Lunar and Martian in-situ PNT frequency bands, and guard bands

Monday 16th of october 2023

International Committee GNSS – 17; Madrid, SPAIN

CNES

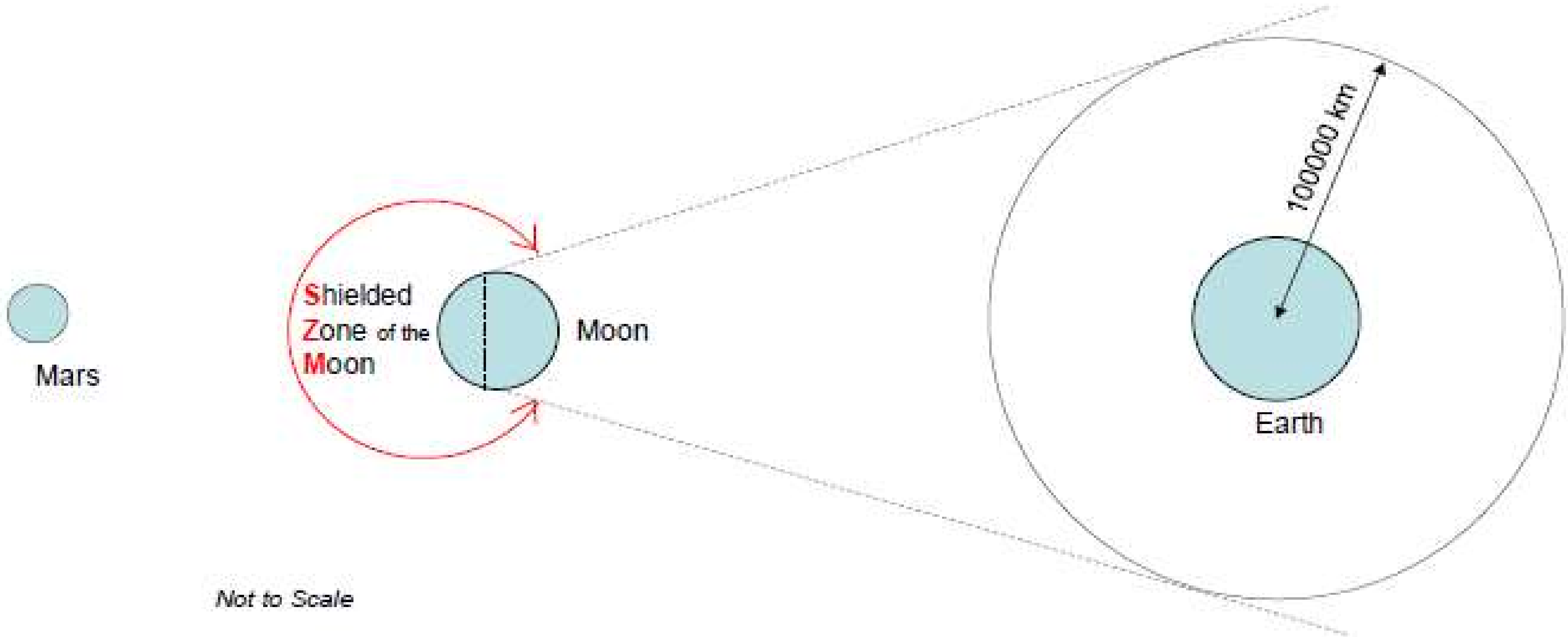
cnes

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

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 frequency (notably in L-band, but also the « 5 GHz » C-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)

What is at stake is continuum RA observations in SZM in L & C bands



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

ITU Res 741 and ITU RR articles 22.22 to 22.25

In the SZM, harmful interference to R.A. is only permitted in bands allocated to a few services, **and not RNSS**:

"22.22 § 8 1) **In the shielded zone of the Moon emissions causing harmful interference to radio astronomy observations and to other users of passive services shall be prohibited *in the entire frequency spectrum except in the following bands*:**

22.23 a) the frequency bands allocated to the **Space Research Service** using active sensors;

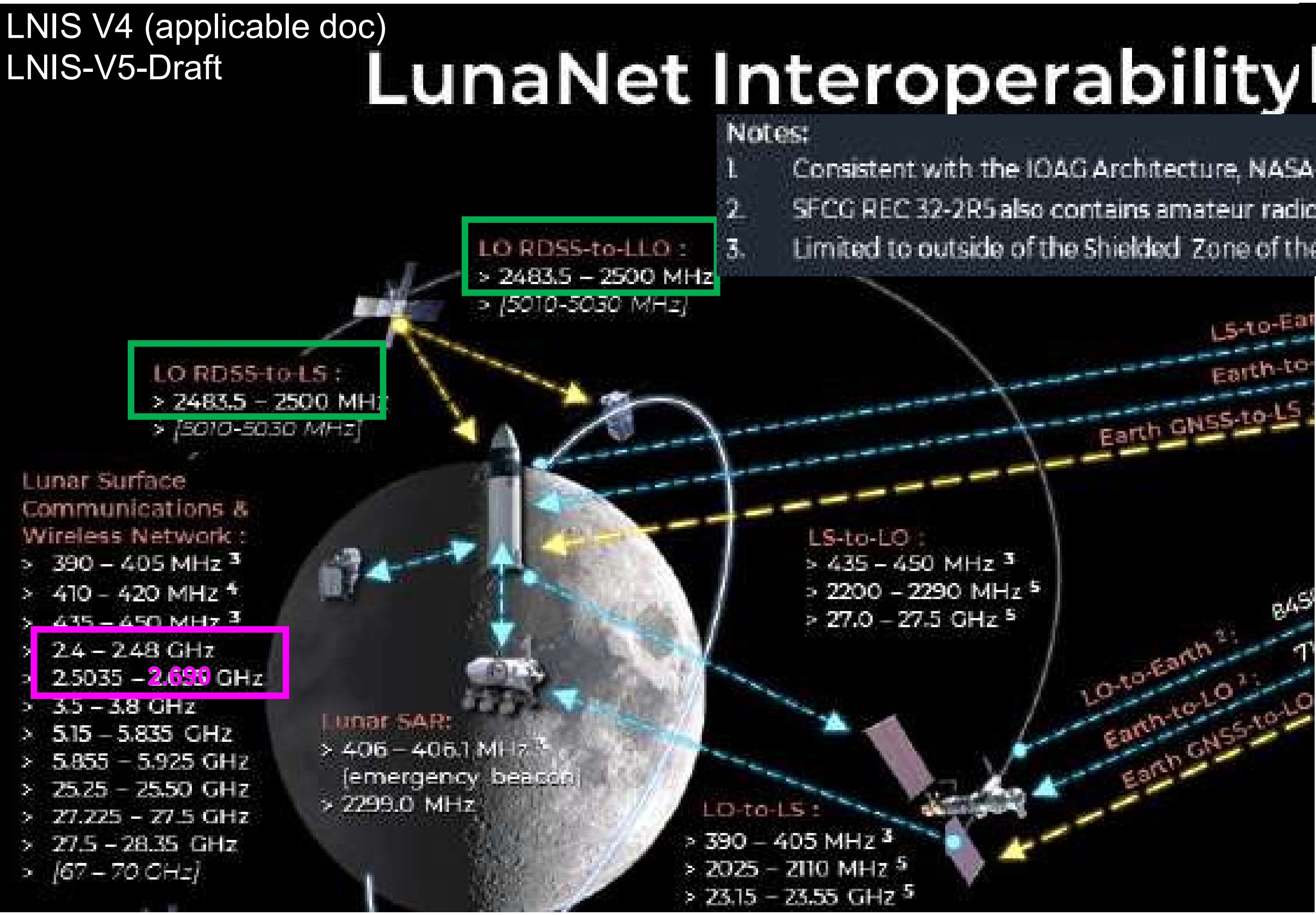
22.24 b) the frequency bands allocated to the **Space Operation Service**, the **Earth Exploration Satellite Service** using active sensors, and the **RadioLocation Service** using stations on spaceborne platforms, which are required for the support of space research, as well as for radiocommunications and space research transmissions within the lunar shielded zone.

According to articles 22.22 - 22.25 of the ITU-RR, the RNSS is not allowed to cause harmful interference to Radio Astronomy at any frequency in the SZM (excepted for a few exceptions)

Protecting RAS in another band at 4990-5000 MHz from OOB emissions at 5010-5030 MHz is therefore irrelevant in the SZM.

LUNANET in-situ PNT: AFS (Augmented Forward Service)

LNIS V4 (applicable doc)
LNIS-V5-Draft



IOAG and SFCG lunar in-situ PNT frequency band (SFCG REC 32-2R5): 2483.5-2500 MHz (but slide 14)

2.2. AFS SIGNAL SPECIFICATIONS

2.2.1. COMPOSITE SIGNAL

2.2.1.1. FREQUENCY PLAN

LSIS-010: Frequency Band
The navigation signal shall be transmitted in S-band between 2483.5 MHz and 2500 MHz.
Note: This is in line with SFCG recommendation 32-2, that identifies the band between 2483.5 MHz and 2500 MHz for "In-situ Lunar based RNSS/RDSS to Lunar Orbit and Lunar Surface."

IOAG and SFCG 3.5 MHz guard band protecting PNT and Surface Wireless links from each other's interferences (SFCG REC 32-2R5)

It is vital for PNT to keep the 3.5 MHz guard bands but 2655 MHz wireless upper limit could become 2690 MHz

Interest of C-band for RA in the SZM for the Radio Astronomers (1)

cnes

C-band (4800-5000 MHz) and **its neighbourhoud** is very important for RA on Earth and in the SZM. This band contains a spectrum line (H_2CO) used for studies of interstellar clouds and of the dynamic formation of the universe (central frequency with Doppler shift **above** and below). It is also used for VLBI observations.

These 2 bands 4.8-4.99 GHz and 4.99-5.0 GHz (primary status on Earth) are observed by radiotelescopes notably in Germany, Italy, Netherlands, UK, Sweden ...

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. **RA Observations in 5000-5030 MHz (a RA band in the SZM) and above are also important for RA in SZM**.

The ASTRON russian Radio Astronomy satellite made observations notably below and **above** 5000 MHz. It has an apogee at 390000 km (a « lunar » distance), and a 10 meters deployable parabolic RAS antenna ➔ ➔ ➔ ➔ ➔

Independantly of ITU REC and ITU RR, there is an interest for RA continuum and VLBI observations in C-band. ➔ This is a sufficient reason to not accept an in-situ lunar PNT C-band

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

ITU-R 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."

5010-5030 MHz is clearly in the neighbourhood of 4990-5000 MHz; this is correlated with the Radio Astronomers interests in C-band (previous slide).

From its creation, SFCG never accepted a text (in any SFCG recommentation) which would contredict an ITU Recommendation.

➔ That is why ITU REC 479-5 looks a sufficient reason to not have 5010-5030 MHz as a lunar in-situ PNT frequency band

Interest of C-band for RA in the SZM for the Radio Astronomers (2)

ITU-R REC RAS.479-5 (Protection of RA in the SZM): for the 300 MHz-3 GHz range:

Resolution B16 of the 1994 XXIIth *General* Assembly of the International Astronomical Union (IAU) recommends that **radiocommunication transmissions in the SZM be limited to the 2-3 GHz band**, but that an alternate band at least 1 GHz wide be identified for future operations on a time-coordinated basis between radio astronomy and lunar communication systems *(NB: these extra 1 GHz could be in several slots)*

This ITU REC RAS 479-5 is one of the reasons why the SFCG and IOAG lunar in-situ PNT 2483.5-2500 MHz has been chosen (and not 5010-5030 MHz)

ITU Res 741 and ITU RR articles 22.22 to 22.25 (E)

cnes

From NASA's SF41-04/D

Notional 5 GHz RNSS Satellite Transmitter Characteristics

Parameter	Parameter Value	Notes
Transmit Power	23 dBW	• 13 dBW for GPS L1-like lunar region service (from Source 1, Table II, Constellation #7) + 10 dB to account for increase in free space path loss between 1575.42 MHz and 5020 MHz
Transmit Antenna Gain	16 dBi	• See figure at right
Transmit Bandwidth	19.72 MHz	• ITU-R M.2031, Annex 2, Table 2-3

From:

Received: 26 February 2021 | Revised: 8 October 2021 | Accepted: 13 November 2021
DOI: 10.33012/navi.504

REGULAR PAPERS

ION — Multi-Objective Design of a Lunar GNSS — PEREIRA ET AL.

Filipe Pereira[1] | Patrick M. Reed[1] | Daniel Selva[2]

TABLE 1
Architecture Design Decisions

	Design decisions (constellation 1)	Value range		Design decisions (constellation 2)	Value range
1	Semi-major axis (SMA)	[3474, 17370] km	8	Semi-major axis (SMA_2)	[3474,17370] km

RAS Protection Negative Margin in SZM		Frequency	5022930000	Hz	
for one RNSS satellite in C-band		Wavelength	0,06	m	
PFD(Ptot) = EIRP/(4*pi*r2)					
One RNSS C-band lunar satellite					
r (m)	**10000000**	10000 km			
r^2	1E+14				
4*pi*r2	1,26E+15				
10log(4*pi*r2)	150,99				
Gant (dB)	**16**		EIRP	39,00	dBW
Pt (dBW)	**23,00**		Free Space Losses	186,46	dB
PFD(Ptot)	-111,99		Pr (0 dB gain Rx ant)	-147,46	dBW
PFD(P10MHz)	-112,45	BPSK(5)			
PFD unit	dBW/m2				
PFD limit	-171	ITU Res. 741 resolve 1			
Neg. Margin (dB)	**-58,55**				

See ITU report (RA.2131) [Annex; slide 26]

Negative margin for protection of RAS in 5010-5030 MHz in the SZM: close to - 60 dB

ITU-RR : 5010-5030 MHz is a Radio Astronomy band in the Shielded Zone of the Moon

Compatibility of GNSS bands for in-situ lunar PNT related to 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-GNSS : 5010-5030 MHz)
Compatibility with **ITU-RR article 22 section V**	**NOT COMPLIANT WITH RR**	**YES**	**NOT COMPLIANT WITH RR**
Compatibility with **ITU-REC 479-5**	**NOT COMPLIANT WITH REC 479-5**	**YES**	**NOT COMPLIANT WITH REC 479-5**
Compatibility of a global in-situ PNT system with RAS needs in the SZM	**NO compatibility**	**YES**	**NO compatibility**

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 payloads would be 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 costs
No obvious RNSS mass market/leveraging	Only one LEO PNT experimental private GNSS cubesat is in orbit transmitting C-band signal above only one ground station.
Less ambiguity resolution possibilities	The smaller the wavelength, the higher the difficulty for carrier phase ambiguity resolution (*in conjuction with other measurements/sensors*), even if carrier multipath is smaller in C-band compared to L or S band.
No accuracy gain	C-band has been thought for GNSS "on Earth" despite the drawbacks above because (1) ionospheric delay, frequency shift 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 !
Impossible to protect RA in the SZM	See content of the previous slides
Doppler range and Doppler dynamic	Doppler (range & dynamic) is twice higher in C-band compared to S band (and 3 times higher compared to L1/G1 band). Hard/soft acquisition and tracking is more complex in C-band
Better science if in-situ C-band is avoided	Continuum RA observations on the Moon are mentioned in the Artemis Science Definition Report (in-situ PNT/GNSS C-band would endanger this !).
In Door (Lunar Habitats, Vehicles, …)	5 GHz signals are attenuated more than in L or S band (9 dB more than 1.5 GHz signals by a 12 cm concrete wall).
Carrier tracking robustness	Poorer at C-band than at L or S band. It depends on thermal noise, oscillator phase noise, vibration-induced phase noise, and dynamic stress. Except for thermal noise, all influences are proportional to the carrier frequency
Cycle-Slip Probability	Depends on effective C/N_0, data rate, and oscillator phase noise. Due to increased phase noise and possibly smaller C/N_0's, the cycle-slip probability at C-band is expected to be larger than at L or S Band.

Martian in-situ PNT frequency band

ITU-R REC RAS.479-5 (Protection of RA in the SZM): for Mars:

6 that in-situ radiocommunication equipment developed for the environment of Mars or other planets should not be deployed in the SZM, but the choice of frequencies for the close proximity links in the SZM should follow the preliminary guidelines contained in Annex 1.

➔ Resolution B16 of the 1994 XXIIth *General* Assembly of the International Astronomical Union (IAU) recommends that **radiocommunication transmissions in the SZM be limited to the 2-3 GHz band**.

Recommendation SFCG 22-1R4

FREQUENCY ASSIGNMENT GUIDELINES FOR COMMUNICATIONS IN THE MARS REGION

Orbit-to-surface:	435-450 MHz [3] 2025-2110 MHz **2483.5-2500 MHz** 7190-7235 MHz 14.5-15.35 GHz 22.55-23.55 GHz

SFCG frequencies "Orbit to Surface" common to Moon and Mars

Orbit to Surface :
2025-2110 MHz
2483.5-2500 MHz
23.15-23.55 GHz

Natural future martian in-situ PNT frequency band: 2483.5-2500 MHz

Annex (page 28 & 29) explains why L band is not possible for a martian in-situ PNT (same type of results for C band)

CONCLUSION : Comparison of C-band with other possible GNSS in-situ bands

NOT COMPATIBLE | **COMPATIBLE**

	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 SZM-RA band 4980-5030 MHz, and above (CONTIUNUUM SZM-RA OBSERVATIONS) .
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	Annex (slides 27, 28 and 29)		Slide 10
Compatibility with martian SFCG com frequencies			
Leveraging mass market Rxs		Annex (Slide 26)	Xona replaced C-band by L band for the 2nd frequency of its LEO PNT (too much drawbacks in C-band)
Spectral separation of some different PNT services if needed			

C-band is not a credible option; For all the reasons presented (also in Annex), CNES do not support C-band for lunar in-situ PNT in SFCG 32-2R6 or in LNIS V5

Annex (1) / back up slides

Some details about RDSS S band (and SFCG guard bands)

(bands to keep for in-situ Lunar PNT)

Reminder ot the Guard Bands and OOB filtering requirements of SFCG REC 32-2R5

Wireless (surface to surface)	2.400 – 2.480 GHz	EVAs	Voice/data (comm & PNT)/ video	3 Mbps (max, rate will drop as distance increases)	2.480-2.4835 MHz is considered as the guard band. Sufficient OOB filtering to protect the 2483.5-2500 MHz LO-to-LS PNT band is necessary. OOB filtering of the harmonic falling in 4.8-4.99 GHz band (secondary RAS) is necessary in the SZM
		Rover - LCT	Voice/data (comm & PNT)/video	30 Mbps (max)	
		EVAs – Landers, Rover	Voice/data (comm & PNT)/video	3 Mbps (max)	
In-situ PNT (orbit to surface)	2483.5-2500 MHz (LO-LS) 2483.5-2500 MHz (LO-LO)	Rover-Orbiter, EVAs- Orbiter, Surface hubs (Hab, Landers, etc) – Orbiter	PNT	10 kbps	Limited to one way PNT transmissions from LO to LS and LO to Low Lunar Orbit (LO to LLO)
Wireless (surface to surface)	2.5035 – 2.655 GHz	EVAs	Voice/data (comm & PNT)/video	100 Mbps (max)	2.500-2.5035 MHz is considered as the guard band. Sufficient OOB filtering to protect the 2483.5-2500 MHz LO-to-LS PNT band is necessary. See Note 9 of Table 1
		Rover - LCT			
		EVAs – Landers, Rover			

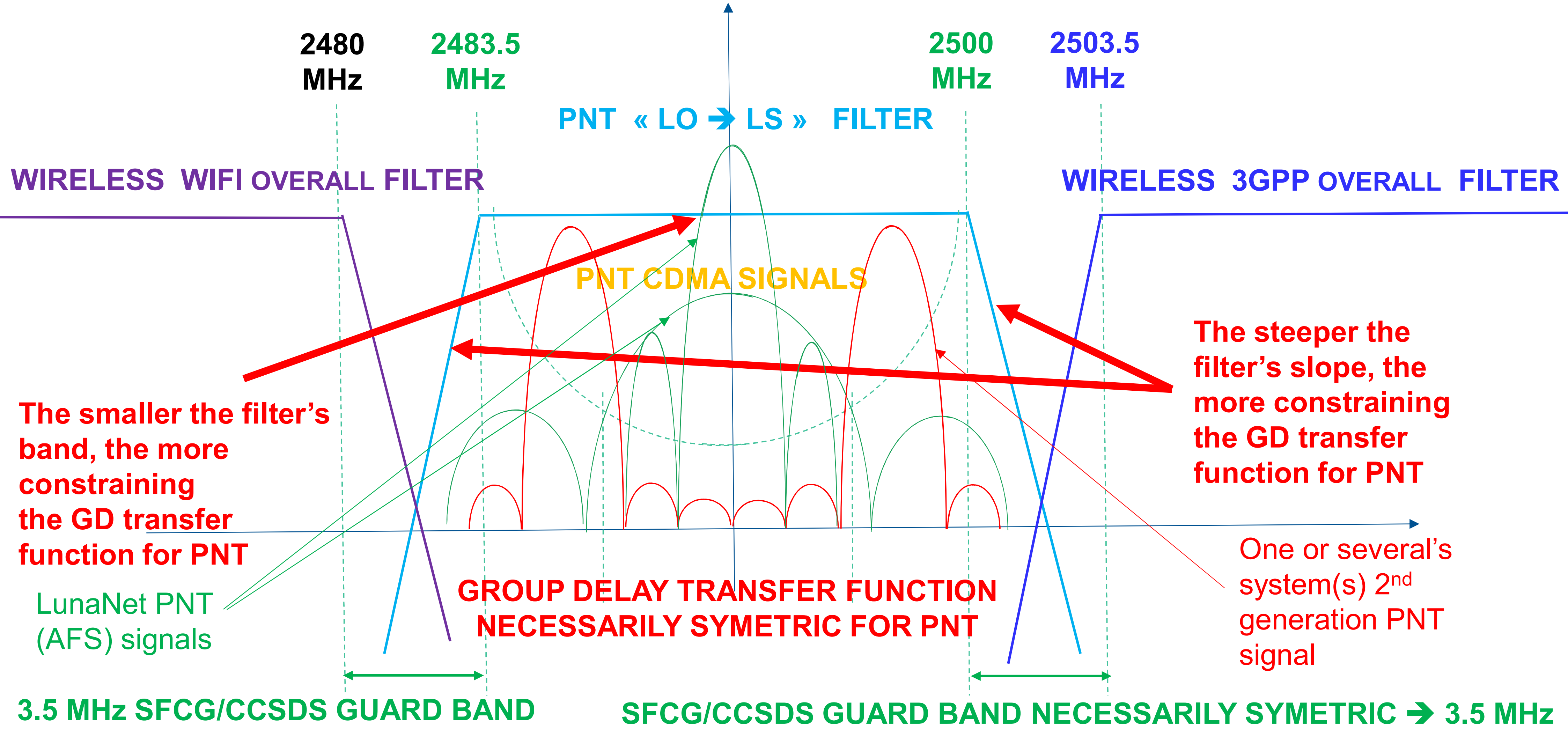
Extract of
SFCG
REC 32-2R5

CCSDS 883.0-B-1 lunar wireless WIFI and 3GPP standard refers to SFCG REC 32-2R5 and specify to respect this (IN FORCE) recommendation

1) Lunar PNT receiver can be on the same « carrier », and very close to a wireless transmitter: Exemples of « carriers »: rovers, astronaut's suits, etc …

2) Without the SFCG guard bands, wireless and PNT bands would « touch » each other

SYMETRIC FILTERING implication of in-situ lunar PNT



Annex (2) / back up slides

Some details about RNSS L and C bands

(bands to avoid for in-situ Lunar PNT)

ITU Res 741 and ITU RR articles 22.22 to 22.25 (A)

The discussion about protecting the 4990-5000 MHz band, using Res. 741 or footnote 5.443B (which refers to Res. 741), is a minor point comparing from the protection of RAS granted by the RR in the SZM.

In the SZM, harmful interference to radio astronomy is only permitted in the frequency bands allocated to a small set of services:

"22.22 § 8 1) **In the shielded zone of the Moon emissions causing harmful interference to radio astronomy observations and to other users of passive services shall be prohibited *in the entire frequency spectrum except in the following bands*:**

22.23 a) the frequency bands allocated to the **Space Research Service** using active sensors;

22.24 b) the frequency bands allocated to the **Space Operation Service**, the **Earth Exploration Satellite Service** using active sensors, and the **RadioLocation Service** using stations on spaceborne platforms, which are required for the support of space research,
as well as for radiocommunications and space research transmissions within the lunar shielded zone.

ITU Res 741 and ITU RR articles 22.22 to 22.25 (B)

The band 5010 - 5030 MHz is not allocated to any of the services mentioned at the end of slide 18,   it is allocated to:

AERONAUTICAL MOBILE-SATELLITE (R) 5.443AA

AERONAUTICAL RADIONAVIGATION

RADIONAVIGATION-SATELLITE (space-to-Earth) (space-to-space) 5.328B 5.443B

So RNSS bands can legitimately be used in space or on the Moon, but such use may not cause harmful interference to radio astronomy at ANY frequency, including in the band 5010-5030 MHz. Protecting RAS in another band at 4990-5000 MHz from OOB emissions at 5010-5030 MHz is irrelevant in the SZM.

In other words: according to articles 22.22 - 22.25 of the RR, the RadioNavigation Satellite Service is not allowed to cause harmful interference to radio astronomy at any frequency in the SZM (excepted for a few exceptions; not for RNSS)

ITU Res 741 and ITU RR articles 22.22 to 22.25 (C)

Res. 741 merely quotes the RA 769 limits that RAS mistakenly applies in bands subject to RR 5.340 where all emissions are prohibited. FN 5.443B and Res 741 specifically refer to RNSS systems and as noted, those may not cause harmful inteference to RAS at any frequency in the SZM.

5.443B In order not to cause harmful interference to the microwave landing system operating above 5030 MHz, the aggregate power flux-density produced at the Earth’s surface in the frequency band 5030-5150 MHz by all the space stations within any radionavigation-satellite service system (space-to-Earth) operating in the frequency band 5010-5030 MHz shall not exceed −124.5 dB(W/m²) in a 150 kHz band. In order not to cause harmful interference to the radio astronomy service in the frequency band 4990-5000 MHz, radionavigation-satellite service systems operating in the frequency band 5010-5030 MHz shall comply with the limits in the frequency band 4990-5000 MHz defined in Resolution 741 (Rev.WRC-15). (WRC-15)

ITU Res 741 and ITU RR articles 22.22 to 22.25 (D)

RESOLUTION 741 (REV. WRC-15)

resolves

1 that in order not to cause harmful interference to the RAS in the frequency band 4 990-5 000 MHz, the pfd produced in this frequency band by any GSO RNSS network operating in the 5 010-5 030 MHz frequency band shall not exceed −171 dB(W/m^2) in a 10 MHz frequency band at any radio astronomy station;

2 that in order not to cause harmful interference to the RAS in the frequency band 4 990-5 000 MHz, over the whole sky, for elevations higher than the minimum operating elevation angle θ_{min}[1] specified for the radio telescope, the epfd produced in this frequency band by all space stations within any non-GSO RNSS system operating in the 5 010-5 030 MHz frequency band shall not exceed −245 dB(W/m^2) in a 10 MHz frequency band at any radio astronomy station for more than 2% of the time, using the methodology in Recommendation ITU-R M.1583-1 and a reference antenna with a radiation pattern and maximum antenna gain given in Recommendation ITU-R RA.1631-0;

3 that the limits referred to in *resolves* 1 and 2 shall apply to RNSS systems as from 3 June 2000;

4 that administrations planning to operate a GSO or a non-GSO RNSS system in the frequency band 5 010-5 030 MHz, for which complete coordination or notification information, as appropriate, has been received by the Bureau after 2 June 2000, shall send to the Bureau the value of the maximum level of pfd as referred to in *resolves* 1 or the value of the maximum level of epfd as referred to in *resolves* 2, as appropriate.

ITU Res 741 and ITU RR articles 22.22 to 22.25 (F)

Moreover, an additional protection factor P specific to SZM (currently between 10 and 20 dB according to discussions with Radio Astronomers in contact with CNES) should be needed for RAS in the SZM to have protection levels better than on Earth.

CNES described its computation of the protection factor P in slide 23

With factor P = 3 dB only, or even 0 dB, a C-band lunar PNT cannot comply with Radio Regulation and/or ITU REC concerning the SZM

CNES justification for the 20 dB protection factor in the SZM

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

Current RA observations on Earth are done with 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:

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

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

Valid in SZM for frequencies bellow 2 GHz (VHF, UHF, L,…), and in RA bands above 3 GHz, like 4970-5040 MHz

* RA observations not necessarily continuous

**** 2 monthes is a minimum**

Desagreements about interpretation of the words astronomy observations and to other users of passive services

If it is interpreted as observations having a regulatory statut in Article 5 of RR, then there would be no protection of RAS in 5010-5030 MHz (and in any other band !!!) in the SZM !!!

If it is interpreted as observations in general, including bands not allocated to this service in Article 5, then RAS has to be protected in the 5010-5030 MHz band in the SZM (and other bands defined by Article 22 section V) in the SZM.

CNES, on the basis of documents issued by WRC which approved this disposition and subsequent UIT-R works, supports the second interpretation

In the case of the SZM, the first interpretation would be a non sense, knowing that the Radio Regulation on protection of RAS in the SZM (page 7), has been built by ITU WRC to protect continuum RAS observation to be necessarily done essentially outside the RA bands allocated on Earth.

The ITU Director's report submited to WRC 2023 (Doc. CPM23-2/236)

- The text of the ITU Director's report submited to WRC 2023 means that ITU request to Administrations to describe how they will implement Section V of Article 22

- but it would be obviously not acceptable for ITU to see an administration answering "I will not do it" ! While interference mitigation measures like the ones presented in slides 30, 31 and 32 (for L and C band) are shown to be not credible

ITU publish the described measures to allow the other countries to determine if they are sufficient or not, but answers to ITU request are needed.

Administrations can make proposals to this WRC 2023 to answer this report !

➔ these informations are additional and sufficient reasons to not include RNSS C-band in SFCG REC 32-2R and in LNIS V5 final.

Detrimental threshold levels of interference to Radio Astronomy observations in ITU-R RA.769

ITU issued another ITU report (RA.2131) entitled: « Supplementary information on the detrimental threshold levels of interference to radio astronomy observations » in Recommendation ITU-R RA.769

RA.2131	Supplementary information on the detrimental threshold levels of interference to radio astronomy observations in Recommendation ITU-R RA.769

This report mention how to interpolate between the table entries of RA. 769 to derive protection thresholds in bands not explicitly mentioned. But 5010-5030 is almost adjacent to 4990 - 5000 MHz.

It can be seen from this report the fact that nothing changed and 22.22 - 22.25 apply to most of frequencies, including 5010-5030 MHz

ITU Res 741 and ITU RR articles 22.22 to 22.25

Res 741 (WRC-15) gives protection criteria for terrestrial radio astronomy operations at 4 990 - 5 000 from out of band emissions of the radio navigation satellite service operating at 5010 - 5030 MHz. The levels in Res 741 are the thresholds for harmful interference in the 4990-5000 band on Earth.

On the Earth, the radionavigation satellite service operating at 5010 - 5030 MHz is required to protect radio astronomy only in the radio astronomy band at 4990 - 5000 MHz at the levels in Res 741.

In the SZM, the situation is different:

According to articles 22.22 - 22.25 of the RR, the radionavigation-satellite service is not allowed to cause harmful interference to radio astronomy **at any frequency** in the SZM.

Therefore the RNSS is also required to protect radio astronomy at Res 741 levels* IN THE RNSS BAND AT 5010-5030 MHz **

*** moreover with an additional protection factor P**

**** even without factor P, a C-band lunar PNT cannot comply with Radio Regulation while RNSS user terminals in the SZM receive enough power to work**

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

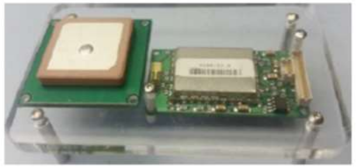
	L-band (RNSS-GNSS : 1164-1300 MHz & 1559-1610 MHz)	S-band (RDSS-GNSS : 2483.5-2500 MHz)	C-band (RNSS-GNSS: 5010-5030 MHz)
NASA	**Not proposed**	**NASA PNT** (IOAG; ICD-V4-september 2022)	(not proposed for LunaNet AFS) (Lunanet ICD-V5: S-band: baseline; C-band: under study for which Coordination with RA would be necessary). AFS ICD: S-band only
ESA	**Not proposed**	**ESA PNT** (IOAG; technical papers)	**Not proposed**
CNSA			
JAXA	**Not proposed**	**JAXA PNT** (TBC)	
US Space Force (studies with MASTEN [ASTROBOTIC ?] and XPLORE)			
Commercial services	**Not compliant with RR in SZM;To not be cofunded by public organismes**	Hybrid govermental + commercial services	**(if any, it would be not compliant with RR)**

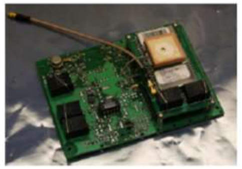
Mass market in GNSS S-band like in GNSS L-band (from hardware point of view)

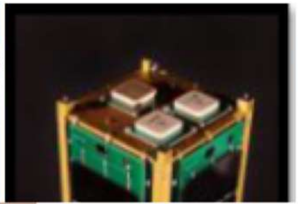
	Operating Region	L Band	S Band	Coverage	Date of Full Operational Capability
Galileo G1	EU	Yes	No	Worldwide	2022
Galileo G2	EU	Yes	No (but G2G filing includes S-band ; experiments ?)	Worldwide	2034
GPS	USA	Yes	No	Worldwide	1995
Glonass	Russia	Yes	No	Worldwide	1996
Beidou-1/2/3 RDSS	China	No	Yes	Worldwide 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	No *	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








etc …

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

Xona-Space: published filing SHERPA-AC1 of the first Xona experimental cubesat only: **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***). But** Xona-Space gave up C-band for the mass market applications private constellation of its Pulsar constellation (there is too much technical drawbacks in C-band). C-band will be replaced by a second L-band frequency in Pulsar. Earth Orbiting GNSS C-bands in China are not decided up to now.

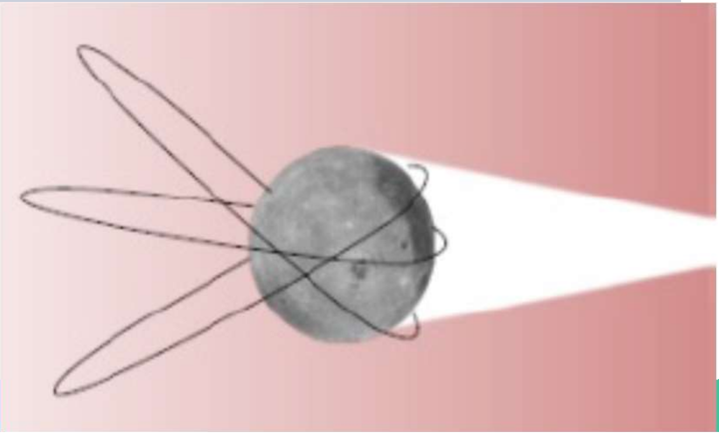
*LEO PNT New commer in L and S band: **Synchrocube** (french private system)*

* JAXA's communication in SFCG in march 2023

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

Tentative « Mitigating » technique	CONSTRAINTS (no such constraint in S 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 or Ops is unlikely.
Orbiter's PNT signal beam steering	L or C 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 or credible to mitigate harmfull interference to RA in the SZM. Figure 4

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

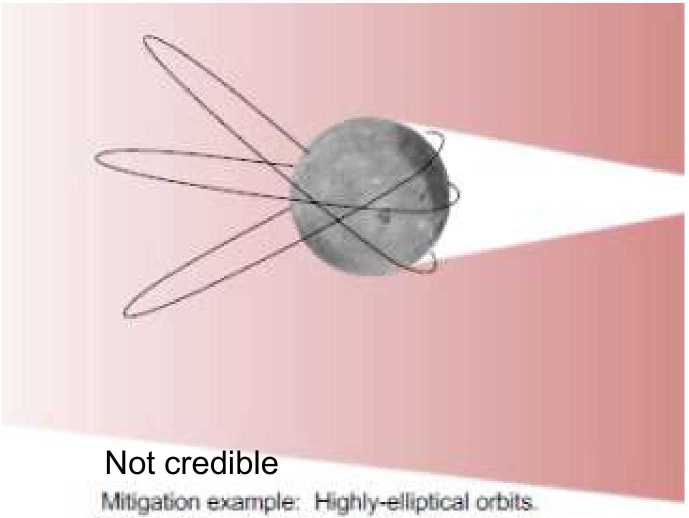


Some other technical drawbacks of L-band for in-situ lunar PNT

cnes

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 endanger this !). Synchronisation performances are less good in L band !

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

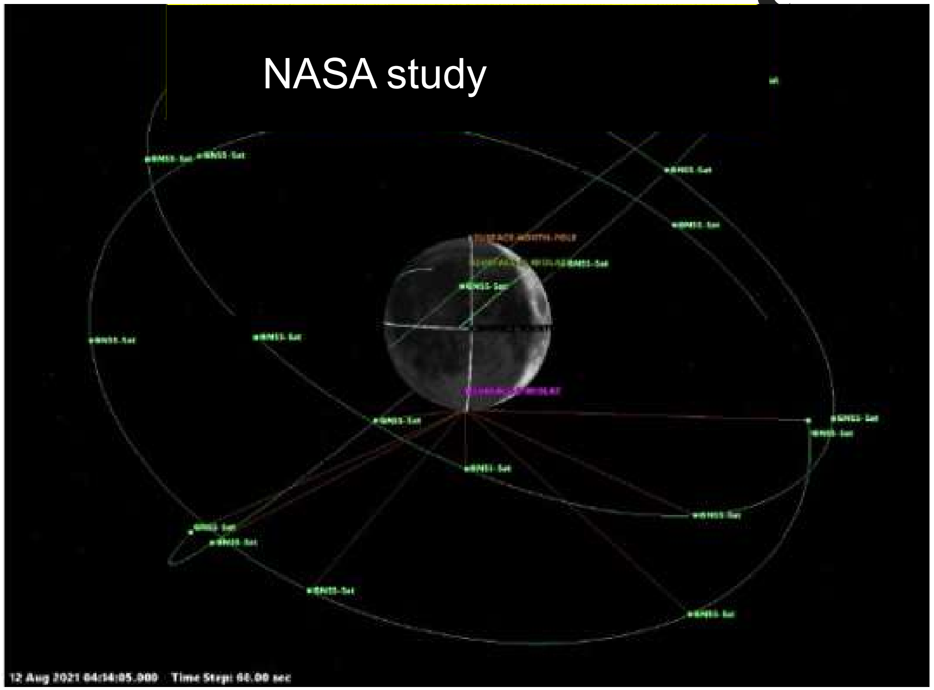


Not credible

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 below, while an exemple of more credible orbital design is presented on the right (used for intra PNT interference scenarii)

-**Reason 1)** = Temporal and operational scheduling constraints mentioned in slide 30, and to consider the presented orbits "SZM centred" would be a big desoptimization.

-**Reason 2)** = 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 3)** = 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 or C-band, the SZM will be covered much more than 20% of the time.

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.**

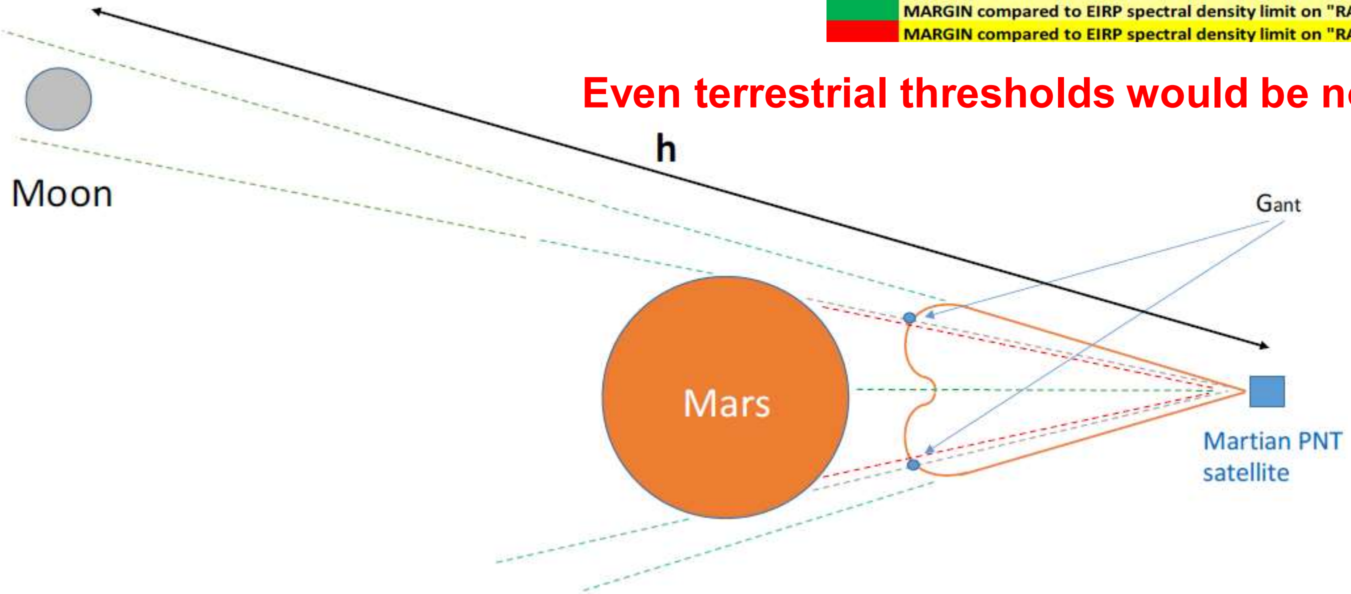
Interference threshold levels for radio astronomy observations in bands for which there is a primary allocation

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 (**slide 23**)

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.

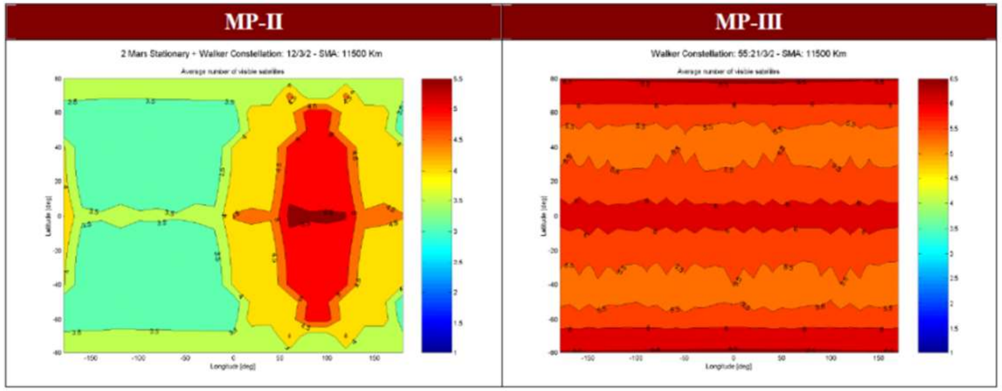
Demonstration of Harmfull Interference to Radio Astronomy in the SZM in case of martian PNT constellation in L-band

cnes

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**	