TONE-BASED COMMANDING OF DEEP SPACE PROBES USING SMALL APERTURE GROUND ANTENNAS

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ABSTRACT

We describe a technique that enables the reception of spacecraft commands at received signal levels as much as three orders of magnitude below those of current deep space systems. It reduces the cost of deep space operations by enabling the use of small aperture ground antennas to control spacecraft during the cruise phase. With the proposed system, referred to as *tone-based commanding*, control of spacecraft at interplanetary distances is possible using ground antennas of the 5 to 10-meter diameter class.

Tone-based commanding involves the reception of commands that are sent in the form of precise frequency offsets using an open-loop receiver. The key elements of this technique are an ultrastable oscillator and open-loop receiver on-board the spacecraft. Both are part of the existing New Horizons (Pluto flyby) communication system design, thus enabling possible flight experimentation with the technique during the long cruise of the spacecraft to Pluto.

1. INTRODUCTION

In recent years, the Applied Physics Laboratory (APL) has been developing an advanced communications architecture for missions that include CONTOUR, New Horizons, and Solar Probe. This architecture includes a highly integrated X-band transceiver system, ultrastable oscillator (USO), uplink radiometrics capability, and open-loop reception capability. The latter capability enables the RF system to downconvert and record weak uplink signals on-board the spacecraft. The transceiver system is implemented on the spacecraft using relatively low power, low mass plug-in cards.

Existing deep space receivers must phase-lock to the uplink signal and generate a data clock for command reception. These processes limit the sensitivity of present-day receivers to about –157 dBm for carrier lock and –145 dBm for reception of the minimum bit rate of 7.8125 bps. The phase-locking processes in the carrier and data tracking loops drive these threshold levels. In the proposed new system, the onboard USO provides the highly accurate frequency knowledge needed to improve the detection of very weak signals. The detection is accomplished by performing a linear downconversion of the received signal, then determining its frequency through the use of an on-board signal processing algorithm. Using this open-loop[1] technique, receiver command sensitivity on the order of –175 dBm ($P/N_o \approx -1.5$ dBHz) should be achievable. This sensitivity enables the commanding of interplanetary probes using a relatively small dish antenna on the ground and a lowgain antenna on the spacecraft. The technique complements existing methods for weak signal, downlink beacon tone reception [1,2].

This paper presents a preliminary design of the toned-based command system including discussion of the hardware elements, stability requirements, timing, and noise performance. Example link budgets are presented for two representative mission scenarios. Finally, a proposed flight experiment with the New Horizons spacecraft is discussed.

2. SYSTEM DESIGN

Block Diagram

Figure 1 shows a conceptual block diagram of the spacecraft portion of the tone-based commanding system. The received RF signal is downconverted to an intermediate frequency and then sampled. These samples are processed to determine the received signal frequency. The accuracy of the frequency measured by the spacecraft receiver will depend on the stability of the ground and spacecraft oscillators, as well as the ability of the ground station to compensate for uplink Doppler shift. Over long

[1] In this paper, "open-loop" refers to the fact that the spacecraft receiver is not phaselocked to the uplink signal.

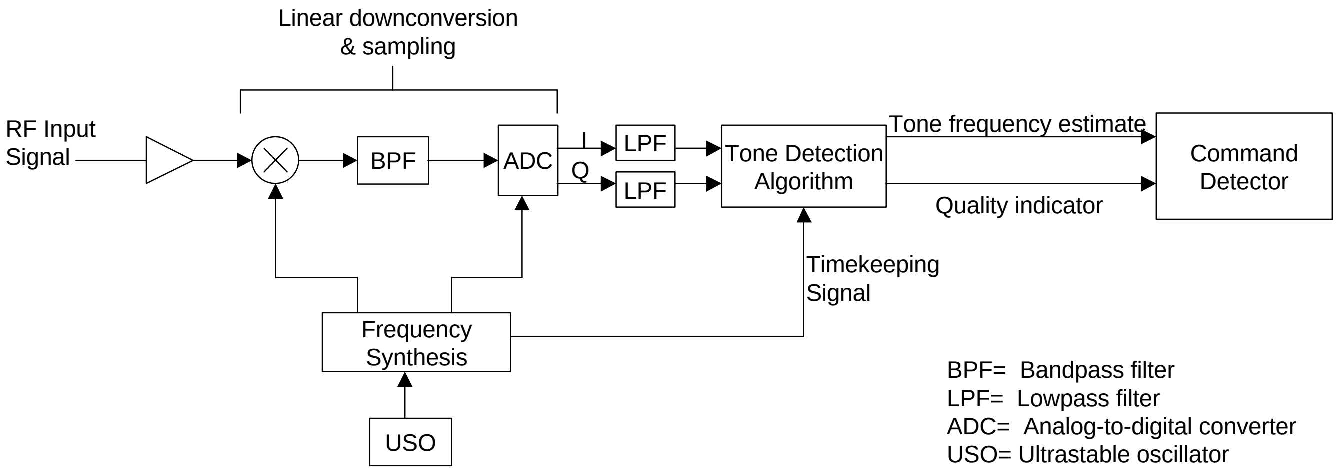

Figure 1. Conceptual block diagram of tone-based command system (spacecraft hardware)

periods of hibernation, the frequency knowledge will degrade as the oscillators drift and the orbit determination model ages. Therefore, the tone detection system should operate differentially, with the frequency difference between successive tones carrying the command information. Alternatively, two tones could be transmitted simultaneously, with the command information carried as the frequency difference between the two tones. For this paper, we will assume that *successive tones* carry the command information. Each tone is actually an uplink carrier signal with its frequency precisely controlled.

Frequency Stability Considerations

The proposed system is essentially a frequency-shift keyed modulation scheme. The number of different commands that can be sent will depend on the receiver detection channel bandwidth and the frequency stability of the system. Shown below are some example parameters of a first-cut system design. The ground station oscillator is assumed to be an atomic frequency standard.

- Uplink signal frequency: 7.2 GHz
- Command tone duration: 60 s
- Detection channel bandwidth: 1500 Hz (two-sided bandwidth after sampling)
- Ground station frequency stability: 1×10^{-12} (over 60 seconds)
- Spacecraft USO frequency stability: 1×10^{-12} (over 60 seconds)
- Spacecraft USO long-term drift: 1×10^{-11} (over 24 hours)

We see that the stability of the measured signal due to the combined ground station/spacecraft oscillators is 1.4×10^{-12} (0.01 Hz) over the 60-second command tone duration. This is relatively small, so the stability of the signal measured by the spacecraft may depend more on the ability of the ground station to predict and remove geocentric and topocentric Doppler shift from the uplink signal. Because we are considering a differential system, the ability to hold the frequency that is observed at the spacecraft constant is the important issue, rather than the ability to achieve a specific frequency.

As a simple illustration of the error that might occur due to compensation for Doppler shift, we can consider a distant spacecraft in the equatorial plane of the Earth and a ground station on the equator. Figure 2 illustrates the Doppler shift profile that would result from such a geometry over the course of a ground station pass. The origin corresponds to the spacecraft at zenith and the ends of the abscissa correspond to the spacecraft at the horizon. The time-delayed curve shown on the figure represents what might occur due to an error in the spacecraft orbital position. We see that a position error at zenith results in a large but relatively constant Doppler frequency error at the spacecraft. A position error at the horizon results in a smaller but more time-varying Doppler frequency error at the spacecraft. Preliminary calculations indicate that a spacecraft position error of 10,000 km at a distance of 6AU would result in a maximum Doppler frequency error of 0.12 Hz at zenith and a maximum variation in Doppler frequency error of 0.0005 Hz over 60 seconds at the horizon. Therefore, spacecraft position errors at this level do not represent a problem for signal stability over 60-second intervals. Further study is needed to fully characterize the stability of the Doppler-compensated uplink signal due to the orbit determination process and media effects.

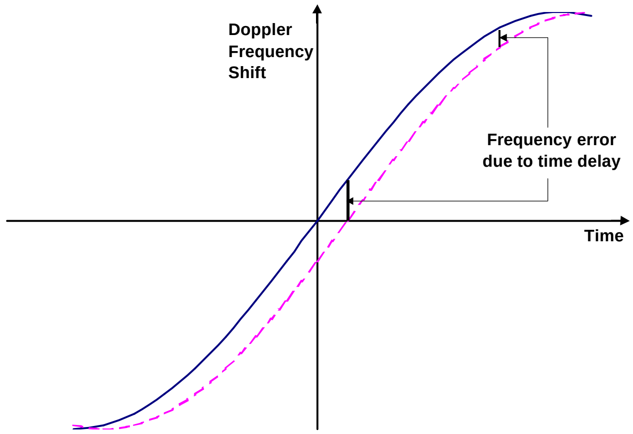

Figure 2. Typical Doppler shift profile as a result of Earth rotation for a distant spacecraft.

Table 1 shows the number of possible signal frequencies and associated command bit rates as a function of signal stability. These numbers are idealistic; in practice the number of commands will less than the number of possible signal frequencies due to practical considerations. The conclusion arrived at by these first-cut calculations, however, is that a useful system (~0.2 bps) can be achieved with only modest frequency stability requirements.

Table 1
Example Tone Command System Parameters

Parameter	Frequency stability over 60 seconds		
	0.0167 Hz	**0.1 Hz**	**1 Hz**
Detection channel bandwidth (Hz)	1500	1500	1500
Tone duration (s)	60	60	60
Maximum number (N) of command frequencies	90,000	15,000	1500
Maximum number (n) of command bits ($2^n \leq N$)	16	13	10
Bit rate (bps) (= n/60)	0.27	0.22	0.17
Duration of discrete Fourier transform (s)	60	10	1
Number of transforms that are noncoherently summed	1	6	60

Fundamental Limitation Due to Noise

The presence of thermal noise in the system will affect the achievable bit rate. In this section, we take a look at the theoretical bit rate that might be achieved with a low signal level system. A well-know fundamental limit in communication theory is expressed by the Shannon-Hartley theorem. According to this theorem, the channel capacity is expressed as:

$$C= B \log_2\{1 + P/(N_0B)\} \qquad \text{bps}$$

where B is the channel bandwidth in Hz, P is the signal power in watts, and N_o is the noise power spectral density in watts/Hz. The noise power spectral density can be expressed as $N_o= kT_s$ where k is Boltzmann's constant (1.38×10^{-23} J/K) and T_s is the receiver system noise temperature in Kelvin.

We assume the received signal power to be –175 dBm, or about 20 dB below the lock threshold of current deep space receivers. We also assume a typical X-band receiver system noise temperature of 324 K. For a channel bandwidth of 1500 Hz, the theoretical channel capacity is $C \approx 1$ bps. This calculation provides a reality check that reliable operation at a bit rate on the order of 0.2 bps might be achieved in practice.

Time Synchronization

In a conventional digital communications receiver, the clock of the received data stream must be recovered to enable synchronous detection of the data. This synchronization typically requires the use of a phaselock loop. However, the use of a phaselock loop introduces a lock threshold and an acquisition delay to the system.

With long tone durations (say 60 seconds), the time synchronization aspect of the proposed open-loop technique should be relatively straightforward. For example, the on-board time knowledge of a USO-based spacecraft is typically accurate to within one second of Earth time over hibernation periods up to one year (this aspect of spacecraft design is usually carefully managed by the mission). The reception of command tones can be pre-arranged to start only at the top of any given hour. The spacecraft processor "looks" for a command tone starting at the top of the hour and, if it detects one, looks for another every tone period after that. To account for small timing errors, some extra time (say one second) can be added to the beginning and end of each tone transmission with only a small penalty to the uplink bit rate.

Table 2
Link Analysis Examples

Parameter	Jupiter Link	Interstellar Probe Link
Ground station antenna size	10-m diameter	70-m diameter
Ground station transmit power	1.0 kW	18.4 kW (as per DSN handbook 810-5)
Ground station antenna gain	54.5 dBic (overall efficiency= 50%)	72.7 dBic (as per DSN handbook 810-5)
Ground antenna pointing loss	0.5 dB	0.15 dB
Path loss at 7.2 GHz	288.65 dB (distance= 6AU)	333.09 dB (distance= 1000 AU)
Atmospheric loss	0.2 dB	0.2 dB
Polarization mismatch loss	0.2 dB	0.2 dB
Spacecraft antenna gain	+7 dBic (low gain antenna)	+15 dBic (medium gain antenna)
Spacecraft passive loss (between antenna and receiver input)	2 dB	2 dB
Spacecraft total received power (at receiver input)	-170.1 dBm	-175.3 dBm
Spacecraft receiver system noise temperature (at receiver input)	324 K (includes 75 K antenna noise temperature, 2 dB passive loss, and 2 dB receiver noise figure)	230 K (includes 75 K antenna noise temperature, 2 dB passive loss, and 1 dB receiver noise figure)
Received P/N_o	+3.5 dBHz	-0.3 dBHz

Link Analysis Examples

To further assess the usefulness of a tone commanding system, we have analyzed two different mission scenarios: (1) a spacecraft operating at Jupiter distance (6 AU) using a 10-meter diameter ground antenna, and (2) a spacecraft operating at an interstellar distance of 1000 AU using a Deep Space Network (DSN) 70-meter diameter ground antenna [3]. These examples serve to establish the received signal levels that might be expected in an actual mission. Table 2 shows the link analysis results for the two scenarios. In the Jupiter mission scenario, the spacecraft is assumed to be in hibernation attitude with a low gain antenna oriented toward the Earth. The ground station transmitter power is 1 kW. The analysis indicates a received signal power of –170 dBm. In the interstellar mission scenario, the spacecraft is assumed to be in hibernation attitude with a medium gain antenna oriented toward the Earth. The ground station transmitter power is 18.4 kW. The analysis indicates a received signal power of –175 dBm. Figure 3 shows the variation in received signal power as a function of distance for the two scenarios.

3. PERFORMANCE IN THE PRESENCE OF NOISE

Many details of the command decoding system remain to be defined; however, some preliminary calculations indicate that reliable performance can be achieved with relatively low signal levels. Detection of the command tone is based on an examination of the power in each frequency bin following a discrete Fourier transform of the downconverted signal. When the highest power level in any frequency bin within the 1500 Hz detection channel bandwidth exceeds a specified threshold, the frequency corresponding to that maximum value is determined to be that of the command tone. The actual command information is determined by the *change* in frequency between two successive tones[2].

The length of the discrete Fourier transform is bounded by the signal stability. In the limit of a very stable USO on the spacecraft and very good compensation of the uplink Doppler shift by the ground, the entire command tone interval of 60 seconds can be processed in a single transform. This approach assumes that the signal remains within one frequency bin width of 0.0167 Hz during the 60-second tone period. As the signal stability becomes worse, the length of the discrete Fourier transform must be shortened to produce wider frequency bins. For example, if the received signal was stable to within 0.1 Hz over 60 seconds, then six discrete Fourier transforms would be performed, each based on ten seconds of data.

To enable preliminary calculations of the noise performance of the tone-based command system, we have considered the three stability cases shown in Table 1. In all

[2] Because the system is differential, an error made in the determination of a received signal frequency will result in *two* command errors. This detail is not addressed in this paper.

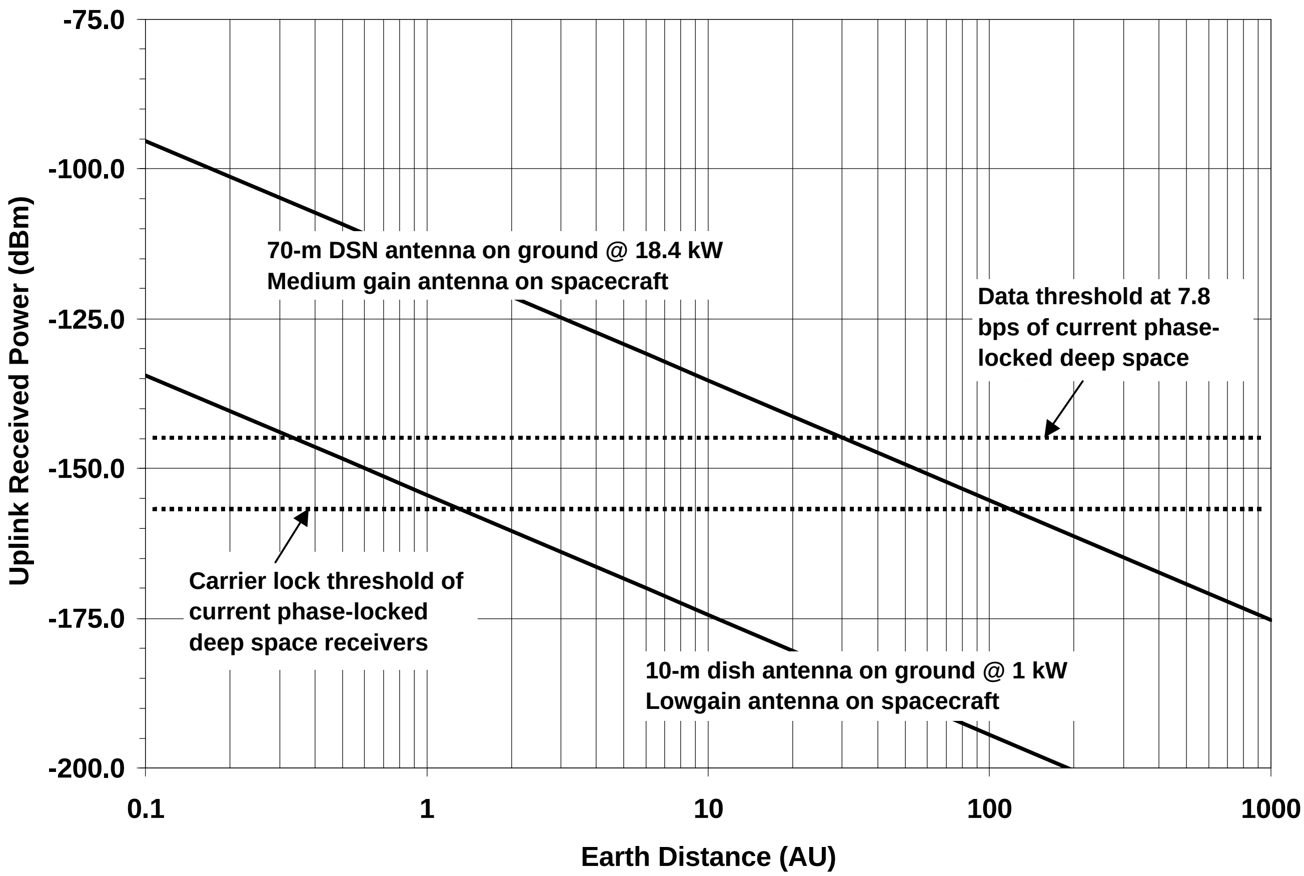

Figure 3. Uplink analysis results for two different mission scenarios

three cases, the complete data record is 60 seconds long and the effective sample rate is twice the lowpass filter (LPF) cutoff frequency, or 1500 Hz. The two-sided bandwidth of the detection channel is 2 x 750= 1500 Hz. The only difference between the three cases is the stability of the sampled signal, which bounds the maximum length of the discrete Fourier transform and determines the number of transforms that must be noncoherently summed.

We apply the Neyman-Pearson criterion to this problem by maximizing the probability of correct tone detection for a given false alarm probability. If we set the false alarm probability to 10^{-8} for each 60-second interval, then false alarms will occur at a rate of once every 190 years. This probability is spread across all of the frequency bins, so the probability of a false alarm at any particular frequency is very much smaller than 10^{-8}. We define a false alarm to occur when no signal is transmitted and the noise results in the power in any one frequency bin crossing a detection threshold. The detection threshold itself would be based on the observed noise level to assure a constant false alarm rate that is independent of changes in the system noise temperature.

Also for the sake of illustration, we set the probability of detection to 99% and compute the signal power necessary to achieve this combination of false alarm and detection probabilities when the system noise temperature is 324 K. The result is shown in Figure 4 as a function of the assumed frequency stability. We see that achieving this level of performance with a signal power approaching –175 dBm will require excellent signal stability (<0.01 Hz over 60 s). Relaxing the stability to 1 Hz over 60 s increases the required signal power to about –171 dBm.

The sensitivity of the probability of detection to changes in the assumed false alarm probability is shown in Figure 5. Increasing the acceptable probability of false alarm by an order of magnitude, for example, would raise the probability of detection to 99.5% for all of the signal power levels shown in Figure 4. The interdependence of the detection and false alarm probabilities is seen to be largely independent of the assumed frequency stability once the signal levels are chosen to meet the 99% detection and 10^{-8} false alarm probabilities.

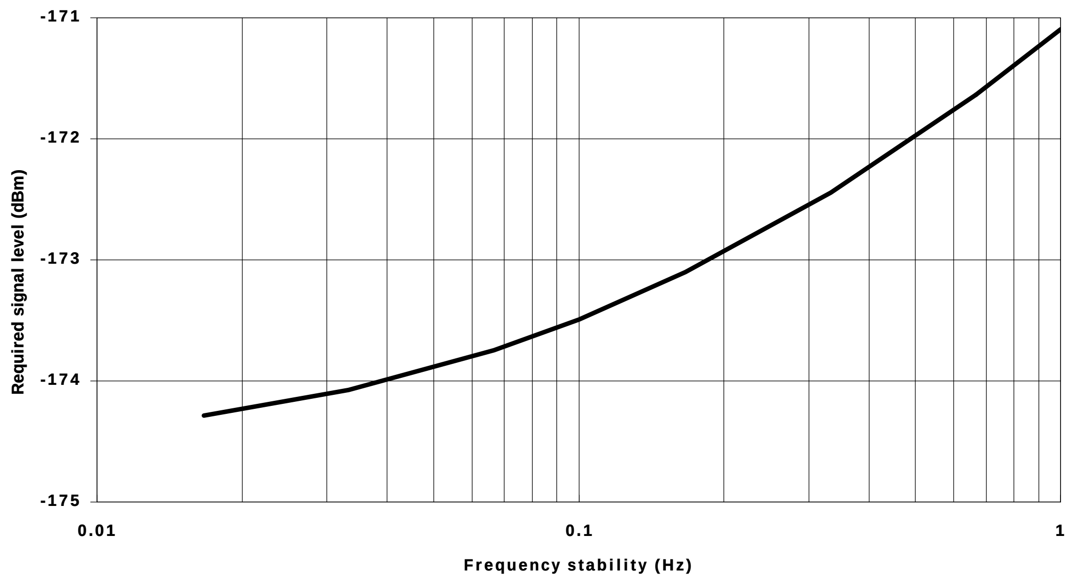

Figure 4. Receiver signal power needed to achieve a 99% probability of correct detection with a false alarm probability of 10^{-8} over 60-second intervals. The two-sided detection channel bandwidth is 1500 Hz. The system noise temperature is 324 K.

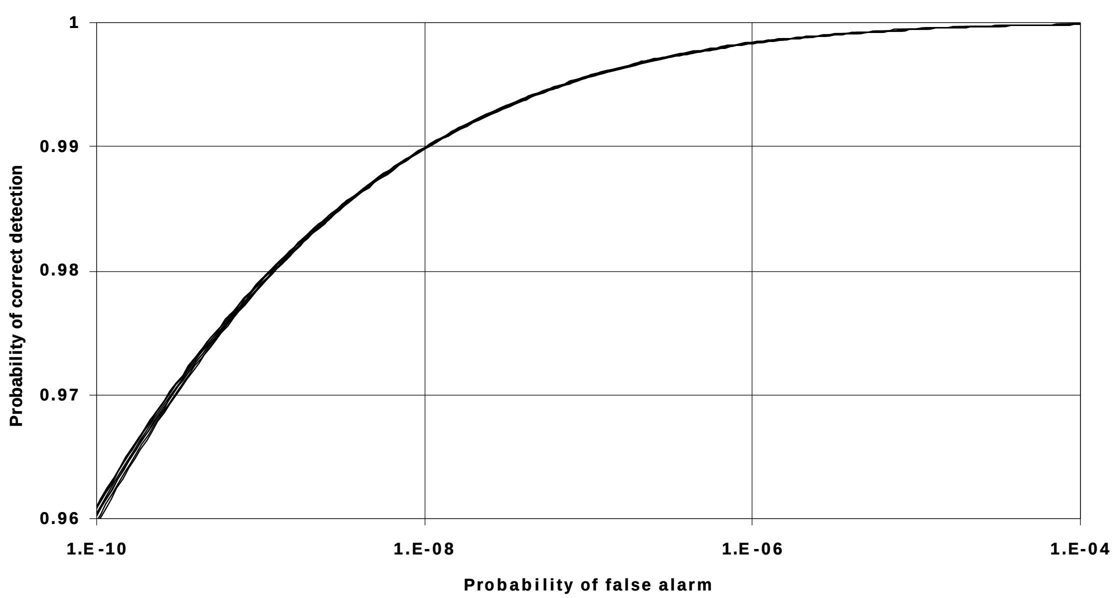

Figure 5. Receiver operating curves. The different plots correspond to signal stabilities of 0.0167 Hz, 0.1 Hz, and 1 Hz. The probability of detection in all cases is set equal to 0.99 for a probability of false alarm of 10^{-8}.

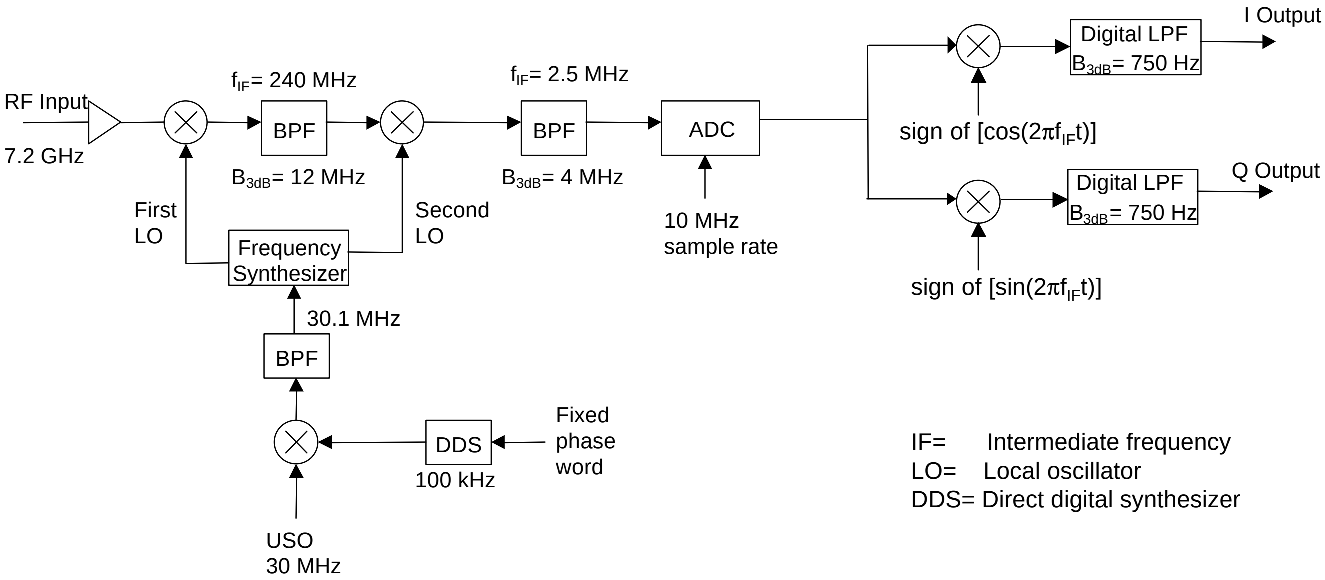

Figure 6. New Horizons uplink command receiver in open-loop configuration

4. NEW HORIZONS FLIGHT EXPERIMENT OPPORTUNITY

The New Horizons mission will launch in January 2006 and fly by Pluto and Charon as early as 2015. This mission is incorporating an advanced RF communications architecture, developed by APL, that includes plug-in X-band uplink and downlink cards, regenerative ranging capability, uplink radio science capability, and a USO. The command receiver can be placed into an open-loop configuration (Fig. 6) for making uplink radio science measurements. In this configuration, the X-band signal is linearly downconverted, then sampled and lowpass filtered to produce complex (I and Q) baseband samples in an output LPF bandwidth of 750 Hz [3]. These samples, 16 bits for I and 16 bits for Q, are output at a 3.3 kilosample/s rate and recorded on the spacecraft solid state recorder (SSR).

The architecture of the New Horizons RF communication system provides a good opportunity to experiment with tone-based commanding during flight. At a convenient time during the cruise phase of the mission, one of the receivers could be put into open-loop radio science mode for reception of simulated uplink commands. Shown below is a general flow for such an experiment:

- One receiver is put into open-loop radio science mode. The spacecraft SSR is configured to record the radio science output of this receiver for the duration of the experiment.
- The DSN transmits an uplink signal that is precisely controlled to present a constant frequency at the spacecraft receiver within $\pm$750 Hz of the receiver center frequency.
- Dummy commands are uplinked in the form of a series of frequency offsets initiated at a prescribed point in time (say at the top of the hour).
- At the end of the experimental period (presumably still within the ground station pass), the contents of the SSR are dumped to the ground.
- The recorded data is analyzed on the ground to decode the commands as if they were actually decoded in flight.

The proposed experiment would need to be incorporated into the mission planning. At first look it appears that it could be done within the bounds of the existing design of the spacecraft hardware and software.

5. CONCLUSION

We have presented the preliminary design of an uplink communication system capable of enabling a ground station with a relatively small antenna (5 to 10-meter diameter) to command a deep space probe. The system takes advantage of highly stable oscillators on both the

[3] The bandwidth is determined by the requirements of the radio science measurement.

ground and spacecraft ends of the link to enable operation at very low signal levels. The uplink command capability it provides complements existing techniques for downlink beacon tone reception. The design of the tone-based command system places realistic requirements on frequency stability and timing. A preliminary noise analysis indicates that reliable operation can be achieved with signal levels as low as –170 to –175 dBm at the spacecraft receiver. Opportunities exist to experiment with this technique on the ground and in flight using the advanced RF communications architecture on the New Horizons spacecraft.

6. REFERENCES

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