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HIGH STABILITY RADIO LINKS

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I. INTRODUCTION

Radio telecommunication links are used for communication with deep space probes. These links consist of sinusoidal carrier signals at radio frequencies (RF) modulated with information sent between the spacecraft and the earth. This carrier signal is a very pure and stable sinusoid, typically derived from an atomic frequency standard whose frequency and phase are used to measure the radial velocity of the probe and from this and other data types derive its trajectory. This same observable can be used to search for space-time distortions cased by low frequency (0.1 to 100 mHz) gravitational radiation (Estabrook and Wahlquist 1975). The purpose of this paper is to discuss how such a system works, what its sensitivity limitations are, and what potential future improvements can be made.

II. OVERVIEW OF EXPERIMENT CONFIGURATION

The instrument or acquisition system discussed here consists of NASA's earth-based Deep Space Network (DSN) of tracking stations, deep space spacecraft, and the data analysis facilities of the general relativity experimenters. Much, if not all, of this same system is also used for spacecraft navigation, VLBI and other types of spacecraft radio science experiments such as the measurement of planetary mass densities and planetary and solar osculations. Examples of the experiments done with the Voyager spacecraft are given by Tyler (1987).

Figure 1 is a schematic representation of how the system works. The basic concept is that an extremely stable monochromatic signal is generated and radiated from the earth to the spacecraft, which receives and retransmits the signal back to earth. At the earth, the signal is received and its frequency is differenced with the same reference signal from which it was originally generated. Any known systematic effects are then removed from this difference leaving a detrended frequency versus time series in which to search for effects of gravitational radiation.

The version of this system currently operating in the DSN consists of an S-band uplink and coherent S-band and X-band downlink signals. A new system is presently being implemented consisting of an X-band uplink and coherent S-band and X-band downlink signals. The first such installation is planned to be completed at the new 34 meter antenna in the Deep Space tracking station complex in Australia this fall, including the test equipment needed to measure and calibrate the system performance, and will first be used with the Galileo spacecraft. For future missions, Ka-band and optical frequencies are planned in order to support higher telemetry rates and further reduce the plasma-induced scintillations on the phase of the propagating signal. The radio frequencies are listed in Table 1.

TABLE 1

DEEP SPACE LINK FREQUENCIES (IN GHz)

BAND	UPLINK	DOWNLINK
S	2.1	2.3
X	7.2	8.4
Ka (proposed)	34	32

RELATIVE PLASMA INSTABILITIES (DELTA-F/F):

S p/down = 12 × X p/down = 225 × Ka p/down

III. LIMITATIONS IN SENSITIVITY

The sensitivity of this system is characterized by its normalized frequency stability, referred to as delta-f/f, which is the uncertainty or instability of the frequency estimates from the system divided by the radio frequency of the signal being measured. This quantity is useful because it is comparable to the dimensionless amplitude of an incident gravitational wave (Estabrook and Wahlquist 1975).

The short and long period limits, which set the time scales over which this type of system is sensitive, are set respectively by the signal strength to noise ratio (SNR) and the time it takes the signal to travel to the spacecraft and back again: the so-called Round Trip Light Time (RTLT) (Estabrook and Wahlquist 1975). The SNR is limited by factors such as transmitter power, antenna gain, receiver amplifier noise, and the distance between the earth and the spacecraft. With all other things being equal, use of higher RF signal frequencies will improve the SNR because antenna gain is proportional to link frequency squared, resulting in delta-f/f improving proportionally with the inverse of the signal frequency cubed.

For the current S-band uplink system, measurements by Armstrong, *et al.* (1987) indicate the short- and long-term limits for the system are due respectively to the downlink SNR and plasma-induced phase scintillations on the S-band uplink signal to the spacecraft. Separation of the plasma noise from the clock noise for certain long integration times has been achieved by Armstrong (1988), and the measured clock noise delta-f/f is 6×10^{-14}.

In the new X-band uplink system, the earth-based equipment has been designed for improved phase stability over that of the S-band uplink system to take advantage of the lower plasma scintillations on the X-band uplink signal. Table 2 is a summary of the expected performance of the new X-band uplink system. It contains a list of error sources and expected levels, measured in square root of Allan variance of frequencies, measured with a 1 Hz filter, for a 1,000-second integration time. The numbers in this table can be viewed as the expected "raw" performance of the system, in the sense that they reflect the stability of the frequency and phase data after the RF signal has been detected but, do not reflect any of the methods which can be used to dig further into the data such as those discussed by Armstrong (1988).

TABLE 2

EXPECTED PERFORMANCE FOR X-BAND UP/DOWN

	COMPONENT	ALLAN SIGMA * 1.0×10^{15} AT 1,000 SECONDS
Earth Transmission	Frequency Distribution	2
	Translation & Amplification	2
	Antenna at Transmission	1
Spacecraft	Amplifiers, Transponder	2
Earth Reception	Antenna at signal reception	1
	low noise amplifier	0.2
	receiver	2
	frequency distribution	2
Frequency Source	H–maser including change over round trip light time (8 hours)	2
	RSS	5
Propagation		<0.6 to 5
Troposphere	plasma (sep > 150 degrees)	1.5 to 15
	Total	5 to 17

Unfortunately, in a system such as this there is very little common mode noise cancellation. The system can be viewed as one arm of an interferometer and would need another arm to provide cancellation of many of the instrumental effects. A spaceborne microwave interferometer, which would use technologies similar to those discussed here and take advantage of such cancellation effects, is discussed in the Allen Anderson paper elsewhere in this volume.

A primary example of the lack of cancellation is the stability of the frequency standard from which the radiated signal frequency is derived. The instability of this standard, during the integration time over which the signal frequency and phase are detected as well as over the RTLT, limits the knowledge of both the radiated and received signal frequencies as well as their difference. It is for this reason that the system is designed with the downlink signal frequency being generated from the ground frequency reference making it as stable as possible. The best frequency standards available are active-type hydrogen masers, which are used by the DSN and currently cannot be flown on deep space spacecraft. The values in Table 2 represent typical active hydrogen maser stabilities for the DSN.

The major equipment improvements made with the X-band uplink capability have been primarily in the areas of frequency distribution and phase coherence, particularly for periods of 1,000 seconds or more where any mechanical movement or changes in temperature can be translated into phase shifts in this equipment. The distribution into the antennas of reference frequencies which retain the stability of the hydrogen maser source has been achieved through the use of an active phase correction loop. Improvements in the phase coherence of the transmitting and receiving equipment, that is, how well they follow the phase and frequency of the reference signal from the frequency standard, have been achieved by reducing the percentage of the uplink signal frequency and the receiver heterodyning frequencies which are derived from tunable elements. In addition, particularly temperature-sensitive components have been ovenized. The transmitter phase errors were reduced with a phase correction loop around the translation equipment (exciter) and the transmitter allowing the exciter to correct for the phase shifts in the transmitter. Measurements of many of these improvements were made in a prototype configuration by Otoshi and Franco (1987). Trowbridge (1975) measurements of the X-band traveling wave maser, and preliminary results of measurements of FET and HEMT low-noise amplifiers employed in the DSN, indicate these devices cause little instability relative to the other system components.

The spacecraft radio equipment sits in a much more thermally and mechanically benign environment than the earth-based equipment and therefore provides excellent stability to the level stated in Table 2 without any modifications specifically for this application. The large parabolic dish antennas, used on the earth, suffer from structural deformations caused by the earth's gravity as they track the spacecraft position across the sky. These distortions change the focal length and hence the signal path length. The values in Table 2 represent a conservative estimate of the residual errors after calibration and removal of these effects.

Phase scintillations due to the earth's troposphere are expected to be the ultimate limit for this type of system even with calibration. The troposphere effects are modeled as wet and dry components that are due respectively to fluctuations of water vapor and the density of the atmospheric constituents (oxygen, nitrogen, *etc.*). The wet component is presently the dominant of the two effects but R. Treuhaft indicates elsewhere in this volume that the dry may not be far behind. The value stated on Table 2 is from Armstrong and Sramek (1982) from measurements taken at the VLA.

As mentioned, plasma irregularities limit the long-term stability of the S-band uplink system. These instabilities as measured by delta-f/f, are proportional to the inverse of the transmission frequency squared, making this frequency very important and an area of continual potential improvement for this system. The relative instabilities for different radio frequencies are listed in Table 1. On the other hand, the inverse frequency dependence allows the plasma effects to be measured and removed by differencing the phase between two-phase coherent signals of different frequencies. The range of values estimated in Table 2 are from the work of Armstrong *et al.* (1979).

IV. POTENTIAL FUTURE IMPROVEMENTS

Table 3 lists some areas of potential major improvement, including what equipment might be involved, and other areas that would mutually benefit from the improvements. All improvements listed here would be beneficial to other spacecraft radio science experiments as well as to VLBI and spacecraft navigation. The items mentioned here are discussed in the DSN Long Range Plan (1988).

As indicated in Table 2, many of the effects are of the same order, implying that improvements will have to be made in a number of different areas to increase the sensitivity by another order of magnitude. Two items in particular in Table 3, namely calibrating the troposphere and improving frequency standards, appear to be the most difficult technical problems to overcome due to the lack of available technologies which will enhance their performance. There is no method currently of calibrating the troposphere at the levels needed. One promising technology for calibrating the wet component is the water vapor radiometer (WVR) which measures water vapor in the antenna beam. However, it is far from being an operating phase calibration system. This and other possibilities are discussed in R. Treuhaft's paper in this volume.

TABLE 3

FURTHER POTENTIAL MAJOR IMPROVEMENTS

CAPABILITY	IMPROVEMENT	EQUIPMENT DEVELOPMENT REQUIRED	COMMON GOOD
Higher frequency links	Reduced plasma & thermal noise instabilities	Exciter, receiver, transmitter, low noise amplifier, spacecraft transponder	Higher TLM rates, closer probing of solar corona GR time delay
Dual frequency links	Calibration of plasma phase effects	Exciter, microwave distribution, spacecraft transponder	GR time delay
Troposphere monitoring	Calibration of tropospheric phase	Water vapor radiometer (wvr)	VLBI and navigation
Optical fiber distribution	Reduced mechanical and thermal instabilities	Optical fiber transmitters and receivers	Connected element interferometer
Beam waveguide (BWG) antenna	Reduced mechanical and thermal instabilities	BWG antenna, laser ranging monitoring of BWG optics	Ease to modify front-end equip.
Improved frequency standards	Stability over shorter and longer periods	Trapped ion superconducting cavity OSC, low temp H-maser, saphire dielectric resonator OSC	VLBI, navigation, spacecraft OSC

The current level of stability provided by the active hydrogen maser has been, and apparently will continue to be for some time, the best frequency standard in the range of minutes to hours until there is a breakthrough of some kind. The frequency standards listed in Table 3 are promising research projects at JPL and elsewhere. Improvements in both ground and spaceborne frequency standards would help both searches for gravitational radiation and other types of spacecraft radio science experiments. Robert Vessot, in particular, has pointed out that if simultaneous measuring systems similar to the system described here were implemented on both the spacecraft and the earth, they would provide information that would allow cancellation of the earth's troposphere. In order to be useful, of course, the spaceborne standard would have to have excellent stability approximately equal to that of the ground standard.

V. CONCLUSION

Much work has be done towards understanding the limitations of this system. The expected sensitivity of the X-band uplink system communicating with the Galileo spacecraft, should provide frequency data with stabilities in the range of 5×10^{-15} for integration times in the thousands of seconds. This represents an improvement over the S-band uplink system of more than an order of magnitude, which has been achieved primarily through the use of a higher uplink frequency and improved radio and timing equipment on the earth. As indicated in Table 2, there are many sources of instability of comparable levels in reaching this level of sensitivity, and therefore a number of areas exist in which technological improvements will be required to gain another order of magnitude of sensitivity. Of these, there appear to be two, namely troposphere calibration and improved frequency standards, which, due to the lack of current technologies which will lead to their further improvement, are the largest technical obstacles that are limiting further increases in sensitivity.

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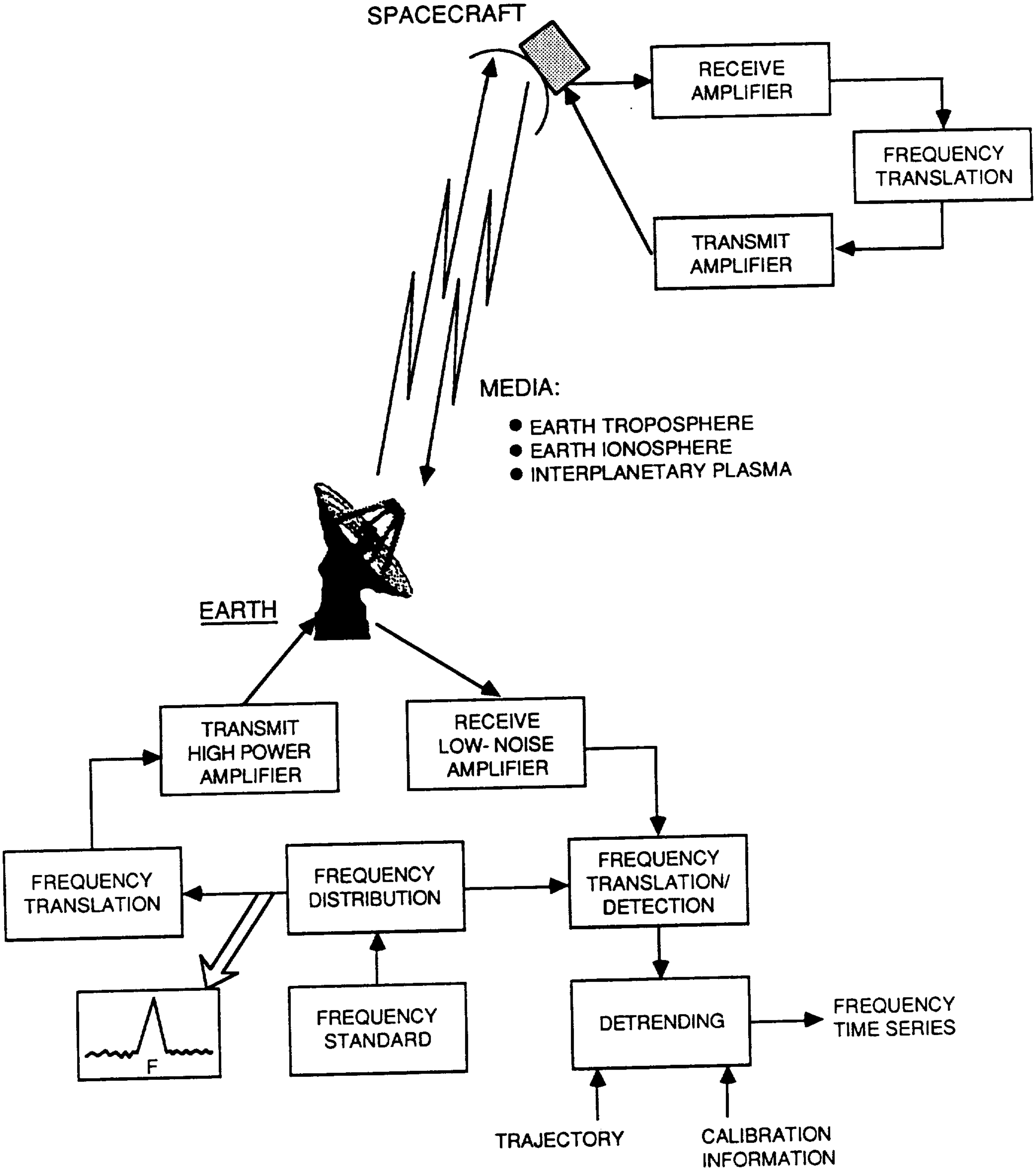

FIG. 1. — Functional Overview

DISCUSSION

REASONBERG: Why is the spacecraft up/down ratio not the same for S, X, and K-band links? Failure to make these ratios the same will make eventual dual-band "up & down" systems less effective than they should be at removing the effect of plasma on the delay and Doppler observables.

KURSINSKI: If two-phase coherent uplink the downlink signals of different frequencies are used, the differential phase between these two signals can be used to estimate and substantially reduce the plasma effects on the phase of the signals. In order to isolate the hi-power transmitted signal from the very weak received signal on the same antenna, it has been necessary to separate the uplink and downlink frequencies via multiplication ratio. Unfortunately, as is apparent in Table I of 'High Stability Radio Links,' there is a difference between the up/down ratios for S- and X-band frequencies. This was done to be compatible with the deep space frequency band allocations assigned by the International Telecommunication Union (ITU). This, unfortunately, means that the plasma effects on the signal cannot be completely isolated via a simple estimate of the differential phase between the two signals received at the earth.

SHAPIRO: Regarding the near future, why can't one use; dual-band (S- and X-band) uplink as well as downlink (the S-band uplink capability already exists and it is not clear why it needs to be dropped) and VLBI calibration techniques, already well developed, to calibrate the relevant electrical paths on the transmitter and receiver parts of the ground system?

KURSINSKI: To isolate the plasma effects, in this situation, implies that the plasma effects on the uplink would have to be estimated via a differential phase measurement between the two uplink signals at the spacecraft and then perhaps one of the uplink signals would be used as the reference to generate the two coherent downlink signals. Such a scheme has been proposed by Jay Breidenthal at JPL using existing equipment and the Galileo spacecraft. Simultaneous S-band and X-band uplink signals could be radiated from different antennas at the same complex and the Galileo transponder, because of its design, may unintentionally be able to simultaneously receive both signals. One method suggested for separating the uplink plasma effects is to offset the two uplink signals from their relative 11/3 ratio by some factor like 1 Hz, which would result in a beat frequency in the downlink signal from which the uplink plasma effects could be measured separately from the downlink effects.

Concerning calibration of the relevant electrical paths, usage of the techniques developed for VLBI is a possibility. The DSN is developing a calibration and` monitoring technique for the X-band uplink capability and based on this question, I will have the modifications necessary to make this compatible with the S-band uplink examined.