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The Mars express MARSIS sounder instrument

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A B S T R A C T

The Mars advanced radar for subsurface and ionospheric sounding (MARSIS) on Mars Express is the first high-frequency sounding radar operating from orbital altitudes since the Apollo 17 Lunar Sounder flown in 1972. The radar operates from a highly elliptical orbit but acquires data only from altitudes lower than 1200 km. The periapsis altitude is 250 km. This radar has been succesfully operating since August 2005. The radar is a dual channel low-frequency sounder, operates between 1.3 and 5.5 MHz (MegaHertz) with wavelengths between 230 and 55 m in free space for subsurface sounding and between 0.1 and 5.5 MHz (wavelengths between 3000 and 55 m) for ionospheric sounding. The subsurface sounder can operate at one or two-frequency bands out of four available bands at either like or cross polarization. The subsurface sounding radar transmits radio frequency (RF) pulses of 250 μs duration through a 40 m dipole antenna. The return echoes are then converted to digital form and temporarily stored on board for some digital processing. A second antenna, a monopole, provides reception for the cross-polarized return and its data are processed by a second channel. This processing reduces the data rate produced by the instrument to rates allowed by the spacecraft communications channel. These processed returns are then sent to Earth by the telecommunications system on the spacecraft. The advances in digital data acquisition and processing, since 1972, have enabled this technique to be used in a compact spacecraft science instrument.. This sounder has obtained returns from several kilometers below the surface of the Mars. The ionospheric sounder operates at altitudes greater than 800 km in a mode that sweeps the entire 0.1–5.5 MHz range. During ionospheric sounding, the transmitter sends a 91 μs tone at 127 pulses per second rate. The frequency sweep takes 7.3 s to complete the 0.1–5.5 MHz range. Operational aspects of the instrument are described, including the selection of frequency bands and receive antenna selection, which are based on the expected solar zenith angle. The process of data take planning as well as data archiving are described. Results of both subsurface and ionospheric sounding are presented.

Contents

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1. Introduction

The Mars advanced radar for subsurface and ionospheric sounding (MARSIS) instrument flown on the European space agency (ESA) Mars Express spacecraft is the first space-borne sounding radar since the Apollo 17 Lunar Sounder in 1972 (Porcello et al., 1974). The primary science objective of MARSIS is to map the distribution of solid and liquid water in the upper portions of the Mars' crust. Three secondary science objectives are subsurface geologic probing, surface characterization, and ionospheric sounding.

The MARSIS instrument is a low-frequency, nadir-looking, pulse-limited radar sounder that uses synthetic aperture techniques. The Mars Express spacecraft is in a highly elliptical 7 h orbit around Mars. Each MARSIS subsurface sounding pass has a duration of 26–30 min. During these operations, spacecraft power and data resources are shared with five other instruments.

The MARSIS subsurface sounding modes can be effectively operated at altitudes lower than 900 km. The MARSIS transmitter generates a swept frequency high-power RF pulse that is delivered to a 40 m dipole antenna for radiation. This radiated energy is reflected from the Martian surface and subsurface back to the radar. Data processing is performed on board in the MARSIS instrument. MARSIS' basic observation geometry and principles of operation are depicted in Fig. 1, and its principal operational parameters of the subsurface sounder are outlined in Table 1. MARSIS utilizes the technique of Doppler beam sharpening (DBS) in order to enhance the ratio of subsurface echoes to surface clutter.

Sounding the subsurface of Mars presents significant challenges as a low-carrier frequency is required to observe returns from below the surface. The ionosphere of Mars limits the frequencies for sounding; it also dictates a time-dependent observational strategy as the ionosphere plasma frequency decreases at night and increases during the daylight hours. The ionosphere is also influenced greatly by solar activity. Incorporated into the MARSIS instrument is an ionospheric sounder to aid the subsurface sounding frequency selection process, measure and remove the dispersion effects of the ionosphere, and study the ionosphere itself. The principal parameters of the ionospheric sounder are listed in Table 2.

Identifying whether returns are coming from the surface or subsurface poses another challenge. To mitigate this, the MARSIS instrument was equipped with a second channel, which utilized a monopole antenna to sense only surface returns away from the satellite track and not returns from the subsurface near the nadir. The MARSIS signal-to-noise design requirement was for a first surface return, which is 50 dB greater than the thermal noise and sidelobe noise at the lowest operating altitude (250 km) without considering the effects of the ionosphere. This signal-to-noise ratio of the surface will degrade with increase in the altitude and as a result of ionospheric effects and increase in the range to the surface.

2. Hardware description

MARSIS consists of ionospheric and subsurface sounders that share much of the MARSIS hardware. The ionospheric sounder operates over a 100 kHz–5.5 MHz frequency range (which corresponds to a wavelength range of 3000–55 m) using a simple low bandwidth pulse and radiates only through the dipole antenna.

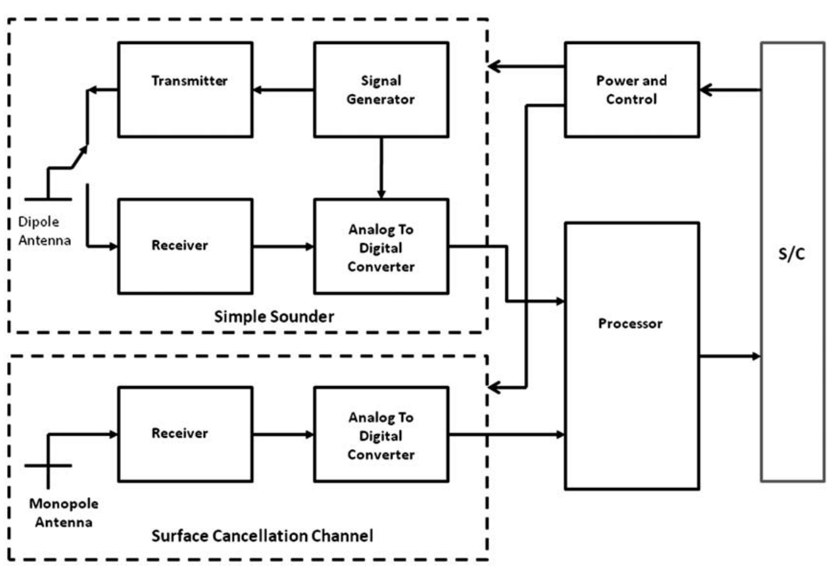

Fig. 1. MARSIS instrument block diagram. The instrument consists of a dual-channel sounder with associated antennas and an on-board data processor.

Table 1
MARSIS subsurface sounder parameters

MARSIS subsurface sounder parameters Parameter	Description
Subsurface sounding altitude range	250–900 km
Dipole antenna length	40 m tip to tip
Monopole antenna length	7 m
Subsurface sounder frequency range	1.3–5.5 MHz (4 Bands)
Peak radiated power	1.5–5 W
Subsurface sounder pulse repetition rate	127 Hz
Subsurface sounder transmit pulse length	250 μs
Subsurface sounder wavelength	60–160 m
Bandwidth per band	1 MHz
Sounder free space depth resolution	150 m
Sounder dynamic range	40–50 dB
Nominal depth window	15 km
Number of processed channels	2 or 4
Number of simultaneous frequencies	1 or 2
Data quantization	8 bits per sample
Data quantization rate	2.8 megasamples per second
Data window duration	350 μs
Data rate output	18–75 Kbps
Data volume	285 Mbit per day
Dc operation power	60 W
Total mass	20 kg

Table 2
Active ionospheric sounder parameters.

Ionospheric sounding mode	
Maximum altitude	1200 Km
Start frequency	100 kHz
End frequency	5.5 MHz
Number of frequencies	160
Transmit pulse length	91.43 μs
Minimum frequency step	10.937 kHz
Pulse repetition frequency	127 Hz
Frequency sweep repetition interval	7.38 s

The subsurface sounder operates over a 1.3–to 5.5 MHz range over four frequency bands of 1 MHz bandwidth each. This frequency range corresponds to a wavelength range of 230–55 m. The subsurface sounder has two separate channels. The first channel is connected to the dipole antenna and contains the transmitter and a receiver. The second channel is connected to the monopole antenna and can only receive. This monopole antenna with a null in the nadir direction is intended to receive only returns from the surface away from the nadir in order to discriminate returns from the top surface and subsurface of Mars. In sites with a rough surface, the subsurface dynamic range is strongly reduced by a surface clutter. One of the techniques used to increase detection performance in the presence of surface clutter is the dual antenna cancellation of the cross-track, and off-nadir echoes. In fact, due to the transmitted polarization, the signal will couple to the monopole antenna only for echoes from the surface in the cross-track direction, while the off-nadir echoes from areas extending in the along-track direction are reduced by the synthetic antenna processing.

The basic block diagram of MARSIS is shown in Fig. 1 and an artist conception of the antennas and spacecraft is shown in Fig. 2. MARSIS consists of: (1) a sounder channel containing a programmable signal generator, a transmitter that drives a 40 m dipole antenna and a receiver with an analog-to-digital converter; (2) a surface cancellation channel consisting a 7 m monopole antenna and a receiver with an analog-to-digital converter; (3) a dual channel data processor; and (4) a digital electronics and power and control subsystem that controls all the sounder functions. By selection of the proper frequencies, pulse durations and frequency sweep rates, the controller is able to perform subsurface and ionospheric sounding. The controller also configures the sounder to operate in a single frequency mode, a dual frequency mode, or a clutter cancellation mode.

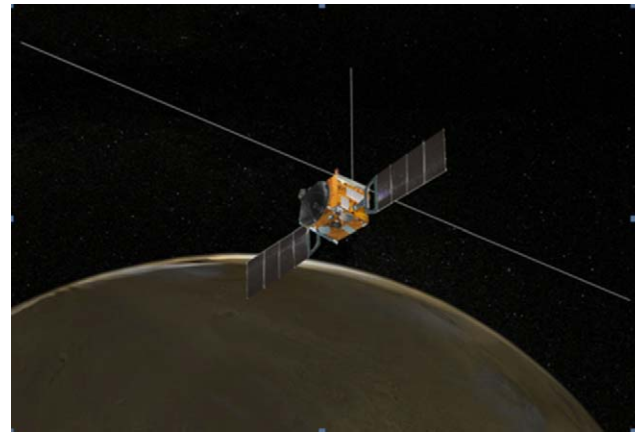

Fig. 2. MARSIS antenna configuration on Mars Express.

2.1. System design and architecture

The sounder's operational range is 0.1–5.5 MHz. In order to operate over this very large frequency range, the transmitter consists of three separate transmitter elements and antenna matching networks. The multi-frequency operating modes (1.3–5.5 MHz) have been designed to reduce signal distortion due to the ionosphere, as well as to understand frequency-dependent effects in the data analysis.

Control of the radar sounder is by selection of modes and frequency bands during the commanding phase of operations. An exception to this mode selection is the ionospheric sounding mode, which configures MARSIS to operate in a rapid frequency-hopping continuous wave (CW) mode optimized for sounding of the ionosphere.

The MARSIS instrument is controlled by the digital electronics subsystem (DES) element. Data are acquired in blocks called frames. Each frame is sufficiently long (typically one to two seconds) to establish a synthetic aperture at the lowest frequency in the frame and to enable the processing of a Fresnel zone of data. An allowance is made to acquire initial echoes to configure the radar for the frame acquisition. During any of the frames, the pulse repetition rate is a constant 127 Hz; sufficient additional data are acquired to aid in the determination of the processing parameters for the frame.

In order to acquire data with a sufficient signal-to-noise ratio, MARSIS employs a chirp signal for transmission in the subsurface sounding modes. This chirp is a 1 MHz bandwidth frequency-swept signal of 250 μs duration. During on-board or ground data processing, the return signal is range compressed, resulting in an increase in the signal-to-noise ratio of about 24 dB.

During the design of the MARSIS electronics, the control of pulse compression sidelobes was an overriding issue. The expected return of the first specular signal was calculated to be very strong compared to the calculated subsurface reflections. In order to prevent the subsurface return from being masked by the sidelobes of the specular first surface reflection, the sidelobe levels were required to be very low. The required impulse response of the system, after passing the received signal through a Hanning weighting function, is for all sidelobes to be below a time-dependent level specified by the solid line in Fig. 3.

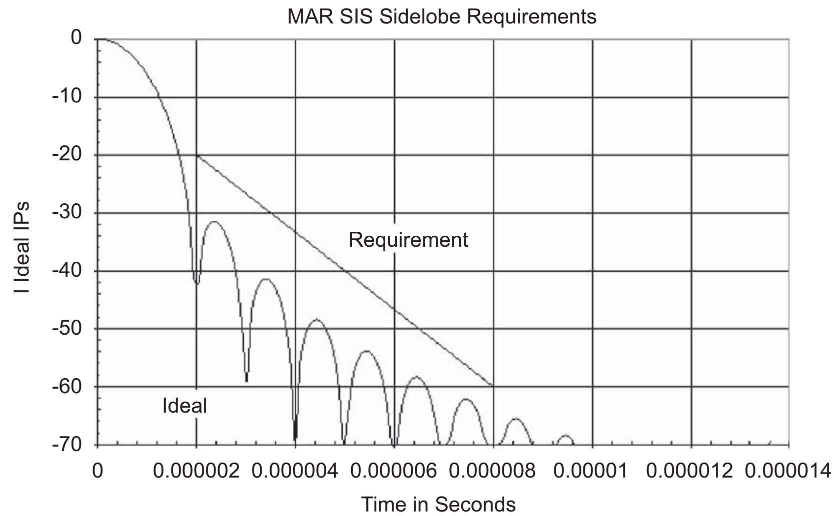

Fig. 3. MARSIS impulse response sidelobe requirement limit and ideal sidelobe response.

2.2. Antennas

The MARSIS antenna subsystem consists of a 40 m long dipole and a 7 m long monopole. The antenna structure is essentially a bridge of two parallel wires running the length of a support tube, which is made of fiberglass and Kevlar layers impregnated with resin. The antenna elements are made of foldable composite tubes that utilize a new technology developed by the Northrup Grumman called foldable flattenable tube (FFT) . Redundant 22 gauge copper wires are cross-strapped inside the elements, which incorporate a hinge design. Each dipole's 3 manufactured sections is bonded together with composite tube splices. Each dipole element is made up of 13 sections that are 1.4 m long and weigh 0.093 Kg apiece. Each tube, originally 38 mm in diameter, is compressed to a 16 mm minor diameter elliptical cross-section of the antenna in its undeployed condition.

Prior to deployment, the antennas are stored in a composite panel container, as shown in Fig. 4. The antenna sections are stacked in the storage container and are released as a group away from the spacecraft by the use of redundant pyro mechanisms. The deployment energy comes from compression forces used to store the sections in the storage compartment prior to launch. The antenna subsystem's principal parameters are listed in Table 3.

Spacecraft dynamics on the deployed mechanical natural frequency restricts the dipole antenna to a 20 m length. At this length, the electrical halfwave resonance of the dipole was 3.5 MHz, derived from a finite element analysis on a wire frame model of the spacecraft and antennas. The wide range of antenna impedance—from over 1500 ohm at 1.3 MHz to a 50 ohm match at 3.4 MHz, and back up to 1500 ohm at 5.5 MHz—pointed to the obvious need for a matching network between the antenna and the transmitter (see Fig. 5).

In the subsurface modes, the sounder is required to operate on any one or two of four bands simultaneously. Since the switching speed and reliability of electromechanical switches preclude the use of a network for each band, a network was designed to cover the frequency range 1.3–5.5 MHz, a fractional bandwidth ($\Delta f/f$) of greater than 1.

The dipole antenna is driven through a network that matches the operating frequency of the radar. Each matching network is designed to radiate over the frequency range of each band as uniformly as possible. During the development of the radar, the sounder is operated into an antenna simulator since all testing had to be done without a deployed antenna. The simulator was a

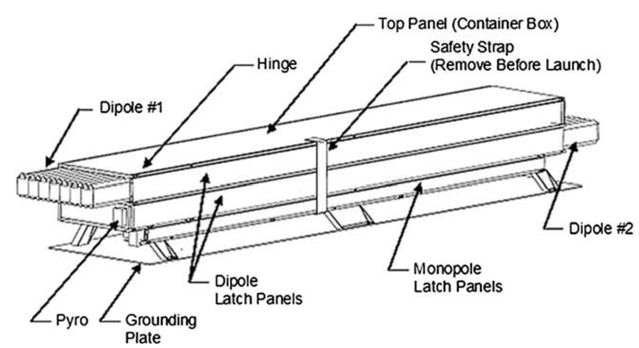

Fig. 4. The MARSIS antennas are launched in the stowed configuration shown.

Table 3
MARSIS Antenna Subsystem Principal Parameters.

Item	Value
Mass (includes storage container and preamplifier electronics)	7.5 kg
Dipole element length	20 m
Monopole element length	7 m
Deployment sequence	Dipole 1, Dipole 2, Monopole
Storage container	1660 × 300 × 200 mm
Deployed natural frequency	>0.08 Hz (dipole)
Dipole gain	2.1 dB
Monopole gain	0 dB
Frequency range	0.1–5.5 MHz

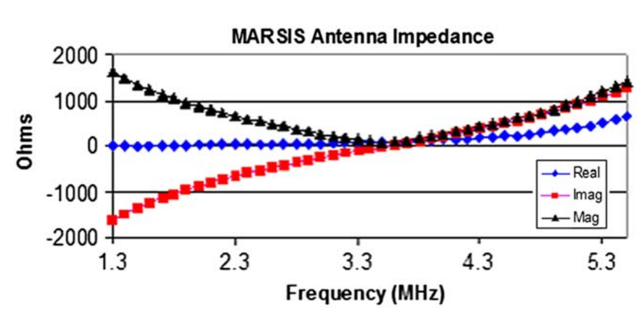

Fig. 5. Dipole antenna impedance: antenna match attained only center frequency of 3.4 MHz.

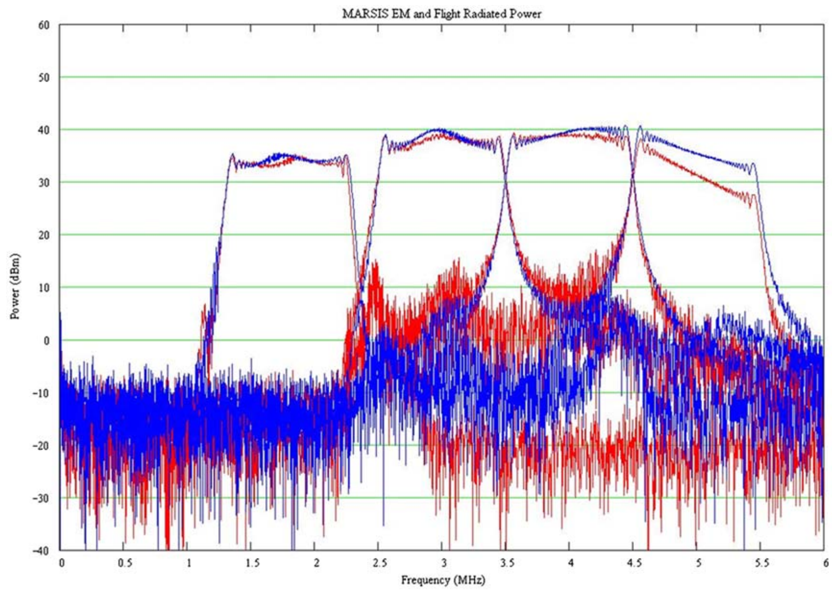

Fig. 6. Predicted (blue lines) and measured (red lines) antenna radiated power. Predicted power was measured prior to flight during ground testing. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

very good representation of the actual antenna as evidenced by the superimposed spectra of radiation into the simulator and space (see Fig. 6). Bands 1, 2 and 3 were stable with a deviation less than 2 dB at any point in the spectra. Band 4 (4.5–5.5 MHz) was not stable since a deviation of about 6 dB was seen between the lowest and the highest frequencies.

The 7 m monopole antenna is receive-only, with a null placed nominally in the nadir direction. The deployed position of the monopole is at the center of the dipole, normal to the dipole. This mechanical arrangement also minimizes coupling between the dipole and the monopole. Since the monopole length is much shorter than the lowest wavelength, a high-impedance, low-noise preamplifier is placed at the base of the antenna to buffer the signal to the receiver. During operation of the subsurface sounder, the noise level in the monopole channel was discovered to be high, limiting its use to a very few data takes.

2.3. Radar sensor electronics

The electronics assembly consists of two boxes. The first contains the digital electronics subsystem (DES) and receiver assembly, while the second box contains the transmitters and interfaces to the antenna. Both these boxes are housed inside the Mars Express structure, while the antenna box is located on the outside of the spacecraft. The monopole antenna contains a preamplifier at the mounting plate of the structure.

2.3.1. Transmitter

The transmitter assembly controls the signal flow between the antenna and the receive electronics. The frequency-swept signal from the receive electronics is amplified and routed to the antenna by separate antenna matching networks to maximize the radiated power. The matching network is implemented as a balanced three-port network, with two transmitter ports and one antenna port. Coaxial feedlines leading to the antenna elements are absorbed into the network design. Careful attention was paid to the transmitter placement and the electrical/mechanical symmetry of the antenna to maximize the common mode rejection of interference signals during receive intervals.

Two class D transmitter modules are used for subsurface modes, one for Band 1 (1.3–2.3 MHz) and the other covering 2.5–5.5 MHz for Bands 2, 3, and 4. The frequency gap between 2.3 and 2.5 MHz allows improved isolation between the transmitters. Due to their broadband nature, voltage standing wave ratio (VSWR) into the matching networks is approximately 18–1. This high VSWR prevents high-efficiency coupling to the antenna. The peak-power output capability of each transmitter module is 400 W, but the effect of the matching networks and the antenna efficiency bring the effective radiated power down to the 5 W region. Electronic switching decouples the transmitter and connects the receive preamplifier to the matching network during receive intervals.

For the active ionospheric sounding mode, the Band 1 transmitter is switched via electromechanical latching relays to a separate broadband output transformer, covering the range 0.1–5.5 MHz. No matching is done for the active ionospheric mode other than the transformer due to lack of available mass and volume that could be allocated to this function.

2.3.2. Receiver

The radio frequency electronics receiver resides in the DES housing. It consists of the chirp/local oscillator distributor and the dual channel receiver radio frequency subsystem-receive electronics (RFS-RX) , which down converts and amplifies the returns from the dipole and monopole antennas. The receiver is composed of a power divider, switches, amplifiers, mixers, bandpass filter banks, and lowpass filters, which provide for two receive channels.

The receiver impulse response must have very low sidelobes in order to detect weak subsurface returns in the presence of the strong surface return. The receiver must also be highly linear to prevent unwanted harmonics from being generated. The receiver diagram for a single channel is shown in Fig. 7. The RF signal from the antenna is first amplified before passing through a bandpass filter that is selectable by control from the DES. Each receive channel has its own selectable bandpass filter. The filter for Band 1 has a larger bandwidth to allow the frequency range 2.3–2.5 MHz to be in the passband during ionosphere sounding mode operations.

Following RF amplification and filtering, the received signal is downconverted and then low pass filtered, amplified and gain controlled. The received signals are then converted to digital form

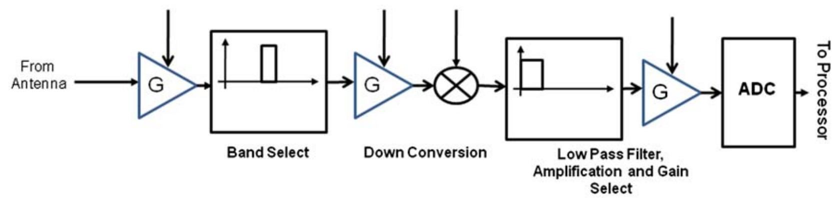

Fig. 7. Single channel receiver diagram.

by two 8-bit analog-to-digital converters, one in each receiver channel. The analog-to-digital convert (ADC) maximum input is set to an input power of +6 dBm with a sampling frequency of 2.8 MHz. The converted signals are then buffered before transfer to the digital electronics.

The power for the receiver subsystem is provided by the power converters, which are located in the DES housing. The total DC power used by the receiver is 4.4 W. The receiver assembly receives chirp waveforms and local oscillator frequency signals from the DES at a nominal power level of 0 dBm. The chirp waveforms are then routed to the transmitter for amplification, and the local oscillator frequency signals are routed to the receiver channels 1 and 2 mixers' local oscillator inputs.

All RFS control signals originate from the DES. The receiver receives the ADC clock signals from the DES with a separate ADC clock input provided for each of the two receiver channels. The frequency of the ADC clock is a 2.8 MHz logic signal with a duty cycle of 50 percent. The RFS-RX provides 8-bit digital sample data to the DES for each of the two receiver channels. The RFS-RX provides a conditioned transmit pulse of the appropriate amplitude and a frequency to the dipole antenna at the correct time under control of the DES. Channel 1 of the RFS-RX receives echoes from the dipole antenna for eventual downconversion and sampling. Channel 2 receives signals from the monopole antenna. Frequency band selection is under control of the DES.

2.3.3. *Digital electronics*

The digital electronics subsystem (DES) implements all the logic of the MARSIS instrument, most of the interfaces with the spacecraft, and the on-board data processing subsystem. The DES configures the sounder electronics to acquire data in one of the five subsurface sounding modes or the ionospheric sounding mode. The DES also selects the frequencies to be used during subsurface sounding by ground command. The DES consists of:

(1) a reference oscillator to provide the coherence required by the instrument
(2) the sounder signal generator
(3) the command and control of the instrument and spacecraft interfaces
(4) the timing generator
(5) the DES echo processor
(6) dedicated power converters

The reference oscillator for the instrument is a numerically controlled oscillator, which is clocked at 28 MHz. The sounder signal generator is a digital chirp generator that generates both a linear frequency-swept signal and pulsed monochromatic signals, depending on the mode of the instrument.

The command and control of the instrument is based on an ATMEL TSC21020F digital signal processor. This processor controls all the timing sequences of the instrument, interfaces with the spacecraft, receives telecommands, stores parameters for data take sequences, collects data from the two digital signal processors and packetizes them into the science data packet together with the auxiliary information. Orbit and velocity determination algorithms are executed during data acquisition for any operational orbit.

The timing generator is derived from the reference oscillator and is used to generate the basic signals of the radar, such as pulse repetition frequency and other related signals.

The MARSIS sounder has five basic operating modes for subsurface sounding and one additional mode for ionospheric sounding. Each mode sets the number of frequencies that may operate the use of the clutter cancellation channel (the monopole channel), if required, the use of pre-summing, and the number of Doppler filters that will be downlinked. The five subsurface sounding modes (SS1–SS5) are:

SS1: 2 frequency bands/2 antennas/1 Doppler filter

This mode allows coherent clutter cancellation on two-frequency bands by means of dual antenna clutter cancellation ground processing. The I and Q (in-phase and quadrature) Doppler processed samples of the zero Doppler filter are downloaded for each frame. Range processing is performed on the ground.

SS2: 2 frequency bands/1 antenna (dipole)/on-board multi-look

This mode carries out onboard non-coherent integration of five looks and downloads a single amplitude-detected averaged echo profile for each synthetic aperture (frame), at two-frequency channels.

SS3: 2 frequency bands/1 antenna/3 Doppler filters

This mode allows downlink, for each frame, of the I/Q data of three Doppler filters collected on the dipole antenna channel at two frequencies. Range processing is performed on the ground.

SS4: 1 frequency band/2 antennas/5 Doppler filters

This mode allows downlink, for each frame, of the I and Q data of five Doppler filters (around the zero Doppler filter) for both the dipole and the monopole channels at one frequency. Range processing is performed on the ground. In this mode it is possible to perform, on the ground, the dual antenna cross-track clutter cancellation with a five look non-coherent integration on each frame.

SS5: 1 frequency band/2 antennas/short pulse (30 μS)/3 Doppler filters

This mode uses a short-pulse waveform to reduce the impact of uncontrolled sidelobes on deep subsurface reflections. The echoes returning after the transmission of four short pulses with the same carrier frequency are pre-summed upon reception, and the I/Q processed data at two antennas and three Doppler filters are downlinked for each frame. Range compression and clutter cancellation are performed on the ground.

The experience gained during early operations of the subsurface sounder limited data acquisition to modes using only the dipole antenna to optimize the use of the downlink channel as the noise in the monopole channel was deemed excessive. These modes are SS2 and SS3. Mode SS3 proved to be more useful than SS2 because the data returned is at three separate Doppler filters rather than multi-look processed on board. As of May 2009, a total of 19.6 Gigabytes of subsurface sounding data at the SS3 mode were acquired. The frequency selection during the planning process is based on the expected solar elevation angle range during each data take. The criteria that is currently used is:

If the solar elevation angle is less than -15°, Bands 1 and 2. If the solar elevation angle is between 0 and -15°, Bands 2 and 3.

If the solar elevation angle is between 0 and 35°, Bands 3 and 4. If the solar elevation angle is greater than 35°, active ionospheric sounding.

AIS: active ionospheric sounding

This is the active sounding mode used when the spacecraft is at an altitude higher that 900 km or when no SS mode is being used. The active ionospheric sounder operates by transmitting a pulse of radio frequency energy and detecting the return in a digital receiver with a 10.9 kHz bandwidth centered on the frequency of the transmitted pulse. The time delay of the echo is determined by sampling the received signal intensities in 160 contiguous 91.4 μs time bins starting at 254 μs and extending to 7.57 ms after the transmitted pulse. After each transmit/receive cycle, the frequency of the pulse is advanced in an ascending time order, with a complete scan consisting of 160 quasi-logarithmically spaced frequencies ($\Delta f/f \approx 2\%$) from100 kHz to 5.5 MHz. A complete scan takes 1.26 s, and the basic sweep cycle is repeated once every 7.35 s. As of May 2009, a total of 9.2 Gigabytes of AIS data have been acquired.

The DES echo processor consists of two identical slave digital signal processor (DSP) boards based on one 21020 DSP each, running at 20 MHz. Each DSP may receive the 8-bit data in two separate FIFO memories from the monopole or from the dipole channel of the receiver. The DES provides a suite of processing functions suitable to meet the science needs of the MARSIS experiment. Different processing algorithms are applied for subsurface sounding modes, active ionospheric sounding mode, or calibration modes following a general preprocessing for the I/Q data synthesis and raw data collection. Final results are made available to the command and control processor in a dedicated dual-ported memory. This memory is also used for data exchange from the command and control DSP to the signal processor boards. The signal processing plays a crucial role in the MARSIS data acquisition process, and it is detailed below.

The design of the data processor on the MARSIS instrument was driven by science and greatly influenced by two mission constraints: the uncertainty in the orbit prediction and the data rate and volume dedicated to MARSIS. Therefore, the signal processing has to be performed onboard in real time.

The subsurface mode processing is accomplished in two steps. The first is an acquisition phase to measure the round-trip delay of a transmit event between the spacecraft and the surface of Mars. This is done in order to set the timing of the receiving window, reducing the uncertainties of the group delay introduced by the ionosphere. A chirp with a bandwidth of 200 kHz and a length of 1 ms is used for this, since a chirp with this narrow bandwidth is less susceptible to the phase distortion introduced by the ionosphere. The MARSIS operating frequencies are very close to the ionospheric plasma frequencies; which needs to be considered in determining the delay of the surface return.

The second step is the tracking phase. In this step, compensation is made for variations in the radar-to-surface distance during the flyby caused by uncertainty in the orbit prediction, Martian topography, and ionosphere group delay. The chirp transmitted has a length of 250 μs and a bandwidth of 1 MHz. The free space resolution is 150 m.

To perform the tracking phase, both azimuth (Doppler beam sharpening) and range compression are implemented onboard. For compensation of the phase distortion caused by the Mars ionosphere, two algorithms are available, the front surface reflection method and the contrast method. Ground command selects which algorithm is executed prior to data acquisition. The ionosphere compensation algorithm selected is applied to the central filter (Doppler filter 0) and the result is used to modify the preloaded reference chirp function to accomplish the range compression of all the Doppler filters involved.

To reduce the data rate, the MARSIS signal is transmitted to the ground after the azimuth compression. It should be noted that MARSIS can operate, if necessary, with preset tracking. In this case, the receiving window position is evaluated starting from the height estimated by an onboard polynomial function. In addition, the ground operator can modify this timing, setting some of the parameters by considering the ionosphere group delay.

Upon data reception, a general preprocessing algorithm for the I/Q data synthesis and raw data collection is executed. In addition, one background parallel task is performed to allow orbit and velocity determination during the data acquisition for any of the operational modes in order to get coarse altitude and velocity values. The 1 MHz bandwidth of the radar echoes allows the use of a fairly low A/D sampling frequency, which makes it possible to easily sample the receive signal at an intermediate frequency without implementing analog phase detectors for the in-phase/quadrature signal derivation.

I/Q elements can be efficiently computed from the digitized signal using the same processing resources allocated for the rest of the processing. This has the advantage of minimizing the hardware for the benefit of mass and power, with the only minor constraint of sampling the intermediate frequency (IF) signal at four times the value of its center frequency. I/Q sample streams are then generated according to the concept scheme of Fig. 8.

Upon reception, echoes are downconverted and digitized to a format suitable for the onboard processor. Four processing channels are implemented, allowing the processing of two-frequency bands received from the dipole and monopole at each pulse repetition interval. The digitized echo stream is then processed by the onboard digital electronics subsystem in order to reduce the data rate and data volume and allow storage of the observed scene within the allocated amount of spacecraft mass memory. Starting from the desired along-track sampling rate of the surface, the basic azimuth repetition interval is identified and all the pulses received within this interval (frame) are processed to yield a single echo profile at one azimuth location.

The subsurface sounding processing is the core of the processor architecture.

Subsurface sounding requires several functions to be implemented on board as shown in Fig. 9.

Radar pulse repetition intervals (PRI) are grouped in frames. Within a frame, a subset of range lines is used to synthesize the synthetic aperture. Since the SAR processing is unfocused, the azimuth resolution is a function of altitude, spacecraft velocity, frequency band, and frame size. Unfocused processing integrates the return signal over a time interval that prevents the phase of the surface return to deviate more than 90°. To avoid gaps in coverage along the ground track, the frame size and the synthetic aperture length are updated continuously during the flyby, with a resulting variable frame length. To keep the same frame size for two operational frequency modes, the synthetic aperture length of the highest frequency is tuned to return the same azimuth resolution of the lower frequency. In this way, continuous coverage along the ground track is ensured for both frequencies. A typical PRI for a two-frequency operation is shown in Fig. 10.

Range processing is performed through a digital implementation of matched filtering. Input echoes are fast Fourier transformed (FFT), using a 512-point complex FFT. The Fourier spectrum is then multiplied by the conjugate of the spectrum of a reference chirp, and the result is then inverse Fourier transformed to the range domain. Doppler filtering is realized in

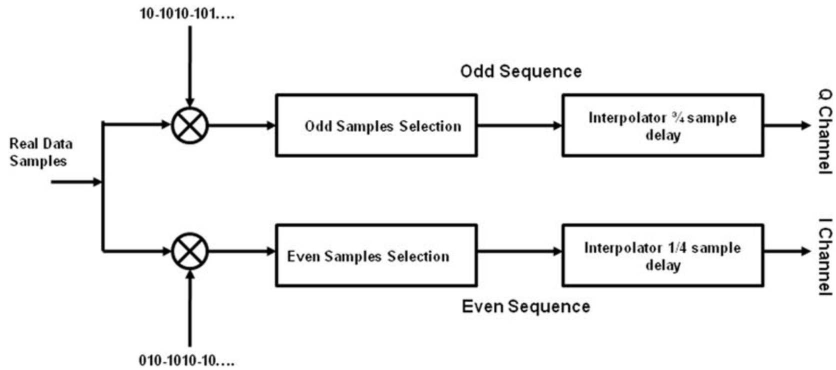

Fig. 8. I/Q synthesis diagram: in phase and quadrature signals synthesized after oversapling of the received signal.

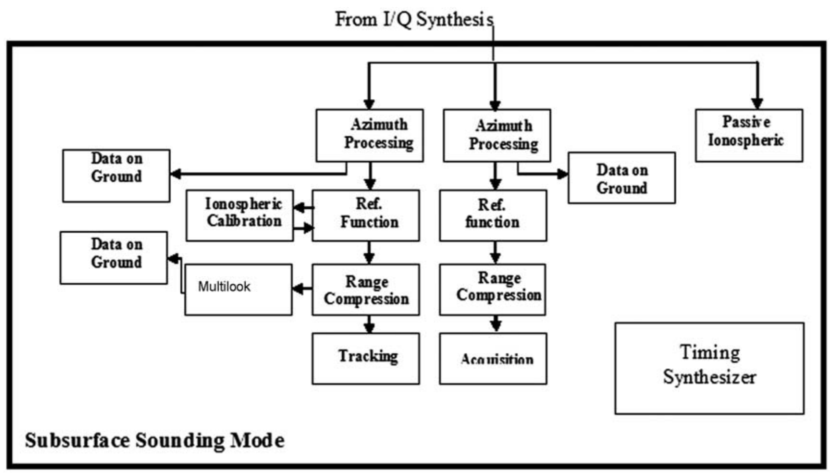

Fig. 9. Subsurface sounding processing functionality.

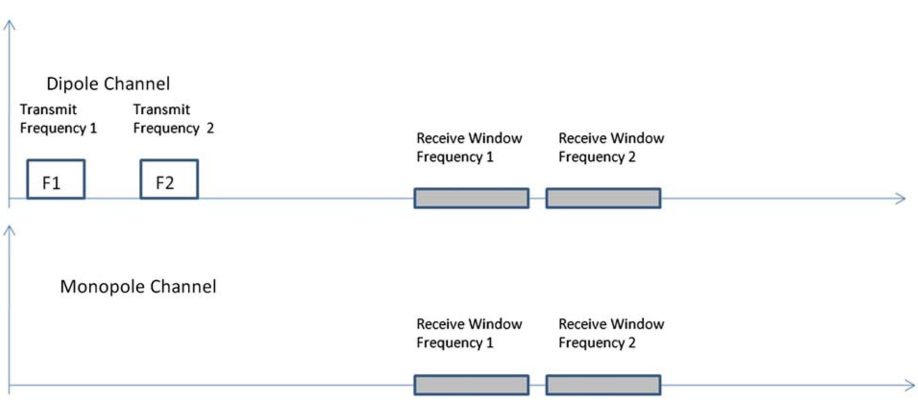

Fig. 10. Typical pulse repetition interval for two-frequency operation. Modes SS1 and SS4 use both channels. Modes SS2 and SS3 only use dipole channel.

the frequency domain by coherently presuming the echoes before applying the reference function. The azimuth processing performs a coherent summation of the radar returns by adjusting their phase. The level of complexity in the phase correction depends on the extent of the aperture length and thus on the azimuth resolution to be achieved. The MARSIS required resolution is 5 to 9 km, which does not require the correction of quadratic or higher-order phase terms; only linear is compensated. This circumstance and the fact that few filters must be synthesized simplify the processor architecture and allow real-time implementation of the processor using the limited computer resources.

After the completion of onboard processing, digitized radar echoes are converted from four-byte real numbers to one-byte integer numbers. This causes a loss of amplitude precision but is deemed to be acceptable as the available dynamic range for signal representation is estimated to be above the signal-to-noise ratio.

MARSIS can be programmed to skip all onboard processing and downlink raw data as they come out of the analog-to-digital converter. This option allows the storage of a number of individual echoes in a memory buffer for subsequent transmission as science telemetry packets. Raw data are acquired only for very limited time intervals and are then transferred over a much longer time span from MARSIS to the spacecraft mass memory. This type of data collection is possible only during the subsurface sounding and such echoes always come in addition to the processed data transmitted to the ground. Thus, the individual echoes are the unprocessed version of a subset of data for some larger observations and used primarily to verify the accuracy of the onboard processing

Another option available in MARSIS for the retrieval of raw data is the use of flash memory chips within the instrument itself. Collection of echoes from the analog-to-digital converter is similar to that of individual echoes, but data are stored in a different physical device, a long-term memory that can be read and cleared for subsequent overwriting only by means of a specific command. Also, this flash memory can be used to store processed data before the final step of data compression. This option can be used to check if truncation of data precision is affecting the results and for higher resolution sounding.

Active ionosphere sounding is a special mode required to complete the science objectives of the mission. The ionosphere of Mars is sensed with monochromatic pulses of approximately 10 kHz resolution and of variable frequency in the range 100 kHz to 5.5 MHz The corresponding echo is then filtered around the central frequency of the transmitted pulse by implementing a tunable direct Fourier transform filter. In this way the spectral/spatial response of the ionosphere is measured over 160 different frequencies.

In addition to subsurface and ionosphere sounding, MARSIS is capable of two more data collection modes that are not science-related, but are used for the testing of the instrument. These are a hardware calibration mode and a receive only mode.

3. Operations and commanding

Mission planning for the MARSIS experiment is driven by the goal of obtaining maximum coverage over the surface of Mars. All periods of operation when the spacecraft is below 900 km altitude are considered data acquisition opportunities for MARSIS subsurface sounding mode, while the periods when the spacecraft is between 900 and 1200 km in altitude are allocated to ionosphere sounding operations.

The MARSIS Operations Center (MOC) located in Rome, Italy, coordinates with the Mars Express science operations center (MESOC) in Darmstadt, Germany, to develop and update data taking plans as needed. It is ofcourse necessary during the mission planning phase to accommodate the data observation strategies of all the instruments on the spacecraft. In nominal operations, a long-term plan and associated command sequences are established for data take timing and mode selection. As needed, updates to this plan are instituted based on near real-time analysis of downlinked data and instrument performance assessment. Under most orbit evolution scenarios for Mars express, high latitude observations are likely to produce some repeated coverage for MARSIS. These opportunities are used to optimize the mode of operation for special studies, such as capturing a segment of raw data for analysis of an area especially promising for subsurface detection.

The aim of the planning and commanding phases is to give flexibility to the principal investigators in finalizing the science requests within the time frame given by the payload operations service (POS), according to the baseline pointing scenario agreed upon with the flight dynamics team. The mission planning is implemented via four plan levels as follows:

1. Long-term plan (LTP): The long-term planning process culminates in the generation of the master science plan and nominally contains the selection of science observation periods and the experiment's main science observation modes imposed by mission conditions.
2. Medium-term PLAN (MTP): This planning is more detailed, subdividing each phase in terms of planning period into quasi-one-month segments.
3. Short-term plan (STP): During the short-term planning, the output from the MTP is refined and undergoes detailed resource and constraint checks using the mission planning system.
4. Very short-term planning (VSTP): On a daily basis, detailed operations requests arise to perform attitude maneuvers, momentum wheel off-loading and orbit maintenance.

The major tasks of the planning chain are the resolution of the overall mission conflicts, while facilitating and maximizing the science return. Spacecraft resources are shared among all the instruments onboard Mars Express. Conflicts arise either due to system constraints or Mars environmental constraints. System constraints arise from spacecraft pointing conflicts, conflicts on the shared onboard data handling (OBDH) bus, or the daily data volume limit. MARSIS transmits its science data to the spacecraft over the OBDH bus, which has a maximum data rate of 98 Kbps. This bus is shared with two optical instruments and, if MARSIS has a low priority, this becomes a significant limiting factor on MARSIS science operations. This may force MARSIS to operate in a low data rate mode. The other system constraint factor is the daily data volume allocations, which depend on ground-station visibility as well as Mars-to-Earth distance.

The surface of Mars and the ionospheric environment play a significant role in the planning of data acquisition during the assigned data takes. When MARSIS is over rough surfaces, where surface clutter will be a limiting factor, the monopole clutter cancellation technique is considered but only used if the rough surface scattering expected is very strong. The noise in this channel is very strong due to the absence of a significant ground plane for this antenna Selection of the frequency bands used is based on the expected ionospheric attenuation and the surface attenuation. The solar zenith angle is the predominant controlling factor of ionospheric effects. Areas with a high crustal magnetic field anomaly also influence the selection of frequency bands.

3.1. MARSIS data archive

After MARSIS data are collected onboard the spacecraft and downlinked, they are stored in the Mars Express project data distribution System (DDS) at the European Space Operations Center (ESOC), Darmstadt, Germany. From there, they are retrieved daily through the MARSIS Operations Center (MOC), located in Rome at Thales Alenia Space and managed by the principal investigator (PI) Infocom Team

After completion of the validation and verification of subsurface data, JPL and the Co-Is provide feedback on the subsurface data to the experiment PI, who is ultimately responsible for archiving of all data and directly produces the subsurface data archive. The University of Iowa produces the level 2 ionospheric data archive and shares with the PI the responsibility for archiving of ionospheric data. All data released by the MARSIS Team for archiving are compliant with the planetary data system (PDS) standards. Data are archived and made available to the scientific community at ESA's planetary science archive (PSA) and NASA's PDS. Subsurface and ionospheric MARSIS data are first delivered to the PSA, which then deliver them to the PDS. Data deliveries take place every six months. The subsurface data delivered to the NASA PDS archive is level 1.2 data, which is basically the raw data received from the spacecraft with some additional header information used to identify the data set.

3.2. Ionospheric data processing and data archiving

The MARSIS level 1a ionospheric data are transferred from the ASDC facility in Italy to the University of Iowa in the US via a data-mirroring process. The level 1a ionospheric data are then processed at the University of Iowa into calibrated level 2 data products that can be displayed and analyzed using software tools developed for that purpose. Both level 2 data and software tools are made available to the MARSIS team through the Iowa MARSIS team website. At approximately 6 month intervals, the level 2 ionospheric data are organized into PDS-compliant structures and delivered to the MARSIS PI, who, in turn, delivers the ionospheric data to the ESA Mars Express science data archive. ESA then, by agreement, forwards the MARSIS data to the NASA PDS. The data stored in the NASA PDS is identical to the data stored at the ESA planetary science archive.

4. Subsurface and ionospheric sounder performance

4.1. Subsurface sounder

The performance of the subsurface sounder portion of the experiment can be measured by the strength of the surface return at the antenna terminals relative to cosmic background noise entering the antenna. Cosmic noise is the predominant noise present in the MARSIS signal channels. The ability of a sounder to detect weak subsurface features depends on the strength of the return. Subsurface returns will have a return power weaker than the surface return due to attenuation in the media and differences in the reflection coefficients of the surface and the subsurface interfaces. To permit a subsurface detection, this power difference can be no larger than the first surface signal-to-noise ratio. Table 4 shows the expected specular signal-to-cosmic noise ratio for each subsurface sounder band in the absence of ionospheric attenuation, full compression of the return, and maximum Doppler filtering of the noise for both 250 and 900 km altitudes. Fig. 11 confirms the dynamic range exceeding 35 dB for both Bands 3 and 4. This figure shows the signal-to-noise ratio of the specular return over approximately 420 frames for both these bands. The x-axis represents the position of the MARSIS instrument along-track, while the y-axis represents the peak observed signal-to-noise ratio for each of the two bands. To obtain this dynamic range, it is necessary to compensate for any distortions due to the radar RF channel or the Martian ionosphere.

The amplitude and phase performance of the antenna, transmitter and receiver, as measured on the ground before flight, showed sufficient stability over the temperature range so that the post flight compensation was not required. Examples of the performance of MARSIS over the Martian terrain are presented in Figs. 12 and 13. The signal-to-noise ratio of the surface return is strongly influenced by the nadir surface roughness.

Within each frame, the noise preceding the surface return, the strength of the surface return, and the signals from potential subsurface returns can all be seen. The power returns have been normalized to the first surface return. The y-axis shows the normalized signal level of the received and processed signals, while the x-axis represents the location or "depth" of the return signal. Fig. 12 for band 4 shows a dynamic range exceeding 45 dB.

Table 4
Subsurface Sounder Specular return signal-to-noise ratios.

Band	Frequency (MHz)	Signal to Noise (dB)	
		H=250 km	H=800 Km
1	1.8	49.3	39.2
2	3	51.1	41.0
3	4	51.1	41.0
4	5	46.5	36.4

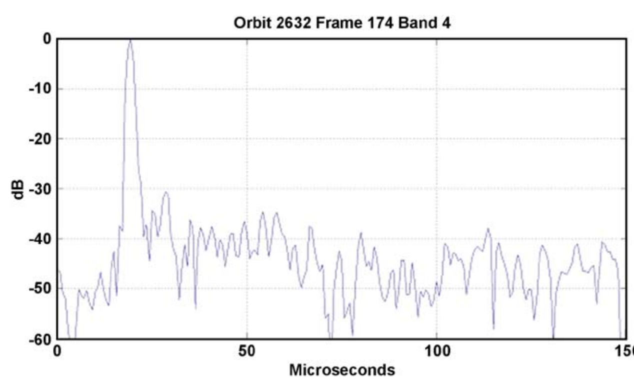

Fig. 12. . Orbit 2632 and Frame ID 175: Band 4 (4.5–5.5 MHz) single frame echo with dynamic range greater than 45 dB. System noise is seen before first surface return (specular return) at T=20 μs. The signal after the specular return contains both surface clutter and subsurface returns.

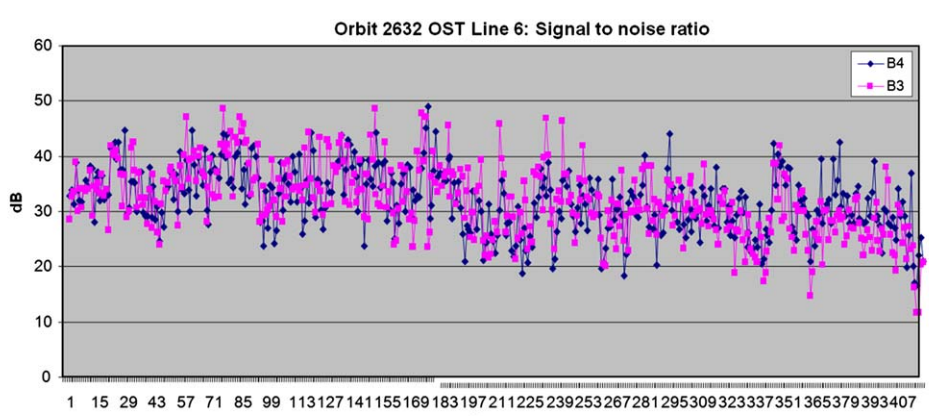

Fig. 11. MARSIS Orbit 2632 signal-to-noise ratio of specular return in Bands 3 and 4. The measured data is for 422 consecutive frames. The maximum signal to noise is about 49 dB occurring in Frames near 170.

Since an individual frame represents the return signal history at a particular location over the Martian surface, the amplitude of these frames can be converted to intensity and plotted on a map following the nadir track of the spacecraft. Examples of the resulting radargrams are shown for Band 3 in Fig. 13. It is possible to see multiple layers in two different regions; both are very flat with no visible surface features, or clutter, that corresponds to delays seen in the subsurface features.

4.2. Ionospheric sounder

A typical active ionosphere sounder ionogram from the Martian dayside is shown in Fig. 14. A weak ground reflection showing significant dispersion is seen at an apparent range of about 560 km. The strength of the return shows the strong absorption seen on dayside ionograms. The ionospheric reflection is clearly visible at a time delay of 3 ms, with a frequency cutoff of 3.06 MHz, indicating a maximum plasma density in the ionosphere of $1.16\times10^5\,e/cm^3$. Also visible are two additional ionospheric reflections at 3.2 and 5.2 ms. These are associated with areas of remnant crustal magnetic field where the field vector is largely normal to the surface. In these regions, solar wind electrons are able to ionize the upper atmosphere, resulting in an upward bulging of the ionosphere. These bulges produce oblique reflections at apparent ranges larger than the nearest ionospheric return.

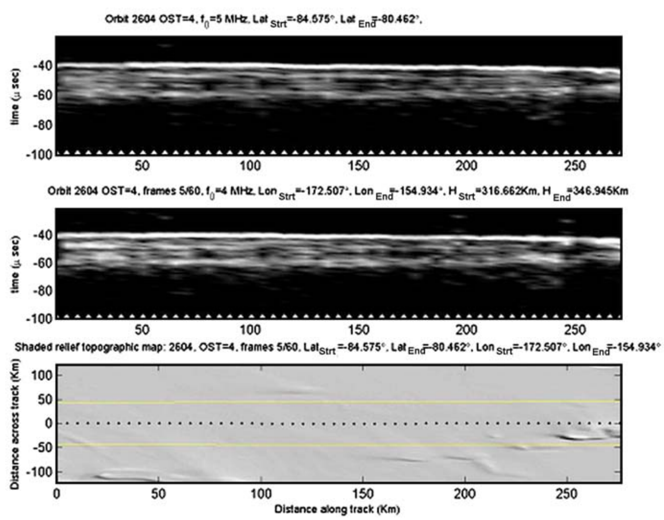

Fig. 13. Radargrams: The yellow lines in the map correspond to the same delay as the deepest echoes, which are believed to come from the subsurface. As can be seen at this range, there are no visible surface features, which would add to the subsurface returns seen in the radargrams. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Also visible in the ionogram are a set of vertical stripes in the upper corner. These are harmonics of the local plasma frequency at 43 kHz, indicating a local plasma density of $23\,e/cm^3$. An unexpected measurement on the MARSIS AIS ionogram is the series of horizontal lines beginning at 1.4 ms. They are the result of electrons being accelerated during the transmit pulse and returning to the vicinity of the spacecraft after one cyclotron period and are known as cyclotron echoes. These pulses become detectable at a plasma density somewhat below the lowest density measurable by the plasma frequency harmonic technique, which is about $11\,e/cm^3$. These bursts must be shorter than the pulse repetition interval by a factor of 1 or 2; otherwise they are not detectable.

The active ionospheric sounder data acquired in orbit around Mars indicates that the RF system is working as designed. However, the dynamic range of the ionospheric sounder is limited to about 50 dB due to limitations in the analog-to-digital conversion, the data compression algorithms, and the fact that no matching network could be implemented within the mass and volume constraints for the ionospheric sounder frequency channel. A wider dynamic range would have been very useful since signals in the AIS mode range from locally excited high-amplitude plasma waves to the galactic noise background level.

The ionogram depicted in Fig. 15 (a plot of echo strength versus time delay and frequency) is from orbit 3058 and shows several features often seen in the MARSIS-active ionospheric sounding data (Gurnett et al., 2005, 2007).

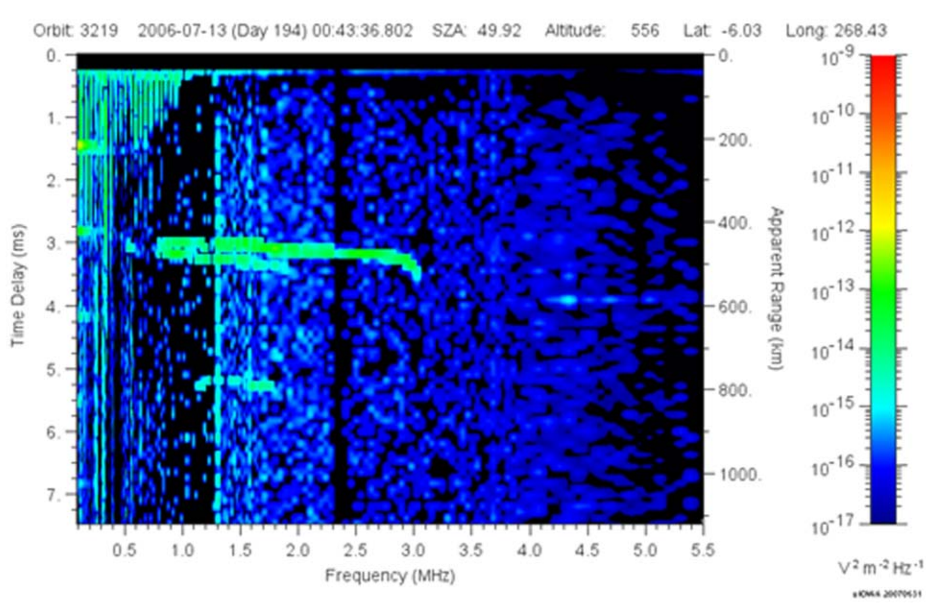

Fig. 14. Active ionospheric sounder ionogram: typical MARS ionogram acquired during Orbit 3219. The horizontal green lines represent strong measured electric fields at frequencies below 3 MHz. At frequencies above 3 MHz, the ionosphere did not significantly absorb the incident waves. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

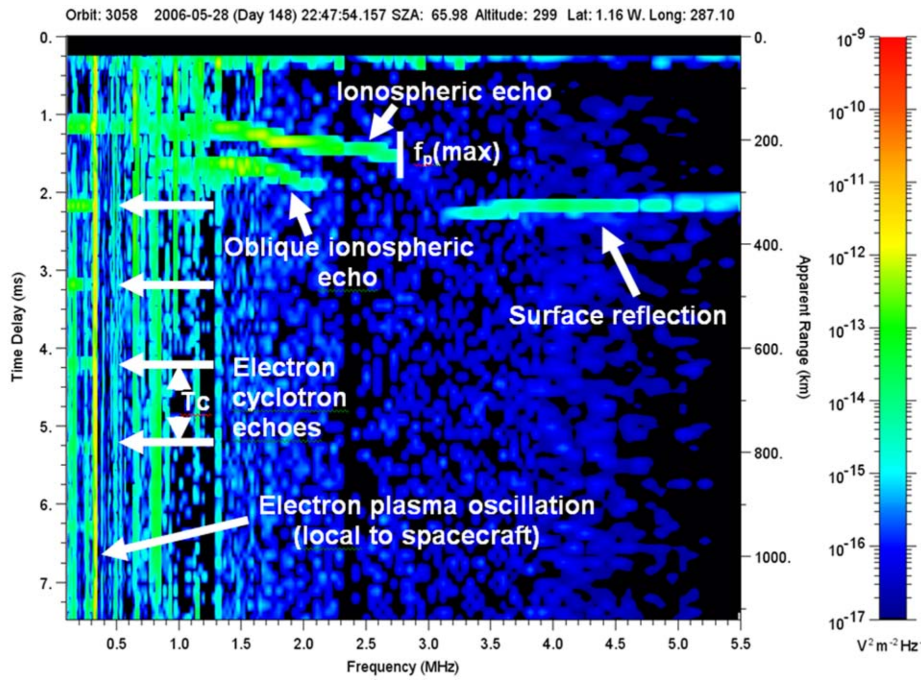

Fig. 15. Mars ionogram acquired during Orbit 3058 showing the effect of various reflections including the return from the surface of the Mars, the primary ionospheric echo, an oblique ionospheric echo as well as returns at the electron cyclotron echos.

5. Conclusion

MARSIS is an innovative instrument, designed to explore the subsurface and ionosphere of Mars in new and exciting ways. It is clear from the earliest MARSIS observations that the instrument is performing well. Furthermore, Mars is "cooperating" with MARSIS, with many features in the subsurface amenable to the sounding technique. The polar regions of Mars display a complex array of subsurface features. Sounding of these areas has already led to a revision in estimates of the global inventory of water on Mars (Plaut et al., 2007). Several non-polar regions also show interesting subsurface structures. While no clear evidence has yet been seen for large-scale aquifers, the search is continuing. Ionospheric sounding has yielded a number of interesting new insights into the structure and dynamics of the Martian ionosphere (Gurnett et al., 2007). The next step in low-frequency sounding of Mars is already underway with the deployment of the shallow radar (SHARAD) on the Mars reconnaissance orbiter (Seu et al., 2007), which operates at a higher frequency than MARSIS, providing finer vertical resolution at the expense of subsurface penetration depth. MARSIS and SHARAD have clearly demonstrated the scientific value of radar sounding as a planetary remote sensing tool. Future missions to other planets and small bodies of the solar system are likely to carry radar sounding instruments to explore the interiors of these bodies.

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