A Highly Integrated S-Band Transceiver System with Two-Way Doppler Tracking Capability

Robert S. Bokulic, Christopher C. DeBoy, Daniel B. Minarik,
John Daniels, Sheng Cheng, Jeffrey H. Sinsky

Johns Hopkins University
Applied Physics Laboratory
Laurel, Maryland
robert.bokulic@jhuapl.edu
(301) 953-6409

Abstract: The present-day emphasis on smaller, lower cost spacecraft missions has generated significant interest in higher levels of integration for spacecraft electronics. One of the more effective approaches is to integrate the core electronics, including the RF hardware, into a single card-based chassis commonly referred to as an Integrated Electronics Module (IEM). This approach has been adopted for the TIMED spacecraft, currently being built for NASA by the Johns Hopkins University Applied Physics Laboratory. Breaking from traditional approaches, TIMED incorporates the S-band transmitter and receiver functions into the IEM along with the spacecraft digital electronics. These RF functions are integrated with portions of the command and data handling system, thus blurring the traditional boundaries between subsystems and resulting in two plug-in cards (uplink and downlink) that perform high level functions for the spacecraft. Although designed for S-band operation, the architecture of the cards is scaleable, permitting them to be adapted to X-band for deep space or high data rate applications. In addition, the cards are capable of performing highly accurate two-way Doppler tracking. Using a noncoherent technique recently developed at APL, velocity accuracy has been demonstrated at the 0.1 mm/s level, thus meeting the stringent requirements of a deep space mission.

Introduction

The TIMED* spacecraft, being built for NASA by the Johns Hopkins University Applied Physics Laboratory (APL), will be launched in early 2000 aboard a Delta 7920 launch vehicle from Vandenburg Air Force Base. This spacecraft will spend the next two years studying the mesosphere, lower thermosphere, and ionosphere regions of the Earth from its 625 km high orbit. The spacecraft incorporates an S-band transceiver system to provide communications with ground stations on Earth. More significantly, the transceiver system is incorporated into an integrated electronics module (IEM) along with the other spacecraft core electronics. This new packaging concept provides a way to significantly reduce the mass and cost of the RF system.

In addition to providing modularity (the RF electronics are packaged on plug-in cards), the transceiver system has been designed with a scaleable architecture so that it can be easily adapted for other missions. For example, the electronics can be readily adapted to X-band for deep space or high data rate applications. In addition, the cards provide the capability for highly accurate Doppler tracking. Using a two-way noncoherent technique developed at APL, the cards have a demonstrated accuracy of 0.1 mm/s. This capability, considered experimental on TIMED, is particularly attractive for missions that do not have a GPS receiver such as deep space probes, highly elliptical orbiters, and lunar missions.

RF Communication System Design

Figure 1 shows a block diagram of one of the redundant IEMs on TIMED, with emphasis on the RF communication system. The spacecraft is nadir pointing, with shaped-beam bifilar helix antennas used to provide coverage in the Earth direction. Hemispherical-beam quadrifilar helices in the zenith direction can be summed with the shaped beam antennas to provide effective omni-directional coverage in the event of a spacecraft attitude anomaly. The primary ground station for TIMED is located at APL.

The uplink card provides command reception capability at 2.0 kbps, using the NASA-standard system of modulating the data first on a 16 kHz

---

* Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics

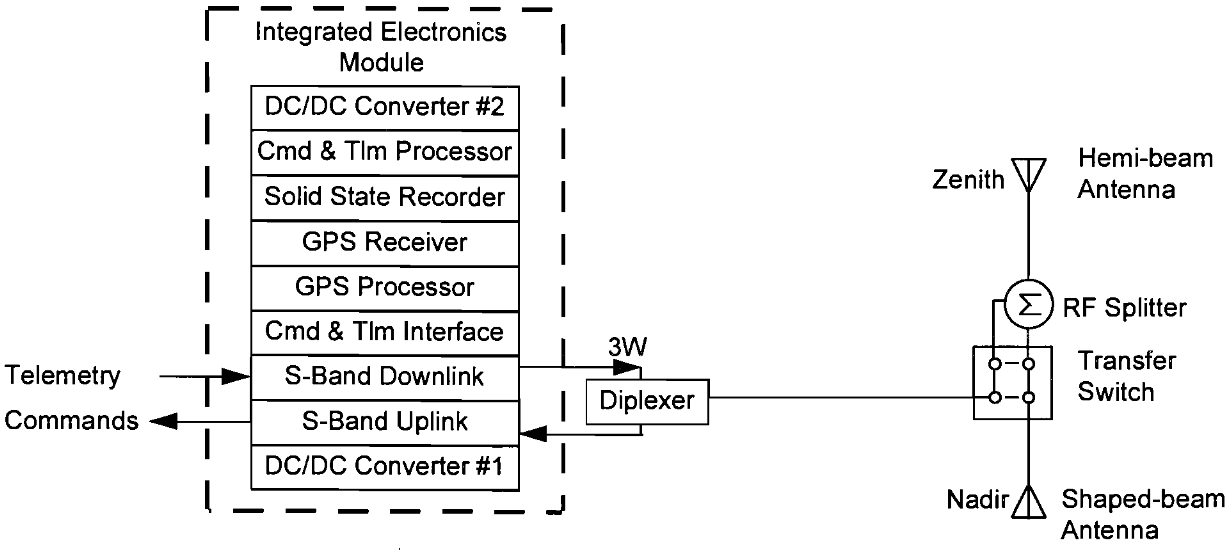

Figure 1. Block diagram of the TIMED integrated electronics module, with emphasis on the RF communication system.

subcarrier before phase modulating it onto an S-band carrier. The uplink card is more than just a command receiver: it also contains a real-time command decoder that is capable of executing any relay command on-board the spacecraft. This level of integration is a natural result of the IEM approach. The card stays powered continuously and can be used to operate the spacecraft in the event of an emergency when all other IEM electronics are turned off. Characteristics of the card are summarized in Table 1.

The downlink card provides a high-rate science downlink at 4 Mbps and a low-rate emergency downlink at 9 kbps. The RF output power is 3 watts. To preserve bandwidth, offset QPSK is used for the high-rate data, along with Reed-Solomon coding. For the low-rate data, residual-carrier phase modulation is used, along with rate 1/2, k=7 convolutional coding and Reed-Solomon coding. The downlink card is more than just a telemetry transmitter: it also contains a downlink framer that accepts packets of data from the peripheral component interconnect (PCI) bus in the IEM and formats them into frames for downlink transmission. Characteristics of the card are summarized in Table 2.

Uplink Card Design

Figure 2 shows a block diagram of the TIMED uplink card. The first and second downconverters incorporate off-the-shelf MMIC amplifiers, active mixers, and AGC attenuators to translate the input signal first to 149 MHz, then to 15.3 MHz. This intermediate frequency (IF) signal is sent to the phaselock loop section, where it is locked to and demodulated. A "long loop" is used to provide a wide tracking range. The output of the phaselock loop section is a 16 kHz subcarrier, which is then sent to the command detector unit (CDU). The CDU is designed using two ACTEL field programmable gate array chips. It uses digital processing to track the 16 kHz subcarrier and demodulate the 2 kbps command data stream. Once demodulated, this data is sent to the critical command decoder (CCD), also designed using an ACTEL chip. The CCD is capable of decoding and executing any of 128 relay commands sent either from the ground (in real time) or from the on-board command processor. It passes all command data received from the RF uplink over the IEM backplane to the command processor.

The uplink card frequency reference is generated from a 30.6 MHz crystal oscillator that is multiplied to a local oscillator frequency of 1890.65 MHz using a frequency synthesizer chip. The synthesizer approach permits the same reference oscillator to be used to generate frequencies in both the uplink and downlink cards. Also shown on Figure 2 is circuitry that accomplishes the noncoherent navigation function. This circuitry, largely located on one of the existing ACTELs, measures the received frequency relative to the on-board oscillator using counters and puts the measurement into spacecraft telemetry.

A photograph of the pre-engineering model uplink card is shown in Figure 3. The RF and analog circuitry (shown) are mounted on one side of an 0.04" thick aluminum heat sink core, with the digital circuitry mounted on the other side.

Table 1. Uplink Card Characteristics

Parameter	Nominal Value
Center frequency	2039.65 MHz
Acquisition threshold	-130 dBm
Noise figure	3.5 dB
Dynamic range	-130 to -50 dBm
Image rejection	60 dB (> 100 dB with external diplexer)
Carrier tracking loop bandwidth (B_L)	400 Hz
AGC loop bandwidth	25 Hz
Tracking range	± 150 kHz
Ground transmitter sweep rate	up to 35 kHz/s at -100 dBm
Command bit rate:	2 kbps
Critical command capability	128 relay commands
Size	6" x 9"
Mass	≤600 grams
DC Power:	4.5 W conditioned power

Table 2. Downlink Card Characteristics

Parameter	Nominal Value
RF output frequency	2214.97 MHz
RF output power	3 W
High-rate modulation	4 Mbps* offset QPSK
Low-rate modulation	9 kbps* residual carrier PM
Coding	Differential (select or bypass) Convolutional (select or bypass) Reed-Solomon (select or bypass)
Spectrum control	NTIA compatible using premodulation filtering
Downlink framer	CCSDS compatible
Bus interface	PCI
Size	6" x 9"
Mass	≤ 600 grams
DC Power	12.7 W conditioned power (transmit) 1.0 W conditioned power (standby)

* Bit rates are prior to any error correction coding.

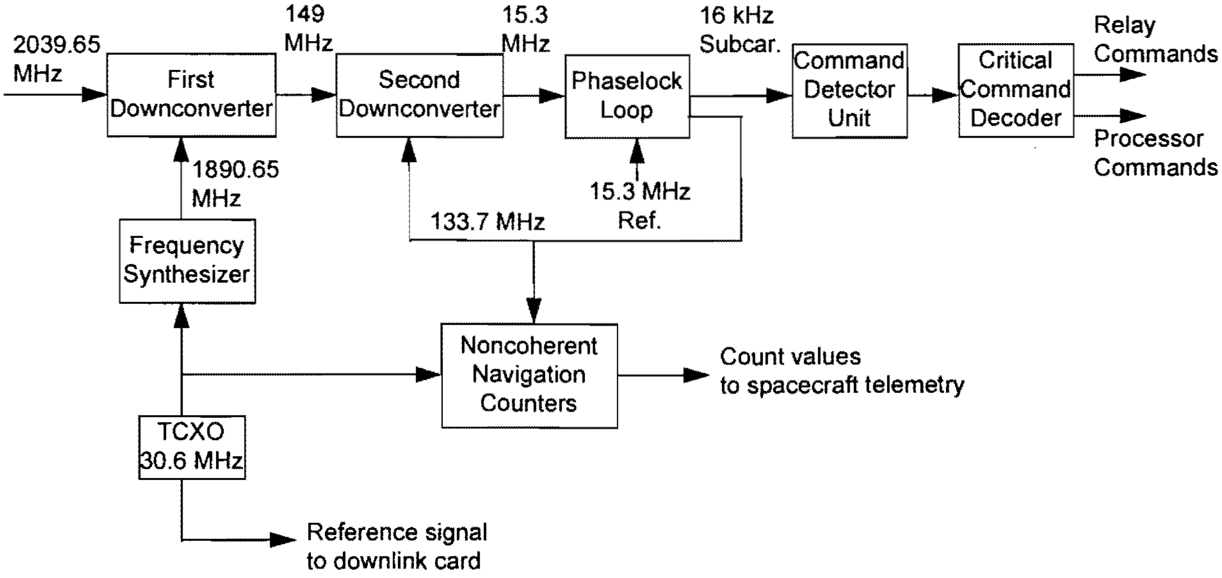

Figure 2. Block diagram of the uplink card

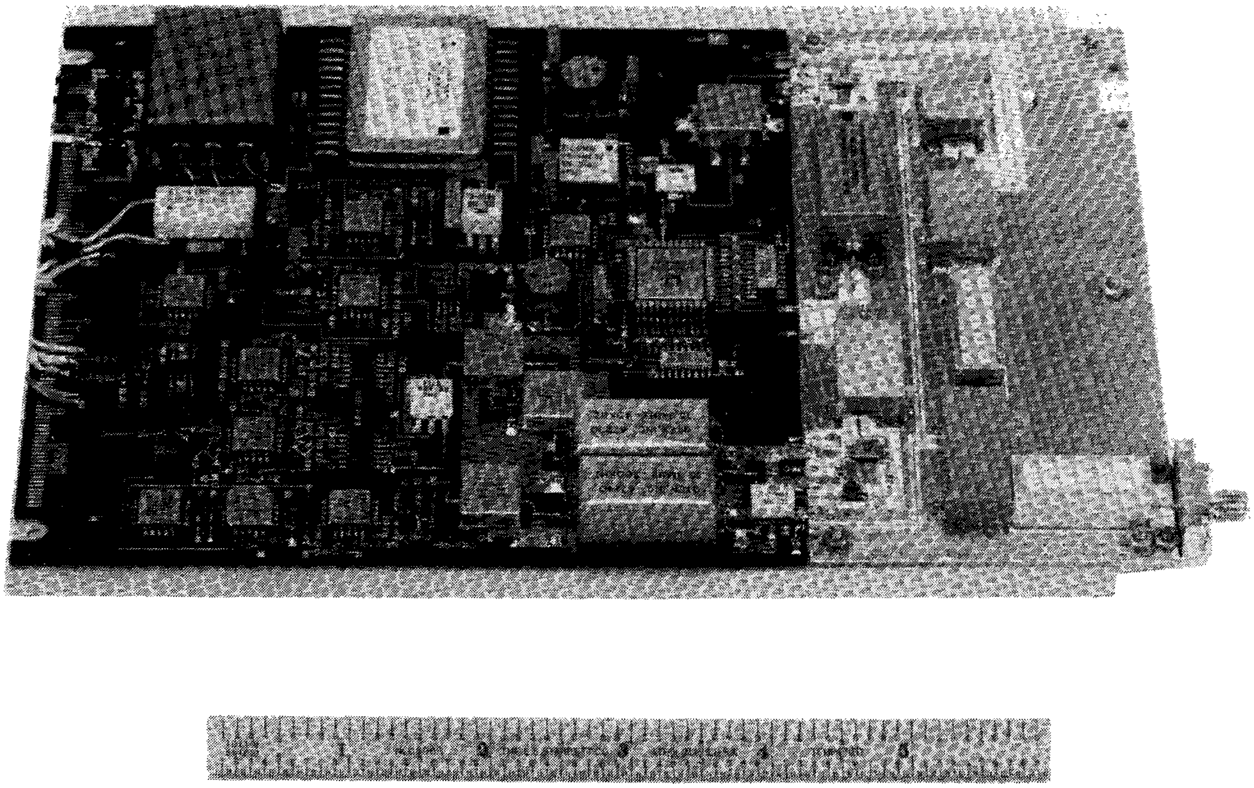

Figure 3. Photograph of the uplink card (RF/analog side shown)

Downlink Card Design

Figure 4 shows a block diagram of the TIMED downlink card. The architecture is kept simple by modulating directly at S-band instead of upconverting from an intermediate frequency. A vector modulator is used to implement both the offset QPSK required for the high-rate data and the residual carrier phase modulation required for the low-rate data. Premodulation filtering is incorporated to control the RF output spectrum.

The downlink card uses a PCI bus to interface with the other subystems in the IEM. Downlink data in the form of packets are received from the bus, buffered, and put into transfer frames using an ACTEL chip referred to as the "framer." The data then goes through a Reed-Solomon encoder to another ACTEL chip referred to as the "modulator driver." This chip performs the functions of differential coding, convolutional coding, and demultiplexing of the data into I and Q symbol streams. The I and Q symbol streams are converted into vector values using look-up tables, after which they are sent through D/A converters for use by the vector modulator.

The ACTEL-based framing and modulation scheme described above has great versatility. For example, each of the coding schemes (differential, convolutional, Reed Solomon) can be bypassed, if desired, via ground commands. Imbalances in the vector modulator can be compensated for by fine-tuning the vector values contained in the look-up tables. Up to eight downlink bit rates can be selected. The design of the downlink frame structure can be changed for future missions by modifying the framer ACTEL design. In addition, the modulator driver ACTEL can be re-programmed to incorporate a subcarrier for low bit rate operation on a future deep space mission. All of these modifications are accomplished with minor changes, if any, to the digital circuit board for each mission.

The 30.6 MHz oscillator input signal from the uplink card is multiplied to S-band with a frequency synthesizer chip. This signal is then modulated and amplified to a 3-watt level using a GaAs FET solid state power amplifier (SSPA). The spectrum is controlled with premodulation lowpass filters.

The mechanical layout of the downlink card is very similar to the uplink card. The SSPA and other analog circuitry are mounted on one side of a 0.04" thick aluminum heat sink core, with the digital circuitry mounted on the other side. To accommodate the heat generated by the SSPA, the heat sink thickness is increased from 0.04" to 0.125" in that area. In addition, the SSPA circuitry is placed close to the edge of the card so the heat can be readily transferred into the cardlocks.

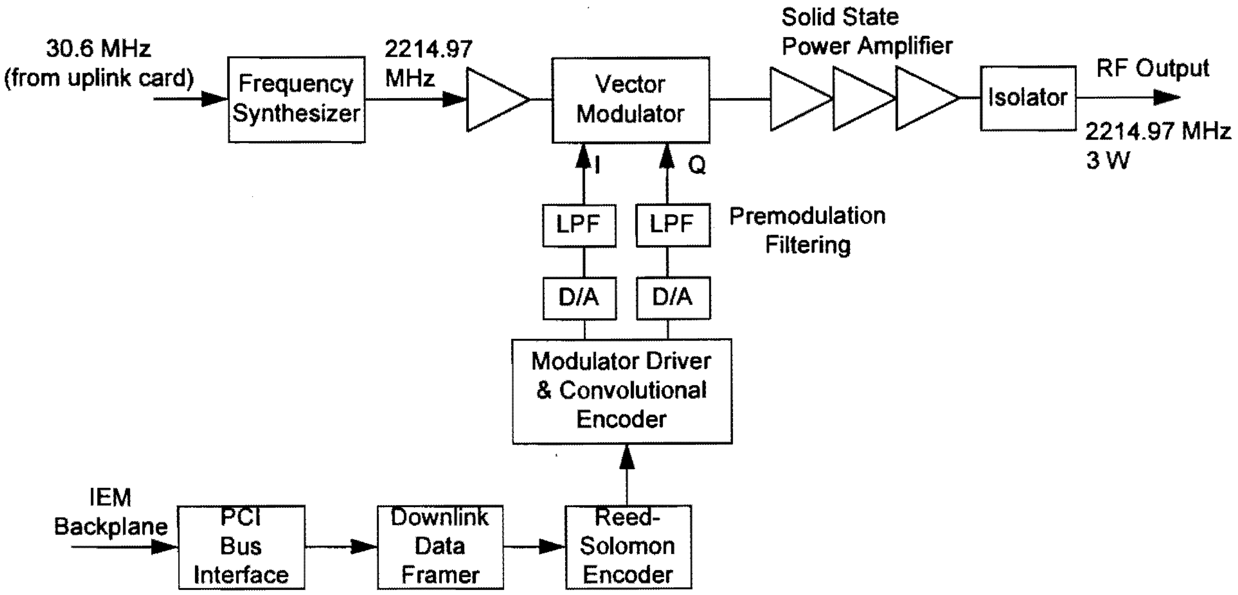

Figure 4. Block diagram of the downlink card.

Electromagnetic Interference Control

Control of electromagnetic interference (EMI) is taken very seriously because of the close proximity of the RF cards to other circuitry in the integrated electronics module. Linear regulators are used to protect sensitive circuitry such as voltage controlled oscillators from conducted noise. In addition, passive filtering is placed at each power supply input on the boards. Spot shielding is used around sensitive RF circuitry such as the low-noise amplifier on the uplink card. Broad-area shielding will also be used, where required, around entire subsections such as the S-band downconverter and frequency synthesizers.

Two-Way Noncoherent Doppler Tracking

One of the more distinctive features of the TIMED RF cards is their capability to perform highly accurate two-way Doppler tracking. This is accomplished with an innovative technique that uses information from the spacecraft telemetry to correct for drifting of the spacecraft oscillator. The technique provides the high accuracy required for deep space missions (0.1 mm/s) and is designed to be compatible with existing ground station assets such as the Deep Space Network. It is incorporated on TIMED for experimental purposes (the primary navigation tool is a GPS receiver), but can provide primary tracking capability on future missions that do not have a GPS receiver such as deep space probes, highly elliptical orbiters, and lunar missions.

Figure 5 illustrates the noncoherent navigation concept. The uplink signal is received and compared with an on-board oscillator in the command receiver. The results of this comparison (phase counts) are placed in the spacecraft telemetry and transmitted to the ground. At the same time, the ground station is tracking the spacecraft as if it had a coherent transponder on board. The Doppler data obtained by the ground station will have significant errors due to drifting of the spacecraft oscillator; however, these errors can be corrected using the counter values from the spacecraft telemetry. Spacecraft oscillator stability is not critical and accurate timetagging on the spacecraft is not required. The additional telemetry required for the technique varies from about 24 bits every second to 24 bits every 60 seconds. The counter circuitry on the spacecraft comes at low cost. For example, on TIMED the circuitry consumes just 0.3 watt in the uplink card and is largely incorporated into an existing ACTEL gate array.

Figure 6 shows the results of a "zero velocity" noncoherent Doppler tracking test performed at APL using the pre-engineering model of the TIMED uplink card. With the experimental hardware located in a laboratory environment, the true velocity of the uplink card was zero. The data shows that gross velocity errors up to 30 m/s occurred when the on-board oscillator was tracked without any correction. However, when the tracking data was corrected using counter values from the uplink card, the velocity errors were reduced to the 0.1 mm/s level. The correction works even in the face of large oscillator drifting, such as that produced by a thermal transient. The system is also designed to handle vehicle dynamics effects. Plans are being made to perform a compatibility test with the Deep Space Network in late 1997/early 1998.

Conclusion

The RF transceiver hardware developed on the TIMED program has provided a significant advancement of the state-of-the-art in spacecraft communication systems. The card-style packaging permits it to be integrated with the rest of the spacecraft electronics as part of an integrated electronics module. Such integration blurs the traditional boundaries between the RF hardware and the command and data handling system, resulting in cards that perform high-level functions for the spacecraft.

The transceiver system also provides Doppler tracking capability through the use of a newly developed two-way noncoherent technique. This technique is highly accurate and designed to be compatible with existing ground station assets.

Acknowledgments

The TIMED program is sponsored by NASA's Office of Space Science. The authors would like to acknowledge the work of Steve Oden, Dan Rodriguez, and John Penn on the critical command decoder, PCI bus interface, and framer chips, respectively. We would also like to acknowledge the work of Jeffrey Will and Lloyd Ellis in fabricating the pre-engineering model hardware.

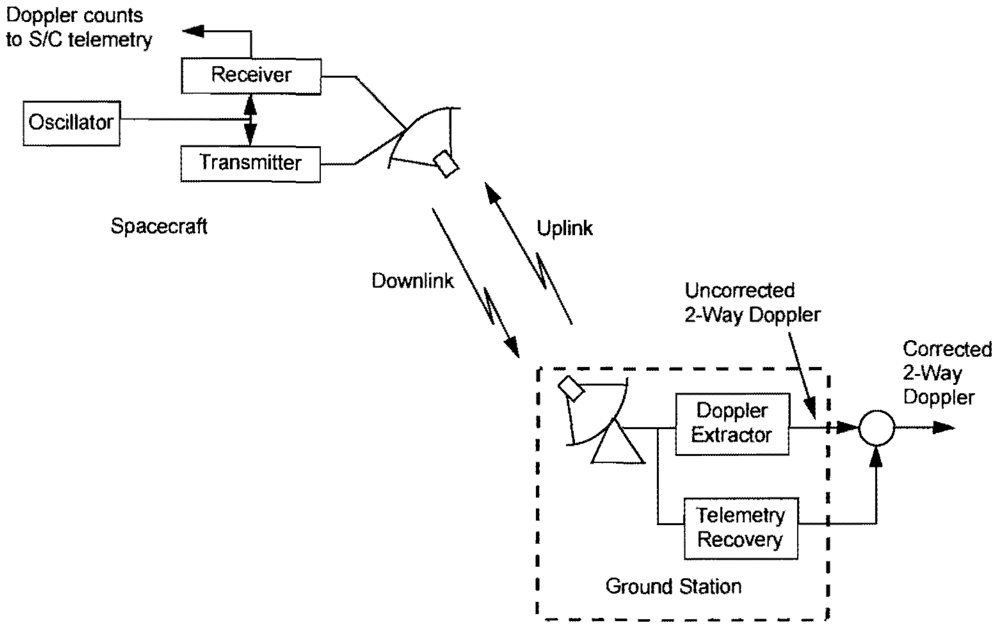

Figure 5. Illustration of the two-way noncoherent Doppler tracking concept.

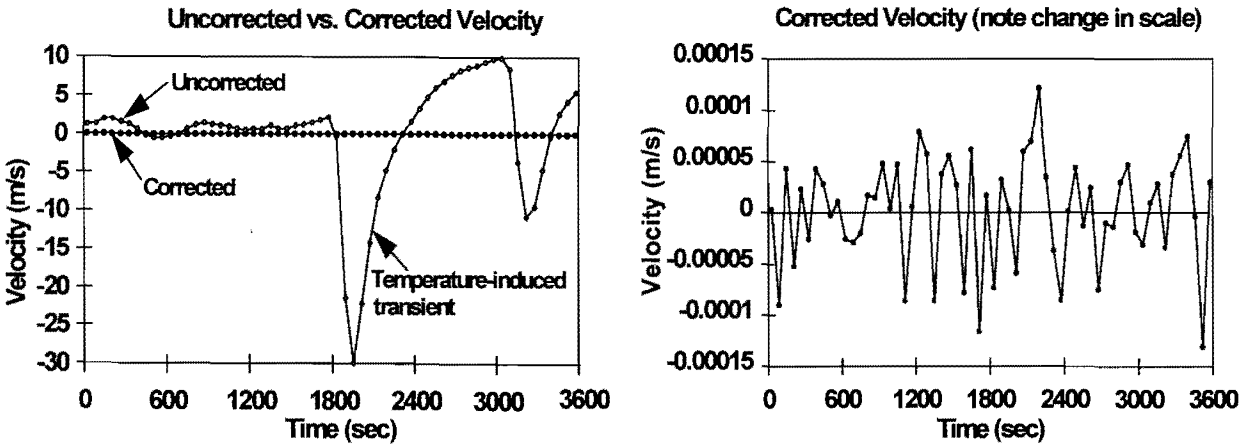

Figure 6. Results of a two-way noncoherent Doppler tracking test performed at APL. Using this technique, gross errors in on-board oscillator stability (left) are readily canceled, producing tracking data accurate to the 0.1 mm/s level (right).

Author Biographies

Robert S. Bokulic

Robert S. Bokulic received his BSEE degree from Virginia Polytechnic Institute in 1982 and his MSEE degree from Johns Hopkins University in 1985. He joined the APL Space Department in 1982 and has been involved in RF communication systems since that time. He is currently working as the lead engineer responsible for development of an S-band communication system for NASA's TIMED spacecraft program. Prior to that, he was the lead engineer responsible for the RF telecommunication system on the NEAR spacecraft. His experience includes work in areas such as link analysis, noise statistics, spectral analysis, phaselock loops, microwave hardware design, and link verification testing. In addition to his work at APL, Mr. Bokulic is the instructor of a communication systems engineering course at the Johns Hopkins University Whiting School of Engineering. He is a member of the APL Principal Professional staff and the IEEE.

E-mail: robert.bokulic@jhuapl.edu

Christopher C. DeBoy

Christopher C. DeBoy received his B.S.E.E. degree from Virginia Polytechnic Institute and State University in 1990, and his M.S. degree in electrical engineering from the Johns Hopkins University in 1993. He has been a member of the engineering staff in the APL Space Department since 1990. For the TIMED program, he has designed the receiver's IF, carrier tracking, and AGC sections, and is now working on developing the flight cards. He is a member of the IEEE and the AIAA.

E-mail: christopher.deboy@jhuapl.edu

Daniel B. Minarik

Daniel B. Minarik is an Electrical Design Engineer who obtained his BS degree in electrical engineering from the University of Maryland in 1990, and his MS degree in Electrical Engineering from the Johns Hopkins University in 1996. He has worked in the Space Department at APL for three years as a resident subcontractor from Orbital Sciences Corporation. His specialties include digital circuit design, analog circuit design, software design, and DSP algorithm design, analysis, and simulation. He is currently involved in designing the digital and baseband analog circuitry for the flight communication system on the TIMED spacecraft program, as well as hardware and software for the RF ground support equipment.

E-mail: daniel.minarik@jhuapl.edu