UPDATE ON
FREQUENCY BANDS
FOR
LUNAR IN-SITU PNT/GNSS CONSTELLATIONS

ICG-16; ABU DHABI; October, 10th 2022

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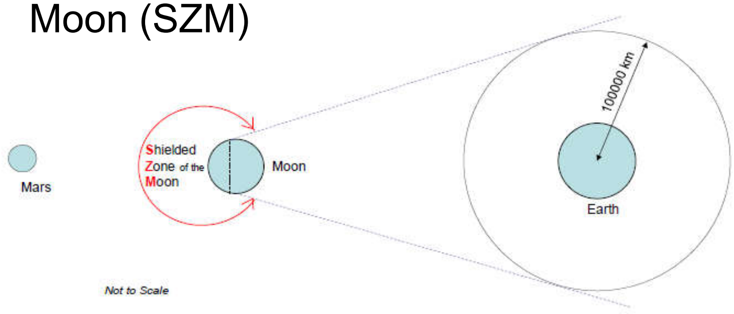
ITU Radio Regulation in the Shielded Zone of the Moon and SFCG recommendations for lunar in-situ PNT

ITU Definition of the Shielded Zone of the Moon (SZM)



RR: ITU Article 22 section V + ITU REC RA 479-5:
Protection of Radio Astronomy in the SZM

Most of communication frequencies **below 2 GHz**, in particular **any RNSS or RDSS frequency L-band**, **are not allowed in the SZM** without agreement of the Radio Astronomy community (**even if declared on a non interference basis:** ITU article 4.4), **and also C-band**

What is at stake is continuum RA observations in the SZM in L-band, and also in C-band

SFCG REC 32-2R4

d) that missions may require Global Navigation Satellite Service (GNSS) signals for accurate Positioning, Navigation, and Timing (PNT) in the lunar region, and that these GNSS signals may originate from either Earth or Moon orbiting satellite constellations;

Table 2: Recommended Frequency Bands for RNSS or RDSS Applications in the Lunar Vicinity

Link	Frequency
Earth-based GNSS to Lunar Orbit and Lunar Surface	1164-1215 MHz 1215-1300 MHz 1559-1610 MHz
In-situ Lunar based RNSS/RDSS to Lunar Orbit and Lunar Surface	2483.5-2500 MHz

Reminder on Lunar SAR frequencies: backup slide 14

Compatibility of GNSS bands for in-situ lunar PNT with Radio Regulation and Recommendations related to protection of Radio Astronomy in the SZM

	L-band (RNSS-GNSS : 1164-1300 MHz & 1559-1610 MHz) *	**S-band** (RDSS-GNSS : 2483.5-2500 MHz)	**C-band** (RNSS: 5010-5030 MHz) *
Compatibility with **ITU RR & REC RA 479-5** *	**NO (ILLEGAL)**	**YES**	**RA band 4.99-5.00 GHz and above**
Compatibility with **SFCG REC 32-2R4**	**NO (Radio Astronomy in SZM at stake)**	**YES**	**NO**

Current situation of the identified lunar in-situ PNT/GNSS-like systems under study

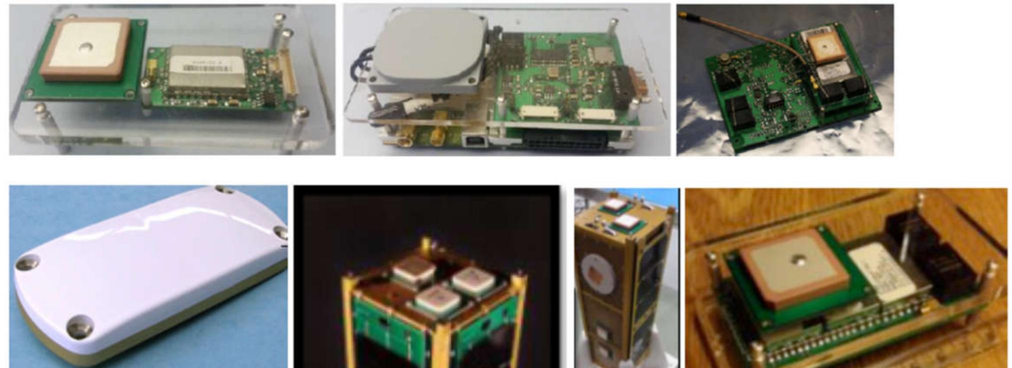
	L-band (RNSS-GNSS : 1164-1300 MHz & 1559-1610 MHz)	S-band (RDSS-GNSS : 2483.5-2500 MHz)	C-band (RNSS-GNSS: 5010-5030 MHz)
NASA	NO	NASA PNT (IOAG; ICD-V4-september 2022)	NO (for short term) (Lunanet ICD-V4: S-band: baseline; C: option for which Coordination with RA on filtering would be necessary)
ESA	NO	ESA PNT (IOAG; technical papers)	NO
CNSA	?	?	?
JAXA (STARDUST system studies)	?	?	?
US Space Force (studies with MASTEN [ASTROBOTIC ?] and XPLORE)	?	?	?
Commercial services	ILLEGAL in SZM;To not be cofunded by public organismes	Hybrid govermental + commercial services	?

Mass market in GNSS S-band like in GNSS L-band

	Operating Region	L Band	S Band	Coverage	Date of Full Operational Capability
Galileo G1	EU	Yes	No	Worldwide	2022
Galileo G2	EU	Yes	No (but G2G filing includes S-band ; experiments ?)	Worldwide	2034
GPS	USA	Yes	No	Worldwide	1995
Glonass	Russia	Yes	No	Worldwide	1996
Beidou-1/2/3 RDSS	China	No	Yes	Worldwide excepted poles	2018
Beidou-3	China	Yes	Yes	Worldwide	2020
NAVIC/IRNSS	India	Yes	Yes	Regional (India)	2018
NAVIC Global	India	Yes	Yes	Worldwide	2030
QZSS	Japan	Yes	No	Regional (Japan)	2024
QZSS-2	Japan	Yes	TBD (S-band is an option)	Regional	2030
Globalstar (with Echo-Ridge service and S-band pilots for measurements used in hybrid positioning)	USA	No	Yes	Quasi Worldwide (Globalstar declared iself COMs+GNSS system in 2018; fig 3)	2021
KPS (Korean Positioning System)	South Korea	Yes	Yes	Regional (Korea)	2030
GNSSaS	UAE	Yes	Yes	Regional (equatorial region)	2028
Xona-Space	USA	TBD	TBD	Worldwide	2026
GEESAT andCentispace	China	Yes	No	Worldwide	2028

TABLE 1 GNSSs in L and/or S-bands.

Globalstar equipments for LEO user satellites



Other GNSS L+S spaceborne LEO equipment (IRNSS, etc…)

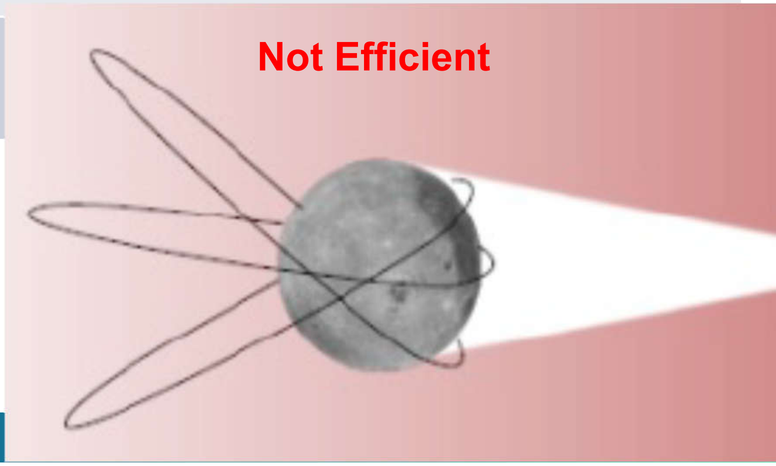
etc …

QZSS-2: Source indicates S-band as possible option, no S-band from other source

Xona-Space: published filing SHERPA-AC1 of the first Xona experimental cubesat: **L-band: 1260 MHz (10 MHz BW;** PSK**)** (*tests Ground Stations in USA and Canada*) ; **C-band: 5020 MHz (20 MHz BW;** PSK; *test GS in San Mateo*)**.** Xona-Space private constellation and Earth Orbiting GNSS C-bands in China are not decided up to now.

Attempting mitigating harmfull interferences to RA in SZM for L-band in-situ lunar PNT ?

« Mitigating » technique ??	CONSTRAINTS (no such constraint in S or C band)
Filtering side lobes	No big reduction of interferences to RA in the SZM; would proclude narrow correlation.
Physical masking	Hardly work for RA in orbit or on the surface. And there will be several in-situ PNT systems.
Temporal / operational scheduling	Each F.O.C constellation shall have a global coverage (safety spec): each manned user shall see everywhere (no obstacle) at least 2 orbiters
	An initial PNT constellation could optimized orbits to cover the south pole. Then, the F.O.C PNT global constellation would be built upon.
	There will be human and/or mobile robots around the Radio Telescopes, OutPosts. Switching OFF the PNT payloads over RTs, OPs, is unlikely.
Orbiter's PNT signal beam steering	L-band Tx would illuminate the outposts & RA observatories, and the PNT users ! Significant cost increase ! The FOC constellations shall each have a global coverage (safety requirement) !
Orbit design	To minimize time above the SZM is also not efficient to mitigate harmfull interference in the SZM (back up slide)



The identified mitigating techniques are not efficient and not credible to protect RA in the SZM from harmfull interferences in GNSS L-band

L-band in SZM would mean deliberatly wiping out Radio Astronomy continuum observations

Other technical drawbacks of L-band for in-situ lunar PNT

Drawback	Why it is a drawback
Interferences to L-band terrestrial GNSS signals	Interference zones size depend of the frequency difference between terrestrial signals and in-situ ones (loss of coverage and safety)
	Less terrestrial L-band frequencies and constellations could be received: loss of accuracy and robustenss.
On board complexity	Lunar orbiting PNT system has to be synchronized by terrestrial GNSS signals in L-band. Receiving and transmiting in GNSS L-bands from a lunar orbiter increase complexity.
Synchronization perfos (for Science, OPS, …)	On board orbiters, filtering of L-band Tx to protect the received L-band(s) is much complex than with Tx in S or C band. More TGD thermal/uncalibrated variations with L-band filters.
Leveraging	Mobile S-band PNT/GNSS terminal could be integrated with the mobile LCT (Lunar Communication Terminal) and/or the (SAR) Search And Rescue terminals (*S-band SAR for Lunanet-V4 and ESA's PNT)* and/or S-band Wireless terminal. Reuse of GNSS and/or MSS and/or mass markets in S-band.
	The low power L-band terrestrial GNSS signals need to be received with a High Gain Antenna, and the Rx needs low acquistion threashold features (for PNT orbiters, spaceships/spacestations/habitats, landers, etc) while the HGA is difficult for small or mobile PNT receivers
Better science if in-situ L-band is avoided	Continuum RA observations on the Moon are mentioned in the Artemis Science Definition Report (in-situ PNT/GNSS L-band would wipe out this !). Synchronisation performances are less good in L band !

Technical drawbacks of C-band for in-situ lunar PNT

Drawback	Why it is a drawback
Link budget and on board power consumption	Extra free space losses in C-band: 12 dB (resp 6 dB) higher than L (resp S) band. Power consumption of PNT global coverage PLDs would be much higher in C-band: extra cost.
Sensitivity to manufacturing imperfections	The higher the frequency, the more accurate the RF circuit manufacturing shall be: impact on user and on-board segment costs
No obvious RNSS mass market/leveraging	Only one LEO PNT experimental private GNSS cubesat is in orbit transmitting C-band signal above one ground station. No PNT constellation in C band is decided.
Less ambiguity resolution possibilities	The smaller the wavelength, the higher the difficulty for carrier phase ambiguity resolution (*in conjuction with other measurements/sensors*)
No accuracy gain	C-band has been thought for GNSS “on Earth” despite the drawbacks above because (1) iono delay and scintillations are smaller: But, the Moon has no ionosphere !
No inter-system interference reduction	It was also believed than GNSS C-band “on Earth” would (2) reduce the risk of inter GNSS system “interference”. But, there is currently no in-situ lunar PNT system !
Complexity to protect RA band 4990-5000 MHz on Earth and in the SZM	Harmfull interferences to RA in 4990-5000 MHz might be mitigated in EO with a complex filter with high rejection features. However, the negative interference margin would be too big in the SZM for a realistic filter (about +20 dB in the protection factor)

Frequencies of future martian PNT/GNSS system

- Mars is regularly in the SZM
- ITU REC RA 479-5 applies to Mars
- CNES computations show that a martian PNT/GNSS in-situ system in GNSS L-band would create harmfull interference to RA in the SZM.

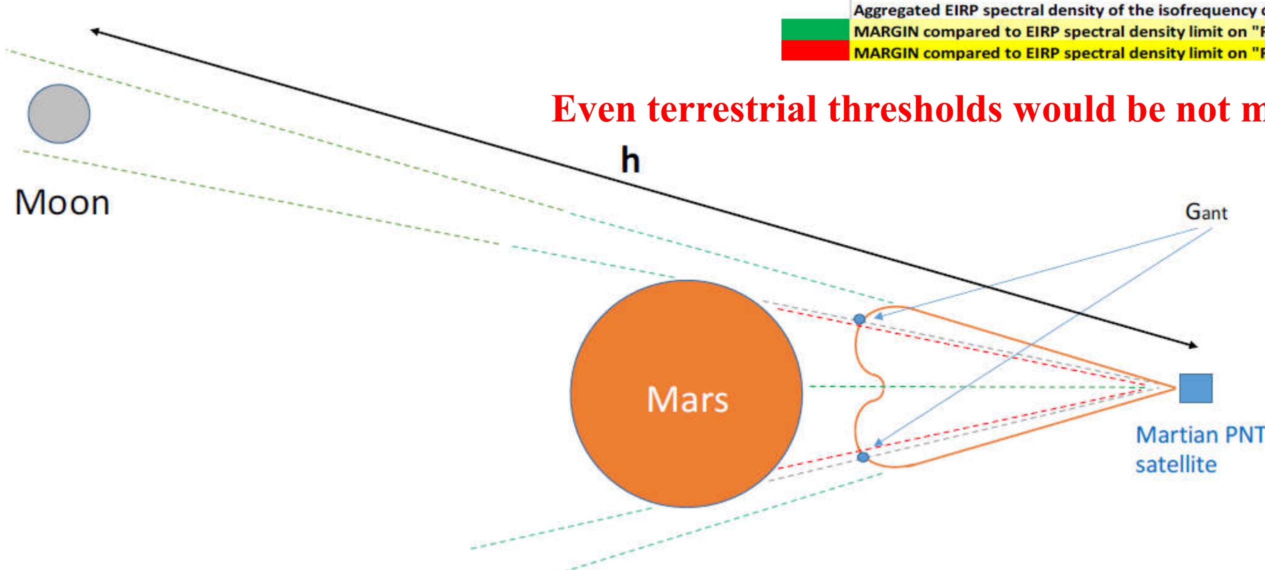
Interference threshold levels for radio astronomy observations in bands for which there is a primary allocation

Radio astronomy band	pfd (dB(W/m²))	spfd (dB(W/(m² · Hz)))
1 610.6-1 613.8 MHz	–194	–238

We compute the margin of EIRP limit in RA in SZM conditions, using a RA-SZM protection factor (**20 dB**) versus RA on Earth (table above). This **20 dB** value is considered representative by French Radio Astronomers, and is demonstrated (**back up slides 17**)

MARGIN compared to EIRP limit on "RA terrestrial conditions" (SZM conditions are much worst)	dB	-5,4
MARGIN compared to EIRP limit on "RA SZM conditions" (SZM conditions)	dB	-25,4
Bandwidth of one PNT frequency channel	MHz	4
Aggregated EIRP spectral density of the isofrequency channels	dBW/Hz	-29,0
MARGIN compared to EIRP spectral density limit on "RA terrestrial conditions"	dB	16,66
MARGIN compared to EIRP spectral density limit on "RA SZM conditions"	dB	-3,3

Even terrestrial thresholds would be not met by a Martian PNT system in L-band

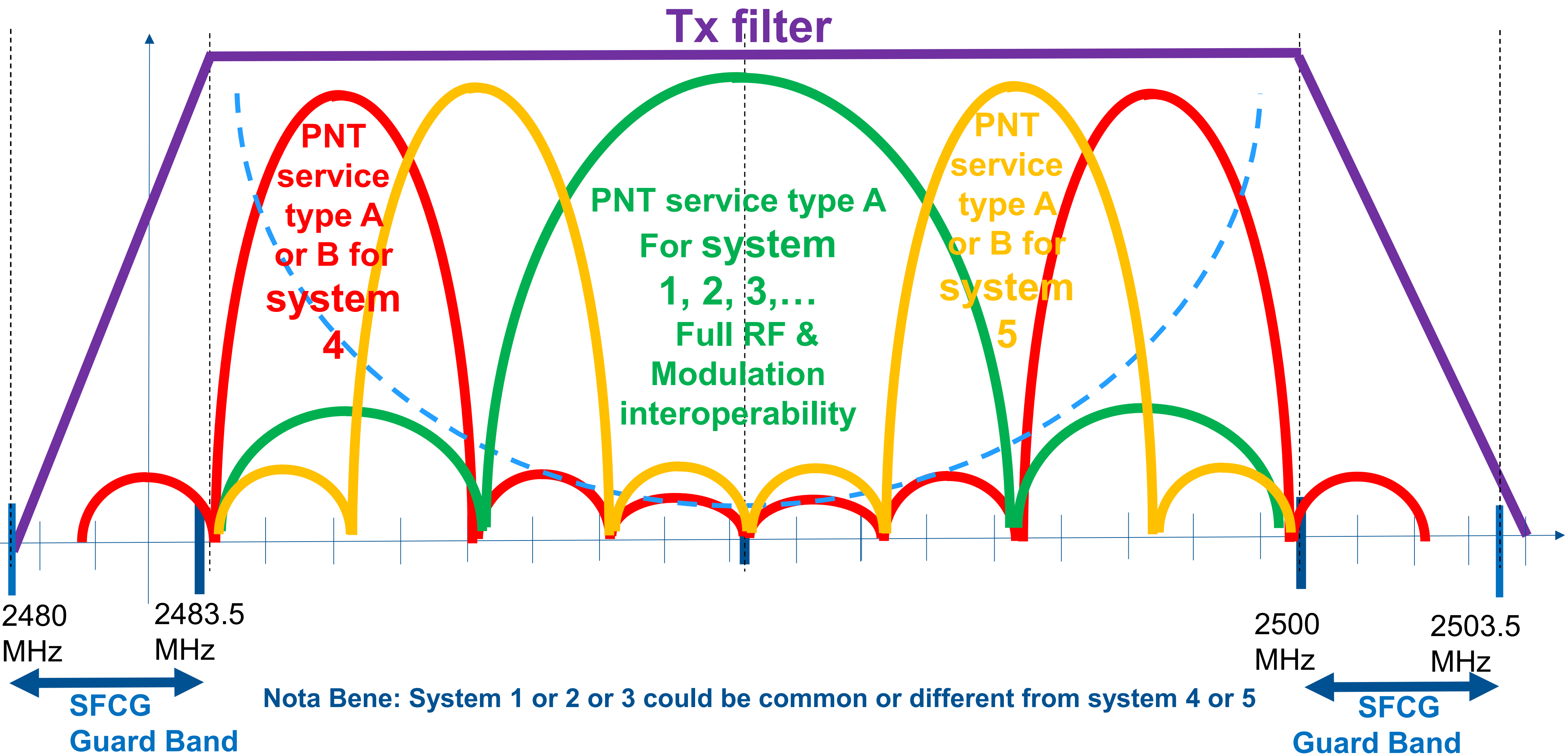


2483.5-2500 MHz is an available SFCG Martian communication band (Orbiter to Surface).

One of the reasons of the adoption of this band by SFCG was its MSS+RDSS feature.

2483.5-2500 MHz is the only SFCG Martian band which is RDSS or RNSS on Earth.

Some lunar in-situ PNT systems and/or services need spectral separation between them



Nota Bene: System 1 or 2 or 3 could be common or different from system 4 or 5

NOT GOOD

Comparison between frequency bands for in-situ lunar PNT

GOOD

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	L-band	S-band	C-band
Interference to RA in the SZM (including Mars issues)	STRONG HARMFULL INTERFERENCES TO CONTINUUM RA OBSERVATIONS/ NO CREDIBLE MITIGATION TECHNIQUES		Harmfull interferences to the RA band 4980-5000 MHz, and above (CONTIUNUUM RA OBSERVATIONS) in the SZM.
Interoperability between in-situ systems	No frequency interoperability with systems in S-band		No frequency interoperability with systems in S-band
Link budget / on board power consumption	+ 0 dB	+ 6 dB	+ 12 dB
Technical drawbacks	Slides 6, 7 and backup slide 14		Slide 8
Compatibility with martian SFCG com frequencies	Slide 9		Slide 9
Leveraging mass market Rxs	Slide 7		Slide 8
Spectral separation of some different PNT services if needed		Slide 10	

S-band is clearly the best choice for lunar in-situ PNT

Annexes

Back up slides

References

https://www.itu.int ➔ Radio Regulation and ITU RECs

unoosa.org/documents/pdf/icg/2021/ICG15/WGS/icg15_wgs_25.pdf

https://insidegnss.com/the-shielded-zone-of-the-moon-protecting-radio-astronomy-from-rf-interference/

https://www.sfcgonline.org/Resources/Recommendations ➔ 1 and 2:

1) Recommendation SFCG 32-2R4: Communication and positioning, navigation, and timing Frequency Allocations and Sharing in the Lunar Region

2) Recommendation SFCG 22-1R4: Frequency Assignment guidelines for communications in the Mars Region

SFCG REC 32-2R4 on lunar SAR, and reminders

Table 3: Recommended Frequency Bands for Search & Rescue Beacon in the Lunar Vicinity

Link	Frequency
LunaSAR beacon	406 – 406.1 MHz[1]
Note 1 of Table 3: Additional SAR beacon transmission above 2 GHz including use in the SZM is under study to complement the 406 – 406.1 MHz capability, which is limited to outside of the SZM usage. It is intended to include these new lunar SAR bands above 2 GHz in SFCG 32-2R5.	

Reminder 1: LunaNet.V4 september 2022 (NASA):
Uplink / SAR Beacon: channel in 2200-2290 MHz; **Downlink /return channel**: SAR message in PNT channel (2483.5-2500 MHz)

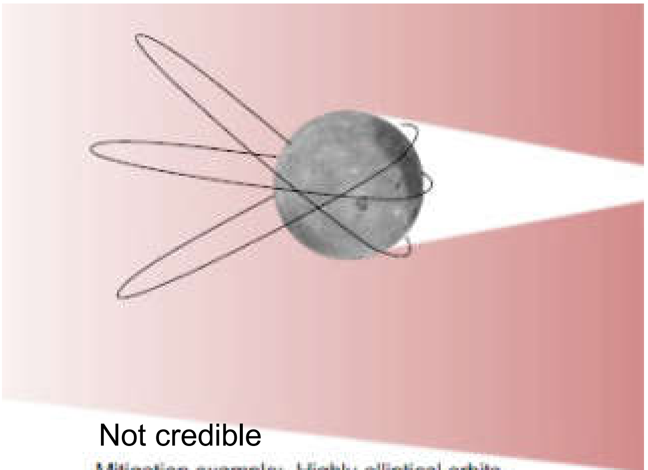
Reminder 2: **ITU RR & ITU+SFCG RECs in the SZM**, and also **adjacent RA band to be protected in the SZM, in addition to the regulatory protection of the continuum observations band below 2 GHz**

406-406.1	MOBILE-SATELLITE (Earth-to-space) 5.266 5.267
406.1-410	FIXED MOBILE except aeronautical mobile RADIO ASTRONOMY 5.149

Reminder 3: **Exceptions outside ITU RR are not manageable** (« *why do they have an exception and not me ?* » ; « *me too, I will not transmit often !* » ; etc)

Reminder 4: **Maritime ITU allocation**: 406-406.1 MHz is used on Earth for maritime distress system, in agreement with Appendice 15 of the ITU RR « Frequencies for distress and safety communications for the Global Maritime Distress and Safety System »

Orbit design for in-situ L-band PNT Txs is not efficient to protect RA in the SZM

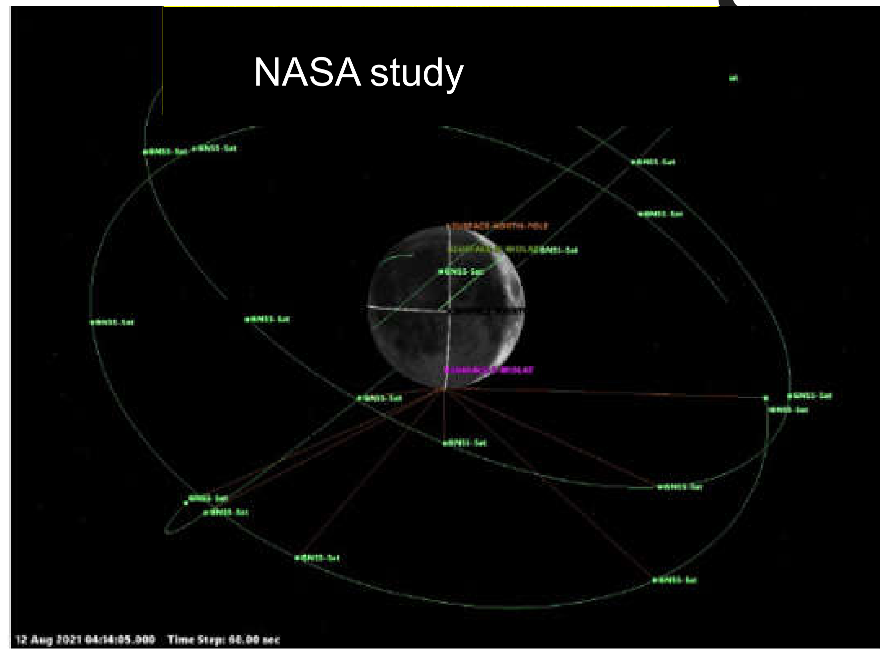


Not credible

Mitigation example: Highly-elliptical orbits. Orbit design can reduce the amount of time emitters are physically present in the SZM to less than 20% of the satellites orbit, to reduce hypothetically the risk of SZM contamination

- The RNSS constellation design
  - Number: 21-satellites-frozen orbits
  - Constellation to require (estimated) little to no station-keeping over life of satellites (~270kg satellites)
  - Provides Coverage to get accurate positioning for users with a GDOP of 6 or less for most locations
  - Constellation Design
    - Orbital Planes: 3
    - Spacing: 120 degree
    - Inclination: 39.670
    - Satellites per plane: 7

Constellation #7 has been selected for our simulations from:
Pereira, F., & Selva, D. (2020, April). Exploring the design space of lunar GNSS in frozen orbit conditions. In 2020 IEEE/ION Position, Location and Navigation Symposium (PLANS) (pp. 444-451).



The proposed orbital mitigation exemple on the left is not efficient for the reasons bellow, while an exemple of more credible orbital design is presented on the right (used for intra PNT interference scenarii)

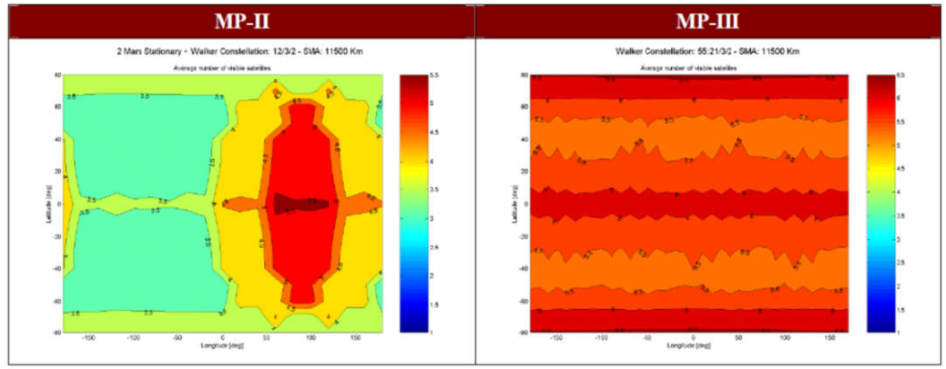
-**Reason 1)** = Reason 1) of slide 6 ;
-**Reason 2)** = Reason 2) of slide 6, and to consider the presented orbits "SZM centred" would be a big desoptimization.
-**Reason 3)** = Considering the mitigation exemple on the left, even if one orbiting PNT Tx would cover the SZM "only" 20 % of the time (inacceptable for RA), the need to optimze geometry also in the SZM would impose this % to be highly increased.
-**Reason 4)** = There will be likely several lunar orbiting PNT systems. Even if all adopt the "SZM HEO orbits" and if several systems would violate the ITU RR by transmitting in L-band, the SZM will be covered much more than 20% of the time.

Demonstration of Harmfull Interference to Radio Astronomy in the SZM in case of martian PNT constellation in L-band

Inputs provided by ESA on internet; preliminary study of a conceptual martian PNT system

	MP-I	MP-II		MP-III
Navigation Service	2-D no real-time	3-D real-time locally		3-D real-time globally
Coverage	Local 1-fold	Local 4-fold		Global 4-fold
Number of Satellites	4	15 (3 MarsStationary +12 Walker)		21
Constellation Pattern	Sparse	MarsStationary	Walker 12/3/2	Walker 21/3/2
Semi-major Axis	6500 Km	20700 Km	11500 Km	11500 Km
Inclination	111.0 deg	0.0 deg	55.0 deg	55.0 deg

Main design parameters of the three MARCO POLO constellations



Average number of visible satellites with MP-II and MP-III constellations

Altitude of martian PNT orbiters			**20700**	**km**
h = Shorter distance of the Mars from ZSM (worst case)		km	54 220 000	m
20*log(h)		dB	214,68	
10*log(4*PI)		dB	10,99	
Spreading Factor	10*log(4*PI) + 20*log(h)	dB	**225,68**	
RA-SZM protection factor versus RA on Earth		dB	**20**	
ITU EIRP limit without spreading loss factor, for the highest RNSS L-band frequency (1610 MHz)		dB(W/m2)	-194	
EIRP limit with spreading loss factor		**dBW**	**31,68**	
EIRP spectral density limit without spreading loss factor, for the highest RNSS L-band frequency (1610 MHz)		dB(W/(m2.Hz))	-238	
EIRP spectral density with spreading loss factor		**dB(W/(m2.Hz))**	**-12,32**	
Number of simultaneous martian PNT orbiters transmitting toward Earth			**1**	
Transmitting antenna gain toward Earth (**Gant**)		dB	**16**	(TBC)
Transmitted power of one frequency channel		**W**	**127**	(TBC)
Transmitted power of one frequency channel		dBW	21,0	
EIRP of one channel		dBW	37,0	
EIRP of one channel		W	5056,0	
Aggregated EIRP of the isofrequency channels		W	5056,0	
Aggregated EIRP of the isofrequency channels		**dBW**	**37,0**	
MARGIN compared to EIRP limit on "RA terrestrial conditions" (SZM conditions are much worst)		**dB**	**-5,4**	
MARGIN compared to EIRP limit on "RA SZM conditions" (SZM conditions)		**dB**	**-25,4**	
Bandwidth of one PNT frequency channel		MHz	4	
Aggregated EIRP spectral density of the isofrequency channels		**dBW/Hz**	**-29,0**	
MARGIN compared to EIRP spectral density limit on "RA terrestrial conditions"		**dB**	**16,66**	
MARGIN compared to EIRP spectral density limit on "RA SZM conditions"		**dB**	**-3,3**	

Altitude of martian PNT orbiters			**11500**	**km**
h = Shorter distance of the Mars from ZSM (worst case)		km	54 220 000	m
20*log(h)		dB	214,68	
10*log(4*PI)		dB	10,99	
Spreading Factor	10*log(4*PI) + 20*log(h)	dB	**225,68**	
RA-SZM protection factor versus RA on Earth		dB	**20**	
ITU EIRP limit without spreading loss factor, for the highest RNSS L-band frequency (1610 MHz)		dB(W/m2)	-194	
EIRP limit with spreading loss factor		**dBW**	**31,68**	
EIRP spectral density limit without spreading loss factor, for the highest RNSS L-band frequency (1610 MHz)		dB(W/(m2.Hz))	-238	
EIRP spectral density with spreading loss factor		**dB(W/(m2.Hz))**	**-12,32**	
Number of simultaneous martian PNT orbiters transmitting toward Earth			**1**	
Transmitting antenna gain toward Earth (**Gant**)		dB	**14**	(TBC)
Transmitted power of one frequency channel		**W**	**79**	(TBC)
Transmitted power of one frequency channel		dBW	19,0	
EIRP of one channel		dBW	33,0	
EIRP of one channel		W	1984,4	
Aggregated EIRP of the isofrequency channels		W	1984,4	
Aggregated EIRP of the isofrequency channels		**dBW**	**33,0**	
MARGIN compared to EIRP limit on "RA terrestrial conditions" (SZM conditions are much worst)		**dB**	**-1,3**	
MARGIN compared to EIRP limit on "RA SZM conditions" (SZM conditions are much worst)		**dB**	**-21,3**	
Bandwidth of one PNT frequency channel		MHz	4	
Aggregated EIRP spectral density of the isofrequency channels		**dBW/Hz**	**-33,0**	
MARGIN compared to EIRP spectral density limit on "RA terrestrial conditions"		**dB**	**20,72**	
MARGIN compared to EIRP spectral density limit on "RA SZM conditions"		**dB**	**0,7**	

Justification for the 20 dB protection factor in the SZM

ITU Interference threshold levels for Radio Astronomy observations has been defined for an integration time **To** of **2000 seconds**

Current RA observations on Earth are done with a cumulated integration time **T1** of at least **2 weeks**

Integ. time **T2** greater than **T1** be regulary necessary in the SZM. Hypothesis: **T2 = 2 monthes***

The protection factor **P** (dB) for RA in the SZM compared to the ITU Interference thresholds level on Earth is therefore:

$$P = 10*\log\left(\sqrt{T_2/T_o}\right) = 17 \text{ dB}$$

With a 3 dB only margin, we have: **P = 20 dB**

Valid in SZM for frequencies bellow 2 GHz (VHF, UHF, L,…), and in RA bands above 2 GHz, like 4990-5000 MHz and its neighbourhood.

*** 2 monthes is a minimum**

Interest of C-band for RA in the SZM for the Radio Astronomers

C-band (4800-5000 MHz) is very important for Radio Astronomy on Earth and in the SZM. This band notably contains a spectrum line used for fondamental studies of interstellar clouds and of the dynamic formation of the universe. This is the H_2CO line at 4829.7 MHz (central frequency with Doppler shift **above** and below). The 4990-5000 MHz extended band is notably used for VLBI observations.

These 2 bands 4800-4990 MHz (secondary status on Earth) et 4990-5000 MHz (primary status on Earth) are observed by big radiotelescopes notably in Germany, Italy, Netherlands, UK, Sweden, etc

Interests of RA observations of C bands from the SMZ include the issue of their radio-pollution on Earth, as well as the interferences in their neighbourhood, and VLBI observations in 4990-5000 MHz considering Moon-Satellites-Earth baselines for instance.

ITU REC RA.479-5 (Protection of RA in the SZM): for the 3-20 GHz range:

The **continuum bands** used by radio astronomers are **in the neighbourhood** of the following bands allocated to the passive services: **4.99-5.0 GHz**, 10.68-10.7 GHz and 15.35-15.4 GHz.