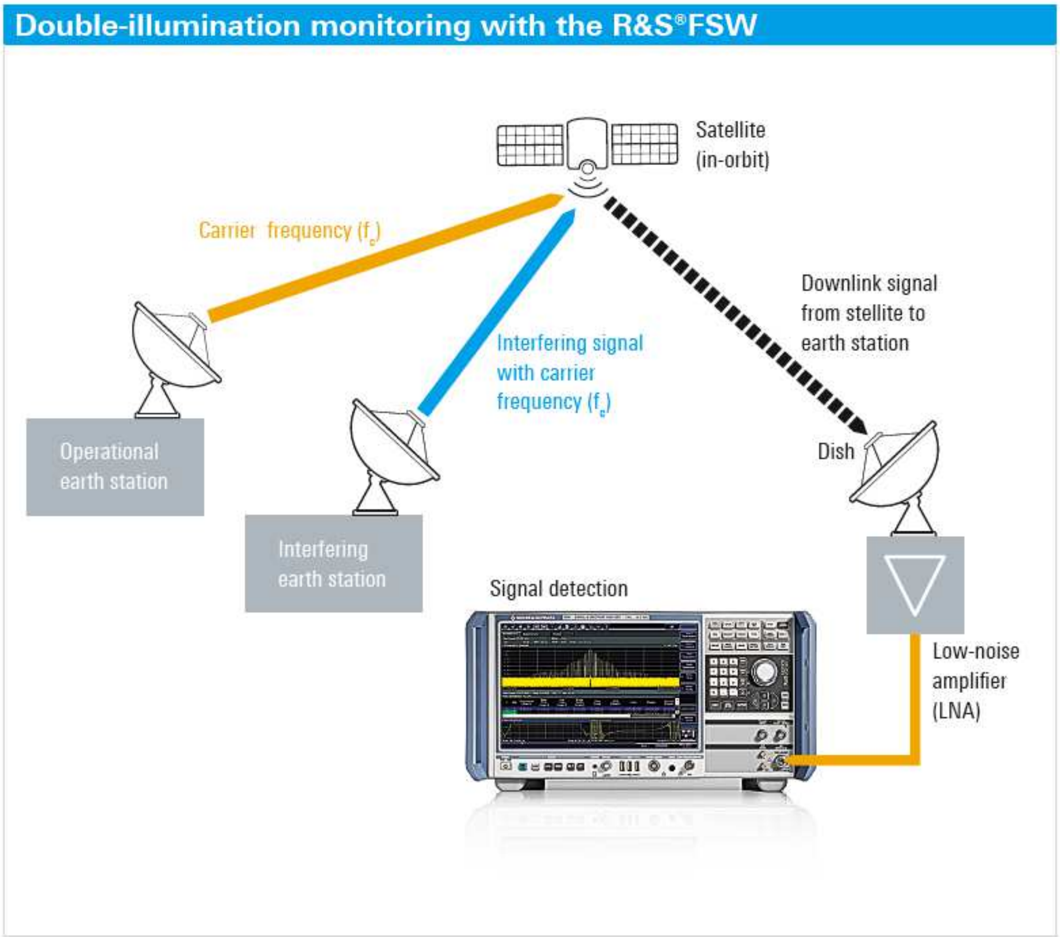


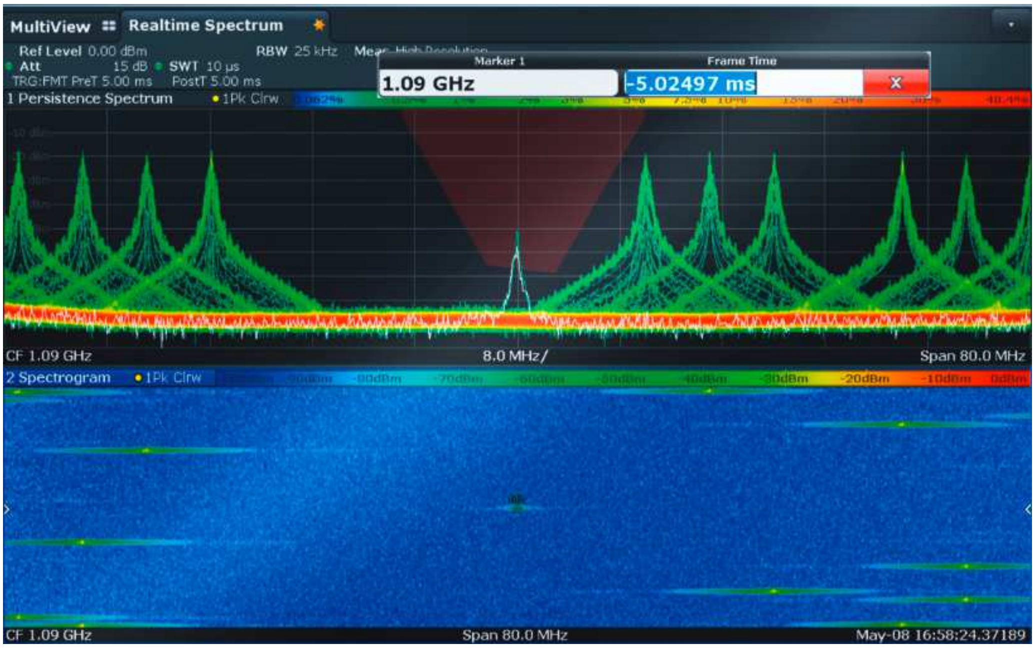
Figure 10: Double-illumination monitoring setup

The real-time measurement application on the spectrum analyzer help RF design engineers to detect short and sporadic interference signals and identify their causes. The FSW is located in the observation Earth station and the double-illumination monitoring setup is shown in Figure 10. The ground station antenna connected to the FSW picks up signal sent from the satellite that is being monitored.

FSW:

- MODE: Real-time Spectrum
- Frequency: 1.09 GHz (adjust the frequency according to the channel that is intended to be monitored)
- Span: 80 MHz (up to 800 MHz is possible)

Figure 11 shows the FSW-B160R option used to analyze a sporadic signal captured using a frequency dependent mask. Marker M1 is used to identify frame time and frequency of the captured signal.



Ref Level 0.00 dBm
Att 15 dB
SWT 10 µs
RBW 25 kHz
TRG:FMT PreT 5.00 ms
PostT 5.00 ms
Marker 1: 1.09 GHz
Frame Time: -5.02497 ms

Figure 11: The real-time spectrum view on the FSW

For visual assessment, the FSW with the FSW-B800R, -B512R or -B160R offers a real-time spectrogram in addition to the instantaneous spectrum and, in persistence mode, a real-time spectrum with the signal amplitudes shown in different colors according to their frequency of occurrence (persistence spectrum). Frequency-dependent masks help the user reliably detect sporadic signals in the spectrum, as the FSW will activate a trigger whenever a spectrum violates a mask.

In Figure 11, the double illumination can be seen as a small peak at the center of the Persistence Spectrum (upper part of screen), whereas a judgement on time (in)variance of the disturbance can be made based on the Spectrogram display in the lower part of the screen.

The FSW with the FSW-B160R/-B512R/-B800R spectrum analyzer option is the instrument of choice when it comes to spectrum monitoring.

6.4 Satellite Carrier Monitoring

Satellite carrier monitoring often involves monitoring large spectrum blocks and analyzing the carriers transmitted from an In-orbit satellite at different frequencies for power and digital demodulation characteristics. The channel power of the entire bandwidth and carrier digital demodulation of the channel is of importance in order to monitor a channel. Other parameters such as Error Vector Magnitude (EVM), signal magnitude and phase and constellation plot of demodulated signals from a satellite can be easily monitored by using the optional VSA mode of the analyzer.

The FSW-K70 is the general purpose vector signal analyzer for single carrier Modulation. It supports the demodulation of all standard single carrier modulation formats from simpler formats such as ASK, MSK up to 1024 QAM. Other features of the FSW-K70 includes

- Equalizer
- Support of 2-ASK, APSK and 4-ASK, 512QAM and 1024QAM
- Support of the FSW user interface, sequencer and MSRA (Multi Standard Radio Analyzer)
- Satellite systems with the 16-APK systems, or user definable modulation formats

In addition a small software tool (available on the FSW) makes the configuration for DVB-S2(X) signals more convenient. For details please refer to the Application Note 1EF93.

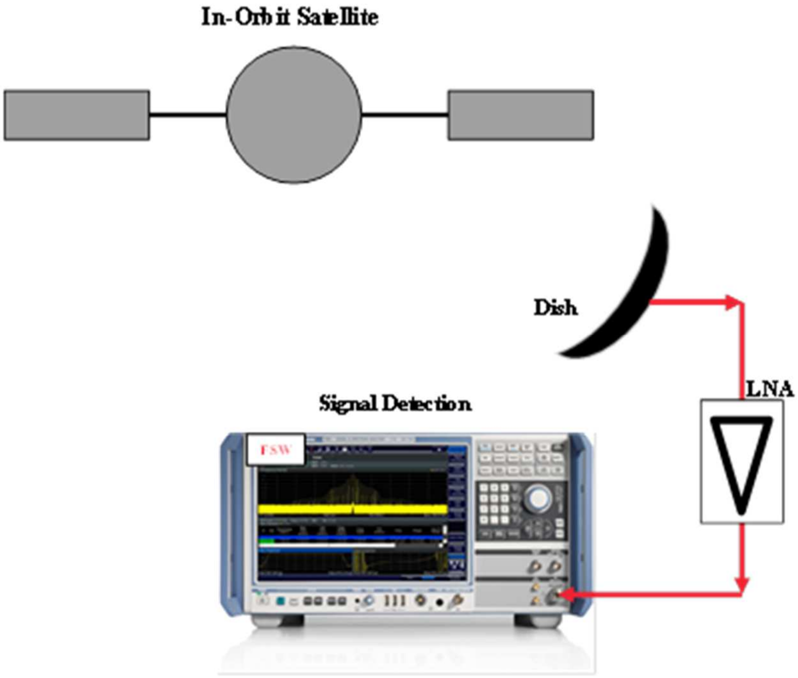


Figure 12: On-Orbit satellite carrier monitoring

Satellite monitoring operation can be performed with high accuracy and speed, by using the setup as shown in Figure 12. Depending on the ground station configuration and frequency band being used, there may be a downconverter that translates the frequency to a lower one before monitoring. R&S spectrum analyzers are available for different frequency ranges (i.e. up to 8/13.6/26.5/43.5/50/67/85 GHz). After the LNA on the receive side there is no requirement for additional frequency down-conversion but if the signal is down-converted, select the FSW accordingly to the required frequency band.

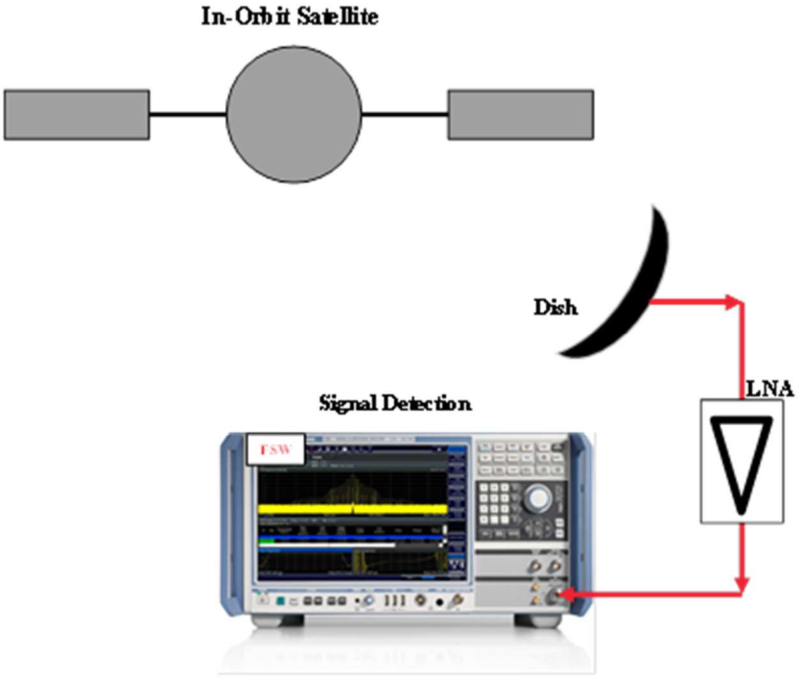


Figure 12: On-Orbit satellite carrier monitoring

FSW:

To activate the VSA application

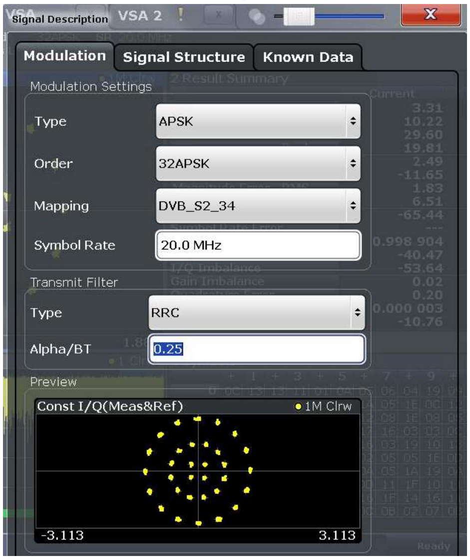
► Press the MODE key on the front panel of the FSW.

A dialog box opens that contains all operating modes and applications currently available on your FSW.

► Select the "VSA" item.

The FSW opens a new measurement channel for the VSA application.

► Select Signal Description.



Type APSK
Order 32APSK
Mapping DVB_S2_34
Symbol Rate 20.0 MHz
Type RRC
Alpha/BT 0.25

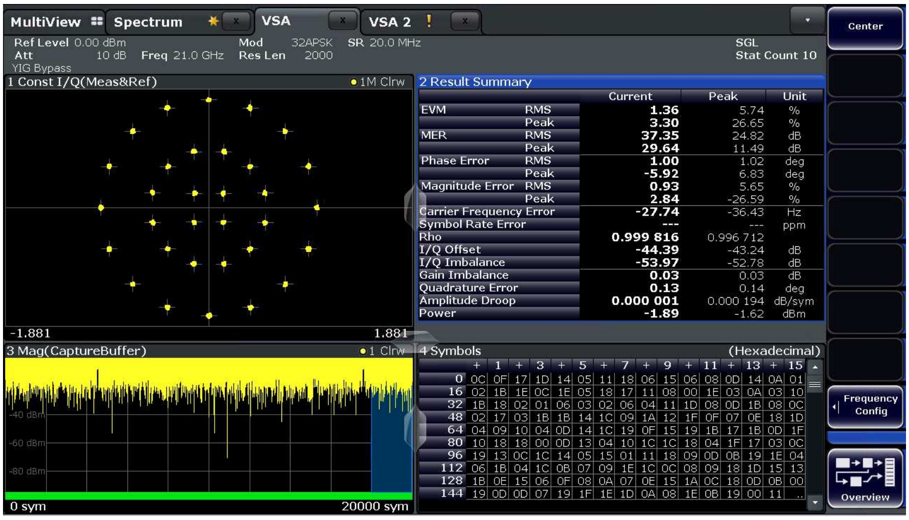
► Define signal modulation parameters

► Next select MEAS CONFIG > Signal Capture > Data Acquisition > 20000 symbols

► Select MEAS CONFIG > Range Settings> Result Range > 2000 Symbols

► Select Frequency > 21 GHz and 30 GHz (for this example)

► From the Result Summary window, all relevant signal characteristics can be monitored



Ref Level 0.00 dBm
Att 10 dB
Freq 21.0 GHz
YIG Bypass
Mod 32APSK
Res Len 2000
SR 20.0 MHz
SGL
Stat Count 10

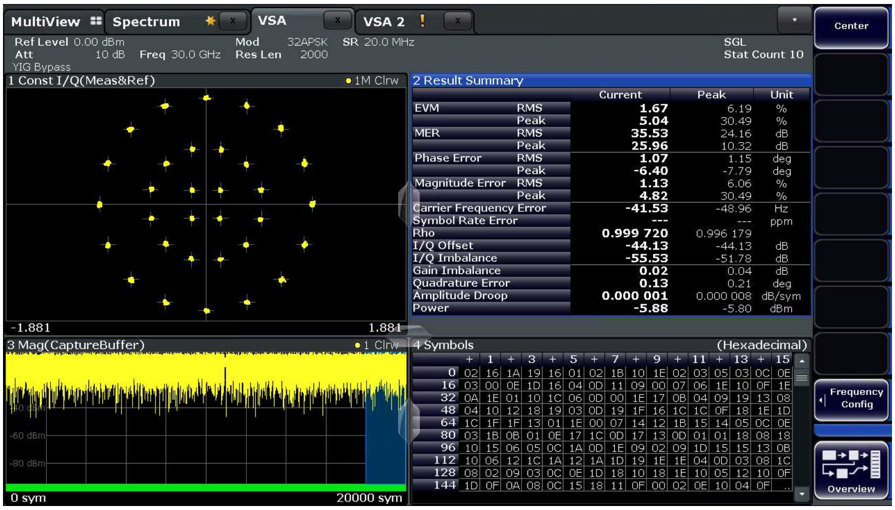
2 Result Summary

		Current	Peak	Unit
EVM	RMS	1.36	5.74	%
	Peak	3.30	26.65	%
MER	RMS	37.35	24.82	dB
	Peak	29.64	11.49	dB
Phase Error	RMS	1.00	1.02	deg
	Peak	-5.92	6.83	deg
Magnitude Error	RMS	0.93	5.65	%
	Peak	2.84	-26.59	%
Carrier Frequency Error		-27.74	-36.43	Hz
Symbol Rate Error		---	---	ppm
Rho		0.999 816	0.996 712	
I/Q Offset		-44.39	-43.24	dB
I/Q Imbalance		-53.97	-52.78	dB
Gain Imbalance		0.03	0.03	dB
Quadrature Error		0.13	0.14	deg
Amplitude Droop		0.000 001	0.000 194	dB/sym
Power		-1.89	-1.62	dBm

4 Symbols (Hexadecimal)

	+	1	+	3	+	5	+	7	+	9	+	11	+	13	+	15
0	0C	0F	17	1D	14	05	11	18	06	15	06	08	0D	14	0A	01
16	02	1B	1E	0C	1E	05	18	17	11	08	00	1E	03	0A	03	10
32	1B	18	02	01	06	03	02	06	04	11	1D	08	0D	1B	08	0C
48	02	17	03	1B	1B	14	1C	09	1A	12	1F	0F	07	0E	18	1D
64	04	09	10	04	0D	14	1C	19	0F	15	19	1B	17	1B	0D	1F
80	10	18	18	00	0D	13	04	10	1C	1C	18	04	1F	17	03	0C
96	19	13	0C	1C	14	05	15	01	11	18	09	0D	0B	19	1E	04
112	06	1B	04	1C	0B	07	09	1E	1C	0C	08	09	18	1D	15	13
128	1B	0E	15	06	0F	08	0A	07	0E	15	1A	0C	18	0D	0B	00
144	19	0D	0D	07	19	1F	1E	1D	0A	08	1E	0B	19	00	11	..

Figure 13: DVB-S2 Signal Analysis using FSW-K70 at 21 GHz



Ref Level 0.00 dBm
Att 10 dB Freq 30.0 GHz
YIG Bypass
Mod 32APSK SR 20.0 MHz
Res Len 2000
SGL
Stat Count 10

2 Result Summary

		Current	Peak	Unit
EVM	RMS	**1.67**	6.19	%
	Peak	**5.04**	30.49	%
MER	RMS	**35.53**	24.16	dB
	Peak	**25.96**	10.32	dB
Phase Error	RMS	**1.07**	1.15	deg
	Peak	**-6.40**	-7.79	deg
Magnitude Error	RMS	**1.13**	6.06	%
	Peak	**4.82**	30.49	%
Carrier Frequency Error		**-41.53**	-48.96	Hz
Symbol Rate Error		**---**	---	ppm
Rho		**0.999 720**	0.996 179	
I/Q Offset		**-44.13**	-44.13	dB
I/Q Imbalance		**-55.53**	-51.78	dB
Gain Imbalance		**0.02**	0.04	dB
Quadrature Error		**0.13**	0.21	deg
Amplitude Droop		**0.000 001**	0.000 008	dB/sym
Power		**-5.88**	-5.80	dBm

4 Symbols (Hexadecimal)

	+	1	+	3	+	5	+	7	+	9	+	11	+	13	+	15
0	02	16	1A	19	16	01	02	1B	10	1E	02	03	05	03	0C	0E
16	03	00	0E	1D	16	04	0D	11	09	00	07	06	1E	10	0F	1E
32	0A	1E	01	10	1C	06	0D	00	1E	17	0B	04	09	19	13	08
48	04	10	12	18	19	03	0D	19	1F	16	1C	1C	0F	18	1E	1D
64	1C	1F	1F	13	01	1E	00	07	14	12	1B	15	14	05	0C	0E
80	03	1B	0B	01	0E	17	1C	0D	17	13	0D	01	01	18	08	18
96	10	15	06	05	0C	1A	0D	1E	09	02	09	1D	15	15	13	0B
112	10	06	12	1C	1A	12	1A	1D	19	1E	1E	04	0D	03	08	1C
128	08	02	09	03	0C	0E	1D	18	10	18	1E	10	05	12	10	0F
144	1D	0F	0A	08	0C	15	18	11	0F	00	02	0E	10	04	0F	..

Figure 14: DVB-S2 Signal Analysis using FSW-K70 at 30 GHz

In Figure 13 and Figure 14, a DVB-S2 signal with 32APSK modulation (Roll-off = 0.25, Symbol Rate = 20 MS/s and code rate 3/4) being analyzed at 21 GHz and 30 GHz.

The FSW-K70 (Vector Signal Analysis) option enables users to flexibly analyze digitally modulated single carriers (up to 8 GHz bandwidth) down to the bit level. The clearly structured operating concept simplifies measurements, despite the wide range of analysis tools. Additionally; FSW-K70P BER (Bit Error Rate) measurements can be done on PRBS data. This measurement application is an extension of the vector signal analysis option FSW-K70. It is an important add on feature BER measurement is required on digital modulated signals with long data sequences like PRBS23, where the sequence is 2^{23} bits long.

7 In-Orbit Satellite Payload Testing System

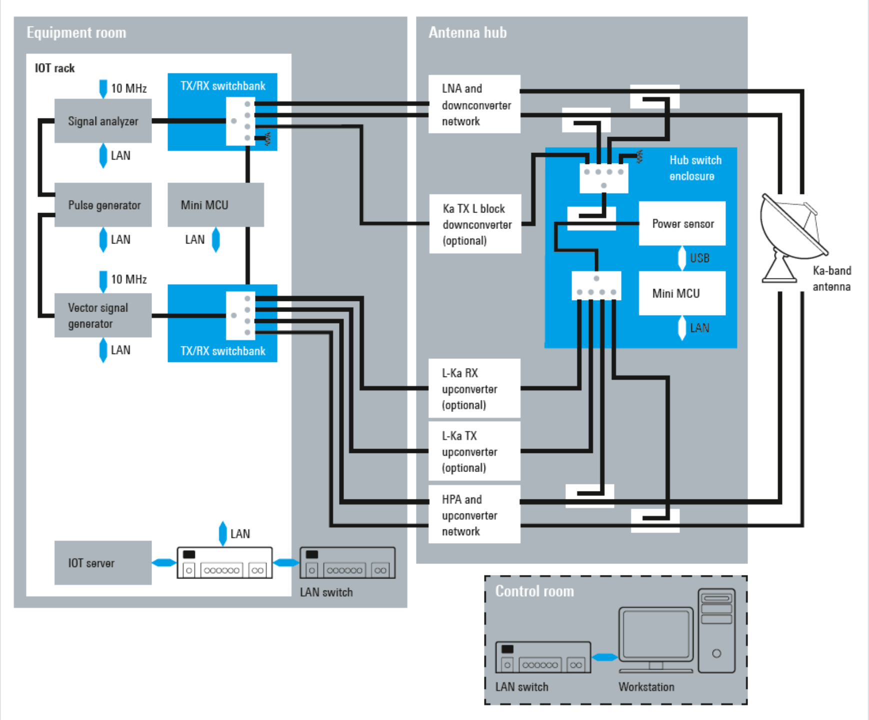
Automated On-orbit Payload Test Systems or otherwise known as IOT Test system, is not a new concept in performing fast and reliable post-launch payload testing. All the typical post-launch measurements i.e. the overall link EVM measurements, long distance group delay measurement and more importantly customer specific test requirements can be automated in a test system.

Fehler! Verweisquelle konnte nicht gefunden werden. shows an automated satellite payload test system built by a test system manufacturer, SED Systems, using instruments from Rohde & Schwarz. Rohde & Schwarz equipment served as OEM for the final Test bench.

Figure 15: Automatized Test System using Rohde & Schwarz Test Equipment [courtesy SED Systems]

This automated test system is a commercial implementation using Rohde & Schwarz COTS instruments such as one FSL spectrum analyzer, two SMBV Vector Signal Generator for generating digitally modulated test signals, one SMB RF and Microwave Signal Generator and one FSUP Signal Source Analyzer for performing Signal/Spectrum and Phase Noise Analysis. A key component of the test system is the software code operating on the system server. The server code is written in C++ and runs on a Linux operating system, communicating with the test instruments and performing the measurements. A Rohde & Schwarz signal generator provides a clean test carrier for the measurements or for use as a calibration source. A second Rohde & Schwarz signal generator can be added for optional measurements that require multiple test carriers. For measurements requiring many test carriers, a Rohde & Schwarz vector signal generator is added.

Block diagram of the test system from SED using Rohde & Schwarz instruments



The main measurement instrument is a Rohde & Schwarz signal and spectrum analyzer, which performs frequency domain or time domain measurements. A pulse generator triggers the synthesizer(s) and signal analyzer for fast-stepped measurements in either frequency or power. In the antenna hub, an SED manufactured hub switch enclosure monitors the transmitted test carriers for power and frequency. Switching and signal routing for both transmit and receive functions are supported. Multiple other features such as long distance group delay measurement, double-illumination monitoring, etc. can be integrated into the test system based on user requirement. Using the graphical interface an operator enters sequences of measurements to be performed, parameter tables for the measurements to be executed, data on the satellites to be measured, and nominal calibration data in preparation for an in-orbit test campaign. During the campaign, the system operates in a fully automated mode, performing the measurement sequences that have been specified. As measurements are performed, results are displayed along with the current status of the system.

Routine calibrations are fully automated. Manual calibrations can be undertaken to support one-time events (for example, when a transmit monitor coupler is replaced) and involve only passive components. The results of these onetime calibrations are input into the system database.

8 Literature

[1] "UCS Satellite Database," [Online]. Available: http://www.ucsusa.org/nuclear_weapons_and_global_security/solutions/space-weapons/ucs-satellite-database.html#.VK0CAivF9WE .

[2] "Grammar in Space: Are Satellites 'In Orbit' or 'On Orbit'," [Online]. Available: http://www.theatlantic.com/technology/archive/2014/11/grammar-in-space-are-you-in-orbit-or-on-orbit/381522/ .

9 Ordering Information

Vector Network Analyzer*

Designation	Type	Order No.
Vector Network Analyzer, 10MHz to 40GHz, Four ports, four generators / sources	R&S®ZVA40	1145.1110.48
Direct generator/receiver access for 4 port ZVA40	R&S®ZVA40-B16	1164.0209.42
Set of cables for the ZVA-K9	R&S®ZVA40-B9	1305.6541.03
Frequency Conversion	R&S®ZVA-K4	1164.1863.02
Embedded LO Mixer Delay Measurements	R&S®ZVA-K9	1311.3128.02
Long Distance Group Delay Measurement	R&S®ZVA-K10	1164.1805.02
Receiver Step Attenuator, Port 1	R&S®ZVA40-B31	1302.5444.02
Receiver Step Attenuator, Port 2	R&S®ZVA40-B32	1302.5450.02
Receiver Step Attenuator, Port 3	R&S®ZVA40-B33	1302.5467.02
Receiver Step Attenuator, Port 4	R&S®ZVA40-B34	1302.5473.02
Generator Step Attenuator, Port 1	R&S®ZVA40-B21	1302.5409.02
Generator Step Attenuator, Port 2	R&S®ZVA40-B22	1302.5415.02
Generator Step Attenuator, Port 3	R&S®ZVA40-B23	1302.5421.02
Generator Step Attenuator, Port 4	R&S®ZVA40-B24	1302.5438.02

Signal and Spectrum Analyzer*

Designation	Type	Order No.
Signal und spectrum analyzer 2 Hz to 43.5 GHz	R&S®FSW43	1331.5003K43
RF preamplifier, 100 kHz to 43 GHz	R&S®FSW-B24	1313.0832.43
Resolution bandwidth > 10 MHz	R&S®FSW-B8	1313.2464.02
Vector Signal Analysis	R&S®FSW-K70	1313.1416.02
BER PRBS Measurement	R&S®FSW-K70P	1338.3893.02
Real-Time Spectrum Analyzer, 512 MHz	R&S®FSW-B512R	1325.4296.06
512 MHz Analysis Bandwidth	R&S®FSW-B512	1313.4296.04
2 GHz Analysis Bandwidth	R&S®FSW-B2000	1325.4750.02
Real-Time Spectrum Analyzer, 800 MHz	R&S®FSW-B800R	1331.6400.16
1200 MHz Analysis Bandwidth	R&S®FSW- B1200	1331.6400.14
2000 MHz Analysis Bandwidth	R&S®FSW- B2001	1331.6916.14
4400 MHz Analysis Bandwidth	R&S®FSW-B4001	1338.5215.14
6400 MHz Analysis Bandwidth	R&S®FSW-B6001	1338.5221.14
8312 MHz Analysis Bandwidth	R&S®FSW-B8001	1338.5238.14
OCXO Precision Reference Frequency	R&S®FSW-B4	1313.0703.02
DIG IQ 40G Streaming out Interface 512MHz	R&S®FSW-B517	1331.6980.02

Designation	Type	Order No.
DIG IQ 40G Streaming out Interface 1GHz	R&S®FSW-B1017	1350.7008.02
Analog Baseband Inputs	R&S®FSW-B71	1313.1651.13
Electronic Attenuator, 1 dB steps	R&S®FSW-B25	1313.0990.02

Vector Signal Generator*

Designation	Type	Order No.
Microwave Signal Generator	R&S®SMF100A	1167.0000.02
Frequency Range 1 GHz to 22 GHz	R&S®SMF-B122	1167.7004.03
Frequency Range 1 GHz to 43.5 GHz	R&S®SMF-B144	1167.7204.03
Frequency Extension 100 kHz to 1 GHz	R&S®SMF-B2	1167.4005.02
OCXO Reference Oscillator	R&S®SMF-B1	1167.9159.02
AM/FM/φM/LOG AM	R&S®SMF-B20	1167.9594.02
Enhanced phase noise performance	R&S®SMF-B22	1415.2204.02
High Output Power	R&S®SMF-B34	1415.2404.02
Step attenuator 43.5 GHz	R&S®SMF-B27	1167.5776.02
Low Leakage	R&S®SMF-B41	1415.0901.02
Power Analysis	R&S®SMF-B28	1415.2104.02

Power Sensor*

Designation	Type	Order No.
100 pW to 200 mW, 10 MHz to 18 GHz three-path diode power sensors	R&S®NRP18SN	1419.0035.02
100 pW to 200 mW, 10 MHz to 33 GHz three-path diode power sensors	R&S®NRP33S	1419.0064.02
100 pW to 200 mW, 10 MHz to 33 GHz (LAN)	R&S®NRP33SN	1419.0070.02
100 pW to 100 mW, 50 MHz to 40 GHz (LAN)	R&S®NRP40SN	1419.0058.02
100 pW to 100 mW, 50 MHz to 50 GHz (LAN)	R&S®NRP-50SN	1419.0093.02

* Other R&S®ZVA models, Power Sensors, Signal Generators and Signal and Spectrum Analyzers are suitable as well. More options are available. The instrument minimum configuration for this application is shown in the table. Please ask your local representative for a suitable configuration according to all your needs.

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Application Note | Ground Station Testing On Satellites In Orbit

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