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1. INTRODUCTION

1.1 PURPOSE

The purpose of this document is the description of baseline communications systems for the exploration of the moon, of Mars and of other solar system bodies.

1.2 SCOPE

This report provides descriptive material only: **it is not part of a Recommended Standard**. This report addresses the physical and data link layer features of the communications systems under consideration.

The communications systems for the moon and Mars regions cover:

- Links between relay orbiters and the surface
  These include links between relay orbiters and landers and any kind of surface elements, be they fixed, like communication terminals or base stations or mobile like rovers and EVAs.
- Surface-surface communications
  These include any links between elements on the surface, be they base stations, relays, rovers, EVAs, … for distances from zero to a few 10s kms. Some of these surface-surface links will be relayed via orbiters to ensure a good continuity of service.
- Orbiter-to-orbiter communications

  Note: Direct surface–to-Earth communications and Orbiter-to-Earth communications are not addressed in this document.

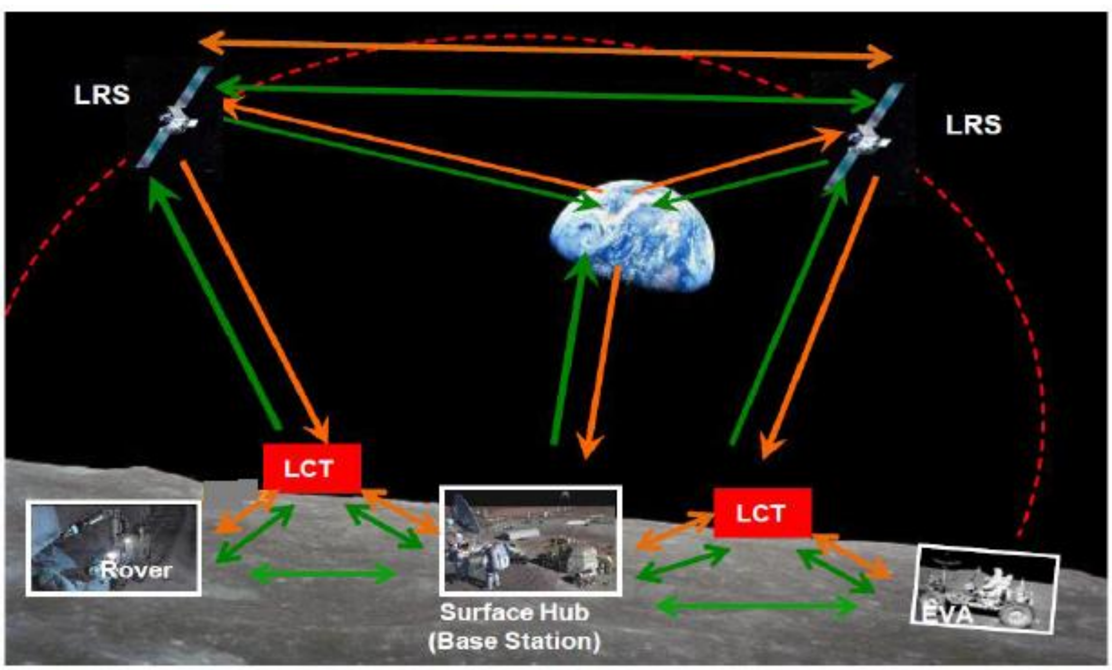

Figure 1: Example lunar local communications

1.3 ORGANISATION OF THE REPORT

This document is organized as follows.

Section 2 addresses agencies missions needs for moon, Mars and other bodies exploration.

Section 3 derives, from the needs expressed in section 2, the high level mission and system requirements for the moon, Mars and other bodies exploration missions.

Section 4 provides the links description, covering physical layer and data link layer parameters.

1.4 REFERENCES

The following documents are referenced in this Report. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Record are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS documents.

[1] **CCSDS 401.0-B-23** ***Radio Frequency and Modulation Systems--Part 1: Earth Stations and Spacecraft.*** **Blue Book. Issue 22. January 2013.**

[2] **CCSDS 413.0-G-2** ***Bandwidth-Efficient Modulations: Summary of Definition, Implementation, and Performance.*** **Green Book. Issue 2. October 2009.**

[3] **CCSDS 414.1-B-1** ***Pseudo-Noise (PN) Ranging Systems.*** **Blue Book. Issue 1. March 2009.**

[4] **CCSDS 414.0-G-1** ***Pseudo-Noise (PN) Ranging Systems.*** **Green Book. Issue 1. March 2010.**

[5] **CCSDS 415.0-G-1** ***Data Transmission and PN Ranging for 2 GHz CDMA Link via Data Relay Satellite.*** **Green Book. Issue 1. April 2013.**

[6] **CCSDS 131.0-B-2** ***TM Synchronization and Channel Coding.*** **Blue Book. Issue 2. August 2011.**

[7] **CCSDS 131.2-B-1** ***Flexible Advanced Coding and Modulation Scheme for High Rate Telemetry Applications.*** **Blue Book. Issue 1. March 2012.**

[8] **CCSDS 131.3-B-1** ***CCSDS Space Link Protocols over ETSI DVB-S2 Standard.*** **Blue Book. Issue 1. March 2013.**

[9] **CCSDS 131.4-M-1** ***TM Channel Coding Profiles.*** **Magenta Book. Issue 1. July 2011.**

[10] **CCSDS 130.0-G-2** ***Overview of Space Communications Protocols.*** **Green Book. Issue 2. December 2007.**

[11] **CCSDS 130.1-G-2** ***TM Synchronization and Channel Coding--Summary of Concept and Rationale.*** **Green Book. Issue 2. November 2012.**

[12] **CCSDS 210.0-G-1** ***Proximity-1 Space Link Protocol—Rationale, Architecture, and Scenarios.*** **Green Book. Issue 1. August 2007.**

[13] **CCSDS 211.0-B-4** ***Proximity-1 Space Link Protocol—Data Link Layer.*** **Blue Book. Issue 4. July 2006.**

[14] **CCSDS 211.1-B-3** ***Proximity-1 Space Link Protocol—Physical Layer.*** **Blue Book. Issue 3. March 2006.**

[15] **CCSDS 211.2-B-1** ***Proximity-1 Space Link Protocol—Coding and Synchronization Sublayer.*** **Blue Book. Issue 1. April 2003.**

[16] **CCSDS 230.1-G-2** ***TC Synchronization and Channel Coding--Summary of Concept and Rationale.*** **Green Book. Issue 2. November 2012**

[17] **CCSDS 231.0-B-2** ***TC Synchronization and Channel Coding.*** **Blue Book. Issue 2. September 2010**

[18] **CCSDS 232.0-B-2** ***TC Space Data Link Protocol.*** **Blue Book. Issue 2. September 2010.**

[19] **CCSDS 132.0-B-1** ***TM Space Data Link Protocol.*** **Blue Book. Issue 1. September 2003.**

[20] **CCSDS 732.0-B-2** ***AOS Space Data Link Protocol.*** **Blue Book. Issue 2. July 2006.**

[21] SFCG HANDBOOK **2014**
https://www.sfcgonline.org/resources/default.aspx

[22] CCSDS 880.0-G-1 ***Wireless Network Communications Overview For Space Mission Operations.*** **Green Book. December 2010.**

[23] **Draft Communication and Navigation Systems Roadmap, J. Rush, NASA,**
http://www.nasa.gov/pdf/501623main_TA05-CommNav-DRAFT-Nov2010-A.pdf

[24] **Lunar Surface Propagation Modeling and Effects on Communications**
Dr. Shian U. Hwu, Matthew Upanavage, Catherine C. Sham
26th International Communications Satellite Systems Conference (ICSSC), 10 - 12 June 2008, San Diego, CA
http://ntrs.nasa.gov/search.jsp?R=20080015374

[25] **NASA Lunar Base Wireless System Propagation Analysis**
Shian U. Hwu*, Barrios Technology, and Matthew Upanavage, ERC Inc., Houston, TX 77058 Shian.u.hwu@nasa.gov
Catherine C. Sham, NASA Johnson Space Center, EV7, Houston, TX 77058
http://ntrs.nasa.gov/search.jsp?R=20070016709

2. AGENCIES NEEDS FOR MOON, MARS AND OTHER BODIES EXPLORATION

2.1 BACKGROUND

Over the past decades, several agencies launched missions to the moon, to Mars and also to other planets like Saturn, Venus, Mercury, Jupiter, as well as to asteroids. Over the years, instruments onboard these spacecraft became more and more complex, delivering more and more scientific data and thus demanding more and more capacity for the transmission medias. State-of-the-art telecommunications technologies were used wherever possible, but still the demand is growing and the development pace must be maintained so that space telecommunication systems always provide all the support necessary for the projects to fully benefit the potential science return offered by their missions.

CCSDS is the unique environment allowing development and maintenance of cross-support between all space missions. The cooperation between agencies for the Mars missions over the past 15 years showed the potential offered by international cooperation. Though fully successful, the cooperation was at a rather low scale as compared with what is planned for the years to come, going up to manned missions to the moon and to Mars in the horizon 2030/2040.

The past decade saw a tremendous development of terrestrial telecommunication systems technologies, covering as well the physical layers (modulation, coding) as the networking layers (internet, …). It is important that CCSDS exploits these new technologies, adapts them to the space environment and makes them available to the space community to fulfill the needs of future missions.

With the current available information, one can anticipate robotic-only missions to the moon up to years 2025-2030 and the first manned missions beyond these dates. In the case of the exploration of Mars, the first manned missions are expected beyond 2040.

2.2 LUNAR MISSIONS

Lunar missions are expected to be the first step towards planetary exploration. So far, missions to the moon remain individual actions of agencies, with one single orbiter and at most one or two landers. The most spectacular missions to the moon were, of course, the NASA manned missions in the late 1960s and in the 1970s. However, these were one-agency, one orbiter/lander types of mission which did not require inter-agencies collaboration in these times. To the contrary, the moon exploration plans for the coming decades foresee multiple agencies involved in the deployment of multiple elements on the lunar surface, supported by several in-orbit relays. Satisfying the needs of such missions will require the use of new frequency bands, new modulation, coding techniques, more advanced protocols and novel system architectures but also inter-agencies coordination and cooperation. The related new CCSDS SLS standards are aimed to cover several generations of lunar missions, and therefore to be provided with an extended flexibility and networking capacity, in order to cover the needs of the lunar infrastructure up to the horizon 2050. This goal concern protocol layers of level 2 (data link) and 1 (frequency, coding and modulation) .

2.3 MARS MISSIONS

It is expected that the needs for Mars exploration will resemble those for moon exploration, though they will be coming later in time. It is therefore likely that a large part of the development performed for lunar exploration will be reusable for Mars exploration. Important communication standard changes are expected vis-a-vis current martian communication techniques, in conjunction with manned missions or with significant growing number of sensors on the martian surface.

2.4 OTHER SOLAR SYSTEM BODIES

It is expected that other solar system bodies (in addition to the Moon and Mars) to be equipped with network of sensors are asteroïds (in particular geocruising ones like Apophis, Phobos and Deimos) and comets. Europa, Callisto, Ganymede, Enceladus, Japetus, Titan, …are also examples of bodies potentially concerned by at least robotic surface exploration before 2050.

3. HIGH LEVEL REQUIREMENTS FOR MOON, MARS AND OTHER BODIES EXPLORATION

3.1 BACKGROUND

The Space Frequency Coordination Group (SFCG) investigated the needs and high level requirements from agencies concerning the exploration of the moon and of Mars. The results of these studies are detailed in two recommendations:

- *Recommendation SFCG 32-2*
  COMMUNICATION FREQUENCY ALLOCATIONS AND SHARING IN THE LUNAR REGION
- *Recommendation SFCG 22-1R1*
  FREQUENCY ASSIGNMENT GUIDELINES FOR COMMUNICATIONS IN THE MARS REGION

These recommendations are, today, the most complete and the most reliable material regarding agencies requirements on communications systems for the future exploration of the moon and of Mars.

The contents of these recommendations are reflected in section 3 of this document.

3.2 **REQUIREMENTS FOR LUNAR** EXPLORATION

3.2.1 LUNAR MISSIONS REQUIREMENTS

A Lunar communication system in 2050 shall provide the following missions, which could progressively be fulfilled up to 2050.

The system includes the Ground End Users (GEU) which can be astronauts or lunar manned outposts, or unmanned like robotic landers, rovers, penetrators, or shelters, automated stations, etc …

The system includes a constellation of Lunar Relay Satellites (LRS) to relay astronauts on surface or in orbiting module at low altitude, and unmanned GEUs according to the following missions

Any astronaut (manned GEU) in EVA on the moon surface shall be able to be in real time radio-contact with the earth, with manned lunar outposts, and with any other astronaut in EVA, whatever his position on the moon surface. In particular, when direct surface-surface communication with the base station is not possible, an alternative link shall be available, e.g. via a relay satellite.

Any astronaut shall be able to communicate with another astronaut in his line-of-sight, without the need of a relay. This requirement is in particular applicable for two astronauts in a crater, where temporary masking of surface-surface communications with the base station may occur.

Any astronaut on the moon surface shall be able to know in real time its position, whatever its position on the moon surface with an accuracy compatible with the mission needs and the security requirements.

Any lunar manned outpost and the earth control center shall know the position of any astronaut on the lunar surface with an accuracy compatible with the mission needs and the security requirements.

Any lunar manned outpost shall be provided with an elevated Base Stations (BS) relaying communications in the vicinity of the lunar manned outpost.

Any lunar region subject to intensive surface exploration shall be provided with one or several elevated Base Stations relaying communications in the said region.

Any unmanned GEU on the moon surface shall be able to communicate with a manned lunar outpost, except when there is no radio visibility with any communicating object of the lunar communication infrastructure. Some unmanned GEU on the moon surface shall be able to communicate with the earth.

Any lunar manned orbital module shall be able to communicate with the Earth, and with any lunar manned outpost targeted for landing when visibility is ensured.

Life-critical communication systems shall meet the safety-of-life requirements.

Communication systems shall be able to support Wireless sensor networks (WSN) of 'star' topology (Figure 2, Figure 3) and of 'multi-hop mesh' topology (Figure 4). The deployment of WSNs will allow the detailed characterization of the surface of the moon.

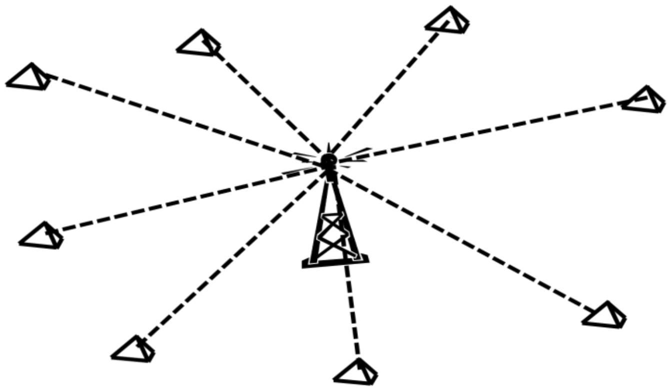

Figure 2 : WSN Star topology, surface gateway

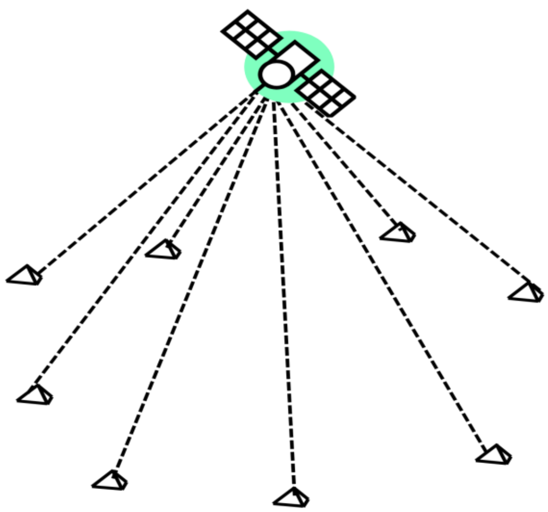

Figure 3: WSN Star topology, in-orbit gateway

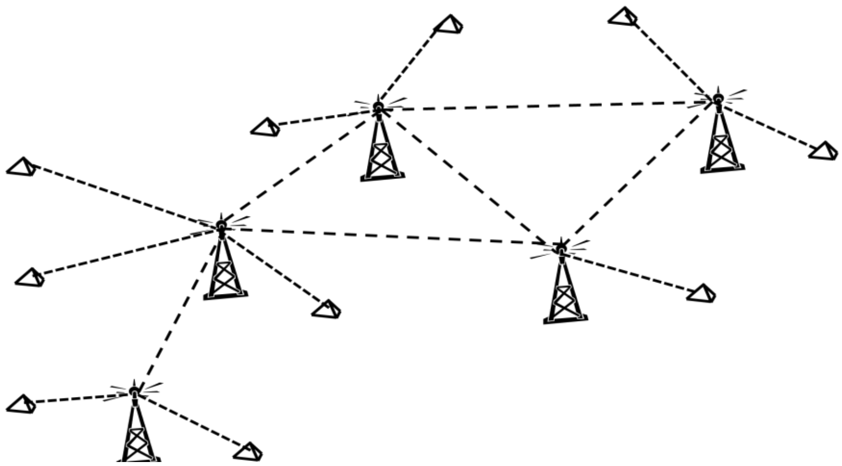

Figure 4: WSN multi-hop mesh topology

3.2.2 LUNAR SYSTEMS REQUIREMENTS

This section presents an exhaustive list of requirements on lunar communications, jointly agreed by all world space agencies. It shall be taken as baseline requirements for lunar exploration in the timeframe of at least 2020-2040. Any changes to these requirements would have to be submitted to space agencies in the SFCG for approval.

3.2.2.1 Background

The choice of technical solutions for the lunar exploration communications infrastructure is driven by several factors:

1. The system architectures are driven by mission requirements. The lunar local communications systems shall include:
    - Lunar Communication Terminals (LCT) which provide the communication interface between the elements on the lunar surface, e.g. base stations, EVAs, rovers, … and the LRS in lunar orbit
    - Lunar Relay Satellites (LRS) to relay communications between Lunar Communication Terminals (LCT) on the moon surface and the Earth
    - Base stations which interface with elements on the lunar surface and can communicate with the Earth either directly or via a LRS
    - Surface elements
2. The selection of frequency bands is dictated by inter-agencies agreements that took place a few years ago.
    - A priority is given to frequencies with a space research (SR) allocation; RF compatibility with other space missions operating in the same bands is being assessed
    - On a case-by-case basis, a few non-SR bands were declared usable, provided that evidence is made of no risk of interference to terrestrial users of the band
    - No band not earmarked by agencies in the frame of the SFCG may be considered for lunar communications. If it happens that a new frequency band

needs to be introduced, a dossier shall be submitted to all agencies concerned, identifying the need that cannot be covered by existing allocations, showing the benefits brought by that new band and making evidence that regulatory issues can be resolved.

3. The choice of technologies is driven by technical and economical considerations, as well as by the timeline.
    - The timeline for a deployment of a first generation exploration mission to the moon is 2025 and beyond, with, before that time, a few individual initiatives that may not require extensive cross-support but might want to embark new technologies in preparation for a future larger scale deployment
    - Existing communication techniques shall be reused if deemed not obsolete by the year 2020 and beyond, so as to reuse, to the extent possible, existing flight hardware and Earth infrastructures
    - Terrestrial technologies shall be considered for use in space, like wireless or other technologies for surface communications; care shall be taken that they are not obsolete by the time they have to be adapted to the lunar environment
    - The safety-of-life issues which place stringent requirements on the communication systems.

The bands earmarked by SFCG and their attributions are listed in Table 1.

Link	**Frequency**
Earth to Lunar Orbit	2025-2110 MHz 7190-7235 MHz 22.55-23.15 GHz 40.0-40.5 GHz
Lunar Orbit to Earth	2200-2290 MHz 8450-8500 MHz 25.5-27.0 GHz 37-38 GHz
Earth to Lunar Surface	2025-2110 MHz 7190-7235 MHz 22.55-23.15 GHz
Lunar Surface to Earth	2200-2290 MHz 8450-8500 MHz 25.5-27.0 GHz
Lunar Orbit to Lunar Surface	390-405 MHz 2025-2110 MHz 2483.5-2500 MHz 22.55-23.15 GHz
Lunar Surface to Lunar Orbit	435-450 MHz 1610-1626.5 MHz 2200-2290 MHz 25.5-27 GHz
Lunar Surface Wireless Network	390-405 MHz

	435-450 MHz 2.4-2.48 GHz 37-38 GHz 40-40.5 GHz
Lunar Relay to Lunar Relay Cross Link	13.75-14 GHz 14.5-15.35 GHz 22.55-23.55 GHz 25. 5-27 GHz 37-38 GHz 40-40.5 GHz

Table 1: Frequency Bands for Lunar Exploration

The following bands have a space research (SR) allocation in the ITU Radio Regulations:

2025-2110 MHz / 2200-2290 MHz
7190-7235 MHz / 8450-8500 MHz
13.75-14 GHz / 14.5-15.35 GHz
25. 5-27 GHz
37-38 GHz / 40-40.5 GHz

The following bands have an inter-satellite allocation:

22.55-23.55 GHz / 25. 5-27 GHz

The following bands may be used for local communications provided that it can be demonstrated that they cannot be cause of interference to terrestrial users of the band:

390-405 MHz / 435-450 MHz
1610-1626.5 MHz / 2483.5-2500 MHz

The following band is an ISM band:

2.4-2.48 GHz

3.2.2.2 Lunar orbit – lunar surface

Depending on the application, links between moon orbit and moon surface shall support data rates ranging from 1 kbps for small elements like probes or rovers to 400 Mbps for LCTs.

Frequency Band	Users	Service Type	Data Rate per User	Number of Users	Notes
390-405 MHz (LO-LS)	Orbiter, Lunar Module, Rover, Lander	Command	1 kbps	3	(1)
435-450 MHz	Orbiter, Lunar Module, Rover,	Data/ Telemetry	8 kbps, 32 kbps, 1Mbps	3	(1)

(LS-LO)	Lander				
1610-1626.5 MHz (LS-LO)	Rover – LGEP	Voice/ TT&C / Data (comm. & nav)	10 kpbs (bi-directional)	> 10	Orbiters used as relays (2) (3)
	EVAs	Voice/ TT&C / Data (comm. & nav)	10 kpbs (bi-directional)	> 10	Orbiters used as relays (2) (3)
	Surface hubs (Hab, Landers, etc)	Voice/ TT&C / Data (comm. & nav)	10 kpbs (bi-directional)	> 10	
2025-2110 (LO-LS)/2200-2290 (LS-LO) MHz	Surface Hubs (Hab, Landers, etc)	Voice/ TT&C	150 kbps (bi-directional)	3	
	LCT	Voice/TT&C	3 Mbps (bi-directional)	1	
	EVAs, Robotics Assistants	Voice/health & status	8 kbps (bi-directional)	8	
22.55-23.15 (LO-LS) /25.5-27 (LS-LO) GHz	LCT	Voice/TT&C/ data/video	200 Mbps/400 Mbps	2	
2483.5 – 2500 MHz (LO-LS)	Rover – LGEP	Voice/ TT&C /Data (comm. & nav)	10 kbps (bi-directional)	> 10	Orbiters used as relays (2) (3)
	EVAs	Voice/ TT&C /Data (comm. & nav)	10 kbps (bi-directional)	> 10	
	Surface hubs (Hab, Landers, etc)	Voice/ TT&C /Data (comm. & nav)	10 kbps (bi-directional)	> 10	

22.55-23.15 (LO-LS) /25.5-27 (LS-LO) GHz	Surface hubs (Hab, Landers, etc)	Voice / TT&C	25/10 Mbps	3	

Table 2: Lunar orbit – lunar surface Communications

Notes

(1) These bands are already used for proximity communications in the Mars region [12] [13] [14] [15]

(2) Number of users depending on number of orbital relays

(3) These bands are used by mobile satellite systems; technology reuse is considered

3.2.2.3 Lunar surface – lunar surface

Besides the basic communications requirements described in Table 3, lunar surface communication systems shall provide the following capabilities:

- Link availability
  - Link availability shall be ensured at any time between two fixed elements on the lunar surface
  - Link availability shall be ensured at any time between two moving elements on the lunar surface in line-of-sight
  - A fixed element (e.g. a base station) shall maintain at any time communications contact with all moving elements (EVAs, rovers, …) under its control, regardless of whether these are in line-of-sight visibility or not. In the latter case, proper measures such as surface relays or orbiting relays shall be available to ensure permanent link availability
- Navigation service
  - The communication system shall provide the means of determining the range between two fixed elements on the lunar surface with an accuracy of less than 1 meter.
  - The communication system shall provide the means of a 2D positioning of any moving element on the lunar surface at any moment with an accuracy of less than 1 meter.

Frequency Band	Users	Service Type	Data Rate per User	Number of Users	Notes
390-405 MHz	Lunar Module	Telemetry, Data	128 kbps,1 Mbps	2	

	Rover, Lander, EVA				
435-450 MHz	Lunar Module, Rover, Lander, EVA	Command	1 kbps	2	
2.4 – 2.48 GHz	EVAs	Voice/data (comm. & nav)/ low rate video	3 Mbps (max, rate will drop as distance increases)	8	
2.4 - 2.48 GHz	Rover – LCT	Voice/data (comm. & nav)/video	30 Mbps (max)	4	
2.4 – 2.48 GHz	EVAs – Landers Rover	Voice/data (comm. & nav)/video	3 Mbps (max)	4	
25.25-25.6 GHz	Base Station to LCT	Voice/data (comm. & nav)/video	20 Mbps	5	
27.225-27.5 GHz	User Radio to LCT	Voice/data (comm. & nav)/video	9.5 Mbps	5	

Table 3: Lunar surface – lunar surface communications

3.2.2.4 Lunar orbit – lunar orbit

Cross links between moon orbiting satellites shall provide the means of relaying in real-time communications for satellite having no line-of-sight visibility of the Earth. These inter-satellite links shall offer high capacity.

The choice of the 13 – 15 GHz band avoids risks of interference with other links.

Frequency Band	Users	Service Type	Data Rate per User	Notes
13.75 -14 GHz	LRS	User data	Up to 300 Mbps	

14.5 – 15.35 GHz	LRS	User data	Up to 300 Mbps	

Table 4: Lunar Relay to Lunar Relay Cross Link

3.3 REQUIREMENTS FOR MARS EXPLORATION

3.3.1 MARS MISSIONS REQUIREMENTS

The requirements cover only robotic missions and do not apply to manned missions.

TBD

3.3.2 MARS SYSTEMS REQUIREMENTS

TBD

The bands earmarked by SFCG and their attributions are listed in **Table** 5.

Link	Frequency
Space-to-Earth:	2290-2300 MHz 8400-8450 MHz 31.8-32.3 GHz
Earth-to-space :	2110-2120 MHz 7145-7190 MHz 34.2-34.7 GHz
Orbit-to-surface:	435-450 MHz** 2025-2110 MHz 7190-7235 MHz 14.5-15.35 GHz
Surface-to-orbit:	390-405 MHz** 2200-2300 MHz 8400-8500 MHz* 16.6-17.1 GHz
Surface-to-surface:	435-450 MHz 390-405 MHz 2025-2120 MHz 2200-2300 MHz
Orbit-to-orbit:	435-450 MHz 390-405 MHz 2025-2120 MHz 2200-2300 MHz 7190-7235 MHz 8450-8500 MHz
Approach Navigation & Atmosphere Radio Science:	8400-8450 MHz

Table 5: Frequency bands for Mars exploration

3.3.2.1 MARS orbit – MARS surface

Depending on the application, links between Mars orbit and Mars surface shall support data rates ranging from low rates for small elements like probes or rovers to very high rates for base stations.

Orbit to surface				
Frequency Band	Users	Service Type	Data Rate per User	Notes

435-450 MHz**		Telecommand	Low rate, with LGA	
2025-2110 MHz			High rate, with MGA/HGA	
7190-7235 MHz			Higher rate, with HGA	
14.5-15.35 GHz			Even higher rate than the 7 GHz band, with HGA	
Surface to orbit				
Frequency Band	**Users**	**Service Type**	**Data Rate per User**	**Notes**
390-405 MHz**		Telemetry	Low rate, with LGA	
2200-2300 MHz			High rate, with MGA/HGA	
8400-8500 MHz*			Higher rate, with HGA	
16.6-17.1 GHz			Even higher rate than the 8 GHz band, with HGA	

Table 6: MARS orbit – MARS surface communications

Note* - Using this band for the surface-to-orbit link is permitted in the near future when users are few. A user must coordinate with missions using the band for the Space-to-Earth link and operate on non-interfering basis. A user mission to be launched after January 1, 2015 must seek a waiver from the SFCG.

Note** - Operation in the reverse direction is permitted in the near term when users are few. A user must coordinate with missions using the band in the proper direction and operate on non-interfering basis. A user mission to be launched after January 1, 2010 must seek a waiver from the SFCG

3.3.2.2 MARS surface – MARS surface

Text to be added

Frequency Band	Users	Service Type	Data Rate per User	Notes
435-450 MHz	Mars Module Rover, Lander	Telecommand/ Telemetry	Low rate, with LGA	
390-405 MHz	Mars Module Rover, Lander	Telecommand/ Telemetry	Low rate, with LGA	
2025-2120 MHz			Low rate with LGA. Higher rate possible with MGA.	
2200-2300 MHz			Low rate with LGA. Higher rate possible with MGA.	

Table 7: MARS surface – MARS surface communications

3.3.2.3 MARS orbit – MARS orbit

Frequency Band	Users	Service Type	Data Rate	Notes
435-450 MHz		Feeder	Low rate	(1)
390-405 MHz		Feeder	Low rate	(1)
2025-2120 MHz		Feeder	High rate	(2)
2200-2300 MHz		Feeder	High rate	(2)
7190-7235 MHz		Feeder	High rate	(3)
8450-8500 MHz		Feeder	High rate	(3)

Table 8: MARS orbit – MARS orbit relays crosslinks

Any of the bands mentioned in Table 8 may be used for inter-orbiters feeders.

Notes

(1) The UHF band (0.3 – 0.4 GHz) is limited in data rate capability to a few Mbps, mostly because it would otherwise require too large antennas.

(2) The 2 GHz band is wide and well-suited for inter-orbit feeders. The band is no more used by deep space missions but heavily used by near-Earth missions; hence the technology is available off-the-shelf.

(3) The 7/8 GHz band is adjacent to the 7/8 GHz deep space band used by spacecraft visiting Mars to communicate with the Earth. It is technically suitable and may offer higher data rate capacity than the 2 GHz band but care must be taken of the risks of interference into the neighboring 7/8 GHz deep space band used for links with the Earth.

3.4 REQUIREMENTS FOR OTHER SOLAR SYSTEM BODIES

TBD

4. FREQUENCY BANDS AND COMMUNICATION LINKS PARAMETERS

4.1 BACKGROUND

The Space Frequency Coordination Group (SFCG) approved in 2012 Recommendation SFCG 32-3 Communication Frequency Allocation and Sharing in the Lunar Region [21]. This prescriptive recommendation identifies the frequency bands that may be used by space missions operating in the lunar region. The recommendation identifies the permitted frequency bands according to their usage, i.e. between the lunar region and the Earth, between a lunar orbit and the lunar surface, between two elements on the lunar surface or between two relays in lunar orbit.

Likewise, in 2002, the SFCG approved Recommendation SFCG 22-1R1 Frequency Assignment Guidelines for Communications in the Mars Region (revised in 2003) [21], covering communications between the Mars region and the Earth, between a martian orbit and the Mars surface, between two elements on the Mars surface or between two elements in martian orbit.

In both recommendations, SFCG leaves it up to the user to select the band(s) that he will be using for his own mission.

This document provides guidelines for the selection of the band according to the data rates and other requirements that are under consideration.

This document provides also guidelines on modulations, forward-error correction coding and data link protocols for each link case.

This document covers only the lunar and Martian local links.

4.2 LUNAR MISSIONS

4.2.1 LUNAR ORBIT – LUNAR SURFACE

4.2.1.1 High rates

For these links, data rates can reach up to 200 Mbps. The user will operate in the 22.55-23.15 GHz band. The links are expected to be between a lunar orbiter and a fixed element on the lunar surface: base station, lunar communications terminal (LCT). Modulation, forward-error correction coding and data link protocols are as per references.

At the moment, modulation/coding/protocols are under study for Earth-space links in the 22.55-23.15 GHz band. It is expected that the technical solutions retained for Earth-space links in the band will be reusable for the lunar orbit-lunar surface links in the same band. However, since the link configuration is of a low orbit to a planet surface, analogies can be made with LEO-Earth links, for which recent studies have demonstrated the high interest offered by VCM/ACM techniques. In the case of the moon, since no atmosphere would introduce propagation uncertainties, VCM would suffice. References [7] and [8] appear in the table below to account for the VCM potential solutions.

Frequency band	Service Type	Data rate	Modulation	Coding	Data Link Protocol
22.55-23.15 GHz	Voice/TT&C/ data/video	200 Mbps	[1] GMSK Filtered OQPSK VCM	[2] LDPC VCM	TC SDLP, AOS
References			[1], [7], [8]	[17], [7], [8]	[18], [20],

Table 9: Lunar orbit-surface high rate link parameters

4.2.1.2 Low/Medium rates

Three frequency bands are available for low to medium data rates lunar-orbit to lunar-surface links.

The 2483.5-2500 MHz band is targeted for voice, TT&C, data (pictures, compressed low image rate videos), for data rate of 10 kbps and above. The signal transmitted from the Lunar Relay Satellites to the lunar surface or to low altitude modules shall also allow accurate navigation or location measurements, like ranging (in conjunction with uplink signal transmitted in the 1610-1626.5 MHz band) or pseudo-ranging, and accurate timing measurement as well. For that reason, each communication channel should combine FDMA and CDMA techniques, to comply with these requirements.

The 2483.5-2500 MHz band is used on earth by Mobile Satellite Systems (MSS) and Radio Determination Satellite Systems (RDSS) which include satellite radionavigaiton systems. This is the only downlink band having allocation for both types of services on earth, and mass market techniques and communication technologies are therefore anticipated in that band to carry both services with a sole signal type.

SFCG validated the 2483.5-2500 MHz band for lunar orbit to lunar surface links after a study report was provided demonstrating RF compatibility with terrestrial users of the band. The study was needed because the 2483.5-2500 MHz band has no space research allocation.

[1] Under development

[2] Under development

Frequency band	Service Type	Data Rate	Modulation	Coding	Data Link Protocol
2483.5-2500 MHz	Voice/ TT&C / Data (4-19omm. & nav)	10 kbps to TBD	Multifrequency channels (OFDM-PN-like or GMSK-PN or Filt OQPSK-PN) TBC		
References					

Table 10: Lunar orbit-surface low/medium rates 2.5GHz link parameters

The 2025-2110 MHz band is widely used for Earth-space links and can accommodate a wide range of data rates. Modulation is to be selected according to the selected data rate. Ranging is possible with PCM/PSK/PM and PCM/SP-L.

Frequency band	Service Type	Data Rate	Modulation	Coding	Data Link Protocol
2025-2110 MHz	Voice/TT&C	150 kbps	PCM/SP-L BPSK	BCH	[18]
	Voice/TT&C	3 Mbps	BPSK		[18]
	Voice/health & status	8 kbps	PCM/PSK/PM	BCH	[18]
References			[1]	[17]	[18]

Table 11: Lunar orbit-surface medium rates 2GHz link parameters

The 390-405 MHz is directly derived from the Proximity-1 standard developed for local links in the Mars region and is particularly suited for links with small elements on the lunar surface operating with low gain antennas. Data rate capabilities are low.

The 390-405 MHz band has no space research allocation and should therefore be employed with EIRPs such that they would in no way interfere with terrestrial users of the band.

Frequency band	Service Type	Data Rate	Modulation	Coding	Data Link Protocol
390-405 MHz	Command	1 kbps	PCM/SP-L	-	
References			[14]	[15]	[13]

Table 12: Lunar orbit-surface low rates UHF link parameters

4.2.2 LUNAR SURFACE – LUNAR ORBIT

4.2.2.1 High rates

For these links, data rates can reach up to 400 Mbps. The user will operate in the 25.5-27 GHz band. Modulation, forward-error correction coding and data link protocols are as per references.

The links are expected to be between a fixed element on the lunar surface (base station, lunar communications terminal LCT) and a lunar orbiter (LRS). Modulation, forward-error correction coding and data link protocols are as per references.

CCSDS has specified modulation/coding/protocol standards for space-Earth or space-space links in the 25.5-27 GHz band [1], [6], [9], [19], [20]. It is expected that the technical solutions retained will be reusable for the lunar orbit-lunar surface links in the same band. However, the link under consideration here is the first case of a planet surface – orbit link at such high rate. Given the rather limited capabilities (EIRP, G/T) of a LCT and of a lunar relay, efficient modulation/coding techniques will have to be considered from the outset. In particular, VCM techniques appear as very promising in this respect. They were developed for space-Earth links and are described in references [7] and [8] but could be readily adaptable to lunar surface – lunar orbit links.

Frequency band	**Service Type**	**Data rate**	**Modulation**	**Coding**	**Data Link Protocol**
25.5-27 GHz	Voice/TT&C/ data/video	400 Mbps	GMSK Filt.OQPSK VCM	LDPC VCM	TM SDLP, AOS
References			[1], [7], [8]	[6], [9], [7], [8]	[19], [20]

Table 13: Lunar surface-orbit high rates link parameters

4.2.2.2 Low/Medium rates

Three frequency bands are available for low to medium data rates lunar-surface to lunar-orbit links.

The 1610 -1626.5 MHz band is targeted for voice, TT&C, data (pictures, compressed low image rate videos), for data rate of 10 kbps and above. The signal transmitted from the lunar surface or low altitude modules to Lunar Relay Satellites shall also allow accurate navigation or location measurements, like ranging (in conjunction with downlink signal transmitted in the 2483.5-2500 MHz band) or pseudo-ranging, and accurate timing measurement as well. For that reason, each communication channel should combine FDMA and CDMA techniques, to comply with these requirements.

The 1610 -1626.5 MHz band is used on Earth by Mobile Satellite Systems (MSS) and Radio Determination Satellite Systems (RDSS) which include satellite radionavigation systems. This is the only uplink band having allocation for both types of services on Earth, and mass market techniques and communication technologies are therefore anticipated in that band to carry both services with a sole signal type.

SFCG validated the 1610 -1626.5 MHz band for lunar surface to lunar orbit links after a study report was provided demonstrating RF compatibility with terrestrial users of the band. The study was needed because the 1610 -1626.5 MHz band has no space research allocation.

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Frequency band	**Service Type**	**Data Rate**	**Modulation**	**Coding**	**Data Link Protocol**
1610 - 1626.5 MHz	Voice/ TT&C / Data (4-21om m. & nav)	10 kbps to TBD	Multifrequency channels (OFDM-PN-like or GMSK-PN or Filt OQPSK-PN) : TBC		
References					

Table 14: Lunar surface-orbit low/medium rates 1.6GHz link parameters

The 2200-2290 MHz band is widely used for space-Earth links and can accommodate a wide range of data rates. Modulation is to be selected according to the selected data rate. Ranging is possible with PCM/PSK/PM, PCM/SP-L and GMSK/PN.

Frequency band	**Service Type**	**Data Rate**	**Modulation**	**Coding**	**Data Link Protocol**
2200-2290 MHz	Voice/TT&C	150 kbps	PCM/PSK/PM PCM/SP-L GMSK GMSK/PN Filt.OQPSK	Conv.Coding LDPC	TM SDLP, AOS
	Voice/TT&C	3 Mbps	GMSK GMSK/PN Filt.OQPSK	Conv.Coding LDPC	TM SDLP, AOS
	Voice/health & status	8 kbps	PCM/PSK/PM	Conv.Coding LDPC	TM SDLP
References			[1]	[6], [9]	[19], [20]

Table 15: Lunar surface-orbit low/medium rates 2GHz link parameters

The 435-450 MHz band is directly derived from the Proximity-1 standard developed for local links in the Mars region and is particularly suited for links with small elements on the lunar surface operating with low gain antennas. Data rate capabilities are low.

The 435-450 MHz band has no space research allocation and should therefore be employed with EIRPs such that they would in no way interfere with terrestrial users of the band.

Frequency band	**Service Type**	**Data Rate**	**Modulation**	**Coding**	**Data Link Protocol**
435-450 MHz	Data/ Telemetry	8 kbps, 32 kbps, 1Mbps	PCM/SP-L	Conv. Coding, LDPC	
References			[14]	[15]	[13]

Table 16: Lunar surface-orbit low/medium rates UHF link parameters

4.2.3 LUNAR SURFACE – LUNAR SURFACE

For surface communications links, several issues are to be taken into account.

- The link continuity
  The lunar terrain presents hills and craters which make it difficult maintaining line-of-sight between transmitter and receiver antennas. Some results of propagation studies are provided in Annex B.
- The navigation service
  The communication system provides the means of determining the range between two fixed elements on the lunar surface.
  The communication system provides the means of a 2D positioning of any moving element on the lunar surface at any moment.

4.2.3.1 High/Medium rates

The high rates for lunar surface concern essentially communications between a lunar communications terminal (LCT) and a base station or possibly a rover equipped with proper high rate transmission means.

The 25-27 GHz band is particularly well-suited for links between two fixed elements. The 2.4 GHz band may be more suited when a rover of EVAs are involved.

Frequency band	**Service Type**	**Data rate**	**Modulation**	**Coding**	**Data Link Protocol**
25.25-25.6 GHz	Voice/data (comm. & nav)/video	20 Mbps to TBD	GMSK GMSK/PN	LDPC	TM SDLP, AOS

			Filt.OQPSK		
27.225-27.5 GHz	Voice/data (comm. & nav)/video	9.5 Mbps to TBD	GMSK GMSK/PN Filt.OQPSK	LDPC	TM SDLP, AOS
References			[1]	[6], [9]	[19], [20]

Table 17: Lunar surface-surface high/medium rates link parameters

Terrestrial standards could be used for short distance (zero to a few kms) lunar surface-surface communications, in the 2.4-2.48 GHz band[3]:

- IEEE 802.11n is used for local links at the International Space Station. Hence space qualified technology exists.
- ISA100.11 a : 2.4 GHz & DSSS/FHSS (IEEE. 802.15.4 physical layer); TDMA protocol; Carrier Sense. Multiple Access with Collision Avoidance (CSMA/CA)
- WirelessHART : 2.4 GHz; DSSS/FHSS (IEEE. 802.15.4 physical layer); TDMA protocol
- IEEE 1451
- ZigBee IEEE. 802.15.4 The standard 802.15.4 is used for local links at the International Space Station. Hence space qualified technology exists.
- ZigBee IP
- 6LowPAN

For longer distances, the following terrestrial standards can be considered [22]:

- Fixed and mobile WiMAX 802.16
- LTE : Mobile Phone standard
- IEEE 802.11 ac

All above mentioned standards fitting into the 2.4 GHz ISM band are limited to line-of-sight links between the rover/EVA and the base station or through relays (Figure 5: Surface Network with relays) or through a mesh network (Figure 6: Surface Network - Mesh Type).

The IEEE norm 802.16e [22] extends the WiMAX technology to mobile users and is well suited for EVAs. The IEEE norm 802.16j will allow the introduction of relays, useful to extend the communication range or to cope with a non-line-of-sight situation.

[3] Details on wireless technology are available in [22] CCSDS 880.0-G-1 *Wireless Network Communications Overview For Space Mission Operations*. Green Book. December 2010

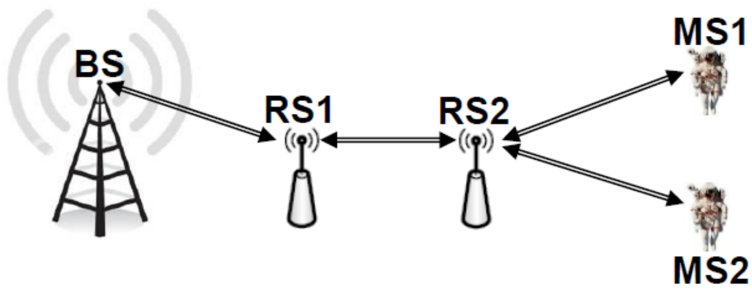

Figure 5: Surface Network with relays

BS: Base Station
RS: Relay Station
MS: Mobile Station

However, each hop induces more latency.

An alternative could be the deployment of a mesh network

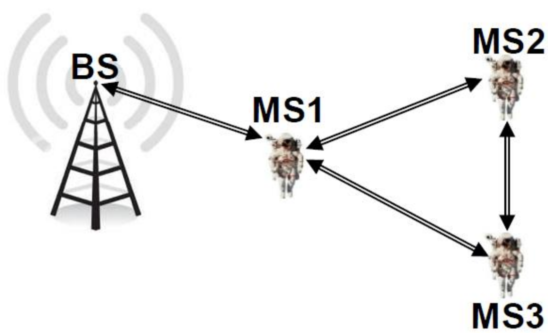

Figure 6: Surface Network - Mesh Type

A mesh network presents the advantage of allowing direct links between astronauts, a requirement especially necessary when two astronauts are visiting a masked area, like a crater.

Surface networks present the drawbacks of:

- Offering rather poor continuity of service due to the terrain, less than 20% according to some studies, unless a large number of relays is deployed (see annex B).
- Offering a poor positioning service where the density of relays is low and the moon surface is not flat

Contrary to terrestrial systems, one cannot imagine deploying relay or base station antennas at 30, 40 or more meters. A maximum reasonable height to be considered is 10 meters. Severe outages are to be expected for the exploration of canyons, craters, etc… as has been shown in several reports. Hence extensive exploration of the moon surface will have to rely on communications via in-orbit relays.

Surface networks based on wireless technology will be useful for short distances and in flat regions. Fixed relays may be needed to allow for positioning through triangulation.

Autonomous navigation for EVAs, rovers, etc … should rely on one or several of the following technologies:

- One way Doppler and Pseudoranging on LRS downlink
- Two way Doppler and Ranging using LRS (lunar relay satellite)
- Inertial Measurement Unit
- Star trackers
- Landmark tracking

Two-way Doppler and ranging via LRS could serve for the location of remote GEUs (Ground End User).

Examples of possible use of wireless technology for short-distance surface communications are shown in Table 18 and Table 19.

Frequency band	**Service Type**	**Data rate**	**Modulation**	**Coding**	**Data Link Protocol**
2.4 – 2.48 GHz	Voice/data (comm & nav)/ low rate video	3 Mbps (max, rate will drop as distance increases)	IEEE 802.15.4		
References					

Table 18: Use of commercial technology for medium rate short-distance lunar surface communications

Frequency band	**Service Type**	**Data rate**	**Modulation**	**Coding**	**Data Link Protocol**
2.4 – 2.48 GHz	Voice/data (comm & nav)/video	30 Mbps	IEEE 802.16		
References					

Table 19: Use of commercial technology for medium/high rate short-distance lunar surface communications

Others bands usable for (very) high data rate are under consideration. They should be addressed with much care because they are currently not approved by the SFCG. It is the case of the 5 GHz bands and the optical band described below.

The band 5.250-5.350 GHz is considered for transmission data rates in excess of 100 Mbps but currently no need exists for such high rates. No indication is available to date regarding the modulation/coding techniques to be used but, given the relative narrow available bandwidth (100 MHz), highly bandwidth-efficient modulation and coding techniques would have to be used. The companion band 5.470-5.725 GHz is much wider for the same foreseen data rates. It is assumed that such transmissions would take place between two fixed points (base station, LCT) on the moon surface. The 5 GHz band is used for ISS local links with 20 MHz channels and the IEEE 802.11n standard; the standard however allows transmission rates well in excess of the needs of 100 Mbps.

Frequency band	**Service Type**	**Data rate**	**Modulation**	**Coding**	**Data Link Protocol**
5.470-5.725 GHz	TBD	>100 Mbps			
5.250-5.350 GHz	TBD	>100 Mbps			
References			TBD	TBD	TBD

Table 20: Very high rate lunar surface communications at 5 GHz

Band extension to other sectors of the 5 GHz band already allocated to Mobile services could be considered:

5150 – 5350 MHz

5725 – 5825 MHz

CCSDS put in place early 2014 an Optical Working Group, which task is to develop standards for optical communications. The applications under consideration are space-to-Earth links for near Earth and deep space missions and also space-to-space communications between two spacecraft in-orbit. The expectations of optics against traditional RF are to offer higher data rates for the same power/mass budget or, alternatively, more compact, lighter and less power consuming terminals for the same data transmission capabilities. Optics might be of particular interest for links between two fixed elements on the lunar surface. Two wavelengths are currently considered for standardization by CCSDS: 1550nm and 1064nm. At the moment, the 1550nm wavelength has been proposed for lunar surface-surface communications.

Frequency band	Service Type	Data rate	Modulation	Coding	Data Link Protocol
1550 nm	TBD	TBD			
References			TBD	TBD	TBD

Table 21: Lunar surface optical communications

4.2.3.2 Low/Medium rates

The frequency bands under consideration for this usage are in the 400 MHz range (UHF). The low and medium rates concern communications between a lunar module and a rover or a lander, between EVAs or between a rover and an EVA, or between a base station and EVAs. This communication system must be to some extent resistant to RF obstacles and operate also in non line-of-sight conditions. The latter conditions still need to be studied with the support of lunar surface RF models. The use of small easily transportable relays may be considered in case of lack of line-of-sight between base station and EVA/rover. The UHF bands should also support navigation capabilities, so that the base station is aware at any moment of the position of the rover and of the EVA, especially when not in direct line-of-sight visibility.

The bands 390-405 MHz and 435-450 MHz have no space research allocation and should therefore be employed with EIRPs such that they would in no way interfere with terrestrial users of these bands.

Frequency band	Service Type	Data rate	Modulation	Coding	Data Link Protocol
390-405 MHz	Telemetry, Data	128 kbps, 1 Mbps	PCM/SPL/PM		
435-450 MHz	Command	1 kbps	PCM/SPL/PM		
References			[14]	[15]	[13]

Table 22: Lunar surface-surface low/medium rates link parameters

The 410-420 MHz band has a space research space-space allocation and can therefore be used without restriction for lunar surface links. The band is currently used for ISS EVA safety-of-life operations. The band allows for low to medium rate transmission rates and the EVA/ISS communications system using this band is a mesh network based on TDMA (any EVA can simultaneously talk with any other EVA and with the ISS operator and be heard by all). This technology, space qualified and demonstrated in-orbit is a preferred choice for local surface-surface lunar communications. The TDMA technique in the 410-420 MHz band is also recommended for WSNs when the gateway is located at the surface of the moon.

Frequency band	Service Type	Data rate	Modulation	Coding	Data Link Protocol
410-420 MHz	Command/Telemetry/Data, voice, low definition video, WSN	Up to 1 Mbps	TBD	TBD	TBD
References			TBD	TBD	TBD

Table 23: Lunar surface low rate communications

4.2.4 LUNAR ORBIT – LUNAR ORBIT

It is expected that lunar communication relays will be orbiting around the moon, relaying communications between the Earth and the lunar surface. In the case of geometric situations such that a relay cannot be in simultaneous visibility of the Earth station and the element on the moon surface, cross-links between lunar relays will be necessary. These cross-links will require operating at high data rates; while the 23/25 GHz bands would appear to be the natural choice for such links, they have not been selected because of the interference risk with links in these bands with the Earth and with the lunar surface. Hence, the 13/15 GHz bands have been selected instead, as they also benefit a space research allocation. Modulation, coding and data link protocol are already standardized by CCSDS.

Frequency band	Service Type	Data rate	Modulation	Coding	Data Link Protocol
14.5 - 15.35 GHz	User data	Up to 300 Mbps	GMSK GMSK/PN Filt.OQPSK	LDPC	TM SDLP, AOS
13.75 -14 GHz	User data	Up to 300 Mbps	GMSK GMSK/PN Filt.OQPSK	LDPC	TM SDLP, AOS
References			[1]	[6], [9]	[19], [20]

Tableau 24: Lunar orbit-orbit communications

4.3 MARS MISSIONS

TBD

4.3.1 MARS ORBIT – MARS SURFACE

4.3.1.1 High rates

TBD

4.3.1.2 Low rates

TBD

4.3.2 MARS SURFACE – MARS SURFACE

4.3.2.1 High rates

TBD

4.3.2.2 Low rates

TBD

4.3.3 MARS ORBIT – MARS ORBIT

Current missions to Mars are already making use of satellites in-orbit to relay to the Earth scientific data produced by elements at the surface of the planet. At some point, more efficient relaying with a global coverage of the planet surface will require links between orbiters, similar to what is foreseen for the moon exploration.

It is expected however that the exploration of Mars will remain unmanned for a long period[4]. Hence, agencies may envisage exploiting new techniques for an improved knowledge of the 'red planet'. Indeed, surface exploration with automatic landers and rovers is likely to further develop; in-situ observation and sample return can bring a lot to a better knowledge of the planet, though limited to the tiny area of observation. On the other hand, global observation of the planet could benefit from methods such as the use of small satellites in formation for a detailed 3-D mapping and observation of the planet surface.

Hence one can identify two categories of orbit-to-orbit links:

- High rate links between relay orbiters
- Low rate links between spacecraft flying in formation
  Formation flying requiring a very accurate control of the relative positions of all spacecraft, the radio links between them will be used for both data exchange and relative navigation

[4] At the end of 2014, the most optimistic plans were considering a first manned mission to Mars by year 2040

4.4 OTHER SOLAR SYSTEM BODIES

N.A.

ANNEX A ACRONYMS AND ABREVIATIONS

ACM	Adaptive Coding and Modulation
AOS	Advanced Orbiting System
BCH	Bose-Chaudhuri-Hocquenghem
BPSK	Binary Phase-Shift Keying
CDMA	Code Division Multiple Access
CSMA	Carrier-Sense Multiple Access
DSSS	Direct Sequence Spread Spectrum
EIRP	Equivalent Isotropically Radiated Power
EVA	Extra-Vehicular Activity
FDMA	Frequency Division Multiple Access
FHSS	Frequency Hopping Spread Spectrum
GEU	Ground End User
GMSK	Gaussian Minimum Shift Keying
HGA	High Gain Antenna
IEEE	Institute of Electrical and Electronics Engineers
ISA	International Society of Automation
ISM	Industrial, Scientific and Medical
ISS	International Space Station
LCT	Lunar Communication Terminal
LDPC	Low Density Parity-Check (code)
LGA	Low Gain Antenna
LGEP	Lunar Science Rover
LO	Lunar Orbit

LRS	Lunar Relay Satellite Orbiter
LS	Lunar Surface
MGA	Medium Gain Antenna
MSS	Mobile Satellite Systems
NASA	National Aeronautics and Space Administration
OFDM	Orthogonal Frequency Division Multiplexing
OQPSK	Offset Quaternary Phase-Shift Keying
PCM	Pulse Code Modulation
PM	Phase Modulation
PN	Pseudo-Noise
PSK	Phase-Shift Keying
RDSS	Radio Determination Satellite Systems
RF	Radio Frequency
SDLP	Space Data Link Protocol
SFCG	Space Frequency Coordination Group
SLS	Space Link Services
SP-L	Split Phase-Level
SR	Space Research
TC	Telecommand
TDMA	Time Division Multiple Access
TM	Telemetry
TT&C	Telemetry, Tracking and Control
VCM	Variable Coding and Modulation
WSN	Wireless Sensor Network

ANNEX B PROPAGATION ON THE MOON SURFACE

Propagation is an important issue for communications on the moon surface. Indeed, the achievement of mission objectives and the preservation of assets requires a continuous monitoring of rovers while exploring the moon surface. Not to mention the security aspects in the case of manned missions.

In most mission scenarios that foresee exploration over radii of several kilometers from the base,l communication obstacles such as hills or craters are to be expected.

At lot of work was performed on propagation models for wireless communications on the Earth surface but these are not directly reusable because:

- Frequencies analyzed are mostly around 800 MHz and 1800 MHz whereas frequencies for lunar surface communications range from 400 MHz to 26 GHz
- Models for Earth surface cover urban and vegetation environment and are thus not representative of the lunar environment

A survey of the literature concerning propagation on the moon surface concluded that many papers are not relevant for the following reasons:

- Either they address only low and very low frequencies (<10 kHz) for which propagation is inherently different from what can be encountered at ultra high frequencies

- Or they are too old (one was from 1963) and remain vague by lack of information in these times on the lunar surface geographical and electrical (conductivity) characteristics

References [24] and [25] conclude that reflections and diffractions on the lunar surface for surface-surface communication links have a significant effect on the link performances and sufficient link margin should be accounted for.

They also demonstrate that special attention should be taken on frequent non-line-of-sight situations that are likely to occur in the visit of craters; radio relays should be deployed to improve continuity of communication in such cases.