

The Electra Proximity Link Payload for Mars Relay Telecommunications and Navigation

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Abstract

To support the coming decade of Mars exploration, NASA is establishing a telecommunications relay and navigation infrastructure in Mars orbit, supporting increased science data return, providing energy-efficient relays for small scout-class mission concepts, gathering engineering telemetry during critical mission events, and providing *in situ* radio-based navigation. A key element of this vision is the Electra Proximity Payload, a telecommunications and navigation payload that will fly on each Mars orbiter, beginning with the 2005 Mars Reconnaissance Orbiter (MRO) and with subsequent flight on the 2009 Mars Telecommunications Orbiter (MTO). We present here the functional requirements, design characteristics, and implementation status of the Electra Payload and its role as a telecommunications node in an evolving Mars orbital infrastructure.

1 Introduction

1.1 Mars Exploration Overview

In the first decade of the 21st century, an extraordinary series of robotic explorers is destined for Mars, representing the most intensive program of planetary exploration in history. Roughly every 26 months, based on the synodic period of the orbits of Earth and Mars, one or more spacecraft will be launched; the resulting mission queue combines orbital remote sensing and *in situ* surface investigations to pursue a science strategy with multiple goals of determining whether Mars has been an abode for past or present life, understanding the Martian climate, characterizing the surface and interior geology of the planet, and taking the first steps towards preparing for the possibility of human exploration at some point in the future [1].

Already in 2001 the Mars Odyssey spacecraft has been successfully launched and inserted into Mars orbit, where its gamma ray and thermal emission

spectrometers are yielding valuable science returns. In 2003, ESA launched its Mars Express Orbiter, which will carry out imaging, spectrometry, and radar sounding of the planet after delivering the Beagle 2 lander to the Isidis region of Mars. In this same opportunity, NASA has launched the two Mars Exploration Rovers, Spirit and Opportunity, robotic field geologists that will explore the Gusev Crater and Meridiani landing sites. In 2005, NASA plans to launch the Mars Reconnaissance Orbiter, featuring a suite of remote sensing instruments including the HiRISE imager (capable of 30-cm surface resolution surface images), the CRISM spectrometer (providing multispectral images down to resolutions of 18m), and the SHARAD subsurface radar sounder (seeking liquid or frozen water in the first kilometer of the Martian crust), as well as several other instruments. 2007 calls for the launch of the first NASA Scout mission. This mission will be competitively selected from four concepts currently being studied: the MARVEL orbiter would seek to detect methane and other atmospheric constituents that may be indicators of Martian life; the SCIM mission would return atmospheric samples collected during a close flyby of the planet, the ARES mission would fly an airplane over the southern Martian highlands, collecting higher-resolution spectroscopy and magnetometer data than can be achieved from orbit; and the PHOENIX mission, utilizing elements of the 2001 Mars Surveyor Lander which was built but not flown after the Mars Polar Lander loss, and targeting it to the northern Martian plains. Finally, in 2009, the decade closes with the launch of the ambitious Mars Science Laboratory, a long-duration, high-mobility rover with precision landing capability, and the Mars Telecommunications Orbiter, the first dedicated planetary telecommunications satellite. Figure 1 depicts the planned mission queue.

1.2 Derived Telecommunications Needs

This ambitious program of exploration presents a number of telecommunications challenges. First and foremost is the need to support an ever-increasing *in*

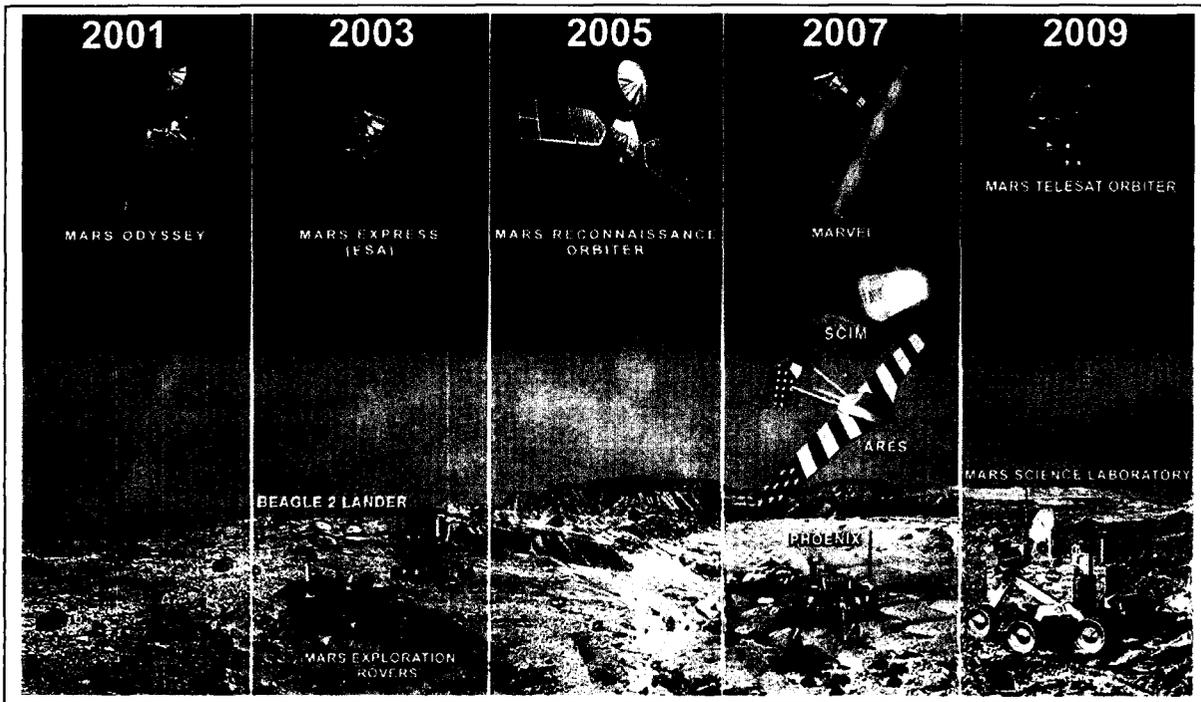


Figure 1: The current decade of Mars Exploration

situ science bandwidth from the surface of Mars. The MER rovers will generate large data volumes based on their PANCAM instruments. With an angular resolution of 300 microradians, three times better than the human eye, and 14 spectral bands distributed over two stereo imaging lenses, the PANCAM generates a full panorama representing an uncompressed data volume on the order of 10 Gbits. Subsequent landers will further drive data volume needs, with a trend towards hyperspectral imaging. In addition, increased mobility will drive bandwidth requirements, as surface operations and science naturally scale data return as a function of distance traversed.

A second key need is energy efficient communications to support innovative scout-class mission concepts. Many exploration platforms, such as balloons, gliders, airplanes, penetrators, and small landers, are severely constrained in mass, volume, power, and energy. For such missions, the high energy-per-bit required for direct-to-earth communications, as well as the operational complexity of pointing a high-gain antenna, are prohibitive. Such mission concepts are enabled by the possibility of relay communications to a nearby orbiter, via simple omnidirectional relay communications links.

A third important consideration is the need for robust capture of engineering telemetry during critical mission events such as Entry, Descent, and Landing (EDL). After the loss of the '98 Mars Polar Lander, which occurred during a period

when there was no communications with the lander, the Mars Program established a policy of striving to ensure adequate critical event telecommunications for subsequent missions. For a sustained program of exploration, it is imperative that in the event of a mission anomaly, adequate telemetry is obtained to understand and learn from that experience for the benefit of future missions.

To meet these needs, the Mars Program is developing an orbital infrastructure providing mission-enabling and mission-enhancing telecommunications relay capabilities [2]. As part of this strategy, each science orbiter will carry a standardized relay

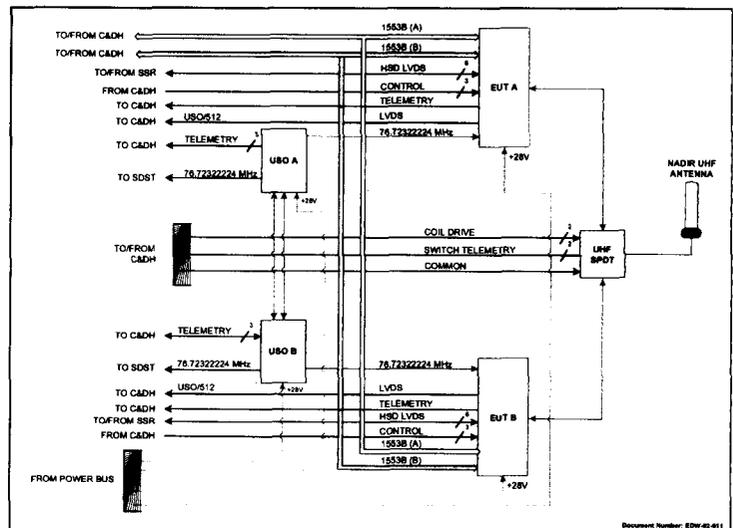


Figure 2: MRO Electra Payload Configuration

#	Requirement	Comment
1	Electra shall support UHF forward and return links in compliance with the CCSDS Proximity-1 Link Protocol.	Ensures interoperability and standardization.
2	Electra shall provide proximity link telecommunications services with the goal of increasing science data return and reducing telecommunication mass/power requirements for a wide range of future Mars exploration assets.	Drives design to achieve state-of-the-art link performance, including low noise figure, low radio implementation loss, and efficient forward error-correcting codes.
3	Electra shall provide radio metric tracking services in support of precision approach navigation, in situ surface positioning, and orbital rendezvous.	Initial implementation will support accurate carrier phase (Doppler) observables, with option for future ranging implementation.
4	Electra shall provide timing services to support time synchronization of Mars exploration assets.	Supports network science applications (e.g., seismic lander networks)
5	Electra shall allow post-launch reconfigurability of protocol and signal processing functions over the orbiter lifetime to support protocol updates and respond to unanticipated user mission scenarios.	Provides program robustness, flexibility, and evolvability for long-duration network infrastructure providing services to multiple users over multiple Mars opportunities.
6	Electra shall support multiple transmit/receive channels to allow interference-free operation in a multi-user, multi-orbiter environment.	Previous Mars relay radios are all single-channel implementations; Electra tunability supports FDMA multi-link operations.
7	Electra shall be designed to support robust capture of engineering telemetry during critical mission events.	Open-loop recording capability enables telemetry recovery in low-signal, high-dynamic environments.
8	Electra shall provide an option to add an 8.4 GHz X-band receive capability to support precision approach navigation and X-band proximity link communications.	X-band link on MTO will allow landers with X-band Direct-to-Earth capability to also obtain extremely high-performance relay link.
9	Electra shall be designed in a modular manner that allows tailoring of the basic payload for future missions.	Modularity allows efficient adaptation of Electra to other mission applications (e.g., low-mass configuration for lander missions)

Table 1: Electra Level 1 requirements.

telecommunications payload for support of surface assets. The MGS, Odyssey, and Mars Express Orbiters carry the first generation of UHF relay payloads. Building on this initial experience, NASA has begun development of a next-generation relay payload, the Electra Proximity Link Payload, which will fly for the first time on the 2005 Mars Reconnaissance Orbiter. In addition, the program strategy calls for flight of a Mars Telecommunications Orbiter in 2009, providing for the first time a dedicated telesat with orbit and flight system elements optimized for its relay telecommunications function.

2 The Electra Proximity Link Payload

2.1 Payload Overview

The Mars Exploration Program has established a multimission effort to develop the Electra Proximity Link Payload for flight on MRO, MTO, and subsequent Mars orbiters. This multimission approach is intended to ensure standardization and interoperability, as well as to achieve significant savings through economies of scale and heritage re-use. Table 1 lists the top-level program requirements on the Electra Project.

The MRO Electra Payload is shown in Figure 2 consisting of the following subsystem elements:

- Dual string Electra UHF Transceivers (EUTs)

- Dual string Ultrastable Oscillators (USOs) for precision navigation and surface positioning
- Nadir pointing, low gain UHF antenna (Mars '98, '01 heritage) with string switch and cabling

The EUT is the core element of the Electra Payload and will be discussed in detail in the next section. The redundant USOs provide a high stability frequency reference for the EUT and for the spacecraft Small Deep Space Transponder (SDST) as well as providing the capability of accurate one-way Doppler navigation. In addition, a USO-derived time reference is provided to the spacecraft Command and Data Handling Subsystem (C&DH) by the EUT to “discipline” the spacecraft clock, providing the required time-tagging accuracy for science data and telemetry. The Electra MRO UHF antenna is a quadrafilament helix with significant flight heritage, having flown on Mars Global Surveyor, Mars Odyssey and the International Space Station.

2.2 Electra UHF Transceiver

2.2.1 Key Design Features

The Electra UHF Transceiver (EUT) is a fully-reconfigurable, frequency-agile transceiver operating in the 390-450 MHz band. The EUT incorporates a modular design with functional elements residing in four stacked modules: a Filtering and Switching Unit (FSU) slice, a Receiver/Modulator (RXA/MOD)

slice, a Baseband Processor Module (BPM) slice, and a Power Amplifier-Power Supply Module (P/A-PSM) slice. The block diagram of the unit, shown in Figure 3.2.1-1, indicates the functions residing in each slice of the unit.

The UHF antenna feed is connected to J2 and passes through a solid state 3:1 RF Switch. The solid state switch allows the antenna to be connected to the diplexer (for full duplex operation), a wideband half duplex LNA (for half duplex receive), or directly to the wideband high power SSPA (for half duplex transmit). The wideband half duplex LNA and the wideband SSPA operates from 390 MHz to 450 MHz. The diplexer splits the total band into 390-405 MHz receive, and 435-450 MHz transmit bands. All switches in the unit are solid state with the exception of one RF relay used to route the SSPA to either the 3:1 solid state switch in half duplex mode, or to the

diplexer for full duplex operation. The RF relay, rated for 200,000 cycles, will only rarely need to be activated. In addition, a separate input RF path is available from an optional external (X-Band) block downconverter, enabling addition of an 8.4 GHz relay capability. All of the receive/transmit switches and low noise amplifiers are resident within the top slice designated "FSU Module".

The downconverter is composed of a low phase noise programmable synthesizer with 56 kHz step size. The synthesizer output is used as the local oscillator to drive a double balanced mixer. The downconverted IF center frequency of 70 MHz is amplified via bipolar transistor amplifiers and filtered with SAW filters, resulting in exceptionally low group delay and amplitude balance across the 7 MHz IF bandwidth. The IF has 70 dB of AGC range and resides in the "RXA/MOD" slice.

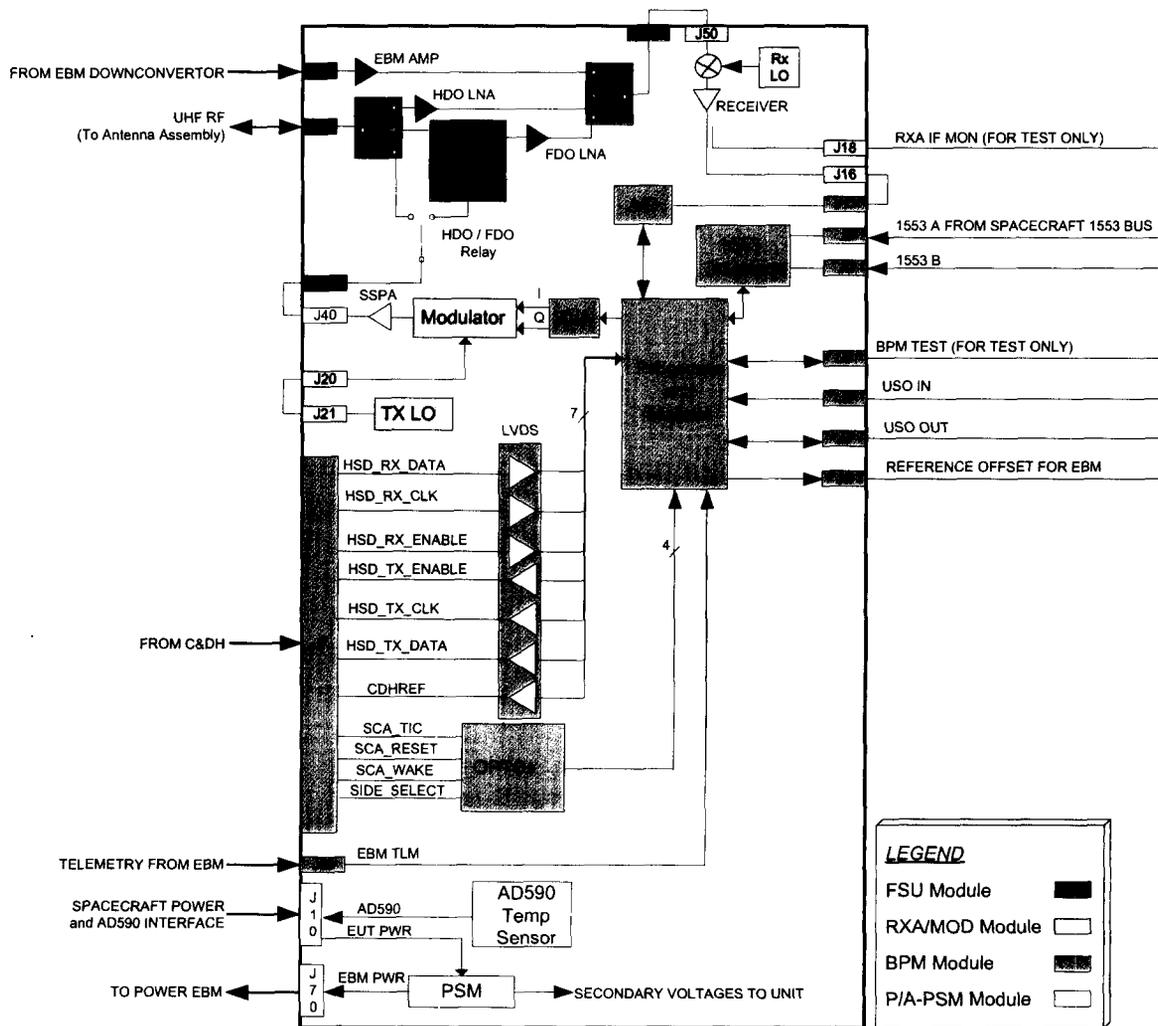


Figure 3: Overall Electra UHF Transceiver block diagram

The IF output is a 70 MHz, 0 dBm signal fed to the Baseband Processing Module (BPM) which digitizes the signal and completes all demodulation functions (acquisition, tracking, demodulation, matched filtering, and bit synchronization).

The BPM, with its resident 1553 interface, LVDS interface, and discrete interface handles all data flow from and to the spacecraft, digitizes health and status signals for telemetry, and handles all payload commands. The BPM controls the synthesizer frequencies and all modes of operation, as well as an optional interface to control the frequency and read the health and status telemetry of an external block downconverter. The link layer protocols are handled by the BPM with its resident SPARC processor. The transmit I and Q waveforms are generated by the BPM, converted to analog waveforms via two 12 bit D/A converters, and passed from the BPM to the RF modulator.

The RF modulator is implemented with a vector modulator which modulates the I and Q waveforms onto the carrier frequency, which is generated by a programmable synthesizer. The carrier frequency can be programmed by the BPM to any frequency in the range of 390-450 MHz, in 56 kHz steps. The unit can be commanded into a self-test mode in which a highly attenuated transmit signal is looped back through the receiver in order to verify the full transmit/receive chain. In full power mode, the modulated waveform is amplified to 0 dBm and passed to the wideband solid state power amplifier. The modulator is packaged within the "RXA/MOD" slice.

The SSPA amplifies the modulated signal to a minimum of 12 watts (15 watts nominal) via a GaAs FET driver and a balanced GaAs FET final Amplifier. The high power RF signal is routed through a low loss isolator and is fed to the RF switching unit, which either drives the antenna directly in half duplex transmit mode (supplying 7 watts minimum to the antenna), or feeds the antenna through the diplexer in full duplex mode (supplying 5 watts minimum to the antenna). The SSPA is housed in the bottom slice, designated the "P/A-PSM" module. This module also hosts the Power Supply, providing secondary voltages to the various EUT slice modules and circuits.

The Power Supply provides the secondary voltages to the various EUT slice modules and circuits. The Power Supply is implemented with switching converters, allowing the primary 28V power bus to

be isolated from chassis by greater than $1M\Omega$. The Power Supply, via digital commands from the BPM, powers only the functions required to provide functionality for the mode, reducing power consumption. The Power Supply assembly also includes a baseplate temperature sensor and is packaged within the "P/A-PSM" slice.

2.2.2 Mechanical Features

The unit is packaged as four slices along logical boundaries, as depicted in Figure 4, allowing for easy assembly and test at the slice level, and easy integration into the final stacked unit. The diplexer and the half duplex receive filter are mounted atop the unit for easy installation on the assembly. The unit dimensions (excluding mounting feet and connectors) are 17.2 cm (W) x 21.9 cm (L) x 14.0 cm (H). The mass of the unit is 4.9 kg. Mass was minimized on the unit by utilization of a gold plated magnesium chassis with weight reduction pockets cut where allowed as governed by the thermal and mechanical load requirements.

The unit has a high emissivity black paint outer finish; however, the primary thermal interface is through the baseplate of the unit. The vast majority of the waste heat is generated in the bottom (baseplate) slice, with the SSPA devices and the power converters mounted directly to the baseplate of the unit. This thermal design minimizes thermal deltas in the unit when in transmit mode. The baseplate is 368 cm² which keeps the thermal density at 171 mW or less per cm².

2.2.3 Baseband Processor Module

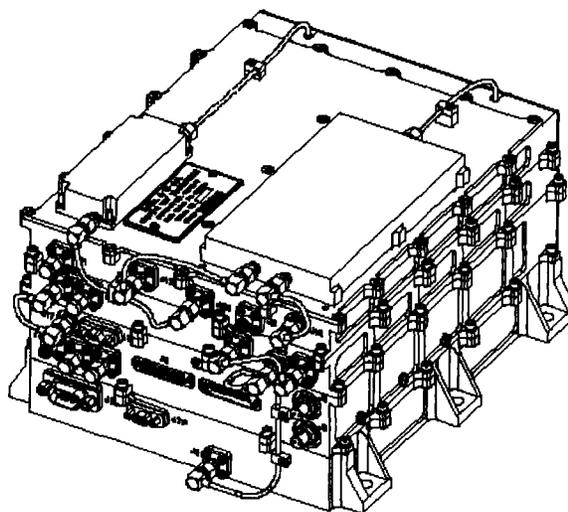


Figure 4: Isometric view of Electra UHF Transceiver

The core of the EUT is the Baseband Processor Module (BPM), a flight-reprogrammable slice which offers digitally-implemented modulation and demodulation functions, provides standardized link layer protocols, manages interfaces with the spacecraft avionics, and implements overall payload control.

To achieve this software-radio architecture, the BPM incorporates two key reconfigurable elements: a Payload Controller (PC) based on a SPARC 32-bit microprocessor, and a Modem Processor (MP) utilizing a large (~ 1Mgate) Xilinx reprogrammable FPGA. In addition, the BPM includes several rad-hard, program-once FPGAs, along with a substantial amount of dynamic and static memory.

Conceptually, one side of the BPM handles the spacecraft interface, with the PC managing 1553 command and telemetry transfers via a dedicated 1553 transceiver chip and supporting the LVDS high-rate relay and radiometric data transfers through the High Speed Data (HSD) FPGA. The other side of the BPM handles the EUT, with the Housekeeper (HK) FPGA managing control and telemetry signals to and from the EUT front end, and the Modem Processor (MP) FPGA modulating a data stream and providing I and Q channels out to the front end and conversely receiving the digitized IF (at 70 MHz) for demodulation.

The MP FPGA does the bulk of the signal processing. The modulation chain within the FPGA includes a V.38 scrambler, differential encoder, Reed-Solomon encoder and interleaver, convolutional encoder and then selection of Manchester or NRZ-L coding into the final digital modulator block. The digital I & Q channels go into an on-board DAC before interfacing to the RFM transmitter. Conversely, the 70MHz receive IF comes into on-board 12-bit ADCs before input to the MP, where the demodulation chain consists of carrier acquisition, DTTL bit acquisition, interface to an off-chip combination Viterbi and Reed-Solomon decoder and deinterleaver auxiliary chip, and then back into the MP for differential decoding and descrambling to produce the recovered data stream. The MP detects Proximity-1 frame boundaries upon receive, but for both forward and return links, the PC takes care of framing data and producing proper Proximity-1 headers and generates ACKs/NACKs for the incoming frames as necessary.

For operation in the long-term spaceflight environment, the BPM has several layers of built-in protection from radiation-induced SEUs. Extensive

EDAC protection, inherent rad-hardness of critical low-level parts, and periodic “scrubbing” of the MP to eliminate any SEUs which might affect the Xilinx FPGA configuration during operation, all combine to ensure that the EUT can maintain basic functionality – and reprogrammability for recovery – even in the face of severe SEU activity.

2.2.4 CCSDS Proximity-1 Link Protocol

The Proximity-1 Space Link Protocol, developed under the aegis of the Consultative Committee on Space data Systems (CCSDS), establishes an international link-layer standard for interoperable *in situ* relay links. Electra implements the Proximity-1 Space Link Protocol, CCSDS 211.0-R-3, January 2002 Version [3] in its entirety with the exception of the two tailored requirements:

- The Electra cannot bypass the Promity-1 protocol in part. It either uses the protocol, or bypasses it completely.
- The Electra does not allow for user source packet reassembly.

Proximity-1 supports several high-level operational modes:

Reliable Bitstream Mode: The reliable bitstream mode accepts a serial data bit stream and provides error-free delivery of the bit stream at the receiving end. This mode is implemented using a full duplex air link permitting data transmission with return acknowledgement. Serial data are encapsulated within a Proximity-1 formatted variable-length transfer frame, providing frame counters and CRC checking. An ACK/NACK protocol with Go-back-N capability ensures reliability at the link layer.

Message Bypass Mode: Message bypass mode is a simplex or full-duplex mode. While this mode utilizes the Proximity-1 transfer frame structure, no ACK/NACK is employed, and hence error-free link-layer delivery is not guaranteed. (This mode can be used when reliable end-to-end delivery is being achieved at a higher-layer in the protocol stack.)

Unreliable Bitstream Mode: In this “protocol-free” mode, the radio simply acts as a bitstream modem, transmitting a serial bit stream without formatting. Received data are output as received without verification. This mode can be used if it is desired to implement the link layer protocol in the spacecraft flight computer.

SPECIFICATIONS:	
Protocol	CCSDS Proximity-1 (Reliable and Expedited Link Layer Protocols)
Modes of Operation:	Half Duplex Rx and Tx, Full Duplex Transceiver with/without Coherent Doppler Turnaround X-Band Block Downconvert Receive, with UHF Tx
Software radio architecture:	Sparc V.7 rad-hard payload controller Xilinx XQVR 1000 rad-tolerant flight-reprogrammable FPGA
Mass:	4.9 kg
RF Transmit Power:	5W Full-duplex, 7W Half-duplex
Noise Figure:	4.9 dB Full-duplex, 3.9 dB Half-duplex (including diplexer and R/T switches)
Full Duplex Rx Frequency:	On Orbit Tunable from 390 to 405 MHz (56kHz steps)
Full Duplex Tx Frequency:	On Orbit Tunable from 435 to 450MHz (56kHz steps)
Half Duplex Rx and Tx Frequencies:	On Orbit Tunable from 390 to 450MHz (56kHz steps)
Half Duplex Tx to Half Duplex Rx Switch Time:	20 milliseconds maximum in both directions
VSWR:	1.5:1 or better over the whole frequency band of operation
Radiation Total Dose:	20 Krad 100 mil Al
DC Power:	68 W (Full-duplex Transceiver), 18.4W Receive Only
Frequency Reference:	Ultra Stable Oscillator Input Clock Distribution, Internal Real Time Clock
Modulation Types:	Suppressed and Residual Carrier Modes
Rx and Tx Symbol Rates:	1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048 kbps
Implementation Loss:	Within 2.0 dB of theory at all rates
Receive Signal Dynamic Range:	-140dBm to -70 dBm
IF Bandwidth:	7Mhz
Coding/Decoding:	K=7, R=1/2 Convolutional (3 bit soft decode), [255,239] RS, [204,188] RS with Interleaving/Deinterleaving
Scrambling/Descrambling:	V.38
Data Transfer Interface	LVDS for Data Transfer
Data Transfer Rate :	10Mbps from/to 64MBit FIFOs
1553B Interface:	Commanded Mode of Operation Commanding of Communications Parameters (Aqu. Range, Loop Bandwidths, Data Rates, etc) Control of CCSDS Proximity-1 Protocol Settings Health and Status Telemetry Peak and Poke Visibility into DSP registers, Control Registers, Status Registers Time Transfer
Discrete Interface:	Side Select Wake Reset Time Valid
Radio Metrics:	Carrier phase/Doppler observables w/ 60 ns time tag accuracy
Self Test:	In-flight full transceiver loop back self-test capability
Optional X-Band Capability:	Power, RF, Control, and Frequency Reference Interfaces for an X-Band Block Downconverter
Prime Power Isolation:	>1Megohm
Tx Phase Balance:	+ 2 Deg, Amplitude Balance: ± 0.25 dB, Carrier Suppression: 30dB
Tx Phase Linearity:	20 deg over any 12Mhz BW, Rx Phase Linearity: 14 deg over any 7Mhz BW
Tx AM/PM:	2deg/dB
Health and Status Telemetry:	Temperature Indicator for Each Slice and Baseplate Temperature Sensor Power Supply Secondary Voltages Tx RF Output Power Received Signal Strength Status of Modem

Table 2: Electra Specifications

2.2.5 Specifications

The specifications for the Electra Transceiver as configured for the MRO mission are summarized in Table 2. Since the transceiver has a software radio architecture, there are capabilities for other modulation waveforms and modes of operation far beyond what is shown in the table. These additional capabilities can be added by simply changing the

software load, and can be performed at any point in time, including on orbit.

2.2.6 Engineering Model Status and Test Results

The development of the Electra UHF Transceiver has progressed rapidly. A form, fit, and function engineering model is fully developed and is currently in test. Each subassembly (or slice) has been fabricated and tested at the slice level prior to



Figure 5: Electra P/A-PSM slice

integration with the other slices. Figure 5 shows the bottom slice (the Power Amplifier and Power Supply) prior to integration with the rest of the unit. Once each slice was tested to assure it was meeting its subassembly specifications, it was integrated with the other slices. The fully stacked (integrated) EUT engineering model is shown in Figure 6. The unit came in under both its mass and power consumption specifications. The mass goal of the unit was 5.0 kg and the engineering model weighs in at 4.9 kg. The power consumption was to be less than 70W in the full duplex mode (the mode of greatest power consumption), and the unit is consuming only 63.4W in this mode.

RF testing of the EUT demonstrated that the transmitter and receiver are both performing well. The receiver is acquiring signals as low as -125dBm at the minimum symbol rate of 4 ksps, and -97dBm at the maximum symbol rate of 2048 ksps. This high sensitivity results in very favorable bit error rate (BER) performance; Figure 7 illustrates preliminary BER curves for data acquired from the EM.

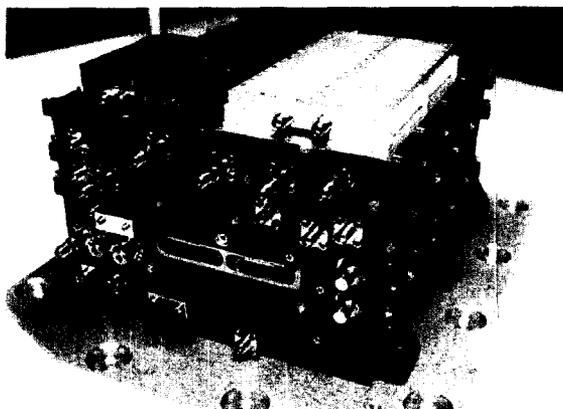


Figure 6: Integrated Electra UHF Transceiver engineering model

The transmitter is also meeting its specification of 7 watts minimum RF output in half duplex mode and is delivering over 9 Watts of power across the transmit frequency band. In full duplex mode, the transmitter is putting out 8.5W, compared to its 5W specification.

Over the next several months, environmental testing will be completed, as well as full testing of the BPM functionality including Proximity-1 protocol, coded BER performance, and Doppler tracking.

3 Future Plans

3.1 EUT Enhancements for MTO

The NASA Mars Telecommunications Orbiter (MTO), to be launched in 2009, is a dedicated long-lived (10 year mission life) telecommunications satellite with a goal of enhanced proximity telecommunications and navigation performance relative to MRO [4]. Increased data rates will be achieved by addition of an X-band relay link and by use of higher efficiency signaling schemes such as QPSK and/or 8PSK. The X-band capability also provides greater navigation accuracy (one-way) for surface assets, Mars orbiters and for approaching spacecraft. One-way approach navigation range at X-band is increased significantly relative to UHF allowing MTO to provide navigation services to incoming spacecraft for several weeks prior to Mars Orbit insertion, reducing the demand on precious DSN tracking resources.

Electra hardware changes needed to support MTO requirements include development of an X-band downconverter to interface with the EUT. The downconverter will enable the EUT to accept an X-band signal (8400 – 8450 MHz) on a switchable

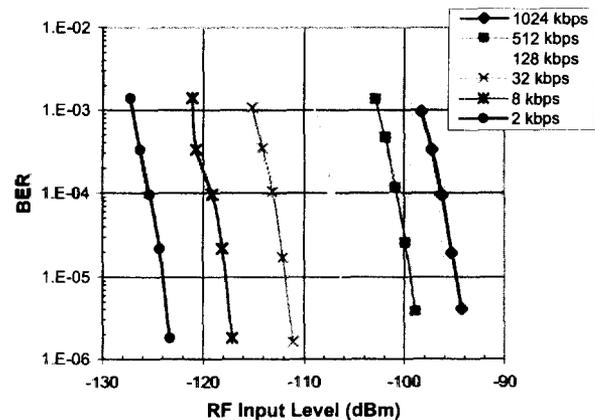


Figure 7: Electra Bit Error Rate performance curves.

secondary receive channel (SRC), downconvert to UHF which will then be processed by the EUT in the usual manner. Modularity of the EUT design allows addition of the downconverter module to the existing electronics “stack” without additional EUT design changes. To meet the MTO 10-year mission life requirement additional upscreening an/or substitution of specific EEE components will be necessary.

Increased EUT data rates will require Baseband Processor Module (BPM) firmware changes, including:

- Extension of maximum symbol rates from 2.048 Msps to 4.096 Msps
- Addition of QPSK and/or 8PSK to the Electra modulator
- Extension of existing carrier tracking loops in the Electra demodulator to support higher symbol rates
- Extension of data transition tracking loop (DTTL) in Electra demodulator to accommodate QPSK
- Modification of internal auxiliary oscillator frequency for improved DTTL timing jitter and higher symbol rates

Additional MTO relay performance improvements will be achieved through the use of steerable medium gain UHF and X-band relay antennas having approximately 15 dBi and 30dBi of gain, respectively. (By contrast, MRO has a single low gain UHF quadrifilar helix).

3.2 Electra Lite

The mass, volume and DC power specifications for the standard Electra EUT may be inappropriate for a Mars lander with stringent mass and energy constraints. Therefore, a smaller lander UHF radio is desired which retains the core functionality, performance and reprogrammability of the standard orbiter EUT. This pending new development is referred to as the Electra Lite UHF Transceiver. The plan is to leverage the current Electra EUT design as much as possible, rather than designing anew “from the ground up”, since there are several advantages to this approach , including:

- Assured compatibility with orbiter EUTs via use of common software/firmware
- Reduced non-recurring engineering costs (NRE) since the current EUT architecture will be maintained to the greatest extent possible
- Reduced recurring engineering costs. Parts

commonality with the standard EUT provides a major reduction in EEE parts costs (shared lot and upscreen charges).

- Reduced ground support equipment (GSE) costs since the standard EUT GSE will be usable for Electra Lite integration and test activities
- Maintenance of design ownership by NASA for ease and cost effectiveness of future software and hardware changes

The first landed mission requiring an Electra Lite is Mars Science Laboratory (MSL) to be launched by NASA in 2009. An Electra Lite development is currently being considered for MSL which will ultimately be determined by NASA funding constraints. The key specifications for this radio are seen in Table 3 and are based upon a recently completed study by CMC Electronics which provides the design approach to meet these requirements.

3.3 Variable Data Rate

Current relay operations typically employ a fixed data rate for the duration of a pass, selected *a priori* based on predicted link characteristics. Because of large changes in slant range, space loss, and transmit/receive antenna gain due to the time-varying

Feature	Specification
Frequencies of Operation	Rx: 390 - 405 MHz Tx: 435 - 450 MHz Half Duplex, non swappable Goal: Full duplex operation with external diplexer
Data Rates	1,2,4,8...2048kbps
Modulation	Manchester, NRZ-L, BPSK Mod index 60 & 90 deg
Channel Coding	Reed Solomon, K=7, R=1/2 Conv code/decode
Spectrum Recording	Open Loop signal sampling <100ksps, 1-8 bits/sample
Receiver Noise Figure (RMS worst case EOL)	3.7 dB max
Carrier Acquisition Threshold	-140dBm
Transmit Power	13 W
Protocols	CCSDS Prox-1 complaint
Programmability	Full reprogrammability
Doppler Observables	1-way
Physical Metrics	
Mass	<2.1 kg
Volume	<2200 cm ³
DC Power EOL	Tx: 40 W Rx: 10 W
Miscellaneous	
Parts Grade	B, with targeted upscreening
TID Capability	4 Krad

Table 3 Electra Lite Specifications

	UHF	X-band
LANDER		
Freq (MHz)	401.0	8425.0
RF Tx Power (W)	10.0	15.0
Ant Gain (dBic)	0.0	38.0
Circuit Loss (dB)	-1.0	-1.0
Total EIRP (dBm):	38.0	78.1
PATH PARAMETERS		
Slant Range (km)	6000.0	6000.0
Space Loss (dB)	-160.1	-186.5
ORBITER		
Ant Gain (dBIC)	12.0	29.9
Sys Temp (K)	500.0	500.0
Received Power (dBm)	-110.0	-81.0
TELEMETRY CHANNEL		
Bit Rate (kbps)	64.0	8192.0
Mod Index (deg)	60.0	60.0
Impl. Loss (dB)	-2.0	-2.0
Req'd Eb/NO (dB)	2.7	10.5
Margin	7.6	7.7

Table 4: MSL-to-MTO Link Budgets

pass geometry, such a strategy underutilizes the potential link capability in terms of integrated data transfer over the pass. In addition, pass-dependent multipath effects and other link uncertainties require operation with a significant link margin.

In the coming year we plan to demonstrate a variable data rate protocol which will allow performance much closer to the theoretical link potential, increasing data return in nominal link conditions, while also providing robustness by enabling a fail-soft reduction in data rate in the event of unfavorable link conditions. In this scheme, the orbiter will monitor the strength of the received lander signal, via the symbol loop signal-to-noise ratio, and adaptively command the lander to an optimal data rate throughout the duration of the pass. This capability would then be available for pre- or post-launch software upload to the MRO Electra, and would be baselined on the MTO Electra payload.

3.4 Ranging and Half-Duplex Navigation Options

While the current BPM implementation provides only carrier phase (Doppler) tracking observables, the transceiver architecture and reprogrammable signal processing support a future upgrade to include a ranging capability. Such a capability could be important for navigation scenarios in which kinematic position information is desired. Key issues here include specification of the ranging signal structure, design and implementation of the ranging

signal processing algorithms, and analysis and validation of the ranging error budget.

A related area of interest is the extent to which high-accuracy radio metric observables can be obtained in half-duplex mode. Half duplex operation offers significant link performance advantages due to elimination of diplexer losses on both the transmit and receive ends; however, traditional high-accuracy Doppler and range observables have typically used full duplex operation with coherent transponding at one end of the link. We plan to examine half-duplex navigation options, including assessment of the reliability of coherent phase connection across half-duplex switching cycles. If the carrier phase can be reliably connected across these gaps, then the combination of the one-way carrier phase measured in each direction should approach the navigation strength of two-way coherent Doppler, limited only by the oscillator stability on the time scale of the half-duplex duty cycle.

4 Data Return Analysis

To illustrate the performance of the Electra payload, consider the proximity link between the 2009 Mars Science Laboratory and the 2009 Mars Telecommunications Orbiter. MSL will communicate to Earth with a high-performance X-band telecom payload incorporating a 15 W SSPA and 1m HGA. This link will support data rates of about 8 kbps to a DSN 34m antenna, and 30 kbps to a 70m antenna, at maximum Earth-Mars separation of 2.67 AU.

Relay communications can be conducted at UHF, with an Electra-derived lander radio and low-gain UHF antenna, or at X-band by pointing the lander HGA to MTO instead of to Earth. MTO will receive these proximity link signals with a steered 12 dBi UHF antenna and a 0.5m X-band antenna. As shown in the link budgets in Table 4, MSL will be able to close a link of 64 kbps at UHF, and 8192 kbps at X-band, via the proximity link to MTO, representing more than two orders of magnitude increase relative to the direct-to-earth link. With visibility from MTO's high orbit of roughly 4 hrs per sol, MSL will be able to return a data volume approaching 100 Gb/sol, enabling rich science return from this highly-capable next-generation lander.

5 Summary

The Electra Proximity Link Payload is being developed to serve as the core "network node" of an evolving Mars telecommunications and navigation orbital infrastructure. Slated for flight on the 2005

MRO and 2009 MTO missions, Electra's reconfigurable architecture will allow flexible evolution of network capabilities, standards, and user interfaces over the long on-orbit lifetime of these relay orbiters. Significant progress has been made to date on the Electra MRO engineering model, with delivery of flight hardware to MRO scheduled to take place in the coming year. The MTO delivery will add an X-band proximity link capability, enabling enormous growth in science return for future MSL-class landers.

6 References

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