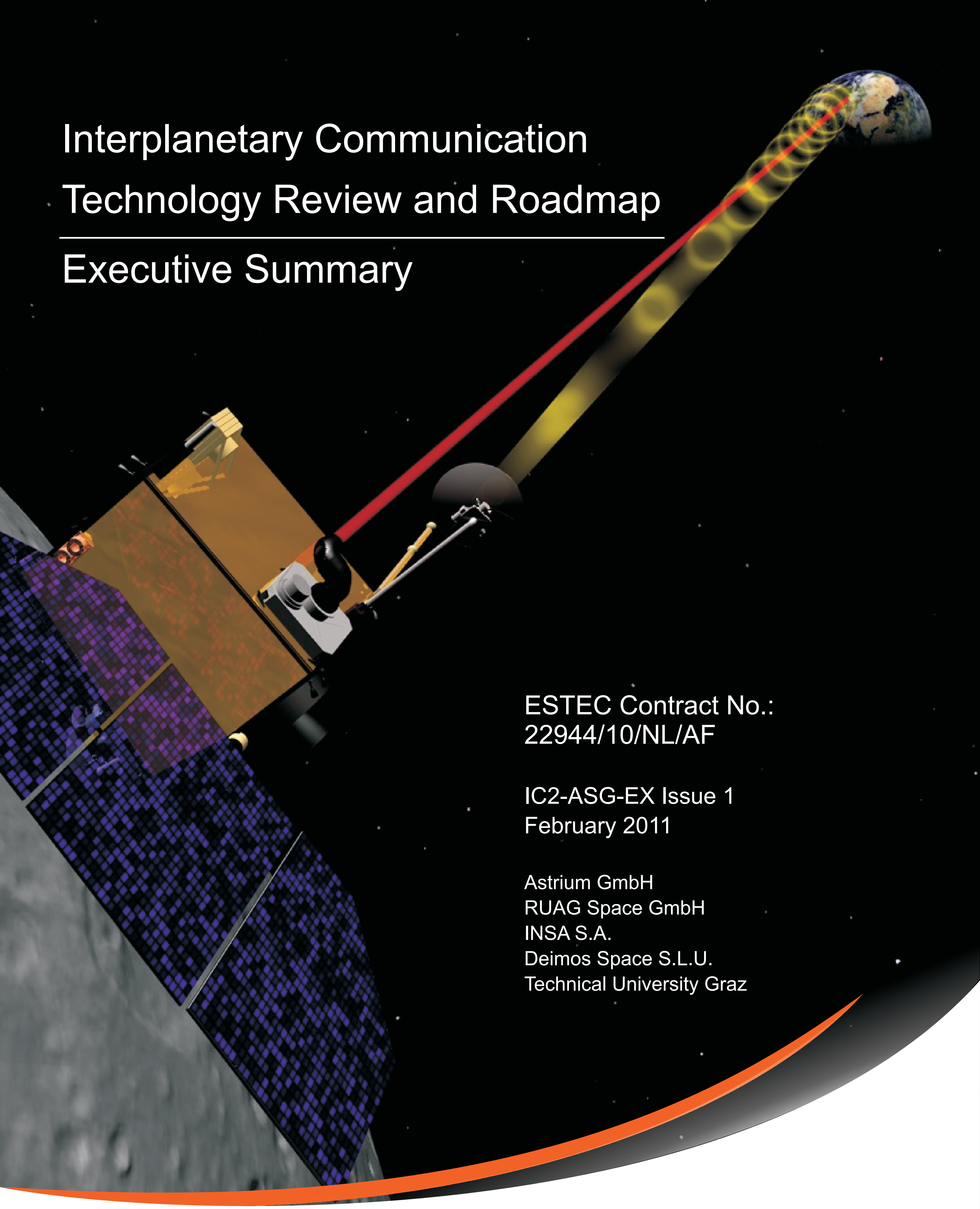

Interplanetary Communication Technology Review and Roadmap

Executive Summary

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RUAG Space GmbH
INSA S.A.
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1 Executive Summary

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- Study lead
- RF systems and protocols

INSA (Spain):

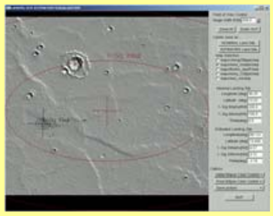
- RF ground segment

RUAG Space GmbH (Switzerland):

- Laser communication

DEIMOS Space S.L.U. (Spain):

- Navigation



Graz University of Technology (Austria):

- Consultancy on protocols

Above: Study team of Interplanetary Communications Technology Review and Roadmap

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Overview

1 Overview

Data transmission to Earth is a notorious bottleneck of interplanetary science and exploration missions. This situation is likely to intensify in the future because the next generation of scientific instruments will generate even higher data rates.

The goal of the study was to propose a technology development roadmap to enhance the communication capabilities of future interplanetary missions. During the study it was found that significant progress in the ESA communication capabilities can be enabled by a coherent set of technology development activities in the areas of radio-frequency (RF) communication systems, laser communication systems and communication protocols. Currently no clear preference can be given between RF and optical communications. Hence it is proposed that both technologies are developed in parallel during the first part of the technology programme until it becomes clear which of the two technologies is preferable considering the balance between performance and technology development risks. The key enabling technologies that have been identified are ground station arraying, large deployable antennas for spacecraft and high power amplifiers in the realm of RF technologies and high power pulse-position modulation laser systems and large photon-bucket-type ground stations for laser communications. The roadmap to develop these technologies foresees first activities in the second half of the year 2012, allowing sufficient time for the necessary programmatic decisions to be taken. The proposed roadmap extends for nearly one decade and hence presents a stable framework also for the development of ambitious technologies.

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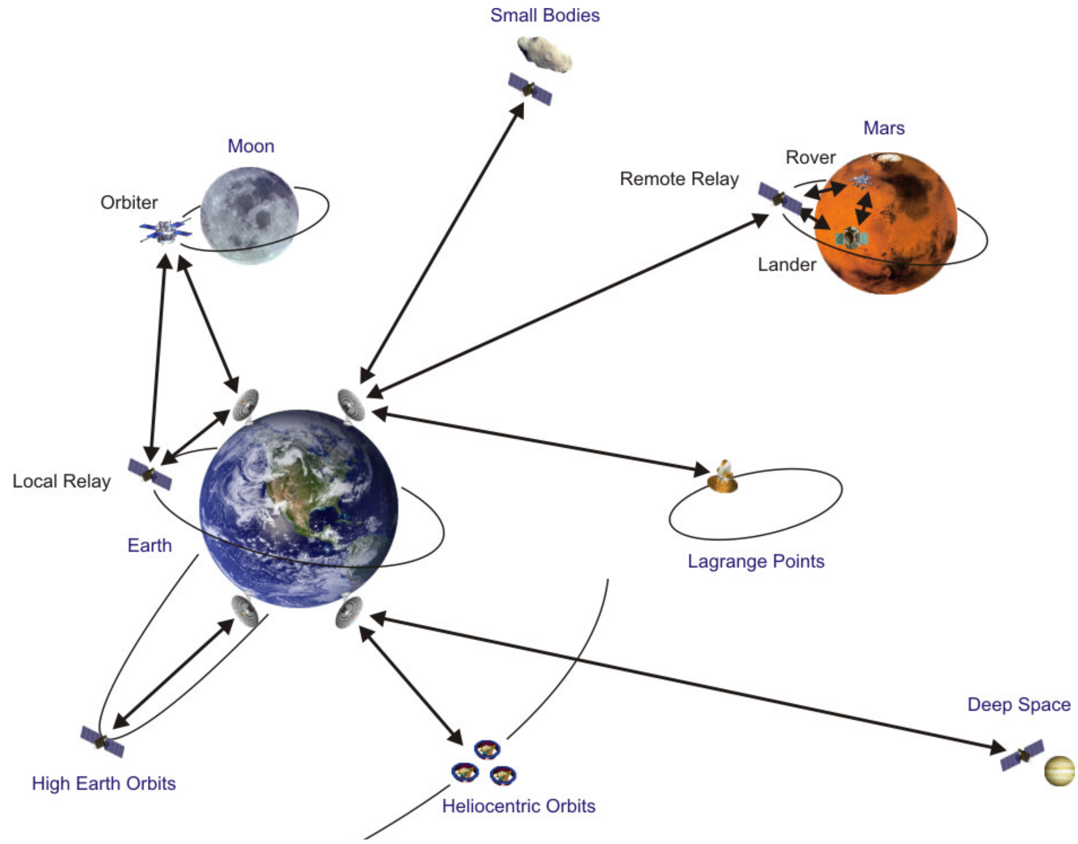

Above: Typical types of interplanetary mission and their communication links

Below: Link topologies of current interplanetary missions
(EoM - end of mission, op - operational, SnF - store and forward, TP - throughput).

Mission Name	Agency	Status	Links	Type of Relay	Topology
Current robotic Missions					
Phoenix	NASA	EoM	Lander ⇔ Ground Lander ⇔ Orbiter ⇔ Ground	SnF & TP	
Mars Exploration Rovers	NASA	op	Rover ⇔ Ground Rover ⇔ Orbiter ⇔ Ground	SnF & TP	
Selene	JAXA	op	Orbiter 1⇔ Orbiter 2 ⇔ Ground Orbiter 1 ⇔ Ground Orbiter 2 ⇔ Ground	TP	
Minerva	JAXA	EoM	Lander ⇔ Orbiter ⇔ Ground	TP	
Huygens	ESA	EoM	Lander ⇔ Ground Lander ⇔ Orbiter ⇔ Ground	TP	
Deep Impact Impactor	NASA	EoM	Impactor ⇔ Ground Impactor ⇔ Flyby ⇔ Ground	TP	
GRAIL	NASA	imp	Orbiter 1 ⇔ Orbiter 2 Orbiter 1 ⇔ Ground Orbiter 2 ⇔ Ground		

2 Communication Architectures

2.1 Current Communication Architectures

The current interplanetary missions of all space agencies are purely robotic. Today the typical interplanetary science and exploration missions are still single spacecraft missions. Examples of these types of missions at ESA are Venus Express, Herschel and Planck. The missions use a direct-to-Earth link for telecommunications and hence have the simplest possible communication architecture.

In addition to the single-spacecraft mission another class of interplanetary missions is common in which a larger spacecraft carries a lander or smaller space element that is deployed close to the mission's target. Recent examples of such missions are Mars Express with Beagle 2 (ESA), Rosetta with Philae (ESA), Cassini (NASA) with Huygens (ESA), Deep Impact, consisting of an Impactor and a fly-by spacecraft (NASA), Hayabusa with Minerva (JAXA) and Selene with 2 subsatellites (JAXA). Amongst the upcoming ESA missions, BepiColombo, carrying the JAXA MMO, and Exomars will belong in this category. For this type of missions it is common that the large spacecraft acts as a command and data relay for the smaller element. Depending on the available resources and other mission constraints the relay may even provide the only link to Earth. This was/is the case for all missions in the above list except Selene.

For the recent NASA Mars surface missions a different strategy was followed. For the Mars Exploration Rovers and the Phoenix lander, first a relay infrastructure in the form of the satellites Mars Global Surveyor and Mars Reconnaissance Orbiter was put in place. Both of these spacecraft have remote sensing as the main mission goal. In addition they are equipped with a UHF telecommunications system with which they can relay data from landers and low-altitude spacecraft to Earth. Both Phoenix and the Mars Exploration Rovers can communicate with Earth via a direct-to-Earth link albeit at a lower data rate than via the relay.

For the development of a technology roadmap for future interplanetary communications it is mandatory to consider also human missions. Since the Apollo programme no human interplanetary missions have been conducted. Hence there is no current communications architecture for human interplanetary missions. Nevertheless it is possible to derive the current capabilities for a putative communications architecture for human interplanetary missions. They can be derived by, on the one hand, studying the communication architecture of the Apollo missions and, on the other hand, analysing the communications architecture used on the International Space Station and extrapolating it to an interplanetary setting. From this a few constitutive rules for a communication architecture for interplanetary missions can be derived: Direct-to-Earth / direct-from-Earth links of extremely high availability are foreseen whenever geometrically possible. Relays are accepted when a direct link is not possible due to resource constraints, e.g. from an astronaut on an EVA to/from Earth, when viewing constraints prohibit a direct link (However it will be a strong system driver to avoid obstructions in the communications link and hence avoid this situation) or to provide a second link of higher data rate. For the latter case also links of more than one hop may be used. The use of two relays within a single link is used on the ISS when the communications during an EVA is routed via the Tracking and Data Relay Satellites (TDRS).

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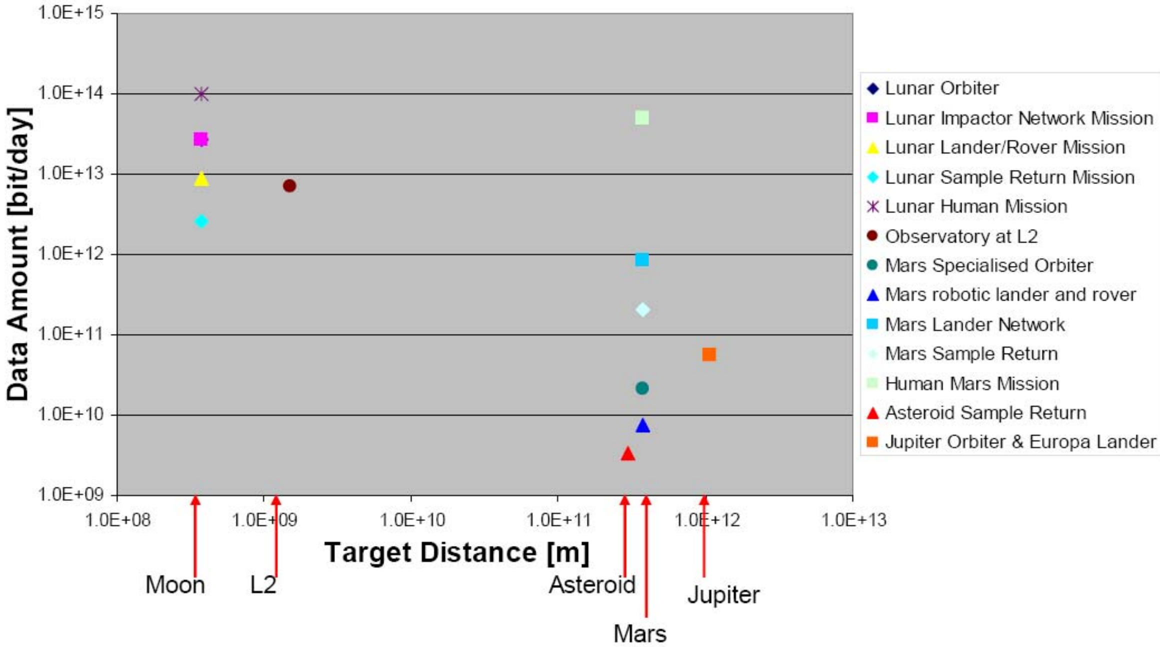
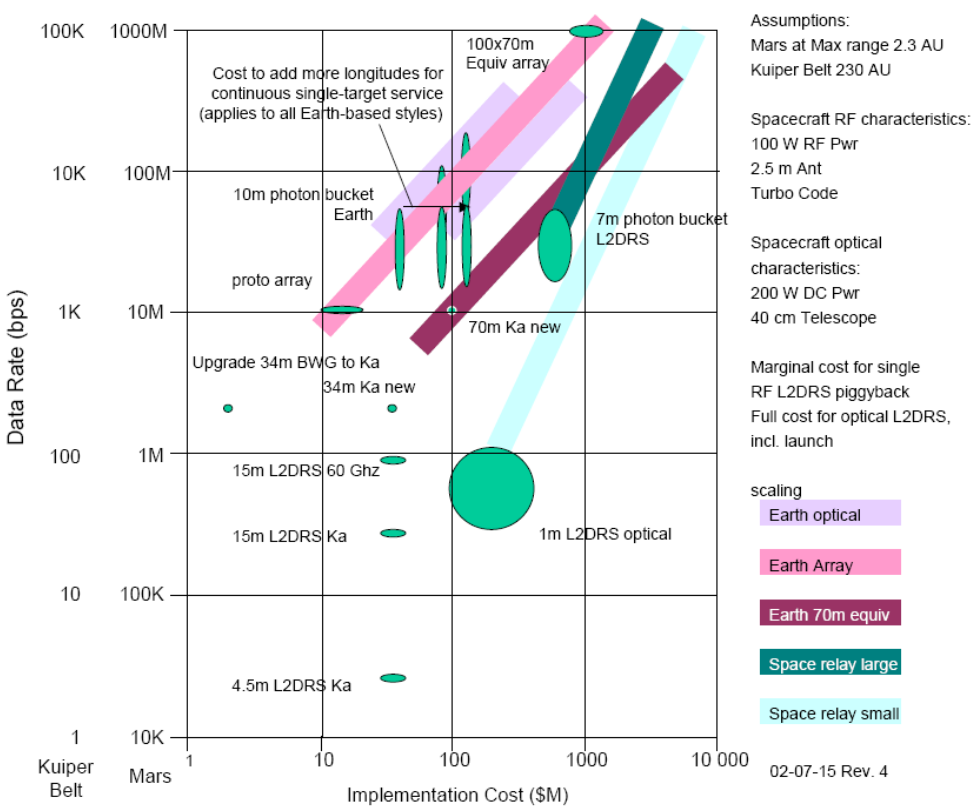


Above: Date rate demands of future interplanetary missions

Below:Performance vs. cost of different data transmission concepts
(source: Breidenthal, Townes SpaceOps 2002)



2.2 Communication-Architecture Drivers

The drivers for future communication architectures fall into three classes: Improvement of telecommunication performance, reduction of operational cost and support of more complex missions.

The improvement of telecommunication performance demands an increase of the transmitted data volume on interplanetary links. Modest increases in the transmitted data volume can be accomplished by an increase of contact time. Larger increases require increases in the data rate that can only be accomplished by improvements in telecommunication technologies.

Another driver is the reduction of operational cost. This is most straightforwardly accomplished by increasing spacecraft autonomy and reducing contact times. Of course, this approach is contradictory to the whish to downlink larger data volumes. Operations cost can also be reduced by using smaller and hence less costly ground stations in phases where data rates are low, e.g. during interplanetary transfer. The ultimate step would be the use of ground station arrays in which aperture could be tailored on demand to the present needs of a certain mission.

Future robotic missions will be more complex than the currently operational ones. In particular they will regularly consist out of several elements that will need to communicate with each other. Examples of such missions are combinations of orbiter and lander and networks of landers and orbiters. For resource reasons and due to constraints from the mission environment it will not be possible to equip all elements with communication equipment for a direct link to Earth. Instead one of the elements will feature a particularly powerful communication system and will act as a relay for the other elements. The element with the powerful communications system may well be a dedicated communication relay. The complexity of missions will further increase with the advent of human interplanetary missions.

2.3 Strength-Weakness Analysis

A strength-weakness analysis for the various aspects of interplanetary communication systems has been carried out. Its results can be outlined as follows: Europe is competitive with other major agencies such as NASA and JAXA considering the system capabilities. If one takes a more granular view and considers equipment and components level then the picture becomes more heterogeneous. For a number of equipments European/Canadian technology is lagging behind technology in the United States (US). On the other hand Europe is leading in some equipment classes.

Concerning research in advanced technologies Europe and Canada show definite weaknesses. Led by NASA/JPL the US have a lively research programme concerning interplanetary communications that covers all aspects of interplanetary communications, including RF space segment, RF ground segment, laser communications, navigation and communication protocols.

In Europe/Canada no comparable research programme exists. Within its ARTES programme ESA fosters research and development of communication technologies. Currently this programme is entirely devoted to near-Earth communications up to GEO and no interplanetary activities are supported. Consequently, advances in interplanetary communications are currently relying on dedicated developments for selected missions such as the development of a Ka-band deep-space transmitter and ground segment for Bepi-Colombo. The early phases of such developments are typically supported by ESA's Technology Reasearch Programme.

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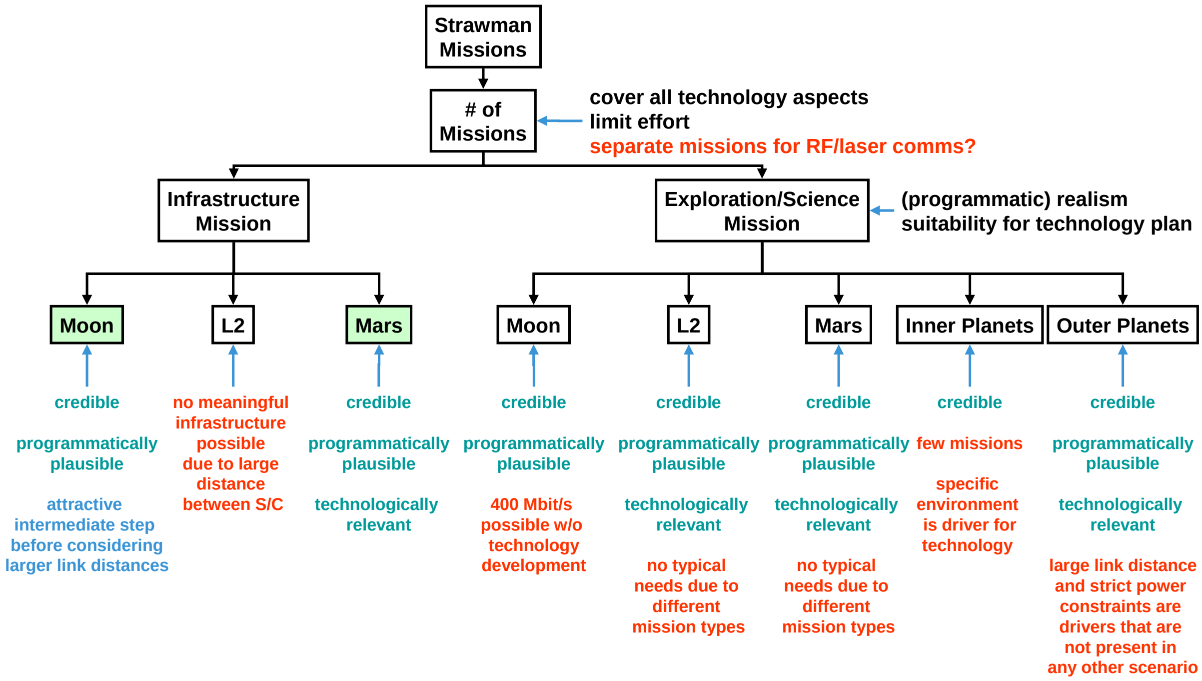
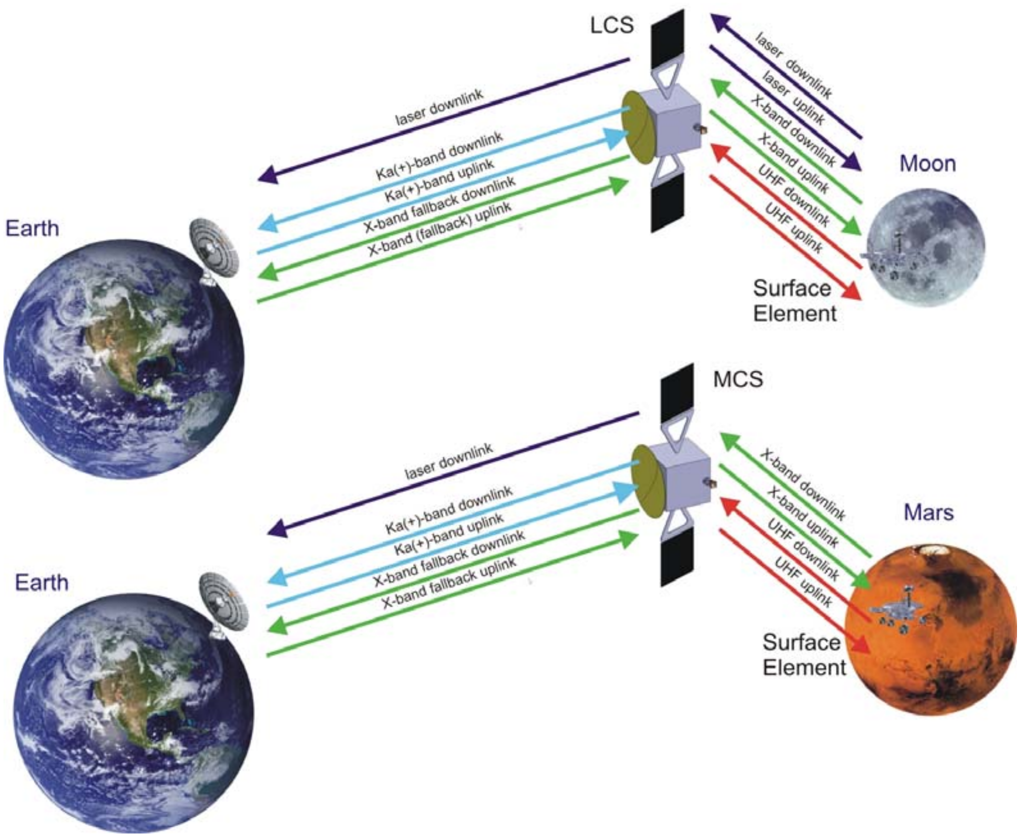


Above: Trade-off for the selection of the strawman missions.

Below: Link architectures of the strawman missions



3 Strawman Missions

The analysis of the current architectures has clearly shown that only a rather slow development will take place unless the development and application of new technologies is actively fostered. On the other hand a dedicated development programme will only be useful if the technologies are applicable for a broad range of missions. In order to assure the broad utility of the technology roadmap developed in the study, two strawman missions have been selected to which the technology developments are tied.

Two principle types of missions can be considered for the strawman missions, science and exploration missions on the one hand and infrastructure missions on the other hand. Science and exploration missions are the classical type of interplanetary missions that have flown up to now: A single spacecraft or a set of spacecraft form a mission that does not interface with other missions.

An infrastructure mission has the goal to support other missions in fulfilling their mission goals. Examples of infrastructure missions in Earth orbit are relay satellites such as Artemis and TDRS.

In a trade-off the following missions have been considered as strawman missions

- Lunar Communication Satellite (LCS),
- Mars Communication Satellite (MCS),

because they best fulfil the following suitability criteria for a strawman mission:

- crediblilty in sense of presenting a consistent mission scenario,
- programmatical plausibility,
- technological relevance,
- avoidance mission specifics, which make its communication technologies inapplicable for other missions.

The full trade-off is summarised in a graphical manner on the upper left side. For the lunar communications satellite (LCS) a launch in 2020 is considered and for the Mars Communication Satellite (MCS) a launch in 2024 is foreseen. For both of these missions, the primary mission goal is providing communications and navigation services to other interplanetary mission. In particular, the mission requirements are formulated in such a way that the performances of both the LCS and the MCS would be able to support human missions.

For the LCS the main requirements are to provide a downlink data rate to Earth of 2 Gbps and provide navigation services at an accuracy in the order of 10 m (1σ) for elements on the lunar surface. For the MCS the key requirements were to provide a downlink data rate to Earth of 50 Mbps at any Earth-Mars distance and to provide navigation services at an accuracy in the order of 10 m (1σ) for elements on the Mars surface.

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LCS Parameters	RF1	RF2	Laser	Remark
Long-haul				
Frequency [GHz] / Wavelength [nm]	27.3	37.5	1550	
Telecommunications				
Data rate [Mbps]	2000	2000	2000	
LCS Aperture [m]	1	1	0.135	
Transmit power [W]	2x100	2x100	2x5	
GS eff. Aperture [m]	12	12	1	
Link directionality	two-way	two-way	LCS -> Earth	
Navigation				
Doppler error [m/s]	1.E-05	1.E-05	N/A	
Ranging error [m]	0.2	0.2	0.01	
Resources				
Mass	32	32	49	w/o margin, Ka/Ka+ is fully redundant
Power	531	531	425	w/o margin
Short-haul				
Frequency [GHz] / Wavelength [nm]	8.15	0.4	1064	
Telecommunications				
Data rate [Mbps]	150	50	2x250	
LCS Aperture [m]	0.5	6 dBi patch	0.035	
Transmit power [W]	100	100	2x0.15	
GN Aperture [m]	0.5	6 dBi patch	0.135	
Link directionality	two-way	two-way	two-way	
Navigation				
Doppler error [m/s]	5.E-04		N/A	UHF navigation was not considered
Ranging error [m]	0.03		0.01	UHF navigation was not considered
Resources				
Mass	29	10	31	same system at LCS and ground node
Power	257	192	184	same system at LCS and ground node

Above: Key parameters of the design of the Lunar Communication Satellite

Below: Key parameters of the design of the Mars Communication Satellite

MCS Parameters	RF1	RF2	Laser	Remark
Long-haul				
Frequency [GHz] / Wavelength [nm]	32	37.5	1550	
Telecommunications				
Data rate [Mbps]	50	50	2x25	
MCS Aperture [m]	10	10	0.38	
Transmit power [W]	2x100	2x100	2x10	
GS eff. Aperture [m]	100	100	17	RF realised by 4x35 m array
Link directionality	two-way	two-way	two-way	
Navigation				
Doppler error [m/s]	1.E-05	1.E-05	N/A	
Ranging error [m]	0.2	0.2	0.01	
Resources				
Mass	231	231	147	w/o margin, Ka/Ka+ is fully redundant
Power	517	517	349	w/o margin
Short-haul				
Frequency [GHz] / Wavelength [nm]	8.15	0.4		
Telecommunications				
Data rate [Mbps]	15	40		
MCS Aperture [m]	0.5	6 dBi patch		
Transmit power [W]	50	50		
GN Aperture [m]	0.5	3 dBi low gain		
Link directionality	two-way	two-way		
Navigation				
Doppler error [m/s]	5.E-04		N/A	UHF navigation was not considered
Ranging error [m]	0.03		0.01	UHF navigation was not considered
Resources				
Mass	29	10		Same system at MCS and ground node
Power	150	192		Same system at MCS and ground node

4 Strawman missions requirements and design

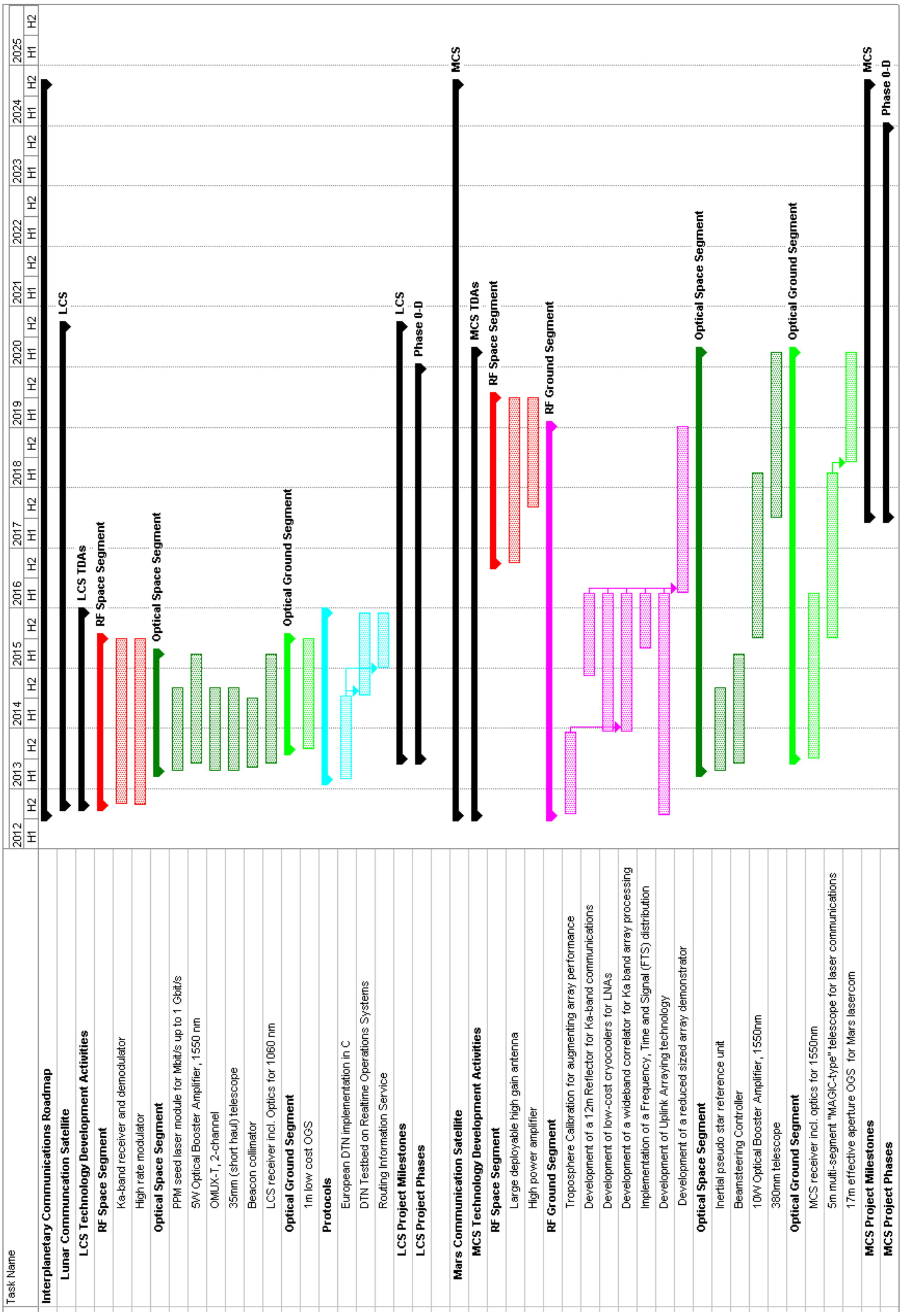
The main figure of merit for the performance of the LCS and the MCS is the data rate they can transmit. The driver for the MCS data rate requirement is the need to support human missions towards the end of its lifetime. For human missions the major driver for the data rate will be the public interest in the mission. In order to satisfy it, the human missions will want provide high quality video of the Mars surface activities. In particular for the initial activities it will be highly desirable to provide the video as a live-stream. To be specific we assume that a 3D video stream of 4k digital cinema format needs to be transmitted. This results in a data rate of 50 Mbps. Significantly higher data rate requirements arise from high-resolution multi-spectral global mapping missions to the Moon. As a consequence a data rate of 2 Gbps is required for the LCS in order to be able to support high resolution multi-spectral mapping missions.

For the both strawman missions the design of the communication system has been carried out. For the LCs, the long-haul link between Earth and the short-haul link between LCS and the lunar surface have been considered. For both links, designs for an RF-system and for a laser communication system have been carried out. All of the designs were found feasible with some limitations: The RF long-haul system would require a bandwidth that is unlikely to be available considering ITU restrictions. For short-haul links to the far side of the Moon a laser link is the preferred solution in order to maintain the lunar far side as a radio-quiet zone for radio astronomy applications. However, a short-haul link based on laser communications seems to require terminals on the lunar surface that are too resource hungry for small robotic missions. As for the LCS, the design of the communication system has been carried out for the MCS. Both the long-haul link between Earth and MCS and the short-haul link between MCS and the Mars surface have been considered. For the long-haul link, designs for an RF-system and for a laser communication system have been considered. For the short-haul links several RF systems have been considered. The key parameters of the designs of both strawman missions are displayed to the left.

5 Technology roadmap

A technology development schedule has been derived for the two strawman missions in a bottom-up approach. This is done in three steps. First the product tree for the communications systems of the strawman missions is established. Next, for the items with a low technology readiness in the product tree the appropriate technology development activities (TDAs) are defined. Finally the TDAs are put into an appropriate sequence to arrive at a consistent development schedule. While a TDA is drafted in any case, it is also analysed for which item a TDA may be omitted in favour of procurement outside of ESA and Canada.

For the space segment, ground segment and protocols software of the communication system of the strawman missions a detailed product tree has been established, containing more than 100 elements per strawman mission. Based on this detailed breakdown, focus is put on all items that have a TRL below 5 within ESA and Canada, i.e. all items for which no demonstration in a relevant environment has been carried out.



Above: Schedule of the Interplanetary Communications Technology Development Roadmap

5 Technology roadmap

For the LCS the focus of technology development is on the space segment. For the RF system, higher power TWTAs and modulators for an appropriate data rate need to be developed. In addition also demodulators in Ka-band for the receive chain are currently not available within ESA and Canada. For the optical communication system a significant number of elements is still at a low TRL. Major drivers are the optical booster amplifier and optical transmit multiplexer.

For the MCS it is assumed that the low-TRL items of LCS have successfully been developed and are available for use with the MCS. Still similar technology issues arise for the space segment of the MCS as for that of the LCS. For the MCS even higher transmit powers are required both, in RF and in the optical. Hence the amplifiers will again require technology development. For the RF system, in addition, a 10 m deployable high gain antenna will be required that is currently not available within ESA member states and Canada.

In addition, major efforts are required in ground segment technologies to enable the performance desired for the MCS. For the RF ground segment downlink arraying is mandatory. A whole set of technology development activities will be required to develop the technologies for ground segment arraying. For the optical ground segment an effective aperture of about 17 m is required which is also preferably implemented as an array of several smaller telescopes.

In order to make the required technologies available for the strawman missions, dedicated technology development activities need to be established. Considering tentative need dates for the technologies within the strawman mission projects the schedule for the TDAs can be established. The overview schedule displaying the sequencing of all TDAs is presented to the left. Several features of the overall TDA schedule strike the eye: While the schedule has been established bottom up based on the two disjunct strawman missions, no gaps and breaks in the TDA activities are visible. On the contrary, nearly all TDAs foreseen for the LCS will also be required for the MCS. This is a consequence of the increasing technical difficulty that has been underlying the selection and sequencing of the strawman missions. Despite the four-year gap between the launch dates of the strawman missions, TDAs for both missions are foreseen to start in the 3rd quarter of 2012. LCS mainly requires TDAs concerning space segment technologies but little effort on the ground segment. For MCS TDAs both, in the realm of the ground segment and in the realm of the space segment, are required.

These finding suggest a different perspective on the established schedule: Rather than considering it as a schedule for providing the technology to certain strawman missions it can be seen as a generic technology roadmap. It proposes the parallel development of space segment, ground segment and protocols technologies to enhance the capabilities of future interplanetary missions. This can easily be verified by considering other interplanetary missions and testing them for the applicability of the technologies to be developed in the roadmap. Obviously, this applicability is fully given as can be seen by considering the usefulness of high-rate Ka-band or laser communication system for future astronomical telescope missions or the potential of large deployable antennas for robotic missions to the giant planets.

Other features of the TDA schedule support its generic applicability as a technology development roadmap for interplanetary communications. The start date of the first TDAs in the roadmap is late enough to allow a programmatic review and decision making to incorporate it within ESAs technology programmes. The end date of the last technology activities in 2020 is early enough not to overstress the patience of decision makers but far enough in the future to provide a stable environment for technology development.