Ensuring Lunar and Martian In situ PNT Coexistence with Surface Wireless by Respecting SFCG Recommendations

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BIOGRAPHIES

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Jacques Sombrin received his engineering degrees from Ecole Polytechnique (Paris) in 1969 and Ecole Nationale Supérieure des Télécommunications (Paris) in1974. He is a life member of IEEE, emeritus member of SEE and member of EuMA. He was awarded the EuMA Career Award in 2015 Microwave Engineer in CNES from 1974, more recently Senior Expert and Assistant Director for Radio Frequencies, in charge of radio frequency research program and roadmaps until 2010. He participated in satellite projects and has been responsible for microwave equipment development (TWT, TWTA, filters...), for microwave instruments and payloads, for space telecom systems architecture and performance. Since 2011, he is a Consulting Engineer and a researcher in TéSA. His current research interests include: "Model and simulation of amplifiers nonlinearity in telecommunication satellites and their linearization",. "Telecommunication systems NPR and EVM characterization, efficiency, and optimization of capacity/power consumption compromise", and "Multipactor effect, microwave breakdown and IMPs".

Philippe Paimblanc graduated as an electronics engineer from the ENAC (Ecole Nationale de l'Aviation Civile) in 2002 and received the same year his Master research degree in signal processing. He performed a PhD at the satellite navigation lab of the ENAC. He is a research engineer at TéSA laboratory, in Toulouse, France. His research activity in satellite positioning and timing has recently focused on GNSS anomaly detection, autonomous positioning and synchronization in nanosatellite swarms, LEO positioning based on 5G signals as well as interference detection.

Antoinette Labeyrie graduated from the French National Institute of Electrical Engineering, Electronics, Computer Science, Hydraulics & Telecommunications (ENSEEIHT), in 2005, obtaining her Master of Engineering with a specialization in electronics and signal processing. She started working for the Signal Time-frequency & Radiodetermination Division at CNES as a subcontractor in 2013 and later joined this division in 2024 as a specialist on GNSS signal processing.

Robin Quintart graduated from ENAC (National Civil Aviation School) in 2017 obtaining a Master of Engineering with a specialization in Telecommunication and Signal processing and a Master in Aerospace Systems - Navigation and Telecommunications (AS-NAT) specialized in GNSS. He started to work as subcontractor for CNES in 2017 for the evaluation of simulators and receivers in the Radiodetermination laboratory of the CNES Signal Time-frequency & Radiodetermination Division. He ater joined this division in 2021 as a specialist in GNSS space based receiver and software defined receiver.

Jean Pla is currently an expert in frequency management at CNES. He was vice chair of ITU-R SG7, a study group dedicated to scientific radio services. He was also European coordinator for previous world radio conference agenda items. He is currently chapter rapporteur of scientific agenda items for the next World Radio Conference of 2027.

Romain Desplats, currently head of Space Spectrum Strategy at CNES. He works with an outstanding team of experts who are dedicated to developing and executing strategies related to the allocation and use of spectrum for spacebased communication and other activities. Together, they work collaboratively to ensure spectrum resources are optimally used to support emerging technologies and meet the ever-growing demand for space-based communication services.

ABSTRACT

CNES is involved in the protection of Radio Astronomy near the far side of the Moon, in a zone defined by ITU as the Shielded Zone of the Moon (SZM).

The 2483.5-2500 MHz band has been chosen for lunar in-situ PNT notably since it is the only band recommended by SFCG (Space Frequency Coordination Group) for lunar in situ PNT. This band is also the only GNSS band recommended by SFCG for radiocommunications from Martian orbit to Martian surface. CNES proposed this band for lunar and Martian frequencies to SFCG. Regarding the protection of Radio Astronomy in Shielded Zone of the Moon (SZM), which is more or less the far side of the Moon and above, this 2483.5-2500 MHz band is well adapted, while it is not the case for any part of the other GNSS bands used on Earth: both RNSS L and C bands constitute each an important threat for Radio Astronomy in the SZM.

SFCG issued two recommendations concerning the protection of lunar in-situ PNT in its 2483.5-2500 MHz band: Recommendation SFCG 32-2R6, so called “Freqs for lunar region”, and Recommendation SFCG 43-1, so called “Protection of lunar S-band PNT”.

Obeying both SFCG RECs 32-2R6 and 43-1simultaneously is mandatory to ensure protection of lunar in-situ PNT from wireless WIFI and 3GPP (like 4G, 5G, …) lunar surface links.

Adjacent to the 2483.5-2500 MHz in-situ lunar PNT band recommended by SFCG 32-2R6, the bands 2400-2480 MHz and 2503.5-2655 MHz are among the bands recommended for lunar surface wireless systems. This means that there is a minimum of 3.5 MHz mandatory guard bands on each side of the 2483.5-2500 MHz PNT band in SFCG 32-2R6 for the protection of lunar in-situ PNT. The SFCG REC 43-1 recommends the PNT devices to implement filtering, and that each lunar surface wireless system should not generate an aggregated PFD exceeding -121dBW/m²/MHz at the input of the PNT receiving antenna. The SFCG REC 32-2R6 recommends the Wireless device to implement filtering when necessary to avoid Out Of Band harmfull interference to PNT.

The paper details these 2 SFCG recommendations which are fundamental for protection of in-situ lunar PNT. It provides some rules to the implementers to respect both SFCG recommendations. A model of PNT receiver response to interference has been developed by TéSA. Different cases are considered, such as astronauts on the lunar surface in a suit equipped with wireless and PNT devices and related antennas on their backpack, with the wireless transmitters (WIFI and 5G) interfering with the PNT reception. Technical justifications of the PFD limit of SFCG REC 43-1 are also provided. These explanations and rules are valid for in-situ lunar PNT, like the AFS (Augmented Forward Service) of LunaNet, but also for the baseline of the future Chinese in-situ lunar PNT service.

This paper presents the Wireless to PNT interference simulator developed by TéSA. The interference results from this simulator were used by CNES to participate to the elaboration of REC 32-2R6 and REC 43-1 in order to contribute protecting lunar in-situ PNT and, consequently, Radio Astronomy in the SZM.

The SFCG recommendation applicable in the Mars region is REC 22-1R4, “Frequency assignment guidelines for communications in the Mars region” , so called “Freqs for Mars region”. In addition to the 2483.5-2500 MHz orbit to surface band, REC 22-1R4 recommends several surface wireless bands, including 2400-2480 MHz and 2503.5-2620 MHz (likely to be extended up to 2655 MHz in a next version). CNES showed that there would also be Radio Astronomy issues with GNSS L and C bands if one of them were broadcast by a Martian radiocom constellation, since Mars is regularly visible from the Shielded Zone of the Moon. The protection measures for a Martian in-situ PNT in 2483.5-2500 MHz would then be similar to the ones described for lunar in-situ PNT systems.

This paper introduces the CCSDS Standard for lunar and Martian 3GPP and WIFI wireless links. This CCSDS Standard specifies to comply with the described SFCG recommendations. The paper finally concludes the systematic need to conduct system studies for each lunar wireless network, combining wireless and PNT, and involving wireless to PNT interference computations.

INTRODUCTION

CNES is involved within the protection of Radio Astronomy near the far side of the Moon, in a zone defined by ITU as the Shielded Zone of the Moon (SZM) as described by figure 1. This involvement concerns the protection of radioastronomy from lunar radars, lunar RF communications and lunar in-situ PNT. Section V of article 22 of the ITU Radio Regulation is dedicated to the protection of Radio Astronomy in the SZM.

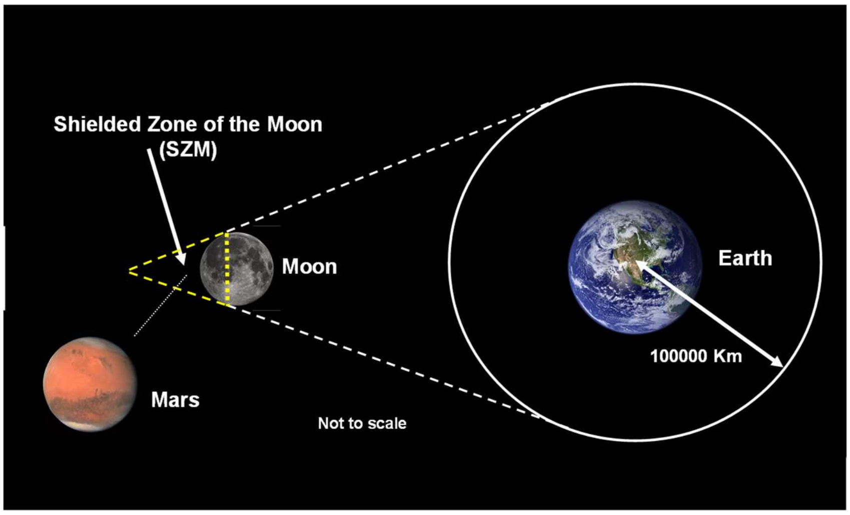

FIGURE 1 ITU Definition of the Shielded Zone of the Moon (SZM)

The 2483.5-2500 MHz band has been chosen for lunar in-situ PNT notably since it is the only band recommended by SFCG (Space Frequency Coordination Group) for lunar in-situ PNT, following an initial proposal from CNES. This band is also the only GNSS band recommended by SFCG for radiocommunications from Martian orbit to Martian surface, also following an initial proposal from CNES. Regarding the protection of Radio Astronomy in SZM, this 2483.5-2500 MHz is well adapted, while it is not the case for any part of the other GNSS bands used on Earth. These other GNSS bands are 1164-1300 MHz and 1159-1610 MHz in L band [1], and 5010-5030 MHz in C band [2], both RNSS L and C bands constituting each an important threat for Radio Astronomy in the Shielded Zone of the Moon [1], [2]. The ITU recommendation RA.479-5, untitled "Protection of frequencies for radio astronomical measurements in the shielded zone of the Moon", refers to the Resolution B16 of the 1994 XXIInd General Assembly of the International Astronomical Union (IAU). Resolution B16 recommends notably for the SZM: "The 300 MHz to 2 GHz range should be reserved for Radio Astronomical Observations", and also protection of the Continuum Bands like the one in the neighborhood (*that is "below" and "above"*) of the 5 GHz "terrestrial" Radio Astronomy band. The RNSS C-band also has at least 8 technical drawbacks when used in the SZM [2], [9], compared to L or S band [2], [9] requiring however a larger antenna.

More generally, it is essential for Radio Astronomers to keep quiet frequency bands, between 3800-5150 MHz [2] for instance, in the Shielded Zone of the Moon, to perform continuum and spectrum line observations. In addition to the 3800-5150 MHz band, there are two other wide bands where radiocommunications have to be avoided in the SZM to preserve Radio Astronomy: from 5925 to 8550 MHz and from 40.5 to 78 GHz.

That is why, to secure Radio Astronomy in the SZM, CNES participates in different groups like SFCG, ICG, IOAG, CCSDS, ITU, … to contribute to the protection of future lunar in-situ PNT receivers in 2483.5-2500 MHz band from potential interferences from the lunar surface wireless links, notably WIFI and 3GPP. By doing so, the 2483.5-2500 MHz band remains viable for lunar in-situ PNT, and therefore the exploration of L or C bands for in-situ lunar PNT, harmful to Radio Astronomy in the SZM, is not necessary anymore. Other reasons for the choice of the 2483.5-2500 MHz band for in-situ lunar PNT are exposed in [1], [2], [9]. One of these multiple reasons is the possibility of leveraging terrestrial S-band PNT technology, like the one of LunaCube, IRNSS/Navic 1.0, Navic 2.0, Beidou-3 non-GEO, Beidou 1, 2 & 3 GEO, Globalstar, FuturNav, KPS, GNSSaS/LEONAV, Synchrocube, … [2], [9].

The goal of this paper is to describe the SFCG recommendations related to lunar and Martian in-situ PNT frequency bands, to highlight their content related to the protection of lunar PNT from wireless interferences, and the technical justifications of the said recommendations.

SFCG RECOMMENDATIONS ABOUT LUNAR IN-SITU PNT

SFCG issued two recommendations concerning the protection of lunar in-situ PNT in its 2483.5-2500 MHz band:

* **Recommendation SFCG 32-2R6** "Communication and Positioning, Navigation, and Timing frequency allocations and sharing in the lunar region" [3], so called "Freqs for lunar region"

and:

* **Recommendation SFCG 43-1** “protection of in-situ lunar region Positioning Navigation, and Timing (PNT) services in the 2483.5-2500 MHz frequency band from unwanted emissions from lunar surface communications systems” [4], so called “protection of lunar S-band PNT”.

SFCG does not actually recommend lunar in-situ frequency band other than 2483.5-2500 MHz.

The Recommendation SFCG 32-2R6 specifies several link types, including the “Earth bases GNSS to Lunar Orbit and Lunar Surface” (type 8) and “In-situ Lunar based PNT to Lunar Orbit and Lunar Surface” (type 9), as depicted by Table 1.

TABLE 1 First extract of SFCG REC 32-2R6 related to lunar PNT: band, PNT & SAR forward messages and limitations.

Link Type	Frequency Band	Users	Service Type	Typical Data Rate per User	Limitations
8.0 Earth based GNSS to Lunar Orbit and Lunar Surface	1164-1215 MHz 1215-1300 MHz 1559-1610 MHz	Lunar Orbiters, Surface hubs (Hab, Landers, Rovers, etc.), LCT	PNT	50 bps	Limited to transmission of signals from GNSS Constellations in the Earth region
Link Type	**Frequency Band**	**Users**	**Service Type**	**Typical Data Rate per User**	**Limitations**
9.0 In-situ Lunar based PNT to Lunar Orbit and Lunar Surface	2483.5-2500 MHz (LO-LS) 2483.5-2500 MHz (LO-LO)	Rover-Orbiter, EVAs- Orbiter, Surface hubs (Hab, Landers, etc) – Orbiter	PNT, SAR Forward Messages	500 bps	Limited to one way PNT transmissions from LO to LS and LO to LO, with the in-situ lunar based PNT service provider at a higher altitude than the lunar orbiting user spacecraft receiving the PNT signal

The L-band signals coming from GNSS constellations in the Earth regions are recommended by SFCG 32-2R6, but, of course, not L-band lunar in-situ signals, due to the threat that L-band represents for Radio Astronomy in the Shielded Zone of the Moon. We have added red boxes in Table 1 to highlight some parts of SFCG REC 32-2R6, like the types of service allocated by SFCG to signals from Lunar Orbit (LO) to Lunar Surface (LS) or to LO in the 2483.5-2500 MHz band, which are PNT, but also Search And Rescue (SAR) forward messages. The SFCG Search And Rescue frequency band to be transmitted by the SAR beacons is 2298.36-2299.64 MHz, which is also in the S-band. The use of the UHF SAR band (406-406.1 MHz) operated on Earth is not planed in the SZM because it is a band below 2 GHz, as recommended by ITU-R REC RA.479-5 to protect Radio Astronomy in the SZM. The “Limitations” cell of Table 1 simply indicates that the lunar in-situ PNT payloads on lunar orbiters are transmitting toward the lunar surface; their signals can be received by user on the lunar surface or orbiters “below” the PNT payloads.

TABLE 2 Second extract of SFCG REC 32-2R6: guard bands and requirement to filter the wireless transmissions:

	Frequency Band	Users	Service Type	Typical Data Rate per User	Limitations
Wireless (Surface to Surface)	2.400 – 2.480 GHz	EVAs	Voice/data (comm & PNT)/ video	3 Mbps (max, rate will drop as distance increases)	2480-2483.5 MHz is considered as the guard band. Sufficient OOB filtering to protect the 2483.5-2500 MHz LO-to-LS PNT band is necessary.
		Rover - LCT	Voice/data (comm & PNT)/video	30 Mbps (max)	
		EVAs – Landers, Rover	Voice/data (comm & PNT)/video	3 Mbps (max)	OOB filtering of the harmonic falling in 4.8-4.99 GHz band (secondary RAS) is necessary in the SZM
In-situ PNT (Orbit to Surface)	2483.5-2500 MHz (LO-LS) 2483.5-2500 MHz (LO-LS)	Rover-Orbiter, EVAs-Orbiter, Surface hubs (Hab, Landers, etc) – Orbiter	PNT, SAR Forward Messages	500 bps	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 Rover - LCT EVAs – Landers, Rover	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

Adjacent to the 2483.5-2500 MHz in-situ lunar PNT band recommended by SFCG 32-2R6, the bands 2400-2480 MHz and 2503.5-2655 MHz are among the bands recommended for lunar surface wireless. The 2400-2480 MHz band is planned, notably for WIFI and pseudolites on the lunar surface, pseudolites beeing a particular case of wireless transmitters. The band 2503.5-2655 MHz is planned, notably for 3GPP 4G and 5G wireless links. This S-band allocation for wireless and PNT means that there are only a minimum of 3.5 MHz mandatory guard bands on each side of the 2483.5-2500 MHz PNT bandwidth in SFCG 32-2R6, as depicted in Figure 2. This contributes to protection of lunar in-situ PNT. Note: the wireless 2655-2690 MHz band has the limitation in SFCG REC 32-2R6 to be usable only outside the Shielded Zone of the Moon.

An important point is that SFCG REC 32-2R6 specifies requirements related to the protection of PNT. As depicted by Table 2, Sufficient Out Of Band (OOB) filtering of the wireless signal by the transmitter in the 2400-2480 MHz is required if necessary to avoid harmful interference to PNT in the 2483.5-2500 MHz band. The same requirement applies for wireless transmitters in the 2503.5-2655 MHz band.

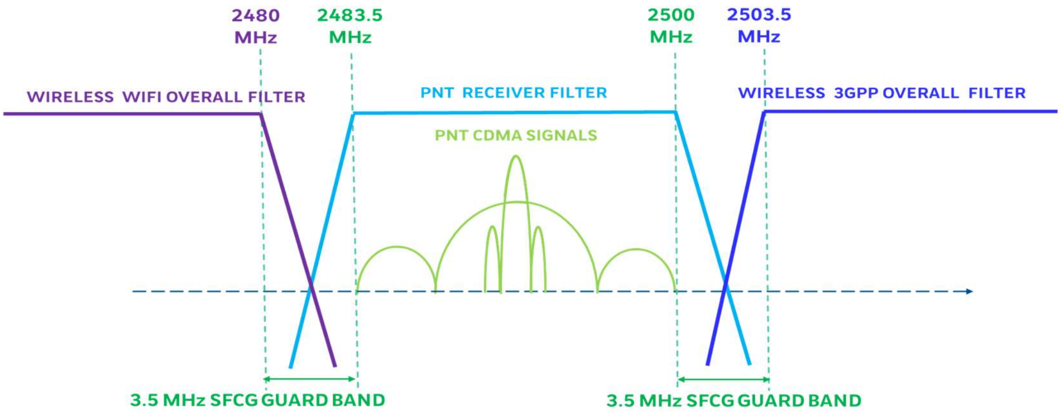

FIGURE 2 SFCG PNT and neighboring Wireless S-bands, and the minimum 3.5 MHz Guard Bands in between.

TABLE 3 Third extract of SFCG REC 32-2R6: Lunar Surface Wireless Network bands.

Lunar Surface Wireless Network	390-405	MHz (Note 4)	**0.0150 GHz (outside SZM)**
	410-420	MHz (Note 8) (Note 10)	**0.0100 GHz**
	435-450	MHz (Note 4)	**0.0150 GHz (outside SZM)**
	2.400-2.480	GHz (Note 7)	**0.0800 GHz**
	2.5035 – 2.655	GHz (Note 9)	**0.1515 GHz**
	2.655-2.690	GHz (Note 4)	**0.0350 GHz (outside SZM)**
	3.5-3.8	GHz	**0.3000 GHz**
	5.15-5.835	GHz (Note 6)	**0.6850 GHz**
	5.855-5.925	GHz	**0.0700 GHz**
	25.25-25.5	GHz	**0.2500 GHz**
	27.225-27.5	GHz	**0.2750 GHz**
	27.5-28.35	GHz	**0.8500 GHz**

There are 12 lunar surface wireless bands allocated by SFCG REC 32-2R6. The total lunar surface wireless cumulated bandwidth is 2,7365 GHz wide, that is about 165 times more than the total bandwidth allocated to lunar in-situ PNT (16.5 MHz). That is why having two minimum guard bands of 3.5 MHz contributing to protecting the 2483.5-2500 MHz PNT band is not a problem to design a suitable lunar wireless network. Among the 12 lunar surface wireless bands, the 3.5-3.8 GHz band and the 5 GHz bands are especially relevant for omnidirectional wireless surface links. The SFCG 5.150-5.835 GHz wireless band is just far enough from the neighborhood (*that is "below" and "above"*) of the 5 GHz "terrestrial" Radio Astronomy band mentioned in ITU-R REC RA.479-5, neighborhood to be protected in the SZM.

We can also note that only one SFCG lunar surface wireless frequency band is allocated below 2 GHz in the SZM (410-420 MHz). This UHF band is currently used for EVA in Low Earth Orbit, while the final targeted bands for lunar surface wireless networks are the bands allocated by SFCG and compatible with WIFI and 3GPP standards, which are all above 2 GHz.

Obeying both SFCG RECs 32-2R6 and 43-1simultaneously is mandatory to ensure protection of lunar in-situ PNT from wireless WIFI and 3GPP (like 4G, 5G, …) lunar surface links (Table 3).

The SFCG REC 43-1 recommends that PNT devices implement filtering, and that a maximum aggregated PFD limit of **-121 dBW/m^2/MHz** at the input of the PNT receive antenna shall be generated by each lunar surface wireless system (Table 4). Also, REC 43-1 "Considering" part suggests avoiding pulsed-like lunar surface wireless links (Table 4), and to have distances greater than **24 cm** between operating wireless and PNT antennas (Table 3 and Figure 4). It also suggests to consider at least 4 wireless transmitters in a given wireless network (even though fewer than 4 wireless transmitters could also be used while respecting the other suggestions and recommendations). All the suggestions made in the "Considering" part of SFCG REC 43-1 are to be considered in addition to the recommendation that lunar wireless surface links comply with the **-121 dBW/m^2/MHz** PFD limit.

TABLE 4 Summary of the texts recommended by SFCG to protect lunar in-situ PNT from lunar surface wireless interferences

Type of lunar Link, related band	SFCG REC	Text of the REC related to protection of PNT, applying to the type of lunar link
Wireless, 2400-2480 MHz	32-2R6, Recommend **1**	2480-2483.5 MHz is considered as the guard band. Sufficient OOB filtering to protect the 2483.5-2500 MHz LO-to-LS PNT band is necessary.
Wireless, 2503.5-2655 MHz	32-2R6, Recommend **1**	2500-2503.5 MHz is considered as the guard band. Sufficient OOB filtering to protect the 2483.5-2500 MHz LO-to-LS PNT band is necessary.
Wireless, 2400-2480 MHz and 2503.5-2655 MHz	43-1, Considering **f**	Considering that lunar surface communications system deployments may require additional RF filtering to reduce the unwanted emission levels in the 2 483.5 – 2 500 MHz band;
Wireless, 2400-2480 MHz and 2503.5-2655 MHz PNT, 2483.5-2500 MHz	43-1, Considering **g**	Considering that the PNT antenna is typically located at least **0.24 meters** from the lunar surface wireless user equipment antenna in order to be in the antenna radiation far field, and at least **17 meters** from the lunar surface wireless base station antenna;
Wireless, 2400-2480 MHz and 2503.5-2655 MHz	43-1, Considering **h**	Considering that unwanted emissions from the lunar surface wireless system typically have bandwidths greater than 1 MHz, and will result in wideband continuous interference rather than pulsed interference to the lunar PNT receiver;
Wireless, 2400-2480 MHz and 2503.5-2655 MHz	43-1, Considering **i**	Considering that analysis of interference from unwanted emissions from a lunar surface wireless system to the lunar PNT receiver may need to consider the aggregate effect of four or more wireless transmitters;
Wireless, 2400-2480 MHz, 2503.5-2655 MHz, and 2483.5-2500 MHz	43-1, Recommend **1**	Recommends that the maximum aggregate unwanted emissions into the frequency range 2 483.5 – 2 500 MHz from each lunar surface wireless system is limited to **-121 dBW/m²/MHz** at the input of the PNT receiver antenna
PNT, 2483.5-2500 MHz	43-1, Recommend **2**	Recommends that lunar surface PNT receiver RF front end operating in the 2 483.5 – 2 500 MHz band have sufficient filtering of signals in the adjacent bands to avoid saturation.

The minimum guard bands of 3.5 MHz between wireless and PNT bands is a minimum to respect. If there is no other way to increase this guard band, that is to consider a wireless channel (WIFI,…) significantly below 2480 MHz, or wireless channels (3GPP, …) significantly above 2503.5 MHz, in order to respect the **-121 dBW/m²/MHz** PFD limit at the PNT receiver antenna input, one or several wireless channels adjascent to the PNT guard bands will have to be excluded.

LUNAR IN-SITU PNT SIGNAL MODEL

To evaluate the PNT's protection efforts needed to avoid harmful interferences from WIFI, 3GPP and other wireless transmissions, it is necessary first of all to model the PNT signal. The AFS signal (Augmented Forward Service) of LunaNet [5], [6], has been considered as a reference, and, in particular, its pilot channel, since its main lobe occupies the widest bandwidth among the two AFS components. These components are a BPSK(1) data channel, and a BPSK(5) pilot channel. NASA, JAXA and ESA current contributions to LunaNet AFS concern a total of 12 first lunar orbiters, and additional(s) orbiter(s) from these or other space agencies could be expected before the Full Operational Capability (FOC).

The future Chinese in-situ lunar PNT service, has a baseline band in 2483.5-2500 MHz, as announced by CAST during the IOAG-ICG lunar PNT forum in February 2025 in Vienna [7], [8]. This NASA/ESA/JAXA/CAST convergence for lunar PNT in 2483.5-2500 MHz will be extremely helpful for Radio Astronomy in the SZM, and also important for interoperability from the lunar in-situ PNT receiver side. The Chinese lunar PNT baseline seems to leverage Beidou-3 in GNSS S-band [7], and could be therefore a BPSK(8)-like filtered signal like the one already transmitted by some MEO and IGSO satellites [9], or a BPSK(4)-like filtered signal, like the RDSS-payload signal transmitted from the beginning by all the GEO satellites of the Beidou system [9]. The BPSK(4)-like filtered signal is assumed, because the smaller the mainlobe's bandwidth, the lower the sensitivity to wireless interferences. The PBSK(5) channel has therefore been considered as the reference for the PNT-Wireless interference simulations made by TéSA and CNES, since it has the widest spectral width among the 3 signal channels mentioned above [BPSK(1), BPSK(4) and BPSK(5)].

The mentioned planned in-situ lunar PNT signal spectra are presented in Figure 3.

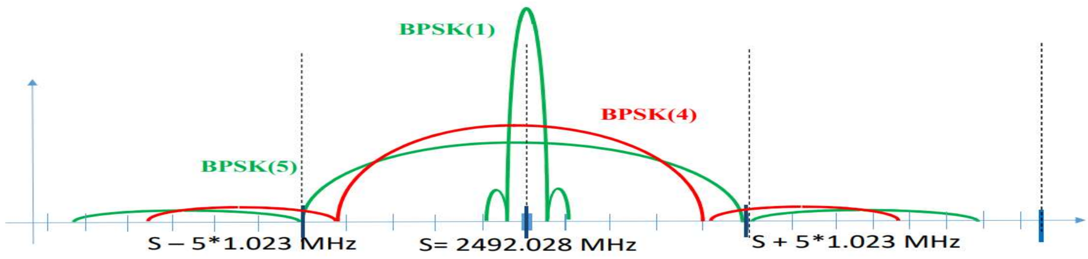

FIGURE 3 Lunar in-situ PNT spectra with LunaNet AFS in green and assumed baseline Chinese lunar PNT in red.

As off [6], the AFS navigation carrier frequency is 2492.028 MHz, like for the other GNSS systems in S-band [6], [9]. The AFS lunar PNT I and Q minimum received power levels are -166 dBW each, at 5 degrees of elevation, at the input of a PNT receiver antenna on the lunar surface. The transmitted power is split 50%-50% between I and Q components [6]. The AFS data symbol rate is 500 sps [6]. The receiver reference bandwidth centered on the carrier frequency to be considered for the correlation losses shall be 15.944 MHz [6]. For each signal component, the correlation loss due to payload distortions shall be below 0.6 dB [6].

DETERMINATION OF THE SFCG REC 43-1 PFD LIMIT, AND WAY TO USE IT.

To determine the PFD limit of SFCG REC 43-1, contributing to protecting PNT from wireless interference, a C/N_0 degradation threshold of 0.5 dB has been defined per interfering wireless network (or system). This 0.5 dB PNT C/N_0 degradation per interfering wireless network has to be a maximum, since there could be several lunar wireless networks operating simultaneously. For instance, we could consider several simultaneous networks among the following local networks: 3GPP 4G LTE, 3GPP 5G, 3GPP 6G, WIFI-6, WIFI-7, Bluetooth, specific not standardized local networks, etc. One can therefore realize that a maximum C/N_0 degradation of 1 dB (for instance) which would be allowed per interfering lunar network (for example due to 3GPP 5G network only) would create significantly too high degradation values. Moreover, for GPS and GALILEO, the triggering coordination degradation threshold is often 0.25 dB, corresponding to the 6 percent degradation criteria widely used in ITU. In addition, ITU-REC M.2030 [10] mentions that allowable degradation ratio for pulsed sources interfering Radio Navigation Satellite System (RNSS) receivers is required to be below 0.2 dB in all the cases.

Moreover, ITU-R M.1903 [11] also states that "an aeronautical safety margin of at least 6 dB is required to protect the GNSS safety applications, and that additional margins may be required". A 6 dB safety margin (I/N = -6 dB) corresponds to a total C/N degradation of 1 dB, while [11] also states that "to support safety-of-life applications, all interference sources must be accounted for". It would be normal to consider lunar astronaut's in EVA on the lunar surface or in low lunar orbit as a critical application equivalent to "safety of life", since the life of the astronaut could be at stake in case of malfunction of its equipment. Therefore, if we have to consider a maximum C/N_0 degradation of 1 dB due to the cumulated wireless networks, it is normal to consider 0.5 dB as the very maximum C/N_0 degradation per lunar wireless network.

If we note ***R*** the ratio between the interfering spectral density ***I*** integrated in the receiver band, and the noise spectral density $\boldsymbol{No}$ integrated in the receiver band, we have:

$$R = I/No \qquad \frac{C}{No_{eff}} = \frac{C}{No + I} = \frac{C}{No(1+R)}$$

The degradation D of the C/No ratio is equal to:

$$D = \frac{No_{eff}}{No} = \frac{No + I}{No} = 1 + R$$

Expressed in dB, we have:

$$D(dB) = 10\,log(1+R) = 10\,log\left\{1 + 10\text{^}\left[\frac{R(dB)}{10}\right]\right\}$$

And:

$$R(dB) = 10\,log(D-1) = 10\,log\left\{10^{\left[\frac{D(dB)}{10}\right]} - 1\right\}$$

We consider, for instance, a PNT receiver noise temperature T of 290 K. The gain of the PNT antenna used in the interference calculations is -3 dB:

$$G = 4\pi S/\lambda^2 = 1/2$$

The antenna effective surface is:

$$S = \frac{G\lambda^2}{4\pi} = \frac{Gc^2}{4\pi f^2} = \frac{9\,.\,10^{16}}{50\,\pi\,10^{18}} = 5{,}73\;10^{-4}\,m^2 \qquad or \quad -32{,}4\;dBm^2$$

The noise spectral density *No* for T = 290 K is k.T, where k is the Boltzman constant, that is *No* = -144 dBW/MHz

We therefore find I (dBW/MHz) = -144 + R = -144 – 9,4 = -153.4 dBW/MHz

This lead to the maximum allowed PFD which is -153.4 + 32.4 = **-121 dBW/m²/MHz**, per lunar wireless network at the input of the considered PNT antenna.

The PFD limit must never be exceeded in any case. Therefore, to keep PNT protected from wireless intereference, it is important to consider the worst case in the design of the global PNT and wireless overall system. This worst case corresponds to the low PNT receiver antenna gain, and the highest system noise temperature at the input of the receiver. This worst case therefore corresponds to the smaller absolute C/N_0 ratio for the PNT receiver, typically at 5 degrees of elevation. As shown by Table 5, it would be useless to consider only the highest antenna gain of the PNT receiver and/or the smallest noise temperature associated PFD limit of **-121 dBW/m2/MHz**. In that case, the PNT receiver would be associated to C/N_0 degradation significantly higher than 0.5 dB per wireless network, which is harmful interferences. That is why the overall wireless-PNT local system shall be sized vis a vis the worst case PNT antenna gain and system noise temperature at the input of the PNT receiver.

TABLE 5. PFD limit for the worst case (low antenna gain and high system noise temperature), and PFD limits which would have been necessary to define in REC 43-1 if the worst case had not been considered

	Antenna Gain (dB)		-3		0		3
	antenna area (dBm^2)		-32,39		-29,39		-26,39
	degradation (dB)		0,50		0,50		0,50
	ratio I/No (dB)	-9,14					
Noise temperature (K)	Noise PSD (dBW/MHz)	Interference PSD (dBW/MHz)	PFD(dBW/m^2/MHz)		PFD(dBW/m^2/MHz)		PFD(dBW/m^2/MHz)
290	-143,98	-153,12	-120,73		-123,73		-126,73
190	-145,81	-154,95	-122,56		-125,56		-128,56

The SFCG recommendation 43-1 suggests that the PNT antenna is typically located at least 0.24 meters from the lunar surface wireless user equipment antenna in order to be in the antenna radiation far field. For the PNT and wireless frequencies of about 2.5 GHz, 24 cm corresponds to twice the wavelength (2λ).This configuration is typically the one of an astronaut's suits carrying both a wireless and a PNT antenna, as depicted on figure 4.

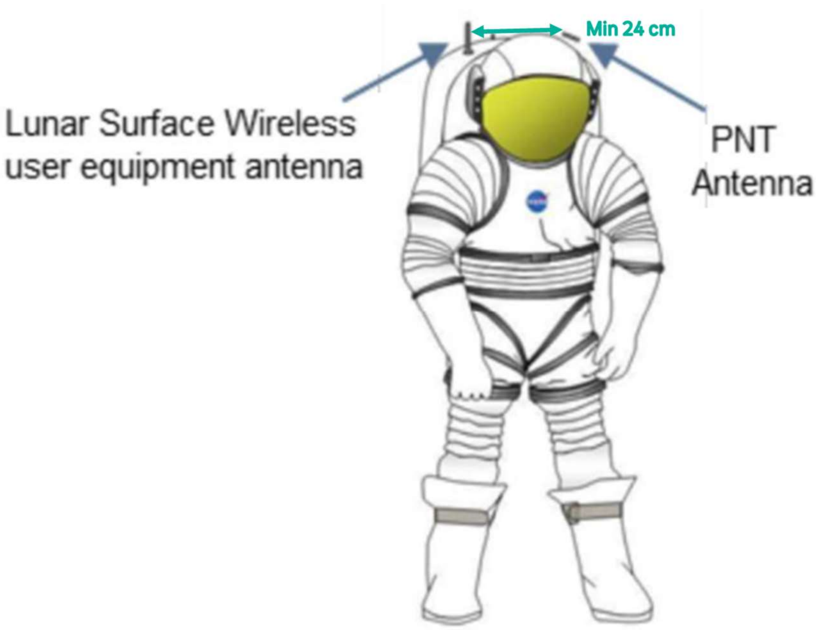

FIGURE 4 Lunar astronaut's suit with both wireless and PNT antennas on the backpack.

PULSED-LIKE WIRELESS LINKS TO BE AVOIDED

This paragraph shows why SFCG REC 43-1 suggests that unwanted emissions from the lunar surface wireless system typically have bandwidths greater than 1 MHz, and will result in wideband continuous interference rather than pulsed interference to the lunar PNT receiver.

In some receivers that are near pulsed transmitters, blanking is performed to reduce to zero the signal, noise and interference received during the interference pulse time, rather than digitizing interference alone. The degradation then is caused by the suppression of the signal during the pulse and the reduction of the integrated signal power. If the receiver continues to operate normally under these conditions, this signal loss is proportional to the duty cycle of the interfering signal.

We assume that the blanking of interference peaks in the receiver is performed, that the emissions are discontinuous and consider that the peak power values are held for a sufficiently short time so as not to disturb the PNT receiver apart from the degradation of the C/N_0 coming from blanking. Assuming that the PNT signal is masked and set to zero by the blanking mechanism for a part of the time called pulse duty cycle (PDC), the effective noise power spectral density is:

$$No_{eff} = No/(1 - PDC)$$

We have neglected in this equation continuous interference and impulsive interference, which do not trigger the blanking. This equation simply considers the fact that the received signal (useful signal and noise) is set to zero during the interfering pulse and blanking operation. We then lose the corresponding integration time. The loss on the signal **amplitude** is proportional to the integration time, while it is the loss on the noise **power** which is proportional to the integration time. The signal power is divided by $(1 - PDC)^2$ while the noise power is divided by $(1 - PDC)$. For the same signal, the effective power density of the noise is greater by $1/(1 - PDC)$.

The degradation of the C/N_0 is equal to $D = 1/(1 - PDC)$.

In dB it is: $D(dB) = -10 \cdot \log(1 - PDC)$

We have: $PDC = 1 - 1/D = 1 - 10^{-D(dB)/10}$

We see that for the degradation to be less than 0.5 dB, the pulse duty cycle must be less than:

$$PDCmax = 1 - 10^{-0.5/1} = 10.9\%$$

This PDC value is the sum of all times when the peak powers of the transmitters exceed the threshold of the blanker, e.g. WIFI, 5G, … transmitters of the astronaut himself and 5G transmitter of base station if in TDD mode. It is also necessary to add the recovery time of the blanker itself after the end of the power pulse. This time is assumed to be significantly shorter than the duration of a 5G slot of 1 millisecond, but values from 1 to 30 microseconds are proposed in the M.2030 document [10].

Furthermore, the 5G station also creates interference when the astronaut is near the transmitter. It would then also be necessary to limit the duty cycle of the station to 10%, and even the total of the station and the astronauts for 5G and WIFI together, which leaves very poor efficiency for this channel. It would be preferable to use the first 5G channel (2500 to 2520 MHz) in FDD for the base station by shifting the band used in the 20 MHz channel to create a guard band and obtain less interference rather than 'using this channel in TDD with limited transmission efficiency. Table 6 gives the degradation of the C/N_0, the raw BER and the loss of symbols due to blanking. All the blocks containing results are “red” (not compliant with the specification), and therefore none are compliant. The table is based on the use of blanking in the PNT receiver.

When using blanking, an average activity of 50% gives an average loss of 3 dB on the C/N_0 and an average activity of 25% gives an average loss of 1.25 dB, assuming that the receiver and its phase loop and time loop work under these conditions.
In TDD, the duration of the frame is shared between the base station and the users, so the activity of each transmitter is halved, as is the transmitted rate but only one channel is used instead of two. The base station's activity, considered to be 25%, remains out of specification. The average activity of the astronaut would be 12.5% and would result in an average degradation of 0.6 dB if the receiver operates in these conditions or if blanking is applied. This remains above the 0.5 dB C/N_0 degradation threshold for a PNT astronaut’s receiver. We can note that if the PNT signal is modulated by symbols at 500 Bauds, blanking at 50%, on 10 ms frames, leads to the loss of 50% of the symbols, i.e. 2 to 3 consecutive symbols every 5 symbols. The bit losses of the message will depend on the error-correcting code and the interleaving.

TABLE 6. PNT signal's C/No degradation versus the type of 3GPP Wireless transmission.

Type of 3GPP 5G Wireless transmission	Duration of blanking or of the desensitization	C/No degradation	Lost symbols	Raw BER
FDD with average activity for the base station	50%	3 dB	2 to 3, over 5	0.25
FDD with peak activity for the base sation (low probability but possible)	close to 100 %	Peak C/No degradation close to infinite	close to 5, over 5	Peak BER close to 0.5
FDD with average activity for an astronaut	25%	1.25 dB	1 over 5	0.125
FDD with peak activity for an astronaut	50%	Peak C/No degradation: 3 dB	2 to 3, over 5	0.25
Semi-static TDD with average activity for the base station	25%	1.25 dB	1 over 5	0.125
Semi-static TDD with peak activity for the base station	50%	Peak C/No degradation: 3 dB	2 to 3, over 5	0.25
Semi-static TDD with average activity for an astronaut	12.5 %	0.58 dB	1 over 10	0.0625
Semi-static with peak activity for an astronaut	25 to 50 %	1.25 to 3 dB	1 to 3, over 5	0.125 to 0.25
Dynamic TDD with average activity for the base station	25%	1.25 dB	1 over 5	0.125
Dynamic TDD with peak activity for the base station (low probability but possible)	up to 100 %	Peak C/No degradation close to infinite	close to 5, over 5	up to 0.5
Dynamic TDD with average activity for an astronaut	12.5 %	0.58 dB	1 over 10	0.0625
Dynamic TDD with peak activity for an astronaut (low probability but possible)	up to 100 %	Peak C/No degradation close to infinite	close to 5, over 5	up to 0.5

It is less obvious to make a calculation if there is no blanker to set the signal and noise to 0 but if a CAG limits the sum of the signal and noise to a set value. In general, the AGC nominal output is set so that the average value of the thermal noise drives the digitizer to -12 dB with respect to its maximum level. Then the digitizer can digitize the signal and noise peaks at +12 dB over the average (2 bits more in the digitizer). During pulses, the AGC will give a noise plus interference level equivalent to the nominal noise level but no signal, while the blanker would cut both noise and signal. The loss in signal amplitude is proportional to the integration time while the noise power remains the same. The equation for effective noise power density then becomes:

$$No_{eff} = No/(1 - PDC)^2$$

The degradation of the C/N_0 is equal to $D = 1/(1 - PDC)^2$.   In dB it is: $D(dB) = -20 \cdot \log(1 - PDC)$

The degradation in dB is then double that obtained in the case of blanking.

We have: $PDC = 1 - 1/D = 1 - 10^{-D(dB)/20}$

We see that for the degradation to be less than 0.5 dB, the pulse duty cycle must be less than:

$$PDCmax = 1 - 10^{-0.5/20} = 5.6\%$$

However, it is likely that the AGC has a time constant closer to the millisecond than the microsecond (loop bandwidth close to kHz and not MHz) and that the time to consider is greater than PDC. The degradation can then be much more than double that of blanking.

To be compliant with the 0.5 dB degradation specification, the interference should not be present more than 5.6 % of the time minus the response time of the AGC. Using less than 5% of its capacity would make the 5G or WIFI channels very inefficient.That is why pulsed like wireless surface to surface links are not recommended, for PNT to remain protected from wireless interferences. Also, the degradations of PNT C/N_0 due to any of all the typical pulsed-like wireless configurations shown by Table 6, are all above 0.5 dB. Such configurations could therefore not be recommended.
Another type of pulsed emission to be avoided in the lunar in-situ PNT S-band is lunar radar transmissions. CNES therefore recommend any space agency or private operator to avoid, by all means, lunar orbital radars operating in the 2483.5-2500 MHz lunar in-situ PNT S-band.

MODEL OF LUNAR IN-SITU PNT RECEIVER

A simulator model of PNT receiver response to wireless interference has been developed by TéSA, and used to derive C/N_0 degradation for the lunar PNT receiver (figure 5).

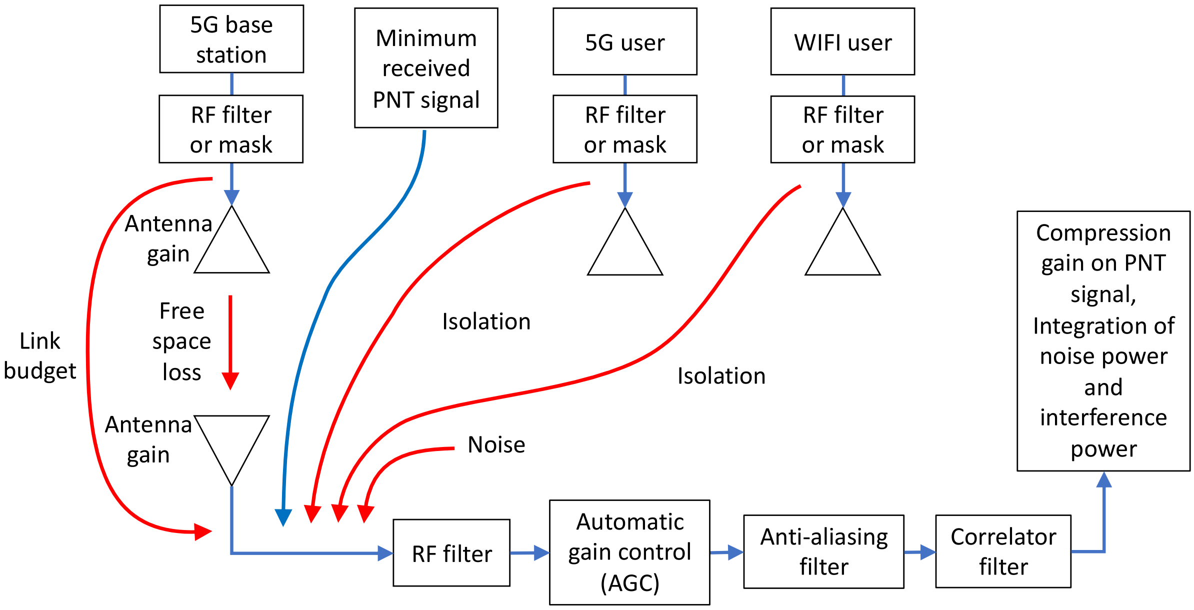

FIGURE 5 TéSA wireless transmitters to lunar PNT receiver interference model.

The signal center frequency and PNT 0 dB bandwidth limit frequencies of the TéSA simulator model are fixed. The slope and maximum rejection of the receiver RF filter can be modified, as well as the noise temperature and PNT antenna gain. The chip frequency is fixed and multipliers for center frequency and modulation of the BPSK or BOC lobe can be chosen by the user. The received power on I (or Q) channel can be modified if necessary. This power is divided by 2 if one lobe of BOC is used instead of BPSK. Oversampling at 3 or 2 can be modified by the user to take into account narrow correlation or not. The PNT PN code compression gain is fixed but could eventually be computed from modulation. The slope and maximum rejection of the anti-aliasing filter can be modified. The parameters for interference cases are as follows: User WIFI, user 5G and base station 5G interference can be combined. If both user and base station 5G interference are present in the channel adjacent to the PNT, TDD duplex mode is assumed, otherwise FDD duplex mode is assumed. The transmitter PSD masks can be modified by the following parameters: using a more realistic RF mask., reducing the useful nominal bandwidth., applying a PFD limit in PNT bandwidth and value of this limit, applying a slope on PFD limit in guard-bands and fixing the value on flux limit steps. The parameters for interference transmitters are as follows: Center frequency, nominal bandwidth, and useful bandwidth of 5G channel are fixed for the minimum value for 0 MHz guard-band. The 5G guard-band can be modified to test cases. The 5G transmitter output RF filter slope and maximum rejection can be modified. The user and base station total power, and activity are fixed. The activity is divided by 2 in the case of TDD duplex mode. The WIFI guard-band can be modified to test cases. The WIFI transmitter output RF filter slope and maximum rejection can be modified. The WIFI total power, and activity are fixed.

An example of configuration handled by the TéSA simulator is provided Figure 6, where WIFI and 5G user equipment interference masks and PFD limit are highlighted in term of PSD (Power Spectrum Density, in dBW/MHz) for a link budget between wireless and PNT antennas on the backpack of an astronaut. The average sum of interferences considers in that example the activity of both transmitters, 25% for the 5G user equipment and 10% for the WIFI (figure 6). The BPSK(5) spread spectrum signal is ploted in green, while the PSD level of the despreaded BPSK(5) signal (compressed signal) is represented by the green point above the BPSK(5) main lobe. We can note that the BPSK(5) PNT signal is below the noise PSD as expected, and that the WIFI and 5G outbound peak PSD is about 125 dB above the BPSK(5) maximum PFD! The flux limit PSD corresponding to the SFCG REC 43-1 PFD limit of -121 dBW/m^2/MHz is also represented on figure 6. The importance of having notably this PFD limit can be seen immediately, even though the configuration on figure 6 is not sufficient enough to protect PNT, since the peak degradation of the PNT C/No degradation is as high as 36.8 dB in that case (Table 7).

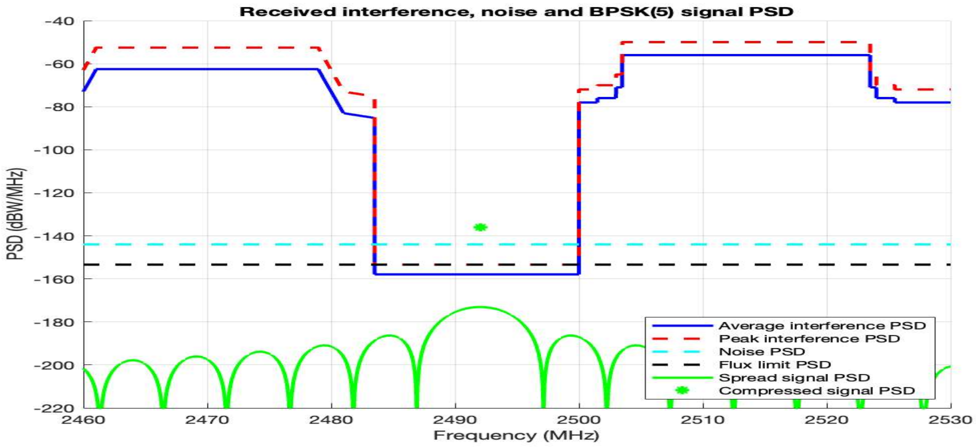

FIGURE 6 WIFI and 5G user equipement interference masks and PFD limit.

The considered distance between the phase centers of the wireless and PNT antenna on the backpack of the astronaut is 30 cm, in the C/N_0 degradation results provided table 7, while the worst case corresponds to a distance of 24 cm (Table 4).

TABLE 7. C/N_0 degradation of a lunar in-situ PNT BPSK(5) signal received by an astronaut, depending on the wireless transmitter configuration on the same astronaut.

	BPSK(5) Peak C/N_0 Degradation	BPSK(5) Average C/N_0 Degradation
Transmitter masks for WIFI and 5G transmitters, no filter at the wireless transmitter output, not any PFD limit in the PNT band	**67.3 dB**	**60.6 dB**
Measured PSD values for 5G user equipment Tx and mask for WIFI Tx, no filter at the wireless transmitter output, not any PFD limit in the PNT	**61.2 dB**	**51.3 dB**
WIFI and 5G user equipment interference masks and PFD limit. Average sum of interferences is lower due to the considered activity of both transmitters, 25% for the 5G user equipment and 10% for the WIFI (figure 6).	**36.8 dB**	**30.7 dB**
WIFI and 5G user equipment interference masks and PNT Rx RF filters	**13.1 dB**	**7.4 dB**
Measured **interference mask** for the 5G Tx, WIFI mask, **3.5 MHz guard band**, oversampling of 2 samples per chip (no narrow correlation) and **PFD limit**.	**0.48 dB**	**0.17 dB**

Table 7 shows that simultaneous interference masks for the wireless transmitters, a 3.5 MHz minimum guard band and the -121 dBW/m^2/MHz PFD limit, are all mandatory to contribute protecting the BPSK(5) PNT signal, without narrow correlation, from both 5G and WIFI interferences.

SFCG RECOMMENDATIONS RELATED TO MARTIAN IN-SITU PNT

The SFCG recommendation applicable in the Mars region is REC 22-1R4, "Frequency assignment guidelines for communications in the Mars region", so called "Freqs for Mars region".

In addition to the 2483.5-2500 MHz orbit to surface band, SFCG REC 22-1R4 recommends several surface wireless bands (table 8), including 2400-2480 MHz and 2503.5-2620 MHz (likely to be extended up beyond 2620 MHz in a next version). We can note the same minimum guard bands of 3.5 MHz apply, as in SFCG REC 32-2R6 ("Freqs for lunar region"), to contribute to protecting the 2483.5-2500 MHz link from Martian wireless interferences in S-band.

TABLE 8 . Summary of the Orbit to Surface and Surface to Surface Martian bands recommended by SFCG REC 22-2R4

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

Surface-to-surface:	390-405 MHz [3] 410-420 MHz [3] 435-450 MHz [3] 902-928 MHz [3] 2025-2120 MHz 2200-2300 MHz 2400-2480 MHz 2503.5-2620 MHz 5150-5835 MHz [5] 25.25-25.5 GHz 27.225-27.5 GHz

CNES has shown that there are also Radio Astronomy issues with GNSS L and C bands if one of them would be broadcast by a radiocommunication constellation in the vicinity of Mars, which is regularly visible from the Shielded Zone of the Moon (Fig. 1). These issues are demonstrated in CNES contributions available on the SFCG web site.

Like in the Moon region, the band 2483.5-2500 MHz is the only GNSS band allocated in the Mars region. This band is, therefore, the natural candidate for Martian PNT. The protection measures for a Martian in-situ PNT in 2483.5-2500 MHz would then be similar to the ones described above for lunar in-situ PNT systems.

CCSDS RECOMMENDATION ABOUT LUNAR AND MARTIAN WIRELESS LINKS

The Consultative Committee for Space Data Systems (CCSDS) issued in 2022 a Recommend Standard titled “Spacecraft Onboard Interface Services – High Data Rate 3GPP and WIFI local area communications” (CCSDS 883.0-B-1, Blue Book, February 2022). This CCSDS standard applies for lunar and Martian wireless links. This CCSDS standard specifies that adopters must ensure compatibility with ITU Radio Regulations and comply with the current applicable SFCG recommendations 32-2R (“Freqs for lunar region”) and 22-1R (“Freqs for Mars region”). As previously described, the current applicable SFCG recommendations referred to in the CCSDS 883 standard are 32-2R6 and 22-1R4. Obviously, since SFCG REC 43-1 was not yet edited by SFCG in 2022, CCSDS lunar 3GPP and WIFI adopters should also comply with REC 43-1.

CCSDS 883 standard specifies for the IEEE 802.11 and WIFI channel plan that “the channel assignments (carrier frequency, main spectral lobes) selected by the adopter when a SFCG band is used shall not be outside the said wireless band currently allocated by SFCG”.

It can be noted that up to 3 GHz, the 3GPP standard allows channel’s central frequency choice in a very flexible manner, that is by step of 5 KHz only. This allows to optimize the choice of the 3GPP lunar or Martian frequency channels, while respecting the 3.5 MHz guard band and, at least in the lunar environment, the -121 $dBW/m^2/MHz$ PFD limit in the 2483.5-2500 MHz band at the input of the PNT receive antenna for the minimum distance (for instance 24 cm on an astronaut suit).

The choice of the WIFI channel central frequency below 3 GHz is less flexible than for 3GPP channel central frequency, as highlighted by Figure 7.

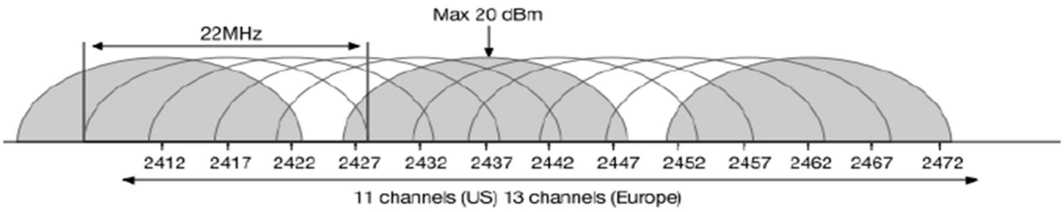

FIGURE 7 The 11 WIFI channels used in the USA.

The SFCG lower Guard band protecting PNT is 2480-2483.5 MHz. The upper frequency of the 13^{th} WIFI channel is 2407 + 5*13 + (22/2) = 2483 MHz, this corresponds to a main spectral lobe above the SFCG limit of 2480.0 MHz. WIFI channel 13 is, therefore, not recommended in lunar and Martian regions, as well as obvioulsy the 14^{th} WIFI channel wich is used only in Japan. The 12^{th} WIFI channel is OK in the lunar region as long as SFCG RECs 32-2R6 and 43-1are complied.

CCSDS 883 standard also specifies that “the use of any non-SFCG wireless frequency band shall be verified by liaising with the CCSDS Space Link Service (SLS) RF and Modulation (RFM) Working Group (WG)” and that “before finalizing their frequency choice, space agencies must ensure clearance from an SFCG waiver when the targeted frequency band is not recommended in the latest applicable version of SFCG RECs 32-2R and 22-1R”. Since a SFCG waiver is granted only in case of consensual agreement of all the SFCG space agencies, the grant of a SFCG waiver for a non-SFCG lunar or Martian wireless frequency band is unlikely.

CONCLUSIONS

The 2483.5-2500 MHz lunar in-situ SFCG band and the 2400-2480 MHz lunar surface wireless band, as well as the 2503.5-2620 MHz lunar surface wireless band, are very close to each other. To avoid lunar PNT from being interfered by neighboring lunar surface wireless frequencies, a system study involving wireless to PNT interference computations is mandatory for each envisioned lunar wireless network. All the texts of Tablet 4, from both SFCG RECs 32-2R6 and 43-1 shall be respected to avoid wireless interference to PNT, whatever the number of transitters in the considered wireless network. To keep PNT protected from wireless interference, the said system study shall consider the worst case in the design of the global PNT-wireless system.

This worst case corresponds to the low PNT receiver antenna gain (that is gain at low elevation), and to the highest system noise temperature at the input of the receiver, this corresponding to the smaller absolute PNT C/N_0 ratio. Similar conclusions could be derived for the design of future Martian in-situ PNT and surface wireless links.

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[11] ITU-R Recommendation M.1903.

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