Mars Express and the NASA landers and rovers on Mars - Sustaining a backup relay in an interplanetary network

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The Mars Express Lander Communications subsystem MELACOM was initially designed to relay data from/to BEAGLE-2 once landed on Mars. But its receiver did not pick-up a signal during all the attempts of communications with the European lander in the two first months of 2004. Fortunately, intrinsic to the design was the capability for cross-support with other landed assets via the implementation of version 2 of the draft Proximity-1 protocol, CCSDS 211.0-R-2, designed to ensure reliable data transfer between remote autonomous communication nodes operating in close proximity. Since then, MELACOM has been successfully used to [1] test the Forward and Return link with the NASA-JPL Mars Exploration Rovers Spirit and Opportunity and with the lander Phoenix, [2] perform Doppler measurements with Opportunity, and [3] record in open loop the Entry, Descent and Landing of Phoenix at Mars (25 May 2008). The purpose was to provide JPL with carrier and tones detection and possible contingency support via full spectrum analysis. In July 2010, in order to complement its own orbiters coverage, NASA requested ESA to provide a backup relay support at Mars with Mars-Express, for the MSL-Curiosity mission, in cruise to Mars since its launch on the 26 November 2011. This support covering the MSL EDL and on-surface operations, is made possible by the third mission extension granted to Mars Express until end of 2014, and by a rephasing of the spacecraft orbit early April 2012.

This paper presents why this support is a new challenge for Mars-Express :

- **In October 2011, the Mars-Express operations concept has been changed and made more robust to mass-memory anomalies experienced since August 2011. This led in particular to prepare for the MSL support, the backup MELACOM radio unit of Mars-Express, not switched on for 8 years in orbit around Mars.**
- **In order to improve the MELACOM capability on the forward and return link, ESOC granted to its UK manufacturer QinetiQ, a contract to develop new software, loaded and tested on Mars-Express with Opportunity before MSL arrives at Mars.**
- **Curiosity's UHF radio is an ElectraLite model, the design of which is different from the CE-505 carried by both MERs and Phoenix. Ground compatibility tests took place at JPL in March 2012 to verify the radio interfaces.**
- **This support has to interface with the new Mars Relay Operations Service (MaROS) infrastructure at JPL which did not exist during the Phoenix mission.**

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- **Wherever possible, it is intended to integrate MSL activities with Mars-Express mission planning and science observations of its payload instruments, in order to prove the concept of MSL operations via the backup relay channel and improve MSL data return. Mars-Express has planning cycles of several months, to be compared to a few Martian days planning cycle for rover operations. Initial test passes from August 2012 after MSL landing should take place to prove link and contingency support capability. Further relay operations between MEX, Curiosity and Opportunity are also considered in the future.**

In conclusion, the paper draws a perspective for these cross-support relay activities and steps towards further building interplanetary network infrastructure.

Nomenclature

ADC	=	*Analog to Digital Converter*
AGC	=	*Automatic Gain Control*
AOCS	=	*AOCS units (Attitude and Orbit Control System)*
ASCII	=	*American Standard Code for Information Interchange*
ASM	=	*Attached Synchronization Marker*
ASPERA	=	*Analyser of Space Plasmas and Energetic Atoms*
A.U.	=	*Astronomical Unit*
CCSDS	=	*Consultative Committee for Space Data Systems*
CORO	=	*Coordination Of relay Operation*
CRC	=	*Cyclic Redundancy Check*
dB	=	Decibel
DDS	=	*Data Distribution System*
DMS	=	*Data Management System of Mars-Express*
DOR	=	*Direct Operations Request file*
DTE	=	*Direct To Earth*
EDL	=	*Entry, Descent and Landing*
EGSE	=	*Electrical Ground Support Equipment*
ELT	=	*Electra LiTe (Curiosity's UHF radio)*
EM	=	*Engineering Model*
ESA	=	*European Space Agency*
ESOC	=	*European Space Operations Center*
FCT	=	*Flight Control Team*
FWD	=	*Forward*
FM	=	*Flight Model*
HRSC	=	*High Resolution Stereo Camera*
IMU	=	*Inertial Measurement Unit*
JPL	=	*Jet Propulsion Laboratory*
MAVEN	=	*Mars Atmosphere and Volatile EvolutioN orbiter*
MCS	=	*Mission Control System*
MELACOM	=	*Mars Express LAnder COMmunications subsystem*
MER	=	*Mars Exploration Rover (MER-A is Spirit, MER-B is Opportunity)*
MEX	=	*Mars Express orbiter*
MEXSIS	=	*Mars Express Spacecraft Interface Simulator (manufacturer SSBV)*
MMH	=	*MonoMéthylHydrazine*
MOC	=	*Mission Operation Center*
MRO	=	*Mars Reconnaissance Orbiter*
MSL	=	*Mars Science Laboratory (rover Curiosity)*
MTL	=	*Mars Express Mission TimeLine (short MTL in RAM : 117 TCs, long MTL in SSMM : 3000 TCs)*
MTP	=	*MEX Medium Term Plan*
NASA	=	*National Aeronautics and Space Administration*
OAF	=	*(MaROS file) Overflight Acknowledgement File*
OBCP	=	*On-Board Control Procedure*
OBDH	=	*OnBoard Data Handling bus*
ODY	=	*Mars Odyssey orbiter*

OEM	=	*Orbit Ephemeris Messages (CCSDS)*
OMEGA	=	*Visible and Infrared Mineralogical Mapping Spectrometer*
OPAF	=	*(MaROS file) Overflight Performance Assessment File*
OSF	=	*(MaROS file) Overflight Summary File*
OSOE	=	*(MaROS file) Orbiter Sequence Of Events*
PHX	=	*Phoenix*
RF	=	*Radio Frequency*
RTN	=	*Return*
SGS	=	*Science Ground Segment (Mars-Express)*
SSBV	=	*Satellite Services BV*
SSMM	=	*Solid State Mass Memory*
SVT	=	*System Validation Test*
TBC	=	*To Be Confirmed*
TBTV	=	*Thermal Balance / Thermal Vacuum test*
TC	=	*TeleCommand*
TCM	=	*Trajectory Correction Maneuver*
T&C	=	*Tracking, Telemetry and Command*
UTC	=	*Universal Time Coordinated*
UHF	=	*Ultra High Frequency*
VILAND	=	*VIsibility of planetary orbiter from LANDer(s)*
VMC	=	*Visual Monitoring Camera*

I. Introduction

Launched on the 2nd June 2003, Mars-Express was designed for a nominal mission from January 2004 to November 2005 and for a possible extension until October 2007. Since, the spacecraft is orbiting the red planet in the frame of another extension running until end 2012. In June 2012, a further extension already approved until end 2014 can be confirmed and a science case for the next 2 years period [2014-2016] should be proposed.

All the units of the spacecraft are still working nominally except a cryo-cooler of the OMEGA spectrometer and the Solid State Memory controllers : Following problems experienced from the 13th August 2011 with the prime unit SSMM-A which brought Mars-Express into Safe Mode, the redundant SSMM (SSMM-B) was set into operations on the 29 of the same month. After 2 new safe-modes (24 September and 16 October 2011), a new way of commanding the spacecraft has been implemented and has allowed to resume the mission, still heavily relying on the SSMM. The nature of the problem is better understood and localized now which has allowed to find mitigations. Concerning the payload instruments, they all provide today the scientific community with a huge amount of valuable data even if one of the two cryo-cooler of OMEGA allowing short wave observations, can't be used anymore since an anomaly occurred in August 2010. This has no impact on the long wave observations with the other cryo-cooler of the instrument or on those in the visible spectrum.

In addition to its TT&C subsystem used for long range communications in X and S-band with the Earth and for Radio Science, MEX embeds a UHF transponder MELACOM, designed to communicate with the lander Beagle-2 early 2004 and later, with the 4 Netlanders . But this program was cancelled and early 2004, the attempts to pick up with MELACOM's receiver a signal from Beagle-2, released by Mars-Express on the 19th December 2003 (a few days before Mars Orbit Insertion), were unsuccessful. Since, MELACOM has been used during many overflights to communicate with NASA landed assets: the Mars Exploration Rovers Spirit, Opportunity and the lander Phoenix.

From July 2010, new contacts between NASA and ESA were established to assess the possibility for Mars-Express to support, as a backup to NASA's prime relay orbiters, Mars Odyssey and Mars Reconnaissance Orbiter, the Mars Science Laboratory mission. Like for the coverage implemented by Mars-Express of the Phoenix mission from its Entry, Descent and Landing at Mars on the 25 May 2008, Mars-Express should record from the 06 August 2012, the UHF signal during MSL EDL in the Gale crater and later, should support on surface operations of the rover Curiosity. Preparing Mars-Express to exercise again for MSL, operations already performed in 2008 to support Phoenix, has been in fact a new challenge for the european mission and will be detailed in this paper. In this context, the paper presents the collaboration between ESA and NASA regarding a network infrastructure at Mars, reminds what has been achieved so far with Mars-Express and MELACOM and gives a future outlook for these joint ESA-NASA activities at Mars.

II. The MELACOM transponder

Apart from its X-Band and S-Band transponders, used together with the High Gain Antenna for the long distances communications with the Earth and for Radio Science (Spacecraft to Earth distance reaching 2.7 A.U. = 400 Millions of km), Mars-Express embeds a UHF transponder “MELACOM” (401-437 MHz) and 2 patch antennas to communicate at closer distances of a few hundred to thousands km, with any landed asset on Mars surface supporting the CCSDS Proximity-1 protocol. See **Figure 1**.

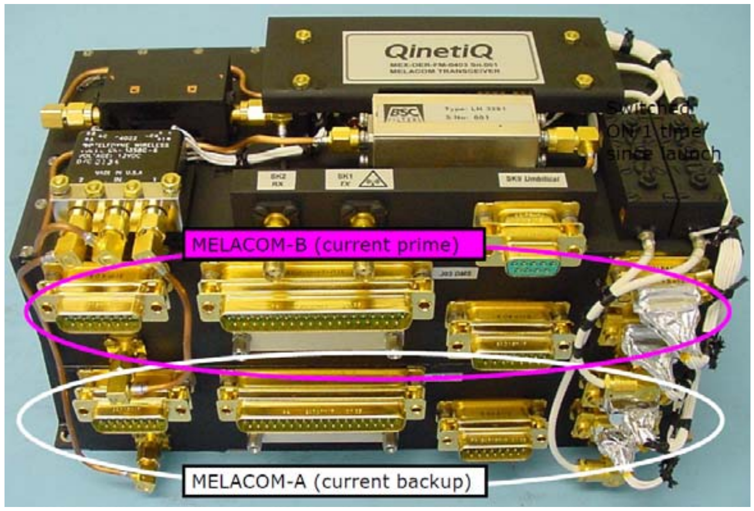

Figure 1 : “MELACOM”, UHF transponder of Mars-Express

The unit can operate today in 4 different modes:

I. A “Canister” mode, in which the UHF received signal (even very weak, and with or without modulation) is down-converted to baseband, fed into a 1 bit ADC and sampled at high frequency. This open-loop recording needs ground post-processing in order to extract together with a timescale, the frequencies that have been detected in the receiver channel. This processing has been presented in a previous paper [INTERNETWORK].
This powerful scanner can also be used to provide onboard UHF interferences characterization.

II. A “Doppler” mode allowing the receiver to sample measurements on how this effect shifts the received signal frequency, once a RF lock is achieved on the incoming carrier.

III. A “Proximity-1 link” mode dedicated to communications with landers or rovers on Mars surface with a full duplex link, allowing to send commands to them (Forward link) and to fetch telemetry data from them (Return Link). In order to do this, MELACOM implements Red book 3 of this protocol (CCSDS 211.0-R-3).

IV. A new “Framed bit stream” mode allowing the receiver, once a RF lock is achieved on the incoming carrier, to fetch telemetry data wrapped into proximity-1 frames, sent by assets at Mars with expedited service via the Return Link. All the data are stored without validity control : any frame valid or not is kept. MELACOM’s transmitter stays powered off without initiating the hailing, so no initial handshake of the usual full-duplex link, nor later, potential retransmission requests.

III. MEX-MELACOM activities with the Mars Explorations Rovers in 2004-2005

As these testing activities needed early in the MEX and MER mission, to validate in flight the interoperable UHF relay service between MEX, Spirit and Opportunity, have been detailed in a previous paper [INTERNETWORK], they are just summarized in the following **Table 1**. While the MER’s primary relay links were via the NASA Mars Global Surveyor and Mars Odyssey orbiters, the demonstration of interoperability with MEX offered additional robustness in the overall telecommunications infrastructure. This first functional validation campaign allowed to successfully test the prime MELACOM A unit’s functionalities : the open-loop recording with the canister mode, the 8kbps Forward and 8/32/128kbps Return link relay service, and the doppler sampling :

Date	UTC Start	Rover	Test	Result
10 Jan 2004	23:30:00	MER-A	Canister mode	Successful (listen in on nominal MER-ODY pass)
06 Feb 2004	00:39:00	MER-A	32 kbps return link, 8 kbps forward link	Successful: 15.3 Mb return; 1 prox frame forwarded
03 Aug 2004	10:40:00	MER-A	Canister mode : MER Tx @ 8 kbps	Successful: 3.8 Mb canister mode file return
04 Aug 2004	12:27:00	MER-B	128 kbps return link	Successful: 43.6 Mb return
06 Aug 2004	12:48:00	MER-A	Canister mode: MER Tx @ 8 kbps	Successful: 3.8 Mb canister mode file return. ODY also recorded canister mode data during this test
13 Aug 2004	18:12:00	MER-B	Doppler	Failed: Signal acquired but Doppler packets not generated on MEX
26 Dec 2004	03:43:00	MER-B	Doppler	New MELACOM software loaded (19 Dec.). Partial Success: Loss of lock near zero-Doppler point
29 Dec 2004	05:39:10	MER-B	Doppler	Partial Success: Loss of lock near zero-Doppler point
19 Jan 2005	19:10:37	MER-B	Doppler	Successful (with range over which the Doppler system sweeps adjusted)
17 Dec 2005	00:18:00	MER-A	8 kbps return link	Successful

Table 1 : MER-MEX first flight functional test campaign from Jan.2004 - Dec.2005

IV. MEX-MELACOM activities with the MERs in 2007-2008 to prepare the Phoenix support

In order to verify the MEX-MELACOM ability to support PHX EDL and also to characterize its ability to support on-surface PHX operations (in routine with both data return and forward commanding, or in contingency scenarios with a support of the same nature or a support based on open-loop recording), a test campaign between Mars-Express and the Mars Exploration Rovers, still healthy and operational, was decided upon in April 2007.

As this second relay test campaign at Mars of MEX orbiter, performed with MELACOM-A, has been presented in the paper [INTERNETWORK], it is only summarized by the following **Table 2** :

Date	UTC Start	Rover	Test	Result
2 Aug 2007	214T21:45:00	MER-A	Across-Track, EDL RF Sequence to Canister	Those 3 passes were cancelled : Dust storm at Mars ⇒ power concern for MER
9 Aug 2007	221T01:36:00	MER-A	Nadir, EDL RF Sequence to Canister	
13 Aug 2007	225T05:25:00	MER-B	Nadir, Carrier Wave to Canister + Aspera Interference Test	
19 Aug 2007	231T09:17:00	MER-B	Nadir, Carrier Wave to Canister + Marsis Interference Test	Successful; Signal detected.
24-25 Aug 2007	236T23:48:00	MER-A	Nadir, EDL RF Sequence to Canister	Successful; Signal detected.
28 Aug 2007	240T15:05:00	MER-B	Across-Track, EDL RF Sequence to Canister	Successful; Signal detected.
2 Sep 2007	245T16:08:00	MER-B	Across-Track, Carrier Wave to Canister + Aspera Interference Test	Successful; Signal detected.
6 Sep 2007	249T07:31:00	MER-A	Nadir, Return Link Only; 128kbps Rtn	Failed; Hardware configuration error
12 Sep 2007	255T11:23:00	MER-A	Nadir, Return Link Only; 128kbps Rtn	Successful; 35.3Mbits of data Return
16 Sep 2007	259T02:41:00	MER-B	Continuous 8kbps Forward / 128kbps Return	Cancelled by JPL for safety concern (DOR untestability prior to flight + MER troubleshooting path not available).
21 Sep 2007	264T03:41:00	MER-B	Nadir, Continuous 8kbps Fwd / 32kbps Rtn	Mixed; 12 TC got rejected by the rover : marginal link budget (TBC); 11.8Mbits of data Return
27 Sep 2007	270T08:27:00	MER-A	Nadir, Single Buffer 8kbps Fwd / 32kbps Rtn	Successful; expected files received by MER; 24.0Mbits Return.
4 Oct 2007	277T00:58:00	MER-A	Nadir, Multiple Buffer 8kbps Fwd / 8kbps Rtn	Successful; expected files received by MER; 5.8Mbits Return.

10 Oct 2007	283T04:51:00	MER-A	Nadir, Multiple Buffer 8kbps Fwd / 128kbps Rtn	Mixed; expected files received by MER but 2^{nd} buffer load discarded by Spirit; 66.1Mbits Return.
15 Oct 2007	288T19:08:00	MER-B	Multiple Buffer 8kbps Fwd / 32kbps Rtn	Cancelled (lack of DSN coverage for MER)
21 Oct 2007	294T23:01:00	MER-B	Nadir, Multiple Buffer 8kbps Fwd / 8kbps Rtn	Mixed; expected files received by MER but 2 TC got rejected by the rover; 4.6Mbits Return.
25 Oct 2007	298T14:01:39	MER-A	Nadir, Multiple Buffer 8kbps Fwd / 32kbps Rtn	Failed; Communication window time miscommunication.
15 Feb 2008	046T22:07:00	MER-B	New Cmd Concept, Nadir; Multiple Buffer 8kbps Fwd / 128kbps Rtn	Mixed; Fwd link successful; 0.2Mbits Return (less than expected).
21 Feb 2008	052T01:17:00	MER-B	Across-Track; 128kbps Rtn only	Mixed; 5.9Mbits Return (less than expected).
26 Feb 2008	057T04:31:00	MER-B	Spot; 128kbps Rtn only	Mixed; 0.2Mbits Return (less than expected).
2 Mar 2008	062T07:38:00	MER-B	New Cmd Concept, Nadir; Multiple Buffer 8kbps Fwd / 32kbps Rtn	Successful; expected files received on board MER; 36.7Mbits Return.
4 Mar 2008	064T07:39:00	MER-B	New Cmd Concept, Spot; Multiple Buffer 8kbps Fwd / 32kbps Rtn	Successful; expected files received on board MER; 5.6Mbits Return.
7 Mar 2008	067T10:56:00	MER-B	New Cmd Concept, Spot; Multiple Buffer 8kbps Fwd / 128kbps Rtn	Mixed; Fwd link successful; 1.5Mbits Return far less than expected.
9 Mar 2008	069T10:43:00	MER-B	Spot; 32kbps Rtn only	Successful; expected files received on board MER; 29.7Mbits Return.

Table 2 : MERs-MEX flight test campaign (Aug.2007 - Mar.2008) to prepare MEX support to PHX

The 2007-2008 tests allowed to introduce a major improvement : the commanding by JPL of MELACOM UHF activities through a new interface based on DOR files, generated by JPL and delivered to ESOC, letting the MEX mission powering ON and OFF the unit (and commanding the spacecraft pointings supporting the relay), and allowing JPL to generate and deliver with short notice, the scenario to be called driving the UHF activity. And because MER and PHX were sharing the same CE-505 UHF transceiver, these MER-MEX tests offered a representative validation of the foreseen PHX-MEX support. This allowed to test both forward and return link bit rates to be used by Phoenix, to characterize different commanding concepts and to try different spacecraft pointing scenarios in order to improve the forward and return proximity-1 link performance.

V. MEX-MELACOM activities with Phoenix in 2008

After the loss in 1999 of Mars Polar Lander, NASA had established a policy of requiring communications during critical events such as Entry, Descent, and Landing, in order to acquire engineering data that could be used to diagnose any potential anomaly that might lead to loss of mission during the event. While MER utilized X-band direct-to-Earth communications to satisfy the critical event communication requirements, the PHX lander had no X-band DTE communications capability once the lander separated from the cruise stage, seven minutes prior to entry. As a result, all PHX EDL communications were performed using the Lander's UHF radio.

One of the key issue to meet NASA's request was a proper phasing of the Mars-Express orbit and the EDL event, allowing Mars-Express to track the descent module with safe angular slew rates, in particular for the reaction wheels and an optimized visibility. Taking the opportunity of the Mars-Express orbit change to a 18/5 resonance orbit for Scientific purpose, achieved through 5 manoeuvers between the 18th November and the 16th December 2007, the phase of the orbit was also changed to optimize the visibility of the Phoenix EDL with minimum additional fuel consumption. Before PHX EDL, only one other manoeuver was implemented (19^{th} January 2008) in order to recover the reference orbit after a safe mode triggered 4 days before onboard Mars-Express.

PHX transmitted a UHF signal throughout EDL, which was received by MEX, ODY and MRO. The high latitude of the PHX landing site allowed all three of these high-inclination orbiters to view the EDL event because they had adjusted their true anomaly (orbit phasing) with respect to the epoch of PHX landing for this purpose. Once processed on ground, the spectrogram recorded by MELACOM (see **Figure 2**) allowed to see :

- the UHF carrier signal (for geometry reasons, only once the PHX cruise stage separation had taken place),
- around two minutes prior to entry, the transition to a 8 kbps modulated telemetry,
- around four minutes after entry (and ~3 min prior to landing), the parachute deployment (its signature was a change in the doppler rate), and the last transition to a 32 kbps modulated telemetry.

The carrier detection was kept throughout the EDL without noticeable attenuation due to plasma. Although PHX continued UHF transmission until 1 min after touchdown, MELACOM could not record this event because of the low elevation of MEX above horizon when it happened.

When preparing the tracking of an EDL, the OEM files for the entry trajectory of the asset arriving at Mars and for the orbiter monitoring the event allow to compute the doppler shift and to overlay it on the Waterfall plots generated. An offset of ~3.1 kHz in the PHX signal recorded by MELACOM with respect to the predict, already noticed during 2 Canister recordings of MER-A and B signal in August 2007, may come from MELACOM reference oscillator. A problem in the initialization of the predicts generator with MEX orbital information could also have created such offset, but as the same tool was used successfully to predict the frequency that the NASA orbiters (also recording the event in open loop) would see, this other cause is unlikely.

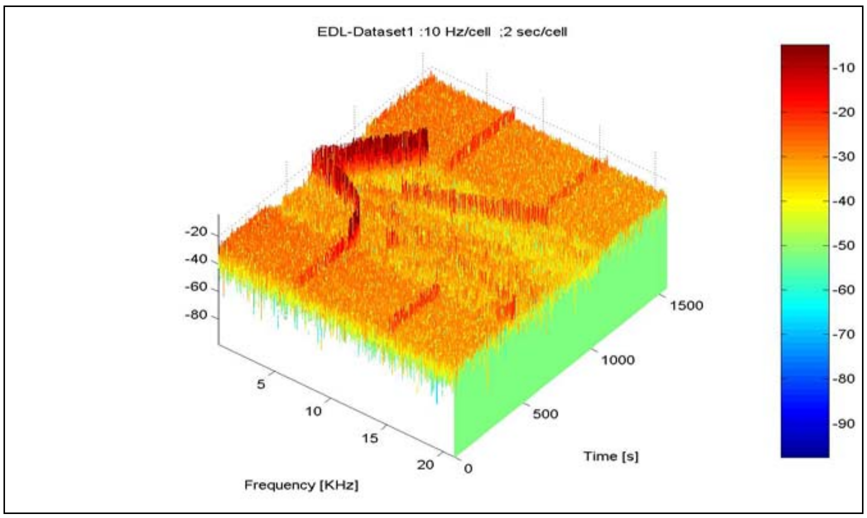

Figure 2 : MELACOM's (Canister mode) Spectrogram of Phoenix EDL RF sequence (25 May 2008)

After Phoenix landing, 3 proficiency relay passes listed in **Table 3** took place with Mars-Express, out of the 15 contact opportunities initially proposed by the orbiter during the critical first week on the Martian surface :

Date	UTC Start	Test	Result
25 May 2008	146T23:21:12	**EDL monitoring** : MEX slew, continuous tracking of EDL RF Sequence to Canister	Successful; EDL sequence recorded No blackout observed, nominal freq. profile constant offset of # 3.1 kHz versus predicted corridor
28 May 2008	149T20:01:20	**On surface** proficiency test 1/3 8kbps Fwd / 32 kbps Rtn	Successful, 30 Mbits of data Return MEX-PHX distance 536km - 2670km
30 May 2008	151T19:55:04	**On surface** proficiency test 2/3 Return Link Only; 32 kbps Rtn	Successful, 14.5 Mbits of data Return MEX-PHX distance 620km - #2600km
31 May 2008	152T23:17:52	**On surface** proficiency test 3/3 Return Link Only; 128 kbps Rtn	Successful, 62 Mbits of data Return MEX-PHX distance #800km - #2600km

Table 3 : MEX UHF supports to Phoenix in May 2008.

After intermittent anomalies experienced with MRO's Electra radio end of May 2008 and a safe mode of ODY early June (orbiter used for time-critical Phoenix command and telemetry relay services), the probability that MEX could be asked to provide an emergency support increased : From the 2nd June, MEX prepared for a situation of both

NASA orbiters unavailable : In addition to the nominal routine science mission timeline, the MEX FCT, Planning and Flight Dynamics teams prepared a backup one implementing only relay operations for every over-flight providing 10deg visibility of Phoenix, where MEX would point MELACOM's antennas boresight or 3dB beamwidth cone to its direction, when not conflicting with ground station passes, spacecraft maintenances (WOL) and earth pointings. The procedure to delete the running mission and activate this special schedule with only relay operations, X-TX communications, data dumps, S/C pointings and maintenances, was also prepared to allow a swap to an emergency support within hours upon JPL's request. A pass list with deadlines for each overflight advertised when to send latest to ESOC, MELACOM DORs commanding products, and when to expect on ground, data dumped from recordings during used relay slots. Hopefully, this emergency support was never activated: the backup plan stopped on the 21 September 2008 at the end of the first extension of the (originally 90 sol) PHX mission.

VI. MEX and JPL activities since 2009 to prepare MEX for the MSL support

A. Set-up of a periodic and end to end verification of the MEX relay function

With the outlook of a possible support to MSL, the principle of a periodic verification of the Mars-Express relay capability once or twice a (terrestrial) year, was agreed in June 2009 between JPL and ESOC, keeping the principle to book for each test a backup slot in order to be robust to late notice cancellation. The objective was to keep using the MEX relay function with one of the MER as long as this would remain feasible, in order to check that the Commanding and the Return chain between JPL and a Mars landed asset, the MELACOM unit and the interfaces set-up for past MEX relay activities were still operational, independently of possible personnel changes on both sides. The **Table 4** below lists the MEX relay activities performed with MERs since the end of its support to PHX :

Date	UTC Start	Rover	Test	Result
26 Oct 2009	299T00:05:00	MER-A	Lander pointing, 8kbps Forward / 32kbps Return	Successful; 1 TC delivered, 13.3 Mbits Return. MEX - MER-A distance 2550km - 3650km
30 Oct 2009	303T00:30:00	MER-A	Lander pointing, 8kbps Forward / 32kbps Return	Successful; 1 TC delivered, 28.4 Mbits Return. MEX - MER-A distance 2400km - 4600km
23 Aug 2010	235T12:54:44	MER-B	Lander pointing not possible, offpointing kept < 27 deg seq. carrier + 8 kbps to Canister	Successful; Signal detected. 43.5 Mbits of open loop data
29 Aug 2010	241T15:50:38	MER-B	RF sequence to Canister	MER-B did not take the pass But onboard interferers successfully recorded 43.5 Mbits of open loop data
14 Dec 2010	348T20:57:40	MER-B	Lander pointing, 8kbps Forward / 8kbps Return	Successful; 1 TC delivered, 7.1 Mbits Return MEX - MER-B distance # 1150km - 2450km
18 Dec 2010	352T15:50:38	MER-B	Proximity-1 link did not take place Checksums verification instead	MER-B did not take the pass
04 Oct 2011 **(*)**	277T15:00:46	MER-B	Lander pointing, low MEX elev. 8kbps Forward / 8kbps Return	Successful; 345 TCs delivered, 6.4 Mbits Return. MEX - MER-B distance 3300km - 4900km
13 Oct 2011 **(*)**	286T23:01:57	MER-B	Lander pointing 8kbps Forward / 8kbps Return	Partially successful, 313 FWD TCs delivered among 422, 4.9 Mbits Return. MEX - MER-B distance # 1600km - 2450km
12 Dec 2011 **(*)**	346T10:08:40	MER-B	Lander pointing 8kbps Forward / 8kbps Return	Unsuccessful due to new MELACOM SW partial delivery of 3*(90+7) FWD TCs, poor RTN link. Problem reproduced on ground, under fix MEX - MER-B distance # 1100km - 2700km
29 Dec 2011 **(*)**	363T21:54:53	MER-B	Proximity-1 link did not take place	MER-B NO-GO for the pass, marginal power : dust levels & coming winter solstice March 2012

Table 4 : Periodic verification with MERs of MEX relay since Oct.2009 (*) : with MELACOM-B, see point B.

The last test pointed out a weakness of a new MELACOM's functionality developed for MSL, allowing to clear its FWD TC buffer (once the landed asset has acknowledged all the TC frames received) for potential refilling by a new dataset of asset TCs, while keeping active the return link. As further MEX MER-B tests are planned prior to

MSL EDL event, some of them should allow to validate in flight a correction currently under development by QinetiQ. After MSL EDL, further activities between Mars-Express and MER-B may take place although the environmental conditions on the Mars surface and remaining lifetime of the rover is difficult to predict.

B. Introduction of MELACOM-B into relay operations

The need to swap end of August 2011 from the prime to the redundant SSMM led to swap as well the UHF radio function to its redundant unit, MELACOM-B. This because the IEEE 1355 High Speed Link between the SSMM A and B controllers, and MELACOM A and B units is not crossed-strapped. When the decision to swap was made, SSMM-B controller had never been used, neither retested since TBTV (in particular during SVT) and MELACOM-B had only been powered ON two times : once on the 20 June 2003 at the start of cruise to Mars, and 7 years and 9 months later, on the 18th March 2011 to compute for the first time since launch, EEPROM checksums. In particular, no RF activity and no data recording into SSMM-B had been performed. On top of that, MELACOM-B software needed to be upgraded to the level of MELACOM-A SW, patched in December 2004 and January 2005.

C. Upgrade of MELACOM's EEPROM software to add two functionalities to the MEX radio

The experience of relay tests with MEX, MERs and Phoenix from August 2007 to May 2008 had shown that a functional upgrade of MELACOM capability would be useful to

- maximize the duration where the proximity-1 link stays active during an overflight (link budget permitting), in order to improve the commanding volume to (and data return from) Mars. The idea was to develop a new TC for the instrument : "Clear FWD TC Buffer" . For large commanding volume using multiple FWD TC buffer loads, this new TC would allow to clear the buffer once its content of lander TC frames has been delivered to (and acknowledged by) its recipient on Mars surface, letting meanwhile the return link active, feeding the SSMM with lander telemetry. So far, only the "Abort Lander Link TC was usable to prepare a buffer reload : it effectively clears the FWD TC buffer, but does it regardless, even if lander TC frames buffered inside have not yet been radiated or acknowledged and also, drops the proximity-1 link preventing MELACOM to receive further lander frames until the proximity-1 link is reestablished (to allow transmission of the next FWD TC buffer content) .
- develop a new simplex capability of the MELACOM radio allowing to acquire a bit stream telemetry at a commanded RTN bit rate, when the hailing and handshake initiating an exclusive radio link is not desirable.

The radio's manufacturer QinetiQ was contacted in November 2010 and started a study which confirmed in June 2011 the feasibility to develop an upgraded software compliant with MELACOM's 128 kbytes EEPROM size. However, concerning the bit stream acquisition, this study pointed out that the stream of bits would have to come from Proximity-1 frames, as the hardware detects the P1 ASMs and uses the frame length from the P1 frame header to drive the detection of the ASMs. The software being only interrupted once a complete frame has been received, if the bit stream does not consist of P1 frames, the hardware will not record the frames and pass them to the software.

Taking benefit of the restoration of their MEXSIS EGSE from end August 2011, QinetiQ took the opportunity to investigate the Canister sampling anomaly detected in August 2007 by MEX FCT : even if commanded at highest rate of 5.262 KHz (16 bits words) = 84192 bit sampling rate, MELACOM samples in reality at lowest rate of 2.631 KHz (16 bits words) = 42096 bit sampling rate. Unfortunately, the attempt by QinetiQ to modify the source code commanding the FPGA involved did not work : only the lowest sampling frequency remains available onboard.

On the MEX FCT side and in order to ease software patching and verification activities of MELACOM flying software image, a memory dump service not implemented by the unit's software was developed on ground, using the checksum functionality to be requested for each individual word belonging to the memory area of interest.

D. Ground compatibility test campaign between a MELACOM and an Electra lite models

MER-A, MER-B and Phoenix being equipped with a CE505 UHF radio, all the background and experience gained so far through the flight relay tests between Mars-Express and these landed assets since 2004 could not fully represent relay activities with MSL, the rover Curiosity carrying a transponder of a new design, the Electra Lite (ELT). This led JPL to perform with QinetiQ ground compatibility tests between an ELT and MELACOM model in March 2012 (similar to those performed with the CE505 in August 2002 and January 2003 prior to MEX launch).

The tests confirmed an anomaly detected during a flight test between MEX and MER-B performed on the 12 December 2011 on the new Clear FWD TC buffer functionality, and allowed to better understand problems detected in February-March 2008 during the preparation for Phoenix, where the 128kbps coded RTN link suffered from many and unexplained drops in the carrier AGC. QinetiQ is currently investigating whether a modification of the TEMIC Viterbi decoder programming would allow to solve the issue and restore a reliable coded RTN link capability of MELACOM at highest rate. For the time being and due to this problem, during Prox-1 contacts from MEX-MELACOM, MSL intends to use Prox-1 links without Viterbi coding on the RTN link.

E. Introduction of Mars-Express into the MaROS infrastructure

The operational interfaces between JPL and ESOC, created in 2007 for the test campaign between Mars-Express and the MERs to prepare MEX support to Phoenix lander, and used since for periodic relay tests with the 2 rovers, had to be updated following the introduction of the Mars Relay Operations Service [MaROS] at JPL, coordinating all the relay activities between the NASA landed assets and orbiters at Mars.

In preparation of Mars-Express support to MSL, JPL and ESOC started in May 2010 this introduction of the European orbiter into the system to streamline and automate the activities from their planning, implementation and execution up to the post-flight analyses, and to allow JPL to command MELACOM UHF activities with short notice, like forwarding sequences of commands via Mars-Express relay to Mars rovers, fetching from them telemetry, or recording in open-loop UHF signal from Mars surface. These activities being inserted into slots booked by MEX MPS and SGS through the longer planning cycles of the orbiter, slots where the radio is switched on and off, the spacecraft is pointed to the target surface site, potential conflicts with other instruments are cleared (exclusion rules about requirements on the spacecraft pointing, RF interferences or power consumption) and some bandwidth is booked in the dump plan to get the relayed data on ground.

This system is accessible via a web browser application and Graphical User Interface, is architectured on a centralized database, and is based on XML file interactions. It handles :

- a strategic Planning Process : Upon a request from an asset, Mars Express can negotiate with it, relay opportunities published in advance, that are to be implemented during a planning period.
- a tactical Commanding Process : Mars Express being primarily a science and not a relay orbiter, it is not expected to be responsive to “last minute” changes to the baseline plan.
- a Forward-Link Commanding Process : data generated by a lander’s operation center, and received on the Mars-Express control system, can be uploaded to MEX S/C which will forward them to the landed asset.
- a Return-Link Data Flow Process : A lander’s operation center by querying Mars Express telemetry can get return-link data transferred by Mars Express. This process is not covered by MaROS.
- a Relay Service Accountability : Mars Express and the landed asset report on and account for data transferred in both the FWD and RTN links. MaROS is a central repository for this reporting for all Mars relay network nodes.

MaROS accommodates several planning cycles and constraints of the relay service providers (orbiters) and users (rovers) allowing these latter to optimize their use of available relay resource (symmetrically to what flight control teams do when they negotiate and use networks of ground stations resources supporting their spacecraft).

The process, still continuously improved, completed and automated, can be resumed as follows :

First, and as part of another process than MaROS, ESOC Flight Dynamics team provides to JPL navigation, each time this is needed, MEX OEM files in CCSDS standard format, and to MEX CORO, VILAND files detailing per MTP, the visibility parameters of all the overflights during the period, over a given landed asset at Mars.

MEX publishes to MaROS an **OSOE** defining its orbits and planning periods. Together with the MEX orbit information, this OSOE allows the rover MOC to identify potential overflight opportunities, select which are those of interest for relay activities, and issue a proposal, possibly transformed later into a formal request to the system. This translates into the generation of **OSF** file(s), notified to MEX MOC. The different versions of this file are fetched by MEX MOC from the system, in order to check the geometry for the proposed contacts with respect to the VILAND predicts, the timings and the nature of the activity. Once agreed on MEX side, the support of the concerned overflight(s) is confirmed to MaROS through the publication of an **OAF**. This acknowledgement will later allow MaROS to generate the MELACOM commanding file and this, up to two hours before the target window for U/L to MEX. This operational interface set-up in 2007 to accommodate late relay product delivery, makes use of

DORs, ASCII files (listing MELACOM sequences) ingested by the ESOC Mission Control System to generate with the S/C database, the final MELACOM commanding.

Mars-Express Mission Planning will have already prepared the switch ON and OFF of the unit, and also the timetagged call to this DOR defining fully the content of the relay activity. For a proximity-1 contact including a forward link activity with a NASA asset on surface, it embeds in particular the hexadecimal stream to be wrapped into proximity-1 frames to be radiated to the asset. As a JPL's DOR is an operational MEX spacecraft product, it is not published to MaROS but ftp-delivered onto an ESA server, then automatically picked-up by a file transfer system and delivered on the MEX MCS. Automated checks on the DOR content are under implementation to allow a GO for U/L at first opportunity, or to feed-back to JPL an error notification blocking the U/L process until a corrected DOR is re-submitted.

Once the overflight has taken place, and the housekeeping telemetry of MELACOM is available on ground, MEX publishes a **ScoreCard** summarizing fixed-value statistics from the overflight, helping to quantify the result in terms of data exchange achieved, quality of the link and measured timings. MEX also publishes an **OPAF** detailing the most important parameters (timetagged) values recorded by the unit during the overflight. The interface allows also to publish predicted values like timetagged geometry predicts needed to assess the relay behavior. The rover MOC provides on its side the same post-pass accountability information.

F. Operational interfaces and adaptated planning process

An operations concept has been defined and existing interfaces between JPL and ESOC validated through many cross-support relays with the MERs and PHX, and upgraded to interact with MaROS, will allow to support different planning cycles between Mars-Express and MSL missions.

MSL will use the regular Telemetry interfaces as developed for the Mars Express science community for fetching rover packets recorded by MELACOM. The ScoreCard and the OPAF published by MEX into MaROS and based on MELACOM parameters housekeeping telemetry completes the information on the overflight.

For the Commanding interfaces however, the 3 months planning cycle of the Mars Express Orbiter are combined with the short planning cycle of MSL. Mars Express is planning operations starting 3 months before the relay activity's MTP start, while rover operations can be planned with few days lead time (and could therefore not be processed through the normal MEX Mission Planning cycles). Hence later rover product delivery compared to the routine Orbiter commanding products. The final rover commanding products and definition of the support type (MSL can select between : RF spectrum recording, Return Link, Forward and Return Link, Prox-1 framed bit stream capture) for a specific pass, are left until 2 hours before the last uplink opportunity to the MEX Orbiter prior to the concerned over-flight. Operations with this late notice can only be supported because the spacecraft resources have already been sized accordingly and booked at mission planning level.

The latency for the commanding of MELACOM and the rover, and for the return on Earth of relayed data fetched from Mars-Express, is dependent on the Ground Stations allocations to the spacecraft and on their status.

The typical schedule is as follows (see **Figure 3**) :

- Upon reception of an OSF from MaROS, insertion of the MELACOM pointing requirements and power + data resources allocation request via an MREQ (Mission Request) into the Medium Term Planning cycle by ESOC, 3 months before start of MTP to which belong the relay activity. Review of potential exclusions.
- generation of the MELACOM Operations Request by ESOC at start of MTP initial analysis (start of concerned MTP - 6 weeks) . This operations request can be then updated up to 0.5 week before STP of activity starts.
- generation of {the MELACOM ON / Call to execute JPL's DOR / OFF commanding, spacecraft pointing commanding, relay data dump commanding} 0.5 week before STP of activity starts.
- generation of the MELACOM UHF activity commanding (DOR file) by MaROS, transfer to ESOC up to 2 hours before the last U/L opportunity to MEX and uplink in the next available Ground Station pass (if the DOR succeeded automated checks under implementation). These checks verify syntax, compliance versus advertised activity, operational integrity and safety.
- execution onboard Mars-Express of JPL's UHF activity (like forwarding rover telecommands and reception and recording of rover telemetry) during the overflight

- dump of the recorded data to ground according to dump plan, in the next available Ground Station pass (allocated data-dump resources can’t be later reallocated to other instruments, if the contact does not take place).
- retrieval of MELACOM-MSL telemetry data from the ESOC DDS archive by JPL for analysis.

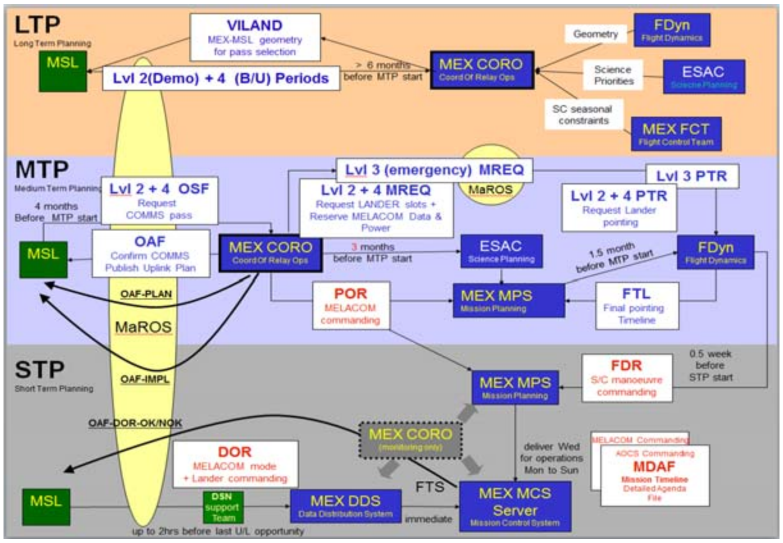

Figure 3 : MEX-MSL Planning interface

Technically, these interfaces allow Mars-Express to support in routine more than one landed asset.

G. MEX manoeuvres and pointings for the relay activity

Although any spending of “fuel” is always minimized on Mars-Express, the spacecraft has performed on the 2 April 2012, a retrograde manoeuvre at pericentre to decrease its orbital period by about 15.5 seconds and adjust its orbit phasing to cover MSL EDL. Advancing it to reduce even more the MMH consumption had a limit as this manoeuvre had to take into account the MSL TCM-1 performed on the 11th January 2012. MEX did not redesign this planned manoeuvre when in early February 2012, JPL informed on a change of MSL arrival time of about 40sec, because this offset was close to the inaccuracy assumed by JPL for the MEX phasing (+/- 30 sec).

In order to reduce the cases where the dedicated pointings used for relay activities are complex to design for Flight Dynamics, the constraint respected so far not to exceed 0.17 deg/sec for S/C slew rates, has been relaxed up to 0.3 deg/sec which preserves the S/C safety : the “lander pointing” introduced in March 2008 to prepare MEX for the support to PHX is now defined as follows : It directs the MELACOM’s antennas boresight towards the rover direction and keeps this pointing (i.e. a null offpointing) along the MEX orbit as long as the S/C slew rates can stay below these 0.3 deg/sec. Otherwise, the pointing accuracy is relaxed and the line of sight of the rover is kept as close as possible to the boresight axis within a +/- 35 deg cone around it (i.e. the offpointing is kept within 35deg).

VII. MEX support to MSL

Like what had been done to record PHX EDL, MEX will record MSL EDL in UHF open loop using the canister mode of MELACOM providing monitoring of the MSL carrier and spectrum.

Figure 4 below depicts the MSL EDL geometry for MEX. The orbiters MEX, MRO, and ODY (which is providing a low-latency monitoring path thanks to its “bent-pipe” capability) will be configured in a specific manner, based on each orbiter’s capabilities, to optimize the overall EDL communication strategy. The long range between MEX and MSL during this phase will allow MEX to slew and keep the MELACOM’s UHF antennas boresight pointed towards MSL with slew rates in the order of 0.2 deg/s. This long range is due to the fact that MEX pericentre’s latitude of the concerned orbit 10946 is almost 70deg south, to be compared to the 4.5deg south of the MSL landing site. During the descent, the closest distance (MEX, MSL) should be 2125 km to be compared to the 1550 km reached between MEX and PHX EDL in May 2008. The unfavourable visibility conditions at touchdown (MSL-MEX distance of 6610 km and MEX elevation above local horizon of only 1.1 deg), should not allow MELACOM to record the landing event. The MEX EDL data will be transmitted as soon as the S/C comes back to

Earth pointing following EDL for post-processing. The recorded dataset will be dumped in total three times to the Earth in order to avoid any data gap due to potential Ground Station problems, bad weather conditions, or network issues. It will be erased onboard MEX only once MSL confirms to have fetched a complete dataset. The recorded data from the 3 spacecraft would be of highest importance in a contingency situation where MSL would not have landed as expected, making the analysis of the sequence of radio tones and telemetry transmitted by MSL during EDL critical for investigations.

The rehearsal (23 October 2007) of the PHX EDL slew (with an interference characterization by MELACOM recording in OpenLoop), and the recording of the real Phoenix EDL on the 25 May 2008, shown that no AOCS unit involved in such tracking slew (Reaction Wheels, prime IMU) interfere MELACOM's receiver channel. Therefore, this test was not reproduced to prepare the slew tracking MSL EDL, but a similar test with a payload configuration representative of MSL EDL monitoring (MELACOM observing together with OMEGA and PFS) took place on the 26 April 2012 (MEX orbit 10598), to detect possible interferences between these instruments.

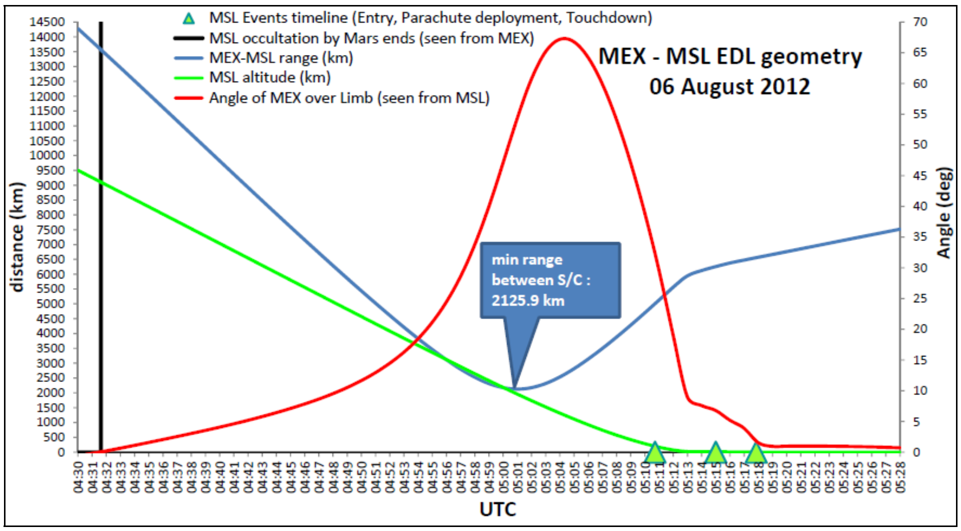

Figure 4 : MSL EDL geometry on the 06 August 2012

While MRO and ODY will provide nominal relay support for Curiosity after landing, the availability of MEX for backup or contingency relay support provides risk mitigation, although the rover has a DTE link capability in X-band (providing lower rate though than the UHF modulated channel), which was not the case of PHX, relying only on UHF once landed. Curiosity will still depend on UHF relay to achieve the bulk of its science data return. Thanks to its elliptical orbit, Mars-Express can provide complementary contact opportunities with Curiosity to MRO and ODY. MEX has proposed up to 10 demonstration relay passes in the first month after landing and later, occasional proficiency passes once or twice a year, similar to the periodic checks of the MEX relay in place with MER-B.

Upon request from NASA/JPL if needed, MEX will also be able to prepare an emergency support for a limited period (increasing periods of UHF visibility of the rover, or providing a backup relay channel in case a NASA orbiter becomes unavailable) : preparation and implementation of relay passes on every MEX orbit where they provide useful UHF coverage of Curiosity, and suspension of MEX science mission. To invoke any of these passes booked via the MaROS interface, even at short notice, the MSL project would simply need to provide each time, a DOR file to the MEX FCT in time for uplink to the MEX spacecraft. For any of these passes Mars Express would use the dedicated pointing for relay activities to optimize the margin of the link between the rover and the orbiter.

The **Figure 5** below shows MELACOM's antennas footprints in green during MEX lander pointing over the MSL landing site (Pericentre orbit 10951, 7 August 2012 15:26Z). These footprints are those of a +/-10deg cone from boresight (i.e. ell within the +/-35deg cone of the 3 dB beamwidth). The blue footprint is the horizon line (disk of the planet as seen from MEX at this altitude) and the light-up/shadow shape shows the day/night terminator.

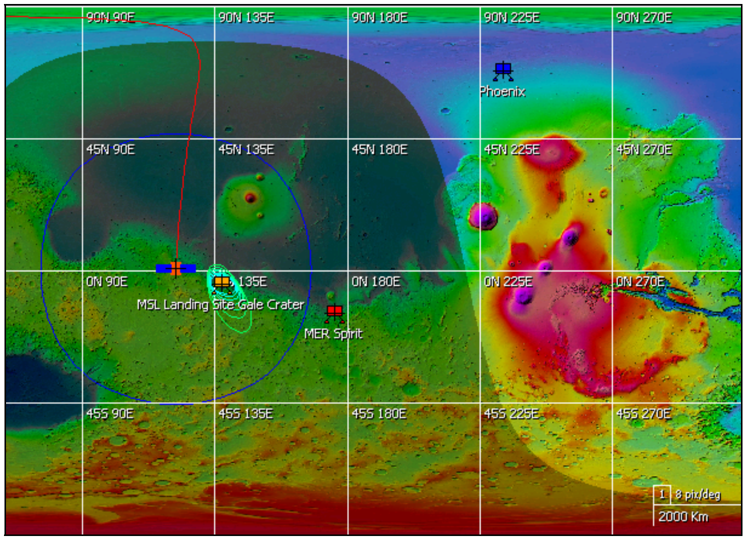

Figure 5 : MEX lander pointing over Curiosity, Pericentre orbit 10951, 7 August 2012 15:26Z

The **Figure 6** below shows between mid 2012 to end 2014, the periodic pattern of seasons with long and frequent 10 deg visibilities of Mars-Express over Curiosity alternating with less favourable seasons for MEX relay. It represents 1041 visibilities ≥ 6mn where MEX is closer from MSL than 6000km and 665 where MEX-MSL distance is within 4000km. Almost all these visibilities allows MEX to keep its UHF antennas pointed towards MSL and for those where this is not the case (because of the S/C slew rate limited to 0.3 deg/sec), the off-pointing would stay below 23 deg (an offpointing of 35 deg would drop the link budget by 3dB with respect to a boresight pointing).

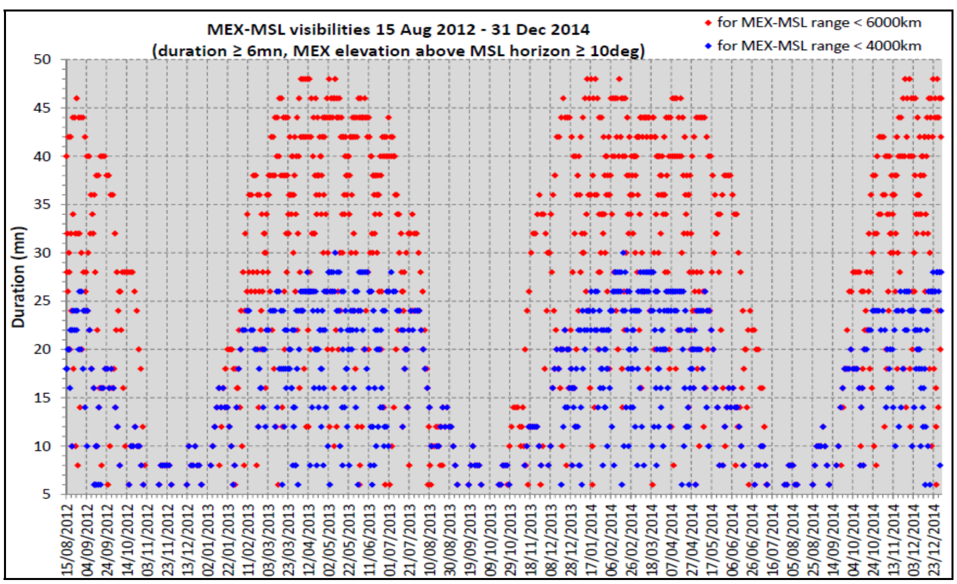

Figure 6 : Visibilities above 10deg of Mars-Express from Curiosity

Figure 7 shows between August 2012 to end September 2014, the offset between the [AOS-LOS] 10deg of MSL and MEX pericentre times and helps to identify in which seasons, a backup relay channel integrated with (i.e. at no cost for) the MEX science planning, could be provided :

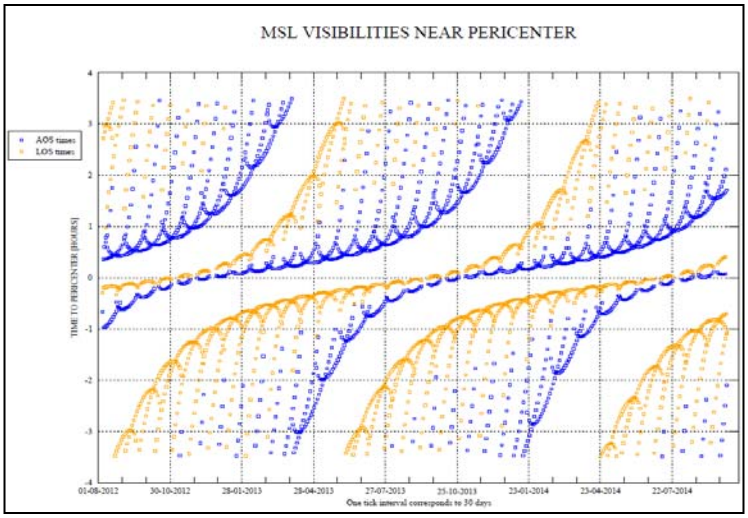

Figure 7 : MSL visibilities of MEX above 10deg with respect to MEX pericentre times

In September 2014, MAVEN with its Electra payload should reach the red planet allowing, on top of its science mission, to complete the relay infrastructure at Mars.

VIII. Lifetime, redundancy and improvement of MELACOM operations and capability

An analysis of the total dose radiation seen by the unit has never been done. It should take into account the solar radiation flux in cruise and at Mars since end 2003, a profile of the sun activity during its cycle 23 and cycle 24 expected to reach a maximum in May 2013, the shielding provided by the structure of Mars Express, by Mars body during sun eclipses seasons, and by the other MELACOM unit as MELACOM-A and B are stacked together. MELACOM's lifetime limiting factors also include the allowed radiation dose for its components like its DC/DC converters or the TEMIC TSS902E Viterbi decoder specified at 50kRAD radiation dose.
One maintenance activity helps to extend the lifetime of the unit : Mars-Express's manufacturer recommends to refresh the EEPROMs flying on the S/C every 10 years in orbit. Taking the opportunity of a new software version upload, this was done for MELACOM-B on the 2 December 2011 but still needs to be done for the A unit.

At the time being, MELACOM-B is the prime UHF radio unit of Mars-Express. The (cold) redundancy provided by MELACOM-A still exists although its SW would need to be upgraded to the version loaded on the B unit, and more important, resuming MELACOM-A prime unit would imply a system reconfiguration on SSMM-A as well, which today and after the problem detected on the 13th August 2011, is not foreseen.

Improvement of MELACOM operations means in particular to ease as much as possible their insertion in the MEX planning which is primarily a science and not relay orbiter planning . Either by scheduling its operations away from pericentres (always used by several instruments) if the range to a rover still allows a UHF link margin of 3dB, or by performing observations in parallel to the others payload instruments when pointing requirements allow, (except with ASPERA and the camera VMC : ASPERA creates strong interferences in MELACOM's receiver channel when the high voltage is used, and VMC because of its exclusive use of the OBDH bus). At Science planning level, exclusion rules have been defined to prevent these instruments to observe when MELACOM is ON. With MEX batteries ageing, the addition of UHF relay activities (increasing the pointed observations during each orbit or the parallel activities with others instruments) may have to be considered carefully in future eclipses seasons, as MELACOM consumes 31-32 watts when it transmits. Conflicts can also come from the limited bandwidth on the downlink to dump the high-priority relay data on ground in low bit-rates seasons. But actually, who can exclude that Mars-Express, designed to be a Science mission, ends up as an orbiting relay at Mars ?

Following MEX SSMM controllers problems in summer 2011, the usage of the short MTL hosting 117 max sized TCs in RAM has replaced the usage of the long MTL (3000 TCs) hosted in the SSMM. The commanding volume of all the activities running the mission has had to be reduced and optimized accordingly, without functional and performances losses. This has been done to command lander pointings for the spacecraft, and is ongoing for the commanding of MELACOM itself by developing OBCPs powering ON and OFF the unit, allowing to replace the existing sequences adding up to almost 25 commands scheduled in the short MTL, by 1 command to call the OBCP powering ON the unit and by another command powering OFF the unit. Note that the size of the Packet store created in MEX SSMM for MELACOM in July 2007, was slightly reduced by ~0.4% in June 2009 to allow an optimization of the SSMM mapping. With still 79.5 Mbytes, this dedicated area can store data from 5 Return Link 128kbps sessions of 20mn or 6 Canister observations of 30mn (would the Ground Station coverage not allow to dump the data between observations). But if one of the 3 memory modules of the SSMM fail one day, this allocation would have to be reduced at least seasonally (as these modules are common to both SSMM-A and B), to allow a fair sharing between the MEX instruments of the 2 remaining working memory modules.

The duration of close overflights being short, typically few tens of minutes, the optimization of the FWD link efficiency and commanding volume deliverable to Mars surface with the existing size limit of MELACOM's TC buffer size (20444 bytes ≈ 90 lander TCs of 218 bytes plus the proximity-1 overhead : ASM, header but no CRC) requires to close the dataflow control loop onboard between MELACOM and MEX-DMS, allowing the DMS to adjust continuously the commanding traffic according to MELACOM's feed-back reflecting the UHF link quality, instead of relying on predefined timings including significant margin delays, often not needed when a good radio-link is established, but insufficient if multiple link drops are experienced with timeouts, frames retransmissions ... This could be achieved by the development of an OBCP which upon reception of MELACOM's events and monitoring of counters refreshed in the radio's housekeeping telemetry, would know when the buffer's content (lander/rover telecommands) has been fully delivered and acknowledged by the asset at Mars, and can then safely be cleared and refilled with a new set of commands while keeping the return link active. But the test on ground of this OBCP before upload on MEX needs an upgrade of the MELACOM's model implemented in the MEX simulator used at ESOC in order to simulate a more representative behavior of the radio's FWD TC buffer. The idea discussed in the past to transform in MELACOM's flight software, the linear FWD TC buffer into a cyclic one with a data flow control handled at MELACOM level only, is now discarded because too complex.

Improvements on MELACOM software side could be discussed :

- Fixing few problems detected so far
- Implementing the access to Doppler readings during a relay pass. This would bring additional information from the proximity-1 link (useful in particular for on surface localization purpose) and should be possible to implement, taking benefit of the RF lock achieved on the incoming carrier.
- Depending on further needs and flying hardware limitations, modifications could also be investigated to support frame formats and enhanced protocols of the next generation of landers.

For any further development on MELACOM's EEPROM software by QinetiQ, the availability in a working state of their MEXSIS ground test environment (restored in 2011 with the support of the manufacturer SSBV in order to test upgrades developed for MSL, 7 years after its last use to test the Doppler mode patch), the MELACOM EM or the former FM spare, and a lander transponder model would be needed, before assessing any reliable development and validation schedule. This ground testing issue with associated expertise to troubleshoot potential problems is a key issue for the long term maintenance and upgrade perspective of operational relays at Mars.

IX. Conclusion

The close cooperation between ESA and NASA about a Martian Telecommunications Network has already given the opportunity to people from Mars Explorations Rovers, Phoenix, MSL and Mars Express teams, from Industry, from Flight Dynamics and Navigation teams, from RF Signal processing area and Ground Stations networks, from Mission Control Systems, and from protocols standardization committees, to work together. If we step back to early 2000 when ESA granted the contract of MELACOM to QinetiQ for a nominal Mars-Express mission lasting until November 2005, we can realize how far the collaboration has gone between the two agencies while discussing possible cross-supports between ODY, MRO, MAVEN, MEX, ExoMars, MERs, MSL with a timescale going around or beyond 2016.

The premise of the first interplanetary interagency network has been established at Mars and will remain as an invaluable asset for all future Mars missions. With the experience gleaned with the Mars Exploration Rovers, the Phoenix lander and the Mars orbiters, the requirements for operating such a wide, heterogeneous and long-lasting relay network infrastructure have expanded from a technical radio-link issue towards overall resources management, including robustness of the communications service, encapsulation of the transported data, planning and scheduling of the contacts and performance assessment of this new “network of networks” - a paradigm very close to the terrestrial Internet. Towards the end of the Mars golden decade 2001-2010, the Space Internetworking Strategy Group (SISG) of the International Operations Advisory Group (IOAG) established a Solar System Internet concept that is summarized in [SSI], as a roadmap for the hopefully also exciting next decade.

Acknowledgments

The authors thank the MER, PHX and MSL projects for providing an opportunity to implement step by step the premises of the interplanetary network at Mars including the MaROS relay coordination infrastructure, the Flight Dynamics teams for all the ad-hoc activities like provision of visibilities files, spacecraft pointings outside routine operations, the Mars Express science planning to have incorporated many relay activities within the daily science activities onboard, and Industry for their efforts to restore the ground tests means and make possible new developments for MELACOM’s functionalities. At last, ESA management to have allowed the test campaigns with the rovers, the support to the Phoenix mission, and for the coming support to MSL, to allow a good trade-off between the objectives of the Mars Express Science mission and the interest of a close collaboration between ESA and NASA around the red planet.

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