Frequency Stability Requirements for Space Communications and Tracking Systems

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Abstract—Space communications and tracking systems impose stringent requirements on stable frequency sources. "Flicker" (1/f) noise and environmental modulation are two types of oscillator instability affecting typical space systems performance. Examples of several systems are presented with the source requirements for each. Earth satellite systems impose stability requirements of the order of 10^{-10} over periods of seconds to hours depending on the individual experiment. A typical system requires phase noise of less than 5^o rms in a receiver of 12 Hz bandwidth at S-band. An example is presented of a spacecraft transponder which must maintain phase noise below 45^o peak-to-peak under vibration of 3g peak from 10 Hz to 10 KHz.

I. INTRODUCTION

FREQUENCY stability considerations in space systems do not differ fundamentally from those of ground communication links, radar systems, or navigation aids. However, the need for minimization of hardware requirements at the space vehicle station and the very large path lengths involved characterize space system stability requirements and measurements in ways which are discussed in this paper for some specific missions. While many factors not related to frequency stability affect space program objectives, only the total error budget assigned to the system stable sources is considered here.

Orbit determination is important for all types of spacecraft. Varying accuracies are specified depending on the individual mission; for example, a navigation satellite would require extremely precise knowledge of the satellite's position as a function of time, but data may be taken over a long period of time to obtain the required precision, thus implying long-term stability of the ground station frequency source.

Determination of orbit parameters for deep space probes requires precise knowledge obtained as soon as possible so as to be able to perform midcourse corrections early in the mission, thus saving motor energy. This requirement implies good short- and medium-term stability of the primary frequency source.

The extreme ranges involved in deep space communications necessitate the use of very narrow band receivers to keep the signal-to-noise ratios high. Phase-lock loop receivers are used to obtain these narrow bandwidths and to obtain precise determination of Doppler frequencies and, thus, range rates for tracking. At the narrow bandwidths required, good oscillator short- and medium-term stability is necessary to keep receiver phase tracking error due to the oscillator's perturbations small enough that the threshold of the receivers is not appreciably degraded. A particularly stringent requirement on the oscillator in the spacecraft is that of maintaining good short-term stability during periods of extremely adverse environmental conditions, e.g., during motor ignition and thrusting.

II. DESCRIPTION OF SYSTEM REQUIREMENTS

A. Phase Lock Receivers

For deep space probes, the system requirements are based on tracking the probe within a certain allowable tracking error. Both the spacecraft receiver and ground receiver are phase-lock loops as shown in Fig. 1. This type of receiver has been analyzed extensively [1]–[4], and it has been shown that, for small phase deviations, the transfer function is given by:

\[
\frac{\theta(s)}{\theta_i(s)} = H(s) = \frac{1 + \tau_2 s}{1 + s(\tau_2 + 1) + s^2 \frac{\tau_1}{2G}}
\]  

where

\[
\theta(s) = \text{phase of output of voltage controlled oscillator (VCO)}
\]

\[
\theta_i(s) = \text{phase of input signal}
\]

\[
\tau_2 = R_2 C \text{ in the loop filter of Fig. 1(b)}
\]

\[
\tau_1 = (R_1 + R_2) C \text{ in the loop filter of Fig. 1(b), and}
\]

\[
G = \text{the open loop phase gain of the receiver.}
\]

For most practical receivers used for deep space tracking, the closed loop response is designed as a Wiener optimum filter [1] for minimum rms phase error in the presence of band-limited white noise and a step input frequency vs. time function (corresponding to a ramp of phase vs. time). For this design, the constants in (1) become:

\[
\tau_2 = \frac{3}{2BN}
\]

\[
\tau_1 = \frac{9G}{8BN^2}
\]

\[
\tau_2 \gg \frac{1}{G}
\]
where $B_N$ is the closed loop noise bandwidth of the receiver:

$$B_N = \frac{1}{2\pi} \int_{-\infty}^{\infty} |H_i(\omega)|^2 d\omega$$

The closed loop response of the receiver is then:

$$H(s) = \frac{1 + s\tau_2}{1 + s\tau_2 + \frac{s^2\tau_2^2}{2}}$$

This response is shown in Fig. 2.

The phase tracking error is measured at the output of the phase detector of Fig. 1. The response of the loop as measured to this point is given by

$$V_a(s) = K(1 - H(s))$$

where $V_a(s)$ = the error voltage and $K$ = constant depending on loop gain and VCO sensitivity.

The receiver threshold (the lowest signal power at which it can track a signal) is the point at which the total tracking error reaches 1 rad rms.

The phase tracking error of such a receiver is composed of three parts: 1) phase noise caused by additive white noise (thermal noise) at the receiver input, 2) errors due to the rate of change of input frequency ("range-rate" errors), and 3) phase noise due to oscillators. The first of these is determined by the signal power, the system noise temperature, and the system bandwidth; the second can be shown to be phase error $\phi_{ON} = \frac{9K}{8B_N} = \frac{9K}{8B_N}$, where the frequency is changing at the rate of $K$ Hz/s.

The third component due to oscillator noise is given by

$$\phi_{ON} = \int_0^\infty S_\phi(\omega) |1 - H(\omega)|^2 d\omega; \text{ (rad)}^2$$

where $S_\phi(\omega)$ is the phase spectral "power" density of the oscillator in rad$^2$/rad/s.

Since the sum of the foregoing components of tracking error must be less than 1 rad$^2$ to maintain phase lock, it is important that the oscillator noise be as small a part of the total as possible to obtain the best system performance. Typical system specifications call for tracking error due to oscillator noise alone to be less than 0.1 rad rms at the design bandwidth. For the range of bandwidths normally used for deep space tracking (1 Hz $< B_N < 100$ Hz), the "flicker" frequency modulation component of noise predominates as is readily seen if one substitutes

$$S_\phi(\omega) = \frac{C_1}{\omega}$$

where $C_1$ is a constant depending upon the quality of the oscillator.

From (4), (6), and (8):

$$\phi_{rms} = \sqrt{\frac{C_2}{B_N}}$$

where $C_2 = \sqrt{9\pi C_1}$, a constant depending on oscillator noise level. This relationship has been verified experimentally for a large number of oscillators. The data are shown in Fig. 3 for various sets of oscillators. The typical oscillators used today produce approximately $3^\circ$ to $5^\circ$ rms tracking error with a receiver having a noise bandwidth $B_N$ of 12 Hz for the wide deviation ("low-Q") units and $2^\circ$ to $3^\circ$ rms with $B_N = 5$ Hz for a narrow deviation ("high-Q") unit measured in receiver-transmitter systems at 2100 to 2300 MHz.
Further improvement in system performance will soon require narrower loop bandwidths and, thus, much lower flicker noise in the main oscillators in order to keep the tracking error due to the frequency generating devices a small portion of the receiver noise.

B. Vibration Modulation

Both the short-term and long-term frequency stability of spacecraft electronics can be adversely affected by environmental conditions. The approach used to meet short-term stability specifications in the Surveyor spacecraft is illustrative of the design of hardware to meet operational requirements. During the phases of the flight in which vernier and retro engine operation occur, the spacecraft is subjected to mechanical vibration. The maximum phase jitter allowable under this condition must be less than that which would cause loss of lock at the spacecraft or on the ground. Figure 4 shows a simplified block diagram of the spacecraft transmitter and receiver. The signal source for the transmitter is selectable from either the transmitter VCXO or the receiver VCXO. When connected to the receiver VCXO the transmitter signal is phase-locked to the received signal. The transmitter utilizes a multiplication ratio of 120, the receiver, 108.

Phase jitter in the spacecraft during vibration occurs because of transmitter-receiver vibration and antenna shaking with respect to the spacecraft, causing variations in the path length between ground station and spacecraft. The portion of the phase error budget assigned to the transmitter-receiver is 15 degrees rms, measured in a phase-locked loop, 425 Hz noise bandwidth, under conditions of 3g zero-to-peak vibration from 10 Hz to 10 KHz.

The phase error is referred to the S-band transmit and receive frequencies. System tests are performed with the complete transmitter and receiver mounted on the vibration table. However, the transmitter and receiver utilize modular construction and it is found in all cases that the phase jitter at S-band is due entirely to the jitter originating in the oscillator modules, multiplied by the appropriate multiplication ratio.

Detailed testing is performed on these modules, at 19 MHz, rather than on the complete transmitter and receiver. Receiver and transmitter oscillator modules were specially built in such a way that the frequency control crystals could be interchanged. It should be noted that in an oscillator-amplifier-multiplier chain, phase jitter can be caused by the vibration of any of the components in the signal path if they are not rigidly mounted with respect to each other and ground. The Surveyor modules are potted with low density foam to secure the components. Tests on modules constructed in this way show that all of the phase jitter is attributable to the frequency control crystals.

The phase jitter at the output of the module under test is measured using a phase-locked loop test set. The loop noise bandwidth is 425 Hz. The test set is calibrated by the use of an oscillator/phase modulator which is itself calibrated by using the vanishing carrier method. The output of the phase-locked loop is observed on an oscilloscope.

The error signal output of a phase-locked loop has a high-pass filter characteristic with respect to phase perturbations of the input signal. The phase jitter test set simulates the response of the actual system receivers and, therefore, no bandwidth corrections are required to refer the test data to the 15-degree system specification.

Conventional crystals exhibit excessive phase jitter when rigidly mounted and vibrated at the cantilever resonance frequency of the crystal mounting wire/quartz plate spring-mass system. Both HC-18 and HC-6 wire mounted crystals of conventional design were tested. These crystals are cemented in the modules with epoxy resin. Phase jitter under these conditions is measured to be as much as 333 degrees (referred to S-band) at approximately 400 Hz vibration frequency on the HC-18 crystals and at 1100 Hz on the HC-6 crystals. These mechanical resonances have approximately one percent bandwidth. These frequencies are found to correspond to the cantilever resonance of the internal spring-mass of the crystal and its mounting wires. Tests on numerous crystals of the HC-18 type show that although the resonant point almost always occurs at 400 Hz, plus or minus 40 Hz, the magnitude of the phase...
jitter varies by as much as 20 to 1 from crystal to crystal. In each case, the modules with the crystals under test are vibrated in all three axes.

Figure 5 is a sketch of a vibration isolator built to reduce the vibration level at the crystal. An isolation factor of approximately 10 is achieved in this unit. The purpose of the third lead is to ground the case of the crystal to reduce phase jitter caused by capacity variation between the isolator and the crystal case at the natural mechanical resonance of the foam-crystal combination. Even with this third lead, it is found that the amount of isolation which can be achieved at 400 Hz is limited by the occurrence of phase jitter at the lower mechanical resonance of the mount. That is, lowering the isolator resonant frequency, by mass loading the crystal case, for example, tends to increase the phase jitter at the isolator resonance since the excursion is increased and, therefore, lead-to-lead and lead-to-case capacitance varies more. The best compromise is found to be at a mount resonant frequency of 150 Hz. More elaborate mounting schemes cannot be used because of space limitations.

Several types of commercially available rugged mount crystals were hard mounted and tested for phase jitter. Although the resonant frequency of these mounts is higher than nonrugged types, they are found to exhibit large phase jitter when vibrated at resonance. Although not much data is available on the subject, the aging rate and temperature behavior of these rugged mounts are reported to be inferior to that of the standard mount.

A type of crystal which is very promising for this application is the ribbon supported, transistor header mounted crystal, which was developed by Bell Telephone Laboratories, Inc. [31]. This crystal is now becoming available from a number of crystal manufacturers. These crystals are mounted on two or three nickel ribbons 1 to 3 mils thick. A sketch of a typical unit is shown in Fig. 6. Because of the mounting method, the length of the supporting ribbons can be made very short, resulting in a very stiff structure. Tests of two or three ribbon crystals show a maximum phase jitter of less than 3 degrees, an improvement of two orders of magnitude, compared to the standard mount. Preliminary tests indicate aging rates equal to or better than those found with conventionally mounted crystals.

\[ \text{C. Orbit Determination} \]

The orbit determination of space vehicles used for geophysical and astronomical observations, for weather observation and prediction, as navigation aids, for communication relay stations for space exploration [7], etc., requires tracking information by which the position and ephemeris of the vehicle can be determined. Tracking and positional accuracy and the reaction speed requirements vary with the mission trajectory. A navigation satellite, for instance, can be tracked over a long period of time over many orbits, and although an extremely accurate ephemeris is required, smoothing of the data reduces the accuracy requirements on a single observation. Rendezvous of two or more vehicles requires much higher accuracy for individual observations since a short time is available to make measurements, particularly at the closing time. Likewise, a high order of tracking and position accuracy is required, and a small time for decision making is available for mid-course correction in a mission such as Mariner. A number of electronic observation methods have been devised to provide the necessary information. Chapter 11 of Baker and Makemson [8] provides a good discussion of electronic and optical observation methods. The April, 1960, issue of these PROCEEDINGS contains several articles which discuss satellite systems for navigation.

Space vehicle tracking systems frequently use several electronic observation methods supplemented by optical observations because no one method provides the most desirable information for all trajectories or for all portions of a particular trajectory. Pulsed radar tracking is used during the boost phase, but inadequate signal strength is available later in the course because of extreme range and small scattering cross section. Therefore, systems have been devised which utilize a transmitter in the spacecraft which may or may not be cooperative with the ground system.

Several typical system examples are described below.

1) An example of a noncooperative system is a satellite transmitting a frequency controlled by an internal ultra-stable oscillator. Doppler shift of the frequency received from the satellite as it passes the receiving stations is measured and processed to obtain range rate. Range is obtained by integrating range rate. Angles are obtained via range data simultaneously obtained from three or more receiving stations.

Oscillators with the ruggedness and power and weight economy required for spacecraft have not been available
with sufficient stability to meet many tracking requirements. Therefore, systems have been devised which minimize requirements of the oscillator in the spacecraft.

2) Transit [9], a Navy navigation satellite, is an example of a system design which minimizes spacecraft oscillator stability requirements. The necessary short-term stability is reduced by making many observations during a pass, and the long-term oscillator drift is corrected using information obtained by the tracking stations.

Transit provides ship navigation information by the use of one-way Doppler. The satellite has aboard an oscillator which has good short-term stability and a memory unit which contains information on the ephemeris of the satellite. Transit is tracked by a system of ground stations which measure the Doppler shift of the radio signals transmitted by the satellite. This information is utilized to compute a new ephemeris and update the satellite memory unit. Correction for long-term oscillator drift is made periodically by ground station transmissions to the satellite.

A ship provided with a receiver and a computer to process Transit transmissions can achieve navigational accuracies of one-half nautical mile. An oscillator in the satellite having a stability of \(10^{-8}\) per hour contributes an error of 0.23 nautical miles to the system error budget.

3) The NASA/Goddard Range and Range Rate System [10] is an example of a cooperative ground station, nonphase-locked space satellite tracking system capable of measuring range, range rate, and direction to a satellite from a single station or as many as three separate accurately surveyed ground stations simultaneously, for accurate trilateration. As a result, the satellite transponder is a three-channel unit capable of responding to three ground stations simultaneously. The signal processing techniques employed permit the utilization of a simple, compact satellite transponder weighing less than 10 pounds and radiating only one watt of power.

Range is determined by measuring the round-trip travel time of an electromagnetic wave between spacecraft and ground station. This is done by measuring the phase of the wave returned to the ground station. The carrier is modulated with a number of frequencies to enable resolution of ambiguities which would arise if a single modulation frequency were used. Measurement of phase is, in principle, a time measurement. The system master oscillator is the “yardstick” by which range is determined. Error in range due to oscillator calibration error is the product of range by the fractional deviation of the oscillator frequency from true value during the measurement.

\[
\text{Range Error} = (\text{Range})(\text{Oscillator Accuracy} + \text{Oscillator Stability})
\]

Accuracy is the maximum fractional deviation of the actual frequency from the true frequency referenced to the United States Frequency Standard.

As an example, a range error contribution from an oscillator having an accuracy of \(10^{-8}\) and a stability of \(2 \times 10^{-8}\) during the measurement period will be a maximum of:

\[
\text{Range Error} = (\text{Range})(10^{-8} + 2 \times 10^{-8}) = 3 \times 10^{-8}R
\]

or three meters in 100 000 kilometers. In practice, much better oscillator stabilities and accuracies than this are used.

Range rate, or satellite velocity relative to the tracking site, is determined by measuring received Doppler cycles per unit of time representing the average velocity over the measuring interval. To determine Doppler frequency, coherence of the transmission is maintained through the transponder after which it is compared against a coherent sample of the transmitter frequency in the ground receiver. In this arrangement, the range and range-rate errors contributed by the spacecraft oscillator are replaced by tracking errors of the phase-locked loop as explained above.

4) The range-rate errors in a Doppler (2-way) transponder system arise from random noise, quantization error, velocity of propagation errors, phase-lock loop tracking error, oscillator noise, etc. The contribution of oscillator noise to range-rate error has been calculated by Develet [11], who assumed a white noise spectrum. A rearrangement of Develet's equation yields the oscillator stability requirements in terms of Doppler cycle counting time, propagation time, and allowable range-rate error.

\[
S = (T/cR)^{1/2}(\Delta \dot{R},c), \quad 0 < (\tau/T) < 1, \quad S = 2(\Delta \dot{R},c), \quad 1 \leq (\tau/T) < \infty,
\]

where

\[
S = \text{oscillator stability for period } T; S = \Delta f/f
\]

\[
c = \text{velocity of propagation}
\]

\[
\tau = \text{propagation time, round-trip}
\]

\[
T = \text{cycle counting period}
\]

\[
R = \text{range, and}
\]

\[
\Delta \dot{R} = \text{range-rate error due to oscillator noise}
\]

Consider now the oscillator requirements for such a transponder range-rate system where a frequency is generated, transmitted, coherently transponded, received, detected against the transmitted signal to yield the Doppler frequency, and the Doppler frequency measured by counting cycles for a known time interval.

A correction in orbit of one mile in one orbital cycle requires a velocity increment of 0.21 meter per second [12]. Therefore, a typical design objective is a range rate accuracy of 0.1 m/s. The transmitter is located on the ground, subject to a gentle environment, and it is reasonable to design it so that its contribution to error is small compared with contributions from other sources. Therefore, assign the transmitter master oscillator 10 percent of the total error budget or 0.01 m/s.
Since the oscillator contribution to range-rate error is a function of range (transit time) and cycle counting period, the required stability is dependent upon the spacecraft mission (orbit). The oscillator stability which will produce a 0.01 m/s range-rate error, assuming white noise, has been calculated using (12) and plotted as a function of cycle counting period for a variety of ranges in Fig. 7. The line marked $T = \tau$ represents the stability requirement for a counting period equal to the transit time. The counting period for most earth satellite range-rate measurements is 0.2 to 4 seconds, which is long enough to get good averaging and short enough to avoid errors from satellite acceleration. Note that, particularly for short ranges, limiting the range-rate error from this source to 0.01 m/s, places severe requirements on the transmitter oscillator stability.

A great deal of discussion of oscillator stability and range and range-rate requirements for these various missions is contained in the literature. (The reader is referred to references [13]–[30] for more detailed requirements for various applications.)

![Fig. 7. Oscillator stability which will produce a range-rate error of 0.01 meter per second.](image)

### III. Conclusion

Short-term stability considerations in all space systems are colored by the severe power, weight, and size restrictions at the vehicle station and the particular mission needs.

Deep space probes use phase-lock loop receivers and narrow tracking bandwidths of 12 Hz or less to maintain signal-to-noise in the face of hundred million-mile ranges and only tens of watts transmitter power. Phase noise can be held at less than 7 degrees rms in 12-Hz bandwidths by the use of atomic standards followed by high quality quartz oscillators on the ground. Phase jitter during spacecraft vibration must be less than that which would cause loss of phase lock. Less than 15 degrees rms phase jitter at the spacecraft transponder can be met by rigidly mounting electronic components and by the use of specially designed frequency control crystals. To meet the range and range-rate accuracies needed to track earth satellites, ground oscillators must be as stable as $10^{-10}$ over measuring times of seconds to hours, depending upon the mission. The stability requirements on the satellite oscillators are minimized by system designs which allow long averaging times or by transmitting the satellite oscillator frequency to the ground where it can be subtracted from the system loop.

### References


[7] Space Log. Publ. quarterly by TRW Systems, 1 Space Park, Redondo Beach, Calif. (Summarizes spacecraft launches and programs.)


