

W H I T E P A P E R

Satellite Communication Systems

GPS Frequency Reference for Earth Stations

The satellite communications infrastructure provides critical services for government and civil applications at increasing carrier frequencies and data rates. Within the ground and space-borne systems are devices that generate microwave level frequencies that form uplinks and downlinks. At the core of these systems are high-quality frequency references that are fundamental to establishing stable, high bandwidth communication links. Minimizing noise levels, particularly phase noise, within earth station equipment is critical to supporting reliable communications. This application note focuses on the value of a GPS frequency reference providing atomic oscillator stability and ultra-low phase noise within the earth station.

FREQUENCY SPECTRUM AND MODULATION TECHNIQUES

Satellite communications are conducted within a licensed RF spectrum between earth stations and satellites. A microwave radio signal is transmitted from an earth station on an assigned frequency band to uplink modulated data to a satellite. The signal arrives at the satellite transponder where it is amplified, filtered, down-converted, and retransmitted to one or more earth stations. The uplink carrier frequency serves as the reference to the satellite down-converter to generate the downlink carrier. It is imperative that the uplinks, rooted by an earth station frequency reference, are stable, accurate and have low noise to enable carrier grade operation at maximum capacity.

Low phase noise is very important as it is multiplied by the earth station up-converter and has filtering constraints for noise close to the carrier frequency. This noise must be minimized to ensure the integrity of analog and digital modulation. In addition, quality of service improves as signal-to-noise (S/N) ratios increase and bit error rates (BER) and loss-of-lock issues are reduced.



Satellite communications utilize super-high frequencies in bands ranging from 1-40 GHz, as shown in Table 1. The evolution to higher frequencies (e.g. Ka-Band) and continued quest to achieve maximum spectral efficiency with sophisticated modulation techniques requires strong S/N ratios. Binary Phase Shift Keying (BPSK) techniques have evolved, along with other forms of complex digital modulation, to double, triple and quadruple the data rates (e.g. QPSK, 8-PSK, 16-PSK) over the same bandwidth, but have a higher sensitivity to noise due to the small phase shifts. Earth station designers balance the choice of modulation techniques with an acceptable BER which is directly related to system phase noise.

Band	Frequency
L-Band	1-2 GHz
S-Band	2-4 GHz
C-Band	4-8 GHz
X-Band	8-12 GHz
Ku-Band	12-18 GHz
K-Band	18-27 GHz
Ka-Band	26-40 GHz

Table 1. Satellite Communication Frequency Bands

The satellite communication bands are further subdivided into many relatively narrow frequency assignments to allow multiple operators to support a wide range of services. The operational carrier frequencies must stay within an assigned frequency range to insure reliable communications and avoid interference with signals and service on adjacent bands. The accuracy and stability of these signals is based upon the frequency-reference oscillators within the earth station.

Medium and large earth stations may have multiple up-converters, down-converters, modems and hardware encryption devices with internal, independent oscillators. These oscillators when operating stand-alone, have differing levels of stability, accuracy and noise that complicate and can compromise earth station operations. Best practice involves connecting these devices to a common GPS based, low phase noise, frequency reference with the long-term accuracy and stability of an atomic frequency standard (AFS). See Figure 1 below.

Oscillator and Frequency Fundamentals and Terminology

To understand the benefits of an external GPS-based frequency reference within an earth station, it is helpful to know some terminology and fundamentals of oscillators and frequency.

Quartz oscillators are based on the piezoelectric resonance of a quartz crystal. High-quality quartz oscillators provide excellent short-term stability and low phase noise. The inherent physics of quartz, however, makes the devices susceptible to environmental effects (e.g. temperature) and aging that impact long-term stability and accuracy. Oven-controlled crystal oscillators (OCXO) protect the crystal within an oven cavity and provide the best performance. Rubidium oscillators, in comparison, provide better long-term stability when not tracking a reference, but have inferior short-term stability and phase noise performance.

Frequency stability refers to how an oscillator's resonant frequency varies when averaged over a stated short or long-term period. Short-term stability is typically measured in decade intervals from 1-100 seconds and long-term stability is typically measured in decade intervals from 100 to 10,000 seconds (approximately 1 day), and sometimes over days and weeks.

Phase noise is related to the rapid movement of zero crossings of the signal, relative to those of an ideal reference standard. The noise is measured relative to the carrier signal power in dBc/Hz at small frequency offsets. Phase noise is one of the most critical noise elements to manage and minimize in earth stations as the noise close to the carrier cannot be filtered, is multiplied, and propagates through the system.

Accuracy is a measure of the oscillator frequency conformity to a traceable standard.

Disciplined means that the oscillator's frequency is being controlled by an external host based on measurements of its frequency relative to a reference signal such as GPS. The disciplining process calibrates the oscillator by continuously compensating for the environmental effects and aging. Should reception of the reference signal be interrupted, the accuracy of the unit degrades gracefully over time because its frequency had been recently calibrated.

GPS Frequency Reference for Earth Stations consists of an instrument with a high quality, low-phase-noise OCXO that is continuously disciplined to signals from the GPS satellite constellation. The GPS satellite atomic

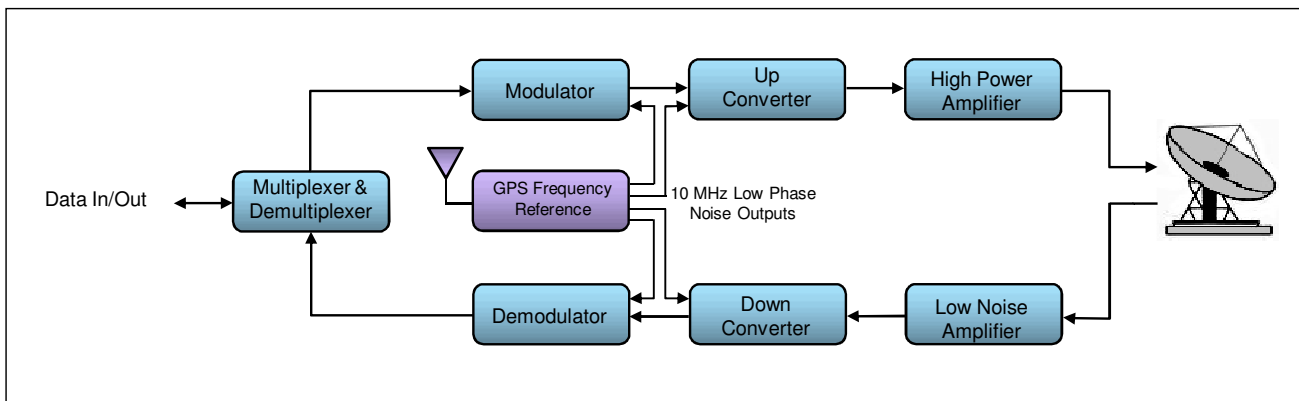


Figure 1. GPS Frequency Reference Connected to Up/Down Converters and Modulators

frequency standards are monitored by the United States Naval Observatory (USNO) who is also responsible for the U.S. national time standard. The USNO measurement data is processed and corrections are uploaded to the satellites each day. When locked to the satellite signals, the GPS frequency standard provides reference frequencies with excellent short and long-term stability and accuracy traceable to USNO with low phase noise.

Earth Station Phase Noise Standard

The Intelsat Earth Station Standards (IESS) are commonly referenced in the industry and outline the performance characteristics and specifications required in earth station systems. IESS 308/309 identifies the maximum allowable phase noise levels as shown in Table 2. Designing to this standard improves system reliability and interoperability by delivering signals with strong S/N ratios to demodulator inputs. Equipment vendors often cite product compliance and performance to this standard.

Carrier (Fourier) Frequency Offset	Single Side Band Phase Noise (dBc/Hz)
10 Hz	-30
100 Hz	-60
1 kHz	-70
10 kHz	-80
100 kHz	-90

Table 2. IESS 308/309 Maximum Allowable Phase Noise

Phase Noise Multiplication in Earth Stations

Up-converters and down-converters generate microwave level carrier frequencies (1-40 GHz) by multiplying signals from a low-frequency reference oscillator. This is typically accomplished by phase locking a high frequency voltage controlled crystal oscillator (VCO) to a 10 MHz reference oscillator. Unfortunately the reference oscillator noise is also multiplied and the close-in phase noise (<1000 Hz carrier offset) propagates through the phase locked loop (PLL) into the system.

Reference oscillator phase noise power levels are increased by 20 log (N) when the frequency is multiplied by a factor of N. The inability to filter the close-in noise makes it imperative to select reference oscillators with the lowest phase noise to allow a comfortable margin to the IESS standard.

Meridian II Precision Timebase

The EndRun Technologies Meridian II Precision TimeBase is a high-performance, modular, frequency standard that is optimized for earth stations. When locked to GPS, an internal, high quality 10 MHz oscillator is disciplined to the satellite atomic-clock-based signals resulting in excellent stability and accuracy (<1E⁻¹³ per day). This meets the needs of the most demanding earth station applications. The Meridian II also serves as a time reference accurate to less than 10 nanoseconds to GPS time.

Meridian II supports multiple 10 MHz oscillator options that allow customers to select the phase noise performance required. The Meridian II can be configured with up to five low phase noise option modules to provide 20 individually buffered, spectrally pure, reference outputs to earth station equipment.



Meridian II Precision TimeBase



EndRun manufactures their own OCXO oscillators to achieve performance and quality not found elsewhere. The proprietary design utilizes a glass vacuum sealed, 3rd overtone, SC cut crystal that is manufactured with the highest quality components and subjected to rigorous testing to guarantee

the industry leading performance. Table 3 lists the Meridian II OCXO oscillator specifications and Figure 2 illustrates typical performance of the Ultra-Stable OCXO.

Phase Noise at 10 MHz dBc/Hz	Medium-Stability OCXO	High-Stability OCXO	Ultra-Stable OCXO
1 Hz	-95	-105	-110
10 Hz	-120	-130	-135
100 Hz	-135	-140	-145
1 kHz	-145	-150	-150
10 kHz	-145	-150	-150
100 kHz	-145	-150	-150

Table 3. Meridian II OCXO Options and Low Phase Noise Specifications

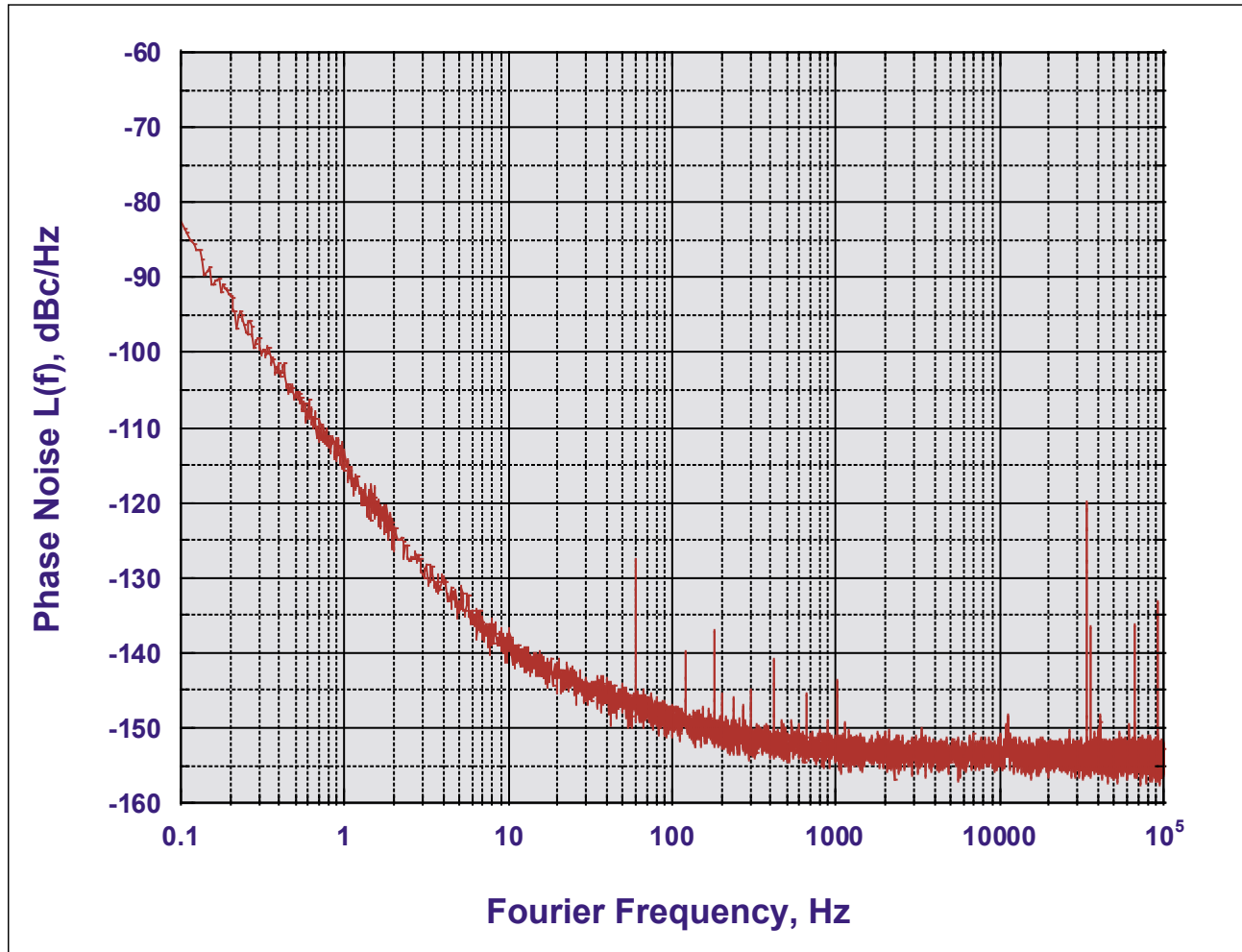


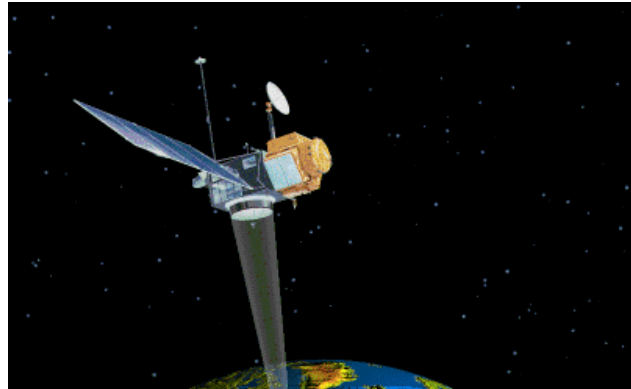
Figure 2. Ultra-Stable OCXO Typical Phase Noise Performance

When selecting the oscillator and estimating phase noise margin to the IESS standard, remember that:

1. The total system phase noise budget as defined by the IESS standard is the RMS sum of all the system components.
2. The oscillators contribute the most phase noise to the system.
3. Close-in phase noise cannot be reduced by filtering.
4. The noise is increased by $20 \log(N)$ when multiplying to a microwave level frequency. For example, when up-converting 10 MHz to 14.5 GHz ($N = 1450$) the phase noise will increase by:

$$SSB \text{ Phase Noise } dBc/Hz @ 14.5 \text{ GHz} = 20 \log(14.5 \text{ GHz}/10 \text{ MHz}) + SSB \text{ Phase Noise } dBc/Hz @ 10 \text{ MHz}$$

Figure 3 illustrates the calculated phase noise margins of the Meridian II OCXO options when up-converted to 14.5 GHz relative to the IESS 308/309 standard. The close-in phase noise <1000 Hz from the carrier is highlighted as it passes through the multiplying PLL into the satellite communication system. Note the Ultra-Stable OCXO provides the best margin relative to the IESS standard.



Summary

Satellite communication systems continue to evolve, maximizing data rates through existing and higher frequency bands with complex digital modulation. To succeed, the earth station reference frequencies must be stable and exhibit extremely low phase noise. A GPS-based frequency reference equipped with a specialized ultra-low-phase-noise oscillator provides the optimal solution. Best practice in earth station design connects up-converters, down-converters, and modems to a GPS frequency reference to ensure the devices have the best stability and S/N ratio to support complex modulation and high data rates.

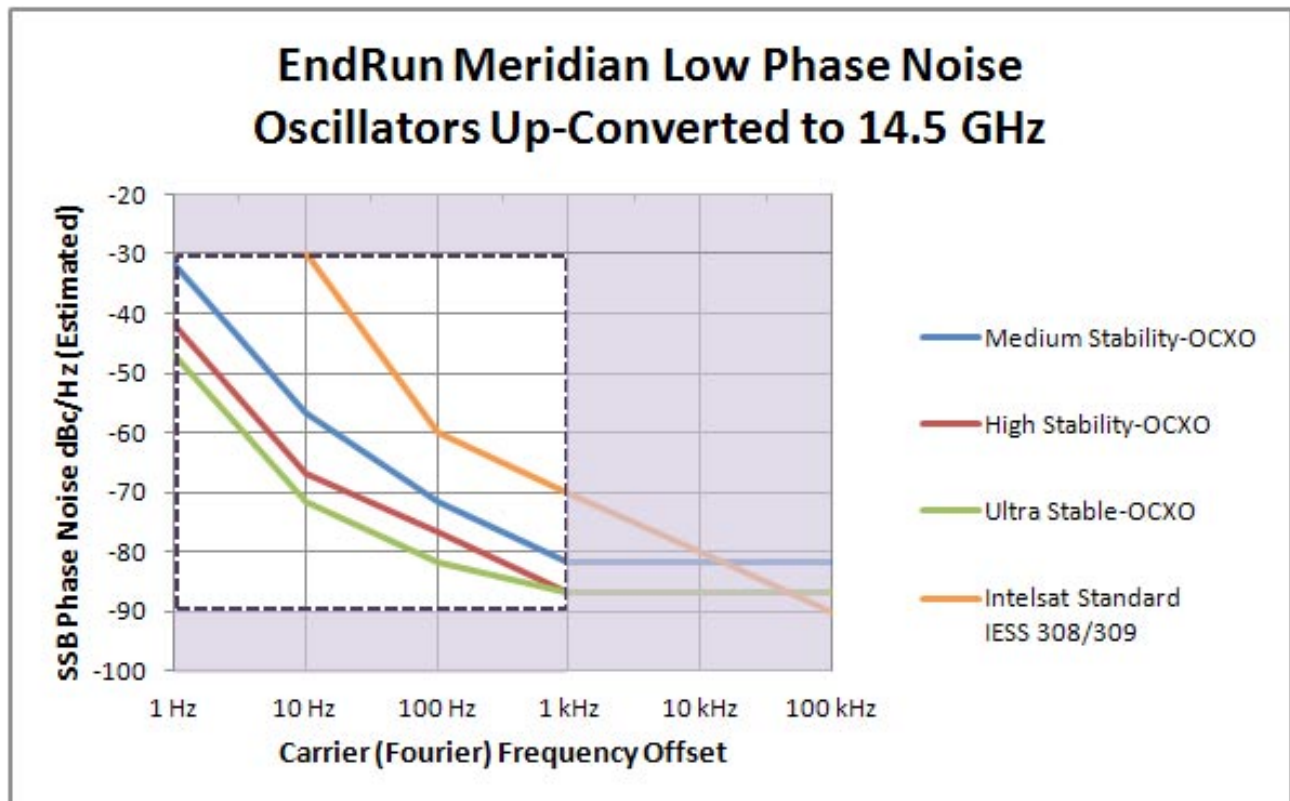


Figure 3. Meridian II OCXO Phase Noise when Multiplied to 14.5 GHz Compared to the IESS Standard for Total System Phase Noise

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