Flexible Coherent Digital Transceiver for Low Power Space Missions[1,2]

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Abstract—A flexible coherent digital transceiver architecture has been developed by the APL in order to enable mission specific performance tailoring while maintaining modularity and minimizing program-incurred cost and risk. The new transceiver architecture is based on the heritage X-band transceiver system that is currently integrated into the New Horizons spacecraft. Using this new architecture, a low power, coherent, X-band digital transceiver has been made that meets the requirements for two-way Doppler tracking. The new transceiver contributes less than 0.01 mm/s to the Doppler velocity error measured over a 60-second interval in coherent mode. Secondary power consumption is 2.8 W in the uplink-only mode of operation including the reference oscillator. Transceiver designs on the TIMED, CONTOUR, and New Horizons spacecraft were noncoherent, which required downlink telemetry in order to support two-way Doppler tracking [1]. The addition of a coherent capability allows this new architecture to be used on missions where carrier-only Doppler tracking is desired. This paper provides a description of the new transceiver architecture and its demonstrated performance.

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1. INTRODUCTION

Modern spacecraft radio navigation is typically performed via two-way Doppler tracking, which is enabled by the use of a two-way coherent spacecraft transponder. This navigation technique limits flexibility in the choice of spacecraft communications hardware. Noncoherent navigation techniques [1] were developed to enable the use of a wider variety of communications hardware, helping to enable smaller, lower cost satellite missions. Two-way Doppler tracking via telemetry-based noncoherent navigation was first demonstrated on the TIMED mission [2] and implemented on the CONTOUR mission [3]. The New Horizons mission to Pluto and beyond is flying a noncoherent navigation communications system [4] due to uplink radio science requirements and power constraints which were mitigated by the development of a low power X-band uplink receiver [5]. The New Horizons X-Band Digital Receiver consumes 2.3 W of secondary power, providing significant power savings over commercially available alternatives, while yielding similar performance and added capability (i.e., regenerative pseudonoise ranging and an uplink radio science instrument).

The New Horizons uplink receiver is paired with a noncoherent downlink transmitter, and fabricated into two separate integrated electronics module (IEM) cards. Both the uplink and downlink cards share a common frequency reference, the USO. The inclusion of a USO is required on New Horizons to provide radio science capability; it is not a requirement of the communications architecture. Since the uplink carrier tracking signal is not used in the generation of the downlink carrier, the New Horizons transceiver system is noncoherent. To provide for two-way Doppler tracking, additional circuitry measures the uplink frequency with respect to the USO and inserts this data into the spacecraft telemetry stream to be downlinked. The Earth station tracks the spacecraft as if it contained a coherent transceiver or transponder and the navigation team then uses a correction factor derived from the telemetered navigation data. The two-way Doppler tracking performance is equal to that of a coherent system, assuming that downlink telemetry is available.

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[2] IEEEAC paper #1131, Version 3, Updated Dec. 16, 2005

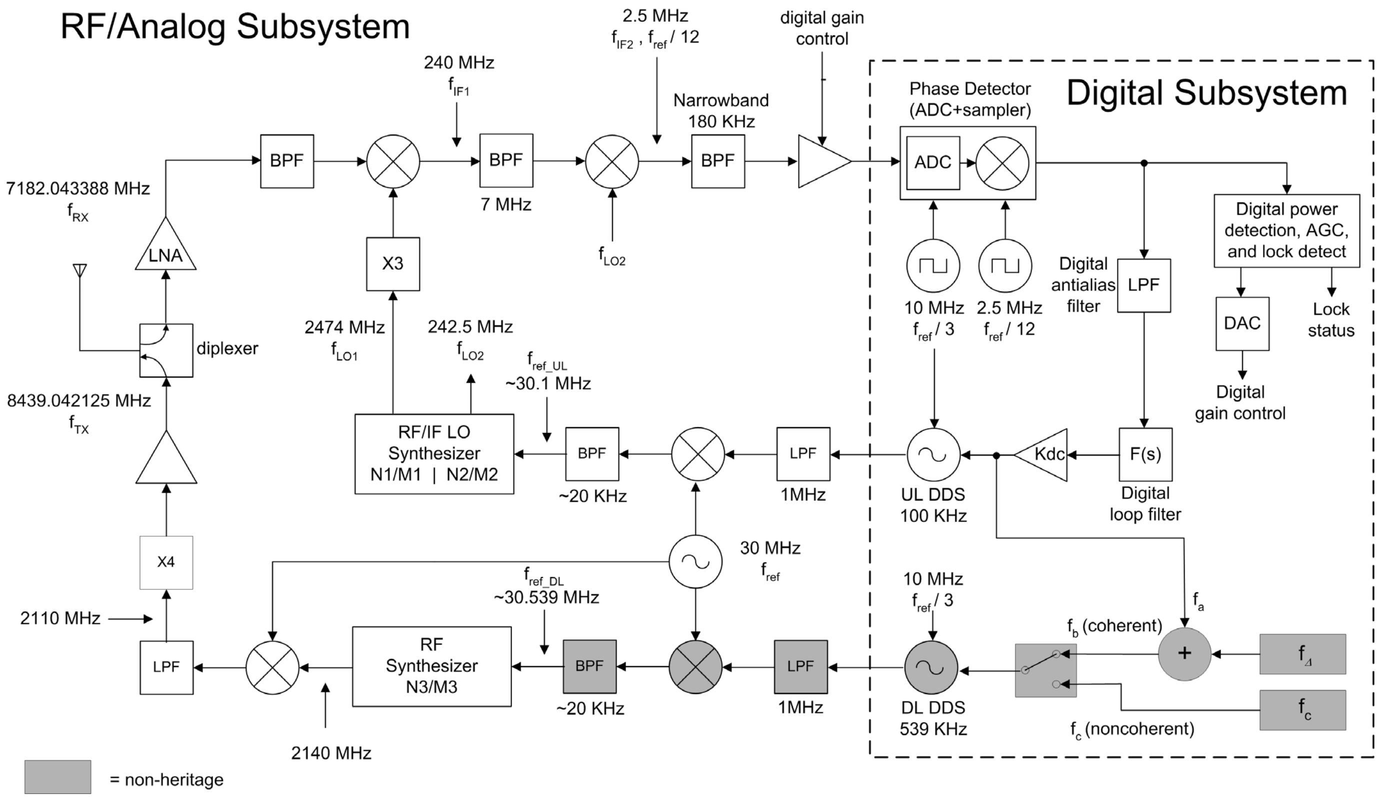

Figure 1 - Basic block diagram of the carrier tracking circuitry of the coherent transceiver configured for X-Band

Doppler tracking of a spacecraft using noncoherent navigation techniques requires sufficient downlink signal to noise ratio (S/N) to transfer telemetry frames without errors. Some missions require Doppler tracking capability at times when the downlink S/N is very low (e.g., operation through low gain antennas at long range during orbital operations) or when the downlink signal is carrier-only. The use of a fully coherent transceiver allows two-way Doppler navigation to be performed using only a carrier.

Leveraging from technologies and digital signal processing techniques incorporated into the New Horizons X-Band Digital Uplink Receiver, a low power two-way coherent X-band transceiver has been developed. The new transceiver requires minimal modification to the heritage New Horizons X-Band transceiver and meets typical spacecraft Doppler navigation requirements while consuming 2.8 W secondary power in the uplink-only mode of operation including the reference oscillator. The new transceiver provides noncoherent, coherent, and radio science modes while maintaining a simple and flexible architecture. An architecture based on frequency synthesis and direct digital synthesis (DDS) techniques eliminates the typical constraints of coherent communications transponders by allowing flexibility in the choice of turnaround ratios, channel assignment, and band of operation (e.g. S, X, or Ka-band) without the need for tuning or replacing the reference oscillator. This flexibility allows the transceiver to be easily tailored to the needs of a given mission without hardware redesign and manufacture (i.e. via software or VHDL code changes). The intrinsic nature of a transceiver, as opposed to a transponder, allows the uplink receiver, downlink transmitter, and reference oscillator to be independently developed, tested, and used in a variety of mission-specific configurations.

A prototype X-band coherent digital transceiver has been assembled for proof-of-concept using prototype hardware from the New Horizons noncoherent transceiver system. This prototype transceiver operates in the X-band, though S-Band operation may be achieved by simply reprogramming coefficients in a field programmable gate array (FPGA) and removing several components. Ka-band band downlink capability may be added by the addition of a multiplier module, which is under investigation. An FPGA-based digital subsystem allows easy incorporation of future performance enhancements such as tone-based commanding [6], spectrum analysis via fast Fourier transform (FFT), RMS power detection, and more. The reported power consumption includes an on-board frequency reference, which provides the stability required by many of these future performance enhancements.

A discussion of the theory behind the new coherent transceiver architecture follows. The results from a proof-of-concept prototype coherent transceiver test are also presented.

2. COHERENT ARCHITECTURE

The New Horizons uplink receiver and the noncoherent navigation enabled downlink transmitter effectively provide a method for spacecraft navigation via two-way Doppler tracking. In order to maintain two-way Doppler tracking capability without the need for noncoherent navigation telemetry, the uplink carrier tracking information must be used to control the downlink carrier frequency, preferably with a downlink/uplink turnaround ratio of 880/749 to be compatible with ground station infrastructure. Since the uplink carrier tracking loop in the New Horizons uplink receiver is DDS-based, the digital carrier tracking information may be processed and passed on to an identical DDS used for downlink carrier generation. It is the processing inside the uplink/downlink interface that removes the onboard reference contribution to the downlink carrier, making the new transceiver two-way coherent capable. A description of the uplink and downlink sections of the new transceiver follows.

Uplink Receiver

Figure 1 provides a block diagram of the new coherent transceiver in an X-Band configuration. By design of the phase-locked loop in the receiver, the second intermediate frequency (f_{IF2}) is forced to f_{ref} divided by 12. The feedback frequency of the DDS, f_a, is dependent on the received uplink frequency (f_{RX}) and the frequency of the reference oscillator (f_{ref}) as follows:

$$f_a = \frac{\dfrac{f_{RX}}{f_{ref}} - \dfrac{1}{12}}{\mathrm{R}_{\mathrm{dig}}\left(\mathrm{R}_1 - \mathrm{R}_2\right)} - \frac{1}{\mathrm{R}_{\mathrm{dig}}} \tag{1}$$

Where:

$$\mathrm{R}_{\mathrm{dig}} = 1/3 \text{ (for New Horizons)}$$

$$\mathrm{R}_1 = N_1/M_1; \quad R_2 = N_2/M_2$$

N_1, M_1, N_2, and M_2 are divider values for the two uplink frequency synthesizers. N_3 and M_3 are divider values for the downlink frequency synthesizer.

Downlink Transmitter

The downlink card architecture (see Figure 1) is comprised of a single synthesized frequency source, an offset mixer, and a multiplier. The shaded items in Figure 1 illustrate the non-heritage downlink components. The synthesizer reference frequency in the *heritage* noncoherent downlink system is f_{ref}, which results in a simple transmit frequency equation in terms of the reference oscillator frequency:

$$f_{TX} = 4 \cdot f_{ref}\left(\mathrm{R}_3 - 1\right); \qquad \mathrm{R}_3 = N_3/M_3 \tag{2}$$

Coherent Uplink-Downlink

Making the downlink frequency coherent with the uplink frequency requires that f_{TX} is related to f_{RX} by a constant ratio. To do this, a point on the receiver card carrying both f_{ref} and f_{RX} information needs to be brought over and "mixed" into the downlink card. We have chosen to use the factor f_a from above to link the two cards together because the digital signal is easily processed and transported. Adding the f_a term into the downlink card at the reference to the frequency synthesizer was chosen due to circuit similarities in the uplink card. The new equation for f_{TX} in terms of f_{ref} and f_{RX} is derived as follows:

$$f_{TX} = 4 \cdot f_{ref}\left(\mathrm{a'}\frac{f_{RX}}{f_{ref}} + \mathrm{b'}\right) \tag{3}$$

Where:

$$\mathrm{a'} = \frac{\mathrm{R}_3}{\mathrm{R}_1 - \mathrm{R}_2}; \quad \mathrm{b'} = \frac{-\mathrm{R}_3}{12\left(\mathrm{R}_1 - \mathrm{R}_2\right)} - 1$$

From this equation it is clear that b′ must be zeroed to remove f_{TX} dependence on the f_{ref} frequency. However, the ratios that make up b′ cannot be varied widely, and ideally should not be varied at all to maintain the proper uplink and downlink channels and to maintain a 30 MHz reference oscillator frequency. Therefore, the exact frequency control word updating the DDS on the uplink card should not be used to update the DDS on the downlink card. A new DDS frequency control word may be derived from the old word using fairly simple mathematics to minimize digital processing.

$$f_b = f_a + f_\Delta \tag{4}$$

$$\mathrm{b}_b' = \frac{-\mathrm{R}_3}{12\left(\mathrm{R}_1 - \mathrm{R}_2\right)} - 1 + \mathrm{R}_3 \cdot \mathrm{R}_{\mathrm{dig}} \cdot f_\Delta = 0 \tag{5}$$

$$f_\Delta = \frac{1}{12 \cdot \mathrm{R}_{\mathrm{dig}}\left(\mathrm{R}_1 - \mathrm{R}_2\right)} + \frac{1}{\mathrm{R}_3 \cdot \mathrm{R}_{\mathrm{dig}}} \tag{6}$$

The new frequency control word for the downlink card DDS is created from f_a and called f_b. This new word has an extra term f_Δ that can be varied independent of other terms to zero out b′. The f_Δ term represents the addition of a constant to the frequency word coming over to the downlink card from the uplink card. This is a simple operation to perform, thereby making the coherent architecture simple to implement. Using this method, the turnaround ratio becomes the following equation:

$$\frac{f_{TX}}{f_{RX}} = \frac{4 \cdot R_3}{R_1 - R_2} = \frac{67264}{57245} \approx \frac{880}{749} \tag{7}$$

This numeric solution is specific to the prototype coherent transceiver system, which uses an integer-N downlink frequency synthesizer. The turnaround ratio will change based on the DSN channel selected and whether or not fractional-N synthesis is used. The advantage in using fractional-N frequency synthesis is that the uplink and downlink carrier frequencies may be better centered within the allocated DSN channels. Fractional-N frequency synthesis is part of the heritage New Horizons uplink receiver and will be ported to the downlink transmitter as part of the new coherent transceiver design.

Error Sources

The most significant error source in this coherent system is the quantization of f_Δ. Other quantization and rounding effects exist in the uplink carrier tracking loop; however, these error sources are extremely small and are dominated by system noise and the following error terms. The phase accumulator in the prototype system DDS is 32 bits, leading to a 32 bit representation of f_Δ. The round-off incurred here causes a small portion of f_{ref} to contaminate the downlink frequency. This error term (Err_Δ) could be as significant as 2^{-33} (or 1 part in 10^{10}), creating a fixed velocity offset of 5.8 mm/s. The use of a 48 bit DDS would reduce the worst case possible fixed error to 88 nm/s. The error contribution equation is as follows:

$$f_{TX} = \frac{4 \cdot R_3}{R_1 - R_2} f_{RX} + 4\left(f_o + f_{drift}\right) R_3 \cdot R_{\text{dig}} \cdot Err_\Delta \tag{8}$$

The first term in the error source is the nominal frequency f_{ref}, and the second term is the drift of the reference oscillator. The nominal value of the reference oscillator (f_o) will cause a constant offset in the downlink frequency that is easily accounted for, and the drift contribution of the reference oscillator (f_{drift}) will be insignificantly small. For the prototype coherent transceiver, the constant offset in f_{TX} is ~ 63.26 mHz, or 7.5 parts per trillion, which was verified during several tests.

3. Performance Requirements

There are two primary performance requirements driving the new two-way coherent X-Band transceiver architecture: 1) two-way Doppler tracking velocity error of ≤ 0.1 mm/s on a 60-second interval at low S/N and 2) low power consumption. The new coherent X-band transceiver consumes 2.8 W secondary power in receive-only mode, which is a considerable savings over commercially available systems. The two-way rms Doppler velocity error requirement must be converted to a frequency stability requirement to be meaningful; the following equation can be used to perform this conversion [7]:

$$\frac{\sigma_f}{f_c} = \frac{2\sigma_v}{c} \tag{9}$$

Where:

σ_f = Allan deviation, Hz
σ_v = Doppler velocity error, m/s
c = speed of light in vacuum, m/s
f_c = downlink carrier frequency, Hz

The minimum achievable velocity error for an X-Band uplink/downlink system is limited by solar phase scintillations for a given Sun-Earth-probe angle as reported in [7], among other effects. For an increasing Sun-Earth-probe angle, this error approaches a minimum for a given integration time. Using the above equation, the Allan Deviation is calculated for the approximate minimum Doppler velocity error due to solar phase scintillations for an X-Band system (Table 1); for comparison, the specified Allan Deviation for the NEAR X-band transponder [8] is also included. Inspection of Table 1 reveals that solar corona effects are significantly higher than the specified residual error of the transponder itself. As a result, the calculated Allan Deviation due to solar corona effects shall be used as an absolute requirement and the NEAR transponder specification shall be used as a goal for the new transceiver. Both meet the typical 0.1 mm/s over 60 seconds precision requirement of deep space navigation.

Table 1 - Allan Deviation Requirements for given RMS Doppler Velocity Errors

Integration Time (s)	Velocity Error (mm/s)	Allan Deviation (parts)	Reason
60	0.05	3.3E-13	solar scintillation
60	0.0069	4.6E-14	NEAR transponder spec
1000	0.03	2.0E-13	solar scintillation
1000	0.00075	5E-15	NEAR transponder spec
60	0.1	6.7E-13	Typical nav spec

The downlink carrier phase noise contributes to phase error in the receiving Earth station's tracking loop. This phase error, if significant, leads to bit error rate (BER) degradation and cycle slipping in the downlink. The effects of transmitter phase noise on the downlink when received by an Earth station may be quantified using the methods in [9] and [10] through which a downlink carrier phase error specification was calculated assuming residual-carrier phase modulation (PM) (Table 2). BER degradation must be minimized for downlink telemetry transmission, though when operating in a carrier-only downlink mode cycle slipping becomes the limiting factor in specifying allowable phase error. Carrier-only performance is important during low S/N mission scenarios that preclude downlinking telemetry and that require two-way Doppler tracking of a spacecraft. Further details later in this paper will tie this phase error requirement into a downlink carrier phase noise requirement.

Table 2 - Downlink Carrier RMS Phase Error Requirements in Ground Receiver Tracking Loop

Criteria	Max RMS Phase Error (degrees)
Negligible BER degradation	6.4
0.2 dB BER degradation	9.1
1 year mean time between cycle slips	15.4

In addition to the above requirements, the new transceiver architecture must support a noncoherent downlink mode and regenerative pseudonoise ranging and radioscience modes. Both of these requirements are met by the New Horizons transceiver and are not affected by the modifications required for the fully coherent transceiver.

4. PERFORMANCE VERIFICATION

A fully coherent X-band transceiver prototype was assembled for proof-of-concept, using prototype hardware of the New Horizons uplink and downlink cards described above (see Figure 2). In this configuration, the uplink receiver secondary power consumption is 2.3 W including the critical command decoder and wideband radio science channel. The downlink transmitter secondary power consumption is 4.7 W; improvements will be made on this for future missions by applying the technologies already incorporated into the uplink receiver for New Horizons. A second DDS (125 mW) was added to the heritage transceiver system in order to obtain coherency. A proof of concept test was conducted in order to demonstrate the Allan Deviation and downlink carrier phase error requirements described above. The test setup consisted of the demonstration transceiver chassis, a downconverter built from connectorized RF components, and a rack of test equipment. A block diagram of the test system is illustrated in Figure 3; the components in red are considered spacecraft systems, the components in black are considered Earth station systems. The Earth station components are linked by a common 10 MHz reference generated in the Agilent E8267C uplink signal generator and distributed through the HP 5087A amplifier. The same 10 MHz reference can also be attached to the Agilent 8663A generator on the spacecraft-side to phase-lock the transceiver reference to the measurement system and perform baseline measurements in noncoherent and coherent downlink modes.

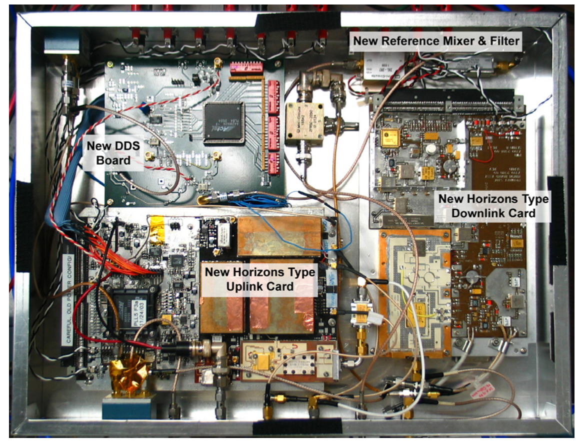

Figure 2: Proof-of-Concept Transceiver Assembly.

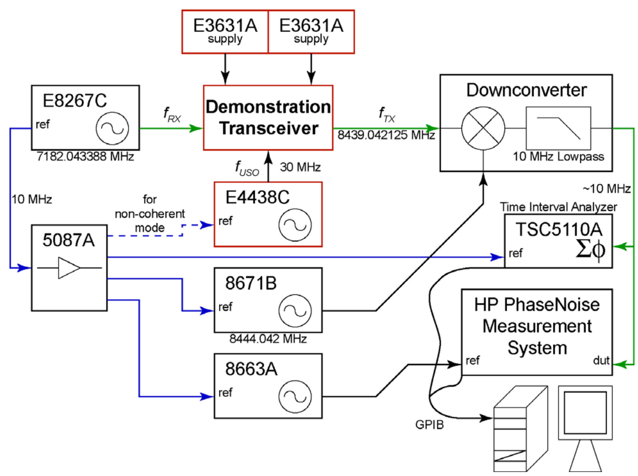

Figure 3: Transceiver Test System Block Diagram

To measure the performance of the prototype transceiver, an uplink carrier (f_{RX}) is generated by the E8267C and transmitted to the uplink receiver. The receiver phase-locks to the uplink carrier, resulting in a coherent downlink carrier frequency (f_{TX}) as defined earlier. The transmitted downlink carrier is downconverted using a connectorized mixer, filter, and amplifier. The local oscillator for the downconversion is an HP 8671B signal generator. The resulting intermediate frequency is approximately 10 MHz; this frequency is conducive to measuring Allan Deviation, phase noise, and other performance metrics.

Allan Deviation

The Allan Deviation of the prototype transceiver system is measured using the time interval analyzer illustrated in

Figure 3. Results from several key measurements are shown in Figure 4. The dashed lines show the specifications and measured results for the transponder used on NEAR. These lines represent our performance goal for the transceiver. The measurement floor of our test equipment is shown in the solid red line. This result was obtained by directly connecting the E8267C to the downconverter box using an 8.439 GHz carrier frequency. The solid orange line shows the transceiver Allan Deviation for a strong S/N in the uplink path (same conditions as the NEAR transponder measurements). Degradation from the residual Allan Deviation of the measurement system itself is primarily due to higher phase noise on the downlink carrier compared to the E8267C signal source. The solid green line shows the transceiver Allan Deviation measured under the same conditions using the Deep Space Network Compatibility Test Trailer (CTT). The CTT ground receiver was configured for a one-sided tracking loop bandwidth of 0.1 Hz. The downlink provided approximately +51 dB-Hz carrier to noise power density ratio (Pc/No) to the ground receiver. The ground transmitter provided approximately +102 dB-Hz Pc/No to the uplink; this corresponds to a received uplink carrier power of -70 dBm at the low noise amplifier input. Only a small portion of the complete curve was assembled due to limited testing time with the CTT. However, the CTT test validates the transceiver test data taken with the Figure 3 test system. Together the green and orange lines show that the new transceiver is capable of meeting and exceeding typical mission frequency stability requirements (0.1 mm/s over 60 seconds) under normal operating conditions (without the presence of 60 Hz signal contamination). A measured Allan Deviation of 2.6E-14 at 60 seconds is illustrated in this test data, which yields a 3.9 µm/s Doppler velocity error. Overall these measurements demonstrate very good performance for a prototype coherent transceiver system, making it acceptable for navigation and communication.

Normally the slope of a coherent Allan Deviation measurement should be 10 dB per decade, similar to the NEAR measured curve. The skew on the slope of our test setup is due to the limited ability of the time interval analyzer to accurately detect the zero crossings of the downlink signal (i.e. a narrowband tracking ground receiver was not available for this test). The 'lump' seen at about 200s is an effect of connecting the entire test system to the same 10 MHz reference clock. The 'lump' seen at .02s is 60 Hz noise.

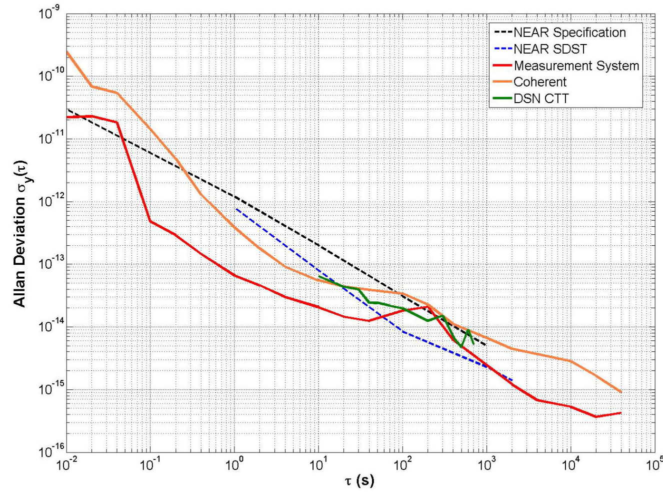

Figure 4: Measured Allan Deviation for Proof-of-Concept Transceiver Test

Phase Noise

In order to predict the downlink carrier rms phase error a model of the downlink carrier phase noise was generated in Matlab. The phase noise model includes uplink thermal noise, a model of the uplink carrier tracking loop bandwidth, and uplink and downlink quantization noise.

Using the coherent downlink carrier phase noise model a simulation of the downlink phase noise and phase error was completed for varying received uplink signal levels in coherent mode in addition to a simulation of noncoherent mode. The assumptions in the model are as follows:

- reference oscillator phase noise comparable to that used in the proof-of-concept test (Agilent 8663A).
- Ground receiver one-sided loop bandwidth = 0.5 Hz. This is used as a worst case with respect to rms phase error estimation.
- Phase error integration from 10^{-2} to 10^{7} Hz offset.

Phase noise was measured on the prototype transceiver for each scenario simulated with the phase noise model. The simulated and measured results are illustrated in Figure 5 and are in good agreement. Figure 5 illustrates that the phase noise model is sufficient for use in calculating worst case phase error. The phase error was calculated based on this model for each scenario and is listed in Table 3.

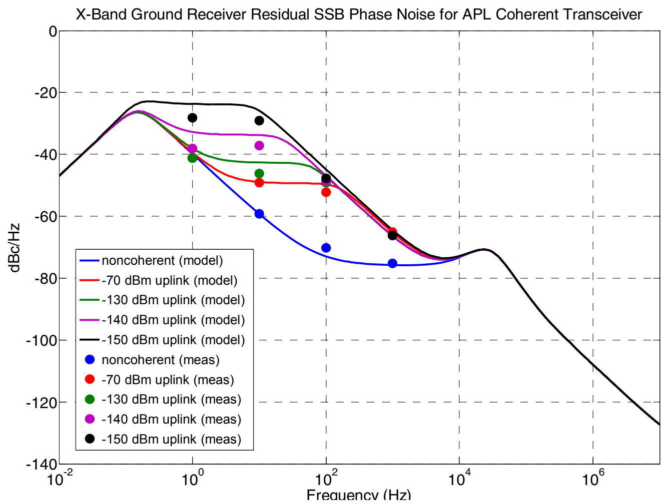

Figure 5 – X-Band Downlink Phase Noise Estimates

Comparison of these phase error estimates to the requirements in Table 2 reveals that there is no impact on BER performance for received uplink signals as low as -130 dBm. In order to limit the downlink BER degradation to 0.2 dB for this transceiver, the uplink carrier power must be ≥ -141 dBm, which is 3.5 dB higher than the typical 7.8125 bps command threshold assuming a modulation index of 0.8 radians; improvements may be made on this threshold and are currently under investigation. Below this threshold, a carrier-only uplink-downlink configuration may be established for two-way Doppler tracking. Since most spacecraft RF links are downlink limited, it is assumed that dropping below the uplink command threshold precludes sending downlink telemetry and thus BER degradation is no longer an issue; at this point, cycle slipping is the pertinent performance metric. The current design will not contribute to cycle slipping for received uplink signals as low as -150 dBm, though improvements may be made on this threshold and are currently under investigation.

Table 3 - Downlink RMS Phase Error in Ground Receiver Tracking Loop for Coherent Transceiver

Transceiver Configuration	RMS Phase Error (°)
Noncoherent downlink	3.7
Coherent downlink, -70 dBm uplink	5.0
Coherent downlink, -130 dBm uplink	5.8
Coherent downlink, -140 dBm uplink	8.4
Coherent downlink, -141 dBm uplink	9.1
Coherent downlink, -150 dBm uplink	15.4

Application to Spacecraft Navigation

The noise in the downlink frequency measurement can be compared to that routinely used to support precise orbit determination in deep space. It is common to base orbit determination on downlink frequency measurements made over 60-second intervals. The Doppler residuals, from all sources are typically less than 1.0 mm/s. At a frequency of 8.4 GHz, 0.01 mm/s corresponds to a round-trip frequency error of 0.56 mHz, or 12 degrees of phase on a 60-second interval. The rms phase errors reported above are below this level for signal powers above -141 dBm. Even the highest estimated phase errors of 15 degrees correspond to a Doppler velocity error of only 0.012 mm/s. These errors are small enough to support precise orbit determination.

5. Conclusions and Future Work

The prototype APL coherent X-Band transceiver has demonstrated acceptable two-way Doppler tracking performance with a Doppler velocity error of 3.9 um/s at 60 s and 0.9 um/s at 1000 s; this meets typical mission requirements. Phase noise measurements of the coherent downlink carrier have demonstrated that the rms phase error is sufficiently low for negligible bit error rate (BER) degradation and cycle slipping as the downlink signal is tracked and demodulated in the receiving Earth station phase-locked loop. Secondary power consumption is 2.8 W in the uplink-only mode of operation including the reference oscillator.

The new transceiver architecture provides a high performance and flexible platform. This flexibility allows the needs of a variety of missions to be met without incurring hardware changes that drive schedules outward and cost and risk higher. The use of digital signal processing as a foundation for this architecture provides an easy way to incorporate future performance enhancements without hardware modifications. This allows overall performance and power consumption to be tailored to the unique requirements of any mission while minimizing incurred cost and risk.

6. Acknowledgements

The authors would like to thank the NASA Science Mission Directorate for sponsorship of the New Horizons program which supported development of the basic technologies required for the new coherent transceiver architecture. The technologies and ideas developed for the X-Band Digital Receiver for the New Horizons spacecraft form the basis of the new architecture. We would also like to thank the DSN for their support and for use of the DTF-21 and CTT-22 test facilities during the performance validation discussed in this paper.

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Biography

Christopher B. Haskins *is the lead engineer for the New Horizons Uplink Receiver. He received a B.S. and M.S. from Virginia Tech in 1997 and 2000, both in electrical engineering. He joined the Johns Hopkins University Applied Physics Laboratory (APL) Space Department in 2000, where he has designed RF/Microwave, analog, and mixed-signal circuitry and subsystems in support of the CONTOUR, STEREO, and MESSENGER spacecraft. He also served as the lead engineer for the development of RF ground support equipment for the CONTOUR spacecraft. Prior to working at APL, Mr. Haskins designed low cost commercial transceivers at Microwave Data Systems. Mr. Haskins is a member of the IEEE.*

Wesley P. Millard *is the lead engineer for the digital subsystems in the New Horizons Uplink Receiver. He received a B.S. in electrical engineering and in computer engineering in 1999, and a M.S.E. in electrical engineering in 2000, both at Johns Hopkins University. Since joining the APL Space Department in 2000, Wes has worked on the STEREO, MESSENGER, and New Horizons programs where he has designed mixed signal circuitry and high efficiency DSP algorithms for FPGA implementation*

Bob Jensen *(M'92) received a B.A. from Cornell College in Mt. Vernon, Iowa, in 1973, and the Ph.D. in physical chemistry from the University of Wisconsin, Madison, in 1978. He joined The Johns Hopkins University Applied Physics Laboratory in 1978 and worked on a variety of nonacoustic detection problems, principally involving radar performance analysis, signal processing algorithms, and rough surface scattering. In 1989, he joined the APL Space Department and has participated in the TOPEX altimeter pre-flight testing, the development and testing of algorithms for the beacon receiver on the MSX satellite, the NEAR telecommunications system, and was responsible for noncoherent Doppler aspects of the CONTOUR mission. He is a member of the APL Principal Professional Staff and the IEEE.*