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THE NEW HORIZONS MISSION TO PLUTO: ADVANCES IN TELECOMMUNICATIONS SYSTEM DESIGN

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ABSTRACT

This paper presents the RF telecommunications system designed for the New Horizons mission, NASA's planned mission to Pluto, with focus on new technologies developed to meet mission requirements. These technologies include an advanced digital receiver — a mission-enabler for its low DC power consumption at 2.6 W secondary power. The receiver is one-half of a card-based transceiver that is incorporated with other spacecraft functions into an integrated electronics module, providing further reductions in mass and power. Other developments include extending APL's long and successful flight history in ultrastable oscillators (USOs) with an updated design for lower DC power. These USOs offer frequency stabilities to 1 part in 10^{13}, stabilities necessary to support New Horizons' uplink radio science experiment. In antennas, the 2.1 meter high gain antenna makes use of shaped sub- and main reflectors to improve system performance and achieve a gain approaching 44 dBic. New Horizons would also be the first deep-space mission to fly a regenerative ranging system, offering up to a 30 dB performance improvement over sequential ranging, especially at long ranges.

The paper will provide an overview of the current system design and development and performance details on the new technologies mentioned above. Other elements of the telecommunications system will also be discussed.

Note: New Horizons is NASA's planned mission to Pluto, and has not been approved for launch. All representations made in this paper are contingent on a decision by NASA to go forward with the preparation for and launch of the mission.

INTRODUCTION

Mission Description

New Horizons is NASA's planned mission to Pluto, with a projected launch date in January of 2006. The fly-by mission seeks to characterize the geology and atmosphere of Pluto and its large moon Charon. At launch, the spacecraft follows a heliocentric trajectory to Jupiter for a fly-by gravity assist in 2007, and then settles into a long 8-year cruise to the outermost planet. The baseline encounter date for the Pluto fly-by is July, 2015. An extended mission for the spacecraft would see fly-by's of one or more Kuiper Belt objects, the set of small planetoids of the outer solar system of which Pluto is considered the largest member.

Pluto is on average 39 AU from the Sun, but due to its highly eccentric orbit will be approximately 32 AU from the Earth at encounter (1 AU = approximately 150 million km.)

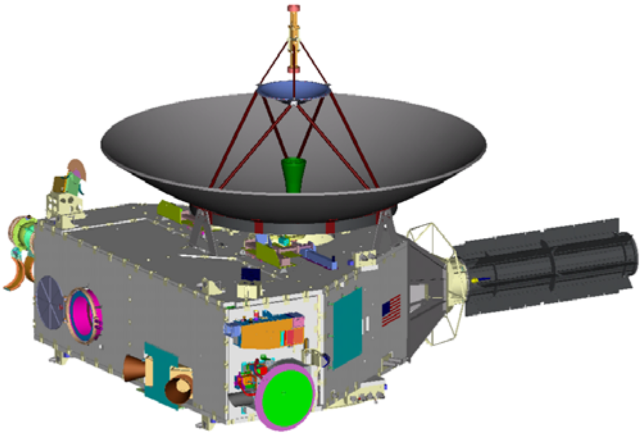

Figure 1 The New Horizons Spacecraft

At that range, the round trip light time to the spacecraft is over 8 hours. Science observations commence in the months preceding encounter, with the most intense instrument activity during the several hours before and after closest approach. The scope of the scientific effort includes ultraviolet, visible, and infrared imaging and spectroscopy, particle detection, and radio science. The mission is led by Principal Investigator Dr. Alan Stern at the Southwest Research Institute, and the spacecraft project is led at the Johns Hopkins University Applied Physics Laboratory.

Challenges for Telecommunications Design

Several mission aspects made for a challenging telecommunications system design. Chief among them were the requirement to minimize power (New Horizons is a power-limited spacecraft), and the significant ranges at which the system must perform. These two drivers impacted the designs of each of the new or advanced subsystems described in the rest of this paper.

TELECOMMUNICATIONS SYSTEM

Overview

A block diagram of the New Horizons RF Telecommunications System is shown in Figure 2. The bulk of the transmit and receive electronics are housed in redundant Integrated Electronics Modules (IEMs). Within each IEM are typical core functions, including the command and data handling system, the instrument interface circuitry, the telemetry interface function, and the solid state recorder. The IEM also contains three cards dedicated to the telecommunications system. The Uplink Card provides the command reception capability, as well as a fixed downconversion mode for the uplink radioscience experiment (REX). The Downlink Card is the exciter for the Traveling Wave Tube Amplifiers (TWTAs), and encodes block frame data from the spacecraft Command and Data Handling (C&DH) system into rate 1/6, CCSDS Turbo-coded blocks. It also calculates and inserts navigation counts into the frame data to support the noncoherent Doppler tracking capability, and is used to transmit beacon tones during cruise periods. The Radiometrics Card contains the uplink Radioscience Experiment (REX) and the Regenerative Ranging circuitry. Inclusion of these RF functions in the IEM helped to further reduce the overall harness requirement and resulted in mass and cost savings while offering a flexible platform for future development.

Two Ultrastable Oscillators (USOs) provide the ultimate frequency reference for the Uplink and Downlink Cards' local oscillators and clocks. The USOs are cross-strapped with a transfer switch and power splitter to retain redundancy in the Uplink and Downlink Cards in the event of a USO failure.

Two 12W TWTAs are used as the high power amplifier for the downlink signal. The selected power level is a compromised between data rate and beamwidth performance and power dissipation in this power-limited spacecraft. The RF Switch Assembly interconnects the

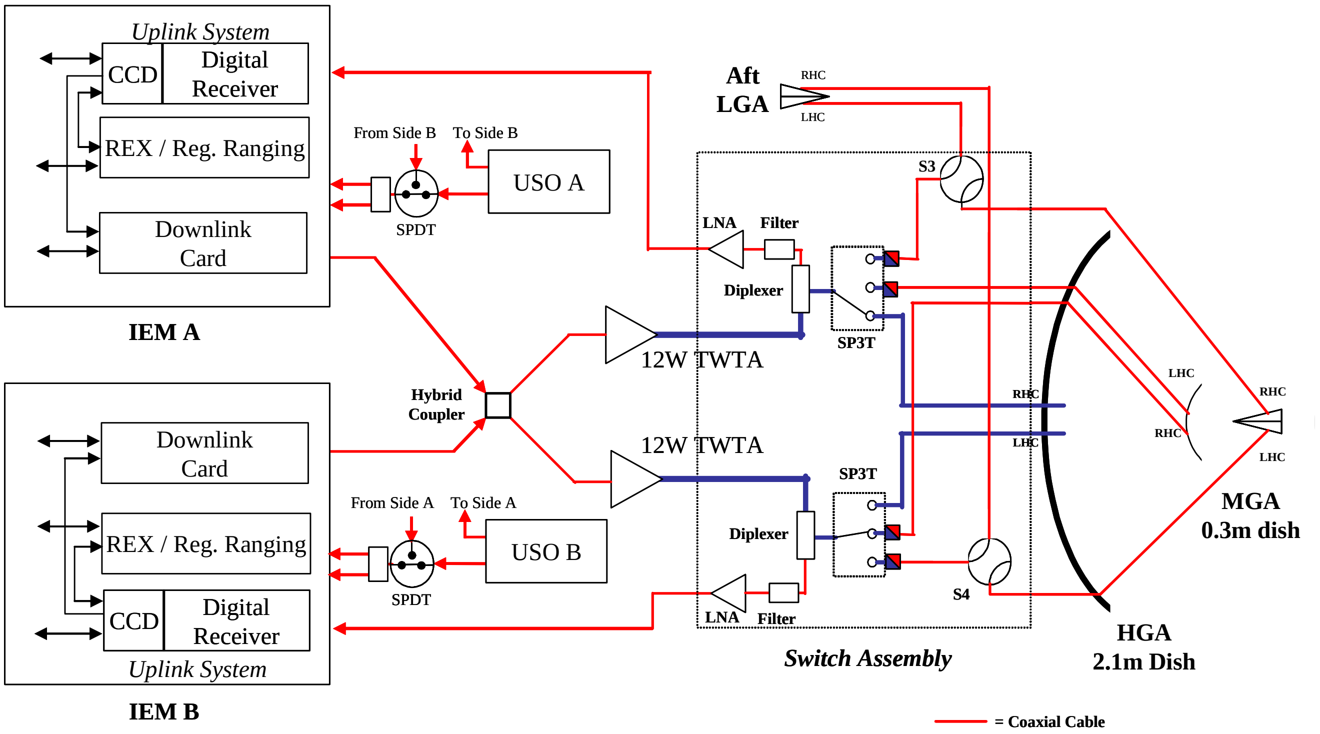

Figure 2 Telecommunications System Block Diagram

antenna suite with the redundant TWTAs and the rest of the communications system.

Polarization Diversity Combining

A hybrid coupler is connected to the Downlink Exciter outputs and TWTA RF inputs. This enables either exciter to work with either TWTA. While its use is routine for deep space missions, it also enables the tantalizing prospect of nearly doubling the post-encounter downlink data rate. If both TWTAs were to be powered at once, then, using one exciter, a dual-polarized downlink signal (LHC and RHC) can be transmitted. The Deep Space Network (DSN) has recently tested their single-antenna polarization combining capability and achieved a processing gain of more than 2.5 dB. Operating in this mode would provide a greater than 44% reduction in the post-encounter playback duration and significant cost savings. However, the spacecraft is power-limited, and it will not be known if the power budget will permit both TWTAs to be turned on simultaneously until later in the mission.

Uplink Radioscience

The RF Telecommunications System also functions as a critical element of an instrument, the REX (Radioscience EXperiment) Instrument. REX seeks to characterize the atmosphere of Pluto and (if one exists) of Charon, and to estimate surface temperatures by recording changes in the received uplink signal at various times during encounter. By having the radioscience experiment on the uplink, rather than the downlink or the turned-around composite signal, more precise estimates of Pluto’s atmosphere and temperature can be made.

The hardware specific to REX consists of an analog-to-digital converter and the REX Actel FPGA, and is co-located on the Radiometrics Card with the Regenerative Ranging System. A wideband IF output from the uplink receiver is fed to the REX circuitry, and the receiver is commanded to a fixed-conversion mode (i.e., carrier tracking is disabled and all LO’s are fixed in frequency.) Any RF input at the receive frequency is directly downconverted and passed to the REX hardware. Two types of measurements are made. As the spacecraft moves into occultation (the time Pluto blocks the uplink signals from the Earth), samples of the REX filter output are stored to determine the changes in phase and amplitude the uplink signal underwent as it moved through different layers of Pluto’s atmosphere. During occultation, the full bandwidth of the REX IF input is integrated, sampled, and later compared to calibrations to determine the effective antenna noise temperature, which can be used to map the physical temperature of the planet.

The REX effort is led by Stanford University, who is responsible for the design of the Actel FPGA. Its inclusion in the RF system mandated tight control of spurious signals in the receiver IF, attention to minimizing the spacecraft system noise temperature (to approximately 200K) and receiver gain variations, and the careful selection of crystal resonators in the USO to achieve the highest level of frequency stability and thus the best performance for REX.

ADVANCED DIGITAL RECEIVER

Overview

Since both uplink command receivers are typically powered on during critical events, any reduction in power consumed by the receiver is doubled. With the limited power available on New Horizons, and with previous X-Band command receivers consuming upwards of 12W primary power each, a development was begun to design a low-power digital receiver and meet all performance requirements, including incorporation of the radioscience interface.

The successful result of this development is the Uplink Card, or Advanced Digital Receiver, for the New Horizons mission. At 2.6W secondary, 4W primary, the new Uplink Card provides greater than 8W in savings over other X-Band, deep-space command receivers. Doubled to account for both receivers being powered, the overall 16W savings are more than the power consumed by 5 instruments on New Horizons; the digital receiver is a true mission enabler.

Design Description

The New Horizons Uplink Card provides X-band carrier tracking, command detection/demodulation, critical command decoding, ranging tone demodulation, a wideband intermediate frequency (WBIF) channel for use by the Radioscience Experiment (REX) and Regenerative Ranging subsystems, and a fixed downconversion mode for REX. The Uplink Card (Figure 3) is an assembly consisting of three separate printed circuit boards (PCB) mounted to an aluminum heat sink. On one side, a multilayer, polyimide PCB contains the circuitry required for the RF, IF, analog, and digital portions of the X-band carrier tracking receiver, ranging tone demodulation, and the WBIF channel. Attached to this polyimide PCB is an RF downconverter board, which consists of a temperature stable microwave substrate, various microstrip circuits, and the circuitry required to complete the first RF downconversion stage in the uplink card. On the other side, a second multilayer, polyimide PCB contains the required circuitry for the command detector unit (CDU) and the critical command decoder (CCD).

Figure 3- Photographs of Uplink Card
a) digital receiver side, b) baseband side (CDU and CCD)

Design Approach

The primary RF carrier tracking, command detection, and turnaround ranging channel performance requirements of the digital receiver system are similar to those of previous deep space RF systems, including both the small deep space transponder (SDST) and CONTOUR RF transceiver systems. Several new design requirements led to a new design approach. These new requirements included reduced power consumption, flexibility in the choice of reference oscillator frequencies, and added support for uplink radioscience (REX) and regenerative ranging. The core receiver design uses a classic double-conversion, superheterodyne approach (Figure 4). The aforementioned RF downconverter board provides several key functions, including power to an external low noise amplifier (LNA) through a microstrip bias tee, band select/image reject filtering, the first downconversion stage, and amplification, tripling, and harmonic filtering of the RF local oscillator (LO). The RF LO is generated at approximately 2474 MHz by a fractional-N synthesizer and routed to the RF downconverter board. The output of the first downconversion stage is the first intermediate frequency (IF), which is approximately 240 MHz. The first IF is bandpass filtered and split into two channels, one narrowband and one wideband. The narrowband channel is used for carrier tracking, automatic gain control, and command demodulation, while the wideband channel is used for turnaround ranging demodulation and generation of the WBIF channel to be used by the REX and regenerative ranging subsystems. Both channels each contain a single-chip receiver integrated circuit (IC), which provides the second downconversion stage, automatic gain control (AGC) amplification, and wideband channel quadrature demodulation.

Downconversion to the second IF of 2.500 MHz makes use of an IF LO, which is generated at approximately 242.5 MHz by an integer-N synthesizer. Upon downconversion to the second IF, separate filtering of the wideband and narrowband channels is achieved via discrete filter circuits external to the aforementioned receiver ICs. The 2.5 MHz narrowband IF (NBIF) channel is processed by a 10-bit, 10 Msps analog-to-digital converter (ADC). The resultant sample data is processed by a field programmable gate array (FPGA), which provides a variety of critical receiver functions. The digital receiver FPGA (DPLL) first demodulates the NBIF to baseband. The baseband data is then processed through the digital portions of the carrier tracking loop, power detection, and AGC system. The DPLL's primary contribution to the carrier tracking loop is in the form of a 20-bit preselect/antialiasing filter and a 64-bit loop filter. The output of the loop filter is used to steer the output frequency and phase of a direct digital synthesizer (DDS), which is in turn used as a carrier tracking reference oscillator in the closed loop carrier tracking system. The DPLL's primary contribution to the AGC system is in the form of a power detection circuit and filtering used to drive a digital-to-analog converter (DAC), which is in turn used to generate a control voltage that sets the gain in the analog portions of the receiver system. The digital baseband data is also filtered to select the subcarrier, which is then forwarded to the CDU for data demodulation and command detection. For the New Horizons mission, this subcarrier is binary phase shift key (BPSK) modulated with commands at data rates of 2000, 500, 125, and 7.8125 bps. The CDU locks to and tracks the 16 KHz subcarrier and demodulates the command data, passing data and clock over to the CCD. In the CCD, designated critical relay commands are decoded, detected, and immediately sent to the power switching system. The CCD also forwards all commands to the C&DH system.

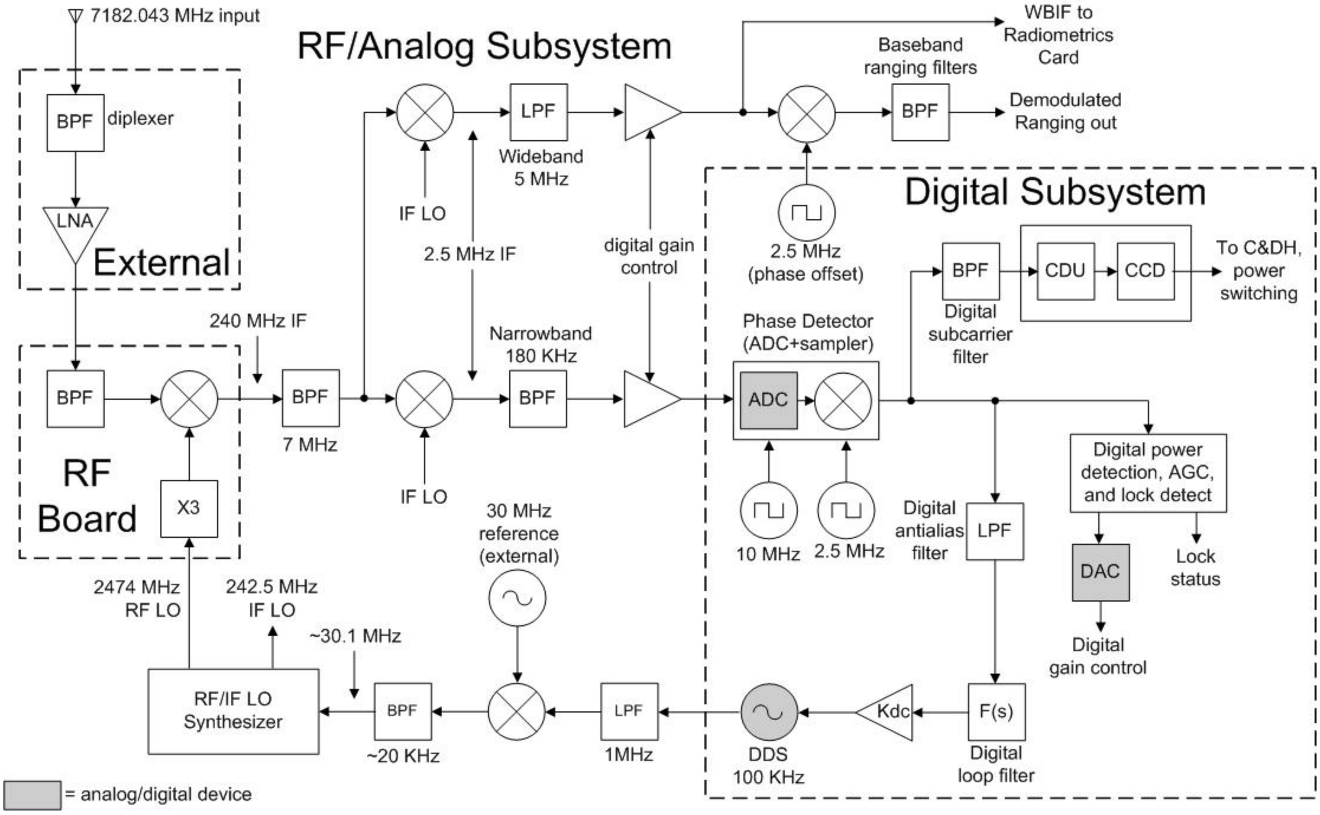

Figure 4 Uplink Card Block Diagram

The 2.5 MHz WBIF channel is buffered and routed to the Radiometrics Card for further processing. The 2.5 MHz WBIF is also demodulated in the quadrature demodulator built into the receiver IC. The resultant baseband channel (or ranging channel) is filtered through several filters designed to limit the noise power in this channel as well as reduce the level of various demodulation products, while at the same time allowing the desired ranging tones to pass through with minimal phase and amplitude distortion. The output of this ranging channel is buffered and routed to the downlink card for modulation onto the downlink X-band carrier. In addition, the ranging channel has the capability to route either the demodulated ranging tones or the regenerated pseudonoise (PN) ranging code produced by the regenerative ranging subsystem to the downlink card.

Carrier acquisition and tracking is provided via a type-II phase locked loop and noncoherent AGC system. Both the RF and IF synthesized LOs are tuned through the use of a common 30.1 MHz carrier tracking reference clock; this clock is generated by mixing the 30 MHz spacecraft frequency reference with a 100 KHz DDS. The DDS phase and frequency is dynamically tuned by the DPLL carrier tracking system to in-turn tune the RF and IF LOs. An open loop, fixed downconversion mode is required for REX; in this mode, the DDS frequency is set at a fixed value that is reprogrammable during the mission. All clocks and frequency sources in the digital receiver system are referenced to the 30 MHz spacecraft reference oscillator.

Features

Performance highlights include the following: total secondary power consumption of 2.5 W (including the integrated on-board command detector unit (CDU) and critical command decoder (CCD)), built-in support for regenerative ranging and REX, carrier acquisition threshold of -157 dBm, high RF carrier acquisition and tracking rate capability for near-Earth operations (2800 Hz/s down to -100 dBm, 1800 Hz/s down to -120 dBm, 650 Hz/s down to -130 dBm), ability to digitally tune to any X-band RF channel assignment (preprogrammed on Earth for this mission) without the need for analog tuning and tailoring, use of an even 30.0 MHz ultrastable oscillator (USO) as a frequency reference, a noncoherent AGC system, and best lock frequency (BLF) telemetry accuracy to 0.5 Hz at X-band and BLF settability plus stability error < +/- 0.1 ppm with zero temperature effects (all relative to USO frequency).

These results highlight the major performance parameters of the operational and functional RF uplink system. One of the key benefits of moving to a more-digital system is increased operational flexibility. Once in place, successive design iterations in future missions may include in-flight reconfiguration of RF channel assignments, and carrier tracking loop optimization for near-Earth, deep space, and interstellar operational modes. A secondary benefit is the ability to leverage from increasing gate array densities and processing unit speeds, thus contributing to further mass, size, and power savings. Finally, further reduction in hardware assembly steps due to lower parts count and fewer solder connections increases the reliability of these systems. (See also [1].)

DUAL SHAPED REFLECTOR HIGH GAIN ANTENNA

New Horizons Antenna System Overview

The NH antenna system is designed to support low- and high-data-rate communications from both a spinning and three-axis stabilized platform. During most of the mission, the spacecraft is spin stabilized (for example, the long cruise to Pluto and during the science playback post-encounter.) Thus, the patterns of the antennas are symmetrical and positioned away from the spacecraft structure to prevent blockage and interference nulls. The resulting design is a stack arrangement of antennas (HGA, MGA, LGA) on the forward end of the observatory as shown in the spacecraft picture in Figure 1. (The spacecraft spin axis joins the center of the HGA reflector with the centers of the MGA and LGA above it.) This configuration is optimum because it satisfies all of the antenna field-of-view requirements and the stringent mass limitations imposed by the mission. It is also based on requirements that the forward low gain antenna be located sufficiently near or ideally on the spin axis and that the LGA will provide communications coverage ± 90° from the spin axis, which limits other locations for the MGA and HGA. Not visible in the spacecraft picture is the aft low gain antenna, which is also placed on the spin axis beneath of the spacecraft.

High Gain Antenna

A highly efficient, 2.1-meter parabolic reflector antenna is required to support the minimum 600 bps at 36 AU post encounter [2]. This diameter reflector was selected after the NH antenna team performed a detailed alignment budget, which included effects due to thermal distortions on the spacecraft bus and the antenna system, dimensional tolerances, measurement knowledge of the antenna bore sight, ground station pointing errors, power margins, and minimum antenna gain. The alignment analysis showed that the HGA system could be accurately aligned to within 0.2° of the spacecraft spin-axis. An additional 0.1° misalignment with the DSN ground station pointing due to ephemeris is allowed for a total alignment budget of 0.3°. A larger sized reflector antenna can be used on spin-stabilized spacecraft with enhanced definition, knowledge, and control of variables in the alignment budget, which increases the engineering cost of the spacecraft. The 2.1-meter reflector is attractive because it is lightweight, meets the communication requirements, and is relatively easy to handle during spacecraft integration.

A communications link analysis established that the HGA is required to provide a minimum antenna downlink gain of 42 dBic, as shown in Figure 5, for angles within ±0.3°. The gain requirement could be achieved with a standard Cassegrain reflector design but the margin at these angles is small, as shown. A key RF design goal for the NH mission is to maximize coverage over these angles, which is accomplished here by modifying the shape of both reflecting surfaces until the aperture fields (amplitude & phase) are uniform.

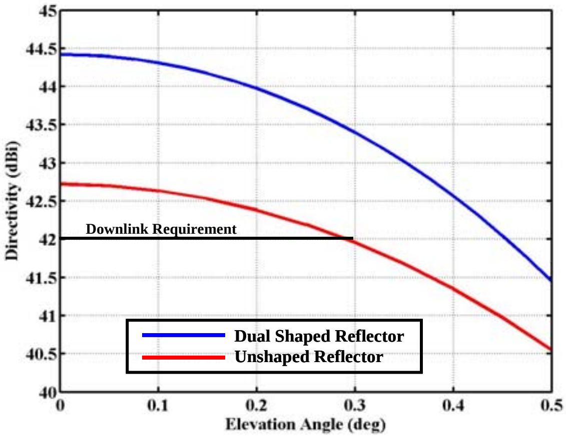

Figure 5 HGA Downlink Gain

Mechanical Design

The mechanical design of the New Horizons High Gain Antenna is dictated by the wide -200°C to +80°C operational temperature range to which the antenna system will be exposed during the life of the mission. The cryogenic operational temperature is expected for the Pluto and KBO encounters, while the upper temperature of +70°C occurs early in the mission. In order to meet critical science and communication mission requirements, the mechanical alignment of the HGA bore sight to the spacecraft spin axis must be maintained to a high degree of accuracy over this temperature range. Composite materials have been used in order to realize these requirements. While more costly and complex in application, composite materials offer a dimensionally stable mechanical design over the expected temperature range as well as a high stiffness and low mass solution required for the launch loads. The fabrication of the HGA reflector utilizes a 0.75-inch thick composite sandwich lay-up with a Korex honeycomb core. The secondary reflector assembly consists of a MGA and HGA sub-reflectors and is a composite laminate shell lay-up. Three (3) composite struts with Invar fittings are used to support the MGA feed horn and a six (6) strut configuration, similar to Voyager and Cassini designs, positions and centers the sub-reflector with the HGA main reflector and feed horn.

NONCOHERENT DOPPLER TRACKING

Introduction

The downlink frequency from the New Horizons transceiver is derived from the USO, but even this excellent frequency reference is not sufficient to support precise and accurate Doppler velocity measurements at the target level of 0.1 mm/s throughout the mission. In order to remove the impact of frequency drift and bias in the reference oscillator, New Horizons has implemented the noncoherent Doppler velocity measurement approach [3] which was successfully demonstrated in 2002 during the demanding Earth orbit phase of the CONTOUR mission [4].

Noncoherent Doppler Tracking

The noncoherent Doppler approach is based on a comparison of the spacecraft frequency reference with the uplink frequency received by the spacecraft. This comparison information is included in telemetry. The ground stations measure the downlink Doppler with the same setup as would be used if the spacecraft communications system was coherent. The telemetered frequency comparison information is used in a software step that converts the observed Doppler frequency to that which would have been observed had the spacecraft had carried a coherent transponder. Doppler navigation is then unaffected by the use of a transceiver.

Accurate alignment in time of the measurements made on the ground and on the spacecraft is critical to meeting the mission navigation requirements. This is accomplished by relating both sets of measurements to the transfer frame boundaries. The frequency comparison made on the spacecraft is applicable on the ground after a one-way light-time delay and the use of transfer frames to carry the timing information naturally accounts for this delay. No knowledge of the light-time from the orbit determination is necessary to perform the Doppler correction. Only the observed Doppler frequency and the telemetered data are required.

The onboard frequency comparison is accomplished through the use of two 16-bit counters and a small amount of associated logic. These counters are included on the downlink card. The counters are sampled soon after the start of each transfer frame and the results are placed into the secondary frame header of the following frame. This delay is necessary because the CRC for the frame has already been computed prior to start of transmission of the frame, as discussed above.

While one set of counter measurements is made after the start of every frame at all data rates and at both frame length, this data alone would be insufficient to support the orbit determination at the lower data rates where the frame durations can be several minutes long. Therefore, the counters are sampled within the frame and these samples are collected by the C&DH system for inclusion in the telemetry.

The implementation of the navigation counters is included in the Actel FPGA that includes the Turbo encoder. No additional components are necessary. The framer is also incorporated into this FPGA, so the inclusion of the counter data into the secondary frame header is easily accomplished.

All of the counter measurements, both those that follow the frame start and those that are made within the frame, are available to the C&DH system through the PCI interface.

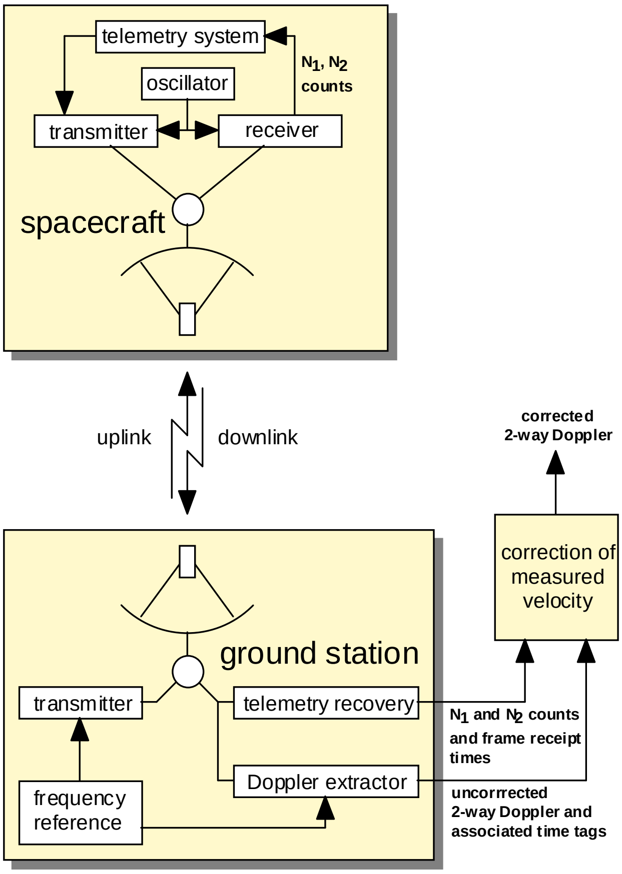

Figure 6 Noncoherent Doppler Tracking Block Diagram

Laboratory testing at APL and compatibility testing with DSN equipment have demonstrated that the use of the noncoherent Doppler approach will meet the mission Doppler velocity requirements.

Real-time USO Frequency Tracking and Ranging

The use of a noncoherent transceiver does impact ranging measurements since the DSN expects the turnaround ranging tones to have a two-way Doppler shift, as they would in a coherent transponder. For New Horizons, as it was for CONTOUR, the uplink frequency will be adjusted to remove the one-way Doppler on the uplink signal. Ranging measurements will then be made as normal. This approach requires only an approximate knowledge of the spacecraft velocity and frequency reference and does not require special spacecraft hardware. The Doppler tracking counts, along with the other metrics in the tracking process, enable the USO to be tracked in real time so that any unexpected changes in USO frequency (e.g., due to spin up or spin down) can be accounted for. Knowledge of the USO's precise drift rate over time is also critical for the REX experiment.

REGENERATIVE RANGING

Metric tracking of interplanetary spacecraft is normally accomplished by sending a phase-modulated RF carrier from one of three available DSN transmitter sites, receiving and retransmitting that signal with a wide bandwidth transponder located in the spacecraft, receiving the transponded signal at a DSN receiver site, and processing the received signal in a way that allows the 2-way range and range-rate (or Doppler) data for the spacecraft to be measured. The range-rate measurements are derived from the Doppler shift of the received carrier whereas the range measurements are derived from the time delay of the modulation component of the received signal. The modulation signal has traditionally been a sequence of sine or square-wave tones with frequencies ranging from 1-MHz down to a few Hertz. The time delay measurements derived from each tone can be combined in a way that allows the ambiguity interval of the composite measurement to be a relatively large fraction of a second. When these measurements are multiplied by the speed of light and combined with the dynamics of motion equations provided by classical or relativistic physics, the 2-way range values can be unambiguously determined.

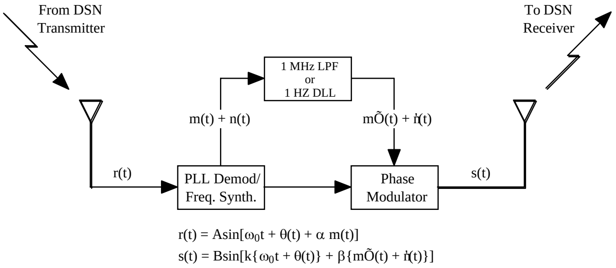

Figure 7 Signal Processing for Spacecraft Tracking

The ranging signal processing that occurs in a conventional transponder or transceiver is shown in Figure 7. A phase-locked loop (PLL) locks to the received carrier and detects the ranging modulation signal which was phase modulated onto the uplink carrier. However, since the amplitude of the received uplink carrier is typically quite small, the recovered modulation signal is usually accompanied by a Gaussian noise whose 1σ amplitude may be equal to or greater than the amplitude of the ranging modulation. A low-pass filter (LPF) is used to reduce the amplitude of the noise as much as possible, but the filter must also be wide enough to pass the highest modulation frequency of 1 MHz with no more than a modest amount of attenuation. As a result, a considerable amount of noise is passed on (turned-around) to the downlink modulator.

The regenerative ranging circuit (RRC) provides a way of substantially reducing the amount of this noise. In this case the 1 MHz LPF is replaced with a delay-locked loop (DLL) that generates an on-board replica of the received modulating signal and adjusts the timing of the onboard signal to align it with what the spacecraft receives. The effective bandwidth of this process will be approximately 1 Hz as opposed to the 1 MHz bandwidth of the transponder. The amount of noise passed on to the downlink modulator will consequently be reduced by several orders of magnitude. This regenerative ranging technique was first developed for deep space applications by Berner, et al., at JPL [5], and New Horizons has adopted their standard for implementation into the flight system. New Horizons will be the first mission to test regenerative ranging in flight.

The modulating signal best suited for DLL tracking is a pseudorandom noise (PRN) code defined in [C]. This code consists of a repeating sequence of N=1,009,470 binary chips clocked at a rate f_{chip} that is proportional to the RF carrier frequency. For the New Horizons mission this frequency will be f_{chip}=2,069,467.087 chips/sec. The corresponding code repetition interval will be $P=N/f_{chip}$=0.487,792,247 seconds. The ranging code is actually a composite code calculated from a set of six periodic binary component generators according to the equation

$$C(i)=C_1(i)|[C_2(i)\&C_3(i)\&C_4(i)\&C_5(i)\&C_6(i)] \tag{2}$$

The length of each component will be $N_1=2$, $N_2=7$, $N_3=11$, $N_4=15$, $N_5=19$, and $N_6=23$ chips, respectively. The analog modulating signal will be derived from the digital PRN chip sequence by replacing each 1 with a positive half-sine pulse of the form $\mathrm{m}(t) = \sin \pi f_{\mathrm{chip}} t$ and each 0 with a negative half-sine pulse of the form $\mathrm{m}(t) = -\sin \pi f_{\mathrm{chip}} t$. The composite code has a strong repeating 1010… pattern occasionally interrupted by a string of three or more 1's in a row. As a result, m(t) consists predominately of an alternating sequence of positive and negative half-sine pulses, thereby generating a sine wave with frequency $f_m = f_{chip}/2 = 1{,}034{,}733.544$ Hz. Since most of the power in the spectrum of m(t) is concentrated at $f = \pm f_m$, the DLL is able to track the phase and frequency of the received code with very low jitter.

A block diagram of the RRC is given in Figure 8. With the exception of the A/D converter, the system is implemented entirely on one Actel RT54SX72S FPGA. The I and Q outputs of the demultiplexer will be $I_k = A\cos\left[\beta\,\mathrm{m}(t_k)\right]$ and $Q_k = A\sin\left[\beta\,\mathrm{m}(t_k)\right]$ respectively, where A is the amplitude of the 2.5 MHz phase modulated signal and β is the modulation index. With β=0.8 radians, these two functions can be approximated as $I_k \approx A\,\mathrm{J}_0(\beta)$ and $Q_k = 2A\,\mathrm{J}_1(\beta)\mathrm{m}(t_k)$, respectively, where $J_0(\beta)$ and $J_1(\beta)$ are zero and first-order Bessel functions of the first kind. The I samples are therefore a measure of signal amplitude whereas the Q samples provide the m(t) modulation function.

The Q samples are provided as input to a 2nd-order DLL that synchronizes the phase and frequency of the local code generator with the received uplink ranging code. The loop has three tracking bandwidths – 4 Hz for signal acquisition, 1 Hz for strong signal tracking, and 0.25 Hz for weak signal tracking. The loop is a discrete-time digital control system with a phase detector, loop filter, number controlled oscillator, and PRN code generator. Phase error between the received uplink code and the local code generator is formed by multiplying the received Q samples by a half-chip advanced version of the local C_1 code and integrating the resulting product for a period of 10, 40, or 160 milliseconds depending on the current loop operating bandwidth. Since the gain of the phase detector is proportional to signal amplitude, the loop has a provision for inserting a compensating gain function which varies inversely with signal amplitude in discrete power-of-2 steps. This function is accomplished by integrating and smoothing the I-samples and using the resulting values to generate an index for a power-of-2 gain table.

The DLL assures that the C_1 component of the local code generator is aligned with the C_1 component of the received ranging code and that the chip edges of the other component generators (C_2 – C_6) are also properly

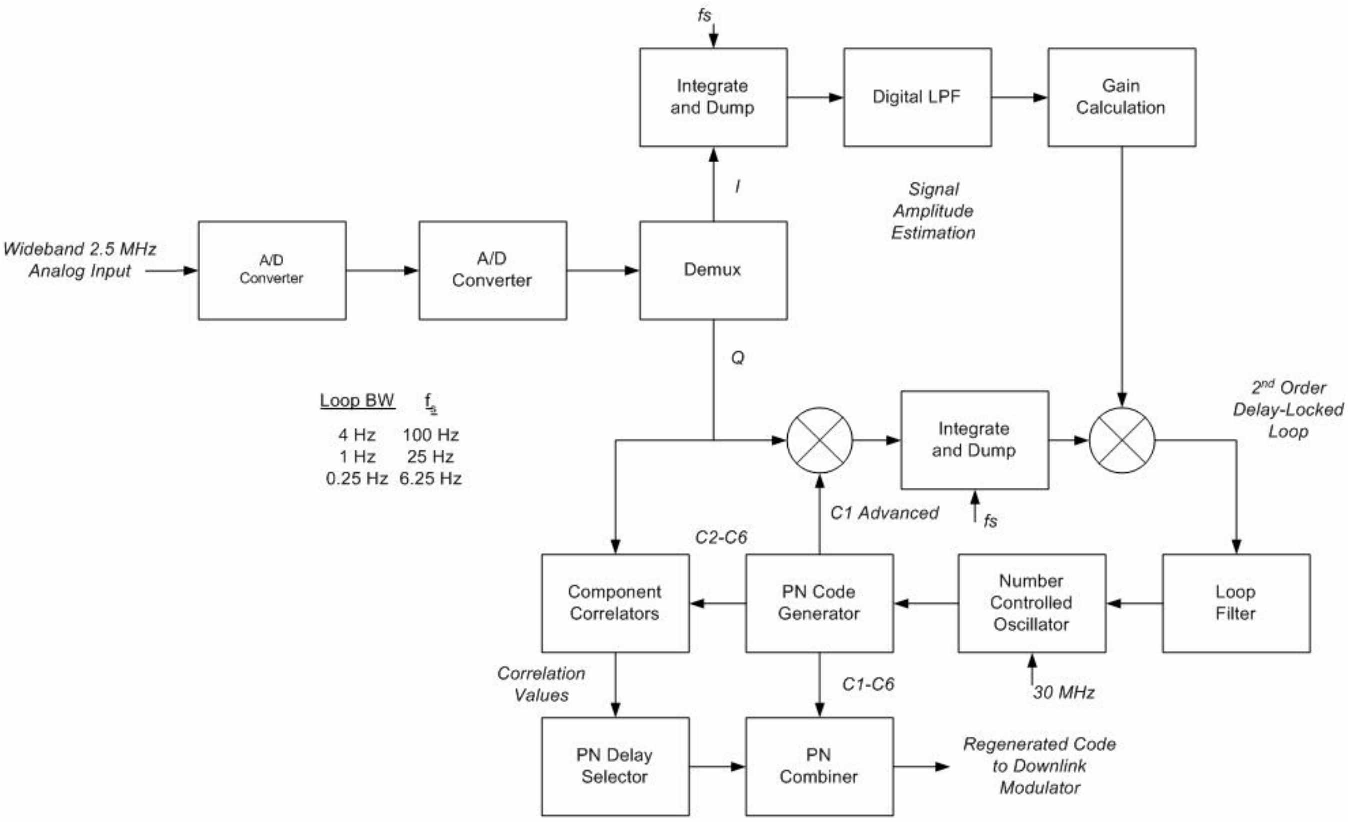

Figure 8 Regenerative Ranging System Block Diagram

aligned. However since there are more than two chips in each of these components, a cyclical shift operation is generally required to properly align the component codes within the corresponding shift register generators. This operation is accomplished by multiplying and accumulating the received Q samples with each bit of each shift register, and selecting the shift position that generates the largest correlation product. Once these decisions have been made, the regenerated composite code is formed and passed on to the downlink modulator.

The tracking accuracy of the RRC is a function of the amplitude of the received RF signal and the tracking bandwidth. At low power levels, the tracking error is dominated by thermal noise whereas quantization errors due to finite bit widths dominate at the higher power levels. Figure 9 shows the predicted accuracy as a function of RF signal level and tracking bandwidth.

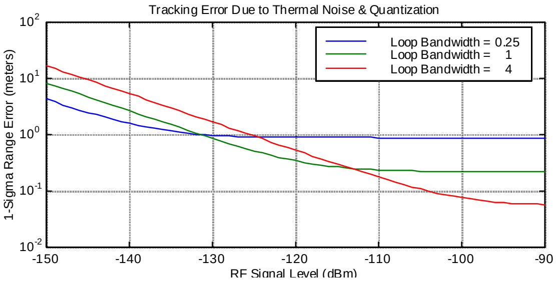

Figure 9 Tracking Error due to Thermal Noise and Quantization

LOWER POWER ULTRASTABLE OSCILLATOR

Overview

The New Horizons Ultrastable Oscillator (USO) is a critical component of the RF telecommunications system and the mission itself. It provides a stable, 30 MHz frequency reference for the Uplink and Downlink Cards' frequency synthesizers, and the ultimate frequency reference necessary for the uplink radio science experiment.

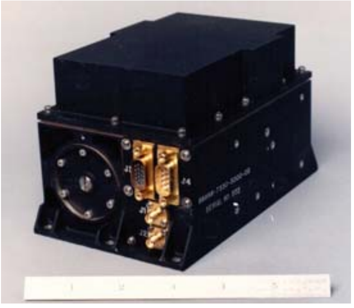

Figure 10 Ultrastable Oscillator Assembly

The USO is a sophisticated precision assembly consisting of over 200 electronic components and many mechanical parts (see photo in Figure 10). Its architecture builds on proven heritage designs developed at APL over the last 30 years, and flown recently on such missions as Mars Observer, Cassini, GRACE, and Gravity Probe B. Fundamentally, it is a pristine version of an ovenized crystal oscillator (OCXO). We use carefully selected, 3rd overtone, SC-cut crystal resonators and maintain them at constant temperature to yield excellent frequency stability (short-term to better than 1 part in 10^{13}) and low noise performance. The significant performance improvement over industry grade OCXOs relies on a cylindrical oven design and very uniform heating which results in very small temperature gradients within the crystal resonator blank. A high-gain thermal control loop keeps the crystal resonator temperature stable to within several thousandths of a degree Celsius over the entire operating temperature range of the USO. Crystal resonators for flight have been carefully selected among twenty units for the best aging and short-term frequency stability.

Performance Highlights

The resolution of the New Horizons uplink Radioscience Experiment depends upon the excellent frequency stability of the USO over the duration of the Earth occultation event at Pluto. Short-term frequency stability (Allan deviation) at 1s and 10 s are specified at $3x10^{-13}$ and $2x10^{-13}$, respectively, with goals of sub-$1x10^{-13}$ performance. Additionally, the designs of several of the boards within the USO were updated to provide efficiencies in steady-state power consumption. This has resulted in a 28% power savings (2.5W vs 3.5W) over previous designs.

A summary of other relevant performance measures is tabulated below.

Parameter	Specification
Output Frequency	30 MHz
Output Power (into 50Ω)	+10 dBm +/- 1 dB (dual output)
Aging Rate	$<1x10^{-11}$ per day (goal)
DC Power	< 3.5W steady-state Achieved ~ 2.5W
SSB Phase Noise	< -125dBc/Hz @ 100 Hz
Frequency stability over temperature	$<1{\cdot}10^{-12}$ per °C
Temperature range	-25°C to +65°C
Mass	< 1500 grams

Table 1 USO Performance Specifications

CONCLUSIONS

Newly developed technologies in the RF Telecommunications System for the New Horizons Mission to Pluto have been described. These include a low-power, mission-enabling digital receiver, a lower-power ultrastable oscillator for precise frequency stability, incorporation of an uplink radio science experiment within the telecommunications system, a noncoherent Doppler tracking capability, and the first planned operational use of regenerative ranging. Development of all the technologies above is complete, and each element is scheduled for delivery and integration to the spacecraft in the fall of 2004.

We are grateful to the NASA's Office of Space Science and the New Horizons Project Office for their support throughout the development of this system, in particular Glen Fountain (program manager), Dave Kusnierkiewicz (mission systems engineer), and Chris Hersman (spacecraft systems engineer). Bob Bokulic and Matt Reinhart figured large in the early design of the system and have been valued counsel since. In addition, many engineers have worked and continue to work to bring the flight system together. In particular we would like to acknowledge the efforts of Laurel Funk, Rich DeBolt, Chris Fry, Steve Fortney, Stuart Hill, Paul Marth, John Penn, Ballard Smith, and Michael Vincent.

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BIOGRAPHIES

Chris DeBoy *is the RF Telecommunications lead engineer for the New Horizons mission. He received his BSEE from Virginia Tech in 1990, and the MSEE from the Johns Hopkins University in 1993. Prior to New Horizons, he led the development of a deep space, X-Band flight receiver for the CONTOUR mission and of an S-Band flight receiver for the TIMED mission. He remains the lead RF system engineer for the TIMED and MSX missions. He has worked in the RF Engineering Group at the Applied Physics Laboratory since 1990, and is a member of the IEEE.*

Chris 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*

Ron Schulze *is currently the lead antenna engineer for the New Horizon mission. He received his B.S. from Virginia Tech in 1989, and M.S. from the Ohio State University in 1991, both in electrical engineering. He started his career at APL in 1991 in the Fleet Systems Department, where he performed propagation analysis studies related to low-elevation radar issues. He joined APL's Space Department in 1997, where he has designed planar micro-strip antennas and equatorial antennas for spin stabilized platforms. Mr. Schulze is also interested in technology development of lightweight inflatable reflector antennas. Prior to working at APL, Mr. Schulze worked at COMSAT Laboratories.*

***Mark Bernacik** was born in Poland in 1960. He studied electrical engineering at Silesian Technical University in Gliwice, Poland. He received his BSEE from the University of Missouri/Columbia in 1989 and graduate work at the University of Kansas. He worked in industry (e.g., Oak Frequency Control (now Corning), Ericsson, Nokia, and Thales) primarily in RF and analog circuit design for crystal oscillators, VCOs, PLL frequency synthesizers, radio receivers/transmitters and related circuits. At the Applied Physics Lab, he is a Lead Engineer for Ultra Stable Oscillator (USO) for the New Horizons mission to Pluto.*

Bob Jensen *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.*

Dennis Duven *received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Iowa State University in 1962, 1964, and 1971, respectively. He was responsible for coordinating and teaching the introductory Automatical Control Systems sequence at Iowa State from 1965-1973. Dr. Duven has been employed by the Space Department of the Johns Hopkins University Applied Physics Laboratory (APL) since 1973. His responsibilities at APL have included analysis and design of the SATRACK I and II missile tracking systems, a Miss Distance Measurement System for the SDI Brilliant Pebbles Program, an autonomous GPS Navigation System for the NASA TIMED satellite, and the Regenerative Ranging System described in this paper.*

Wes 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.*