Lunar PNT Spectrum Session: Moonlight Context

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Introduction

This presentation will cover the following aspects:

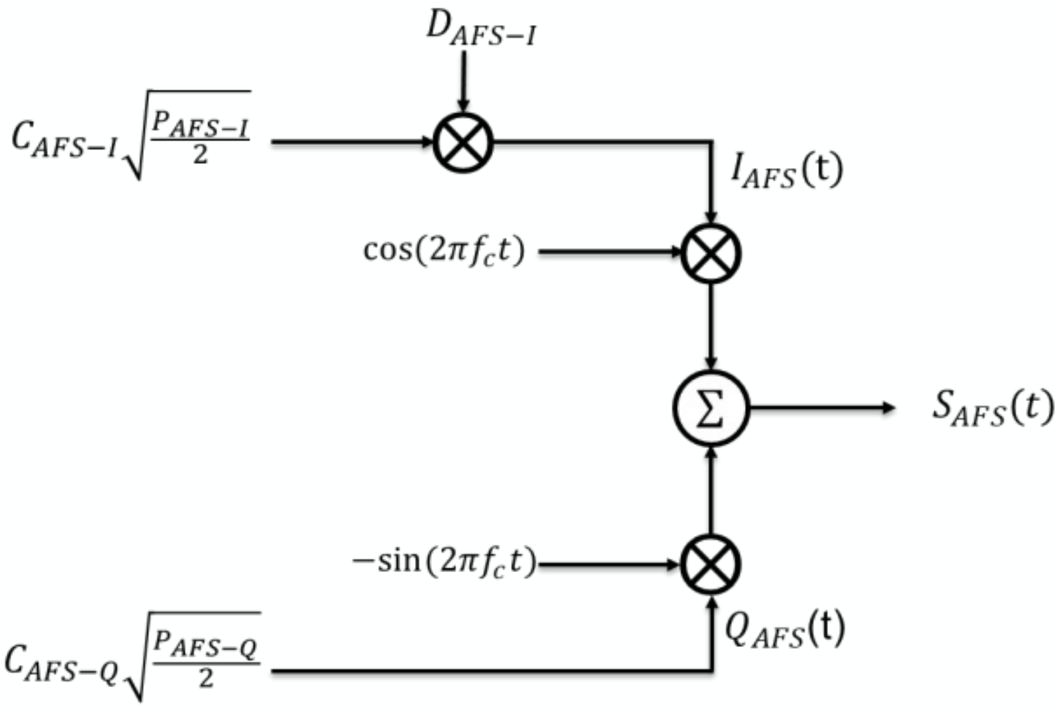
a. **Moonlight PVT service transmit spectrum occupancy**

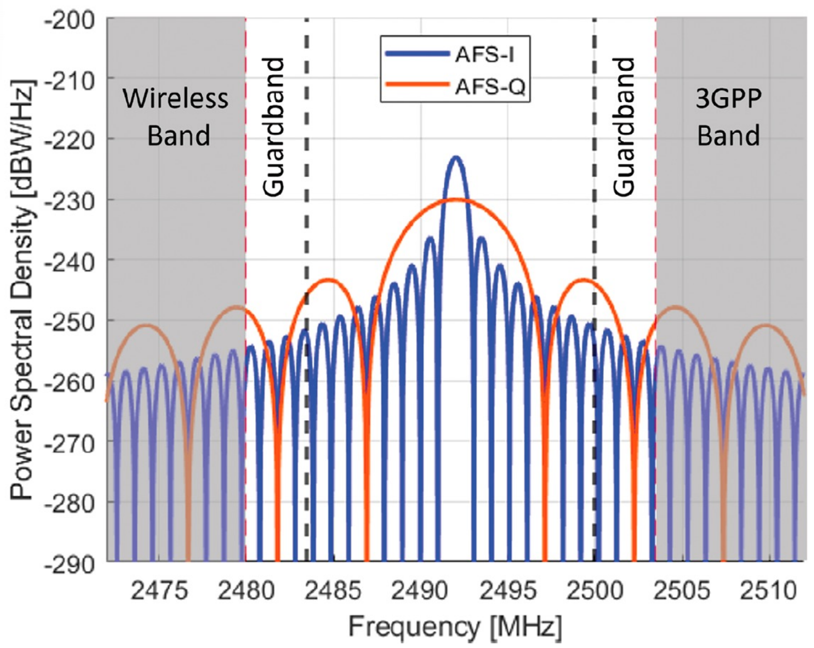
b. **Moonlight Navigation receiver considerations to ensure precision and accuracy requirements**

c. **considerations to assure sharing of the 2483.5 -2500 MHz band with in-band PNT services**

d. **considerations to assure sharing of the 2483.5 -2500 MHz band with adjacent band with surface networks below 2483.5 MHz and above 2500 MHz**

(a) LunaNet – Augmented Forward Signal (AFS) main features as in Moonlight





Following SFCG frequency recommendation
Guard bands unders study

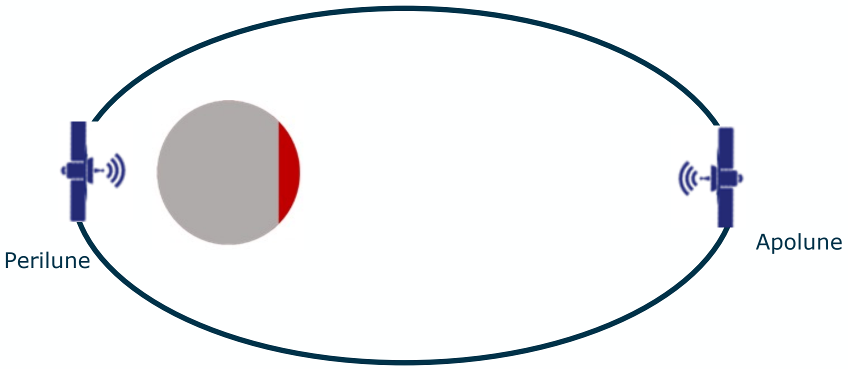
	Modulation	Primary Code	Secondary Code	Tertiary Code	Data Rate
AFS-I (Data)	BPSK(1)	2046 chips / 2 ms	n/a	n/a	500
AFS-Q (Pilot)	BPSK(5)	10230 chips / 2 ms	4 chips / 8 ms	1500 chips / 12 sec	n/a

(a) Moonlight overview

/// The Moonlight shall be interoperable with other systems according to the LunaNet interoperability Spec (LNIS).

/// The chosen NAV satellite orbits are ELFO and the service volume addressed is a region around the South Pole [-70°;-90°] (SV1, SV2).

/// In case of nadir-pointing satellite, the minimum slant-range corresponds to the satellite altitude (90 deg elevation) while the maximum one with an EOC (Edge Of Coverage) user (minimum 5 deg elevation).



/// As from LNIS specifications, the Power on ground requirements are the following

	Within SV1-SP		Outside SV1-SP
	minimum Power [dBW]	maximum Power [dBW]	maximum Power [dBW]
PoG	-160	-147	-141

(a) Summary of Moonlight main requirements and design constraints

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Physical Link Characteristics

Figure	Requirement
AFS Frequency (S-band) BW	2483.5 MHz-2500 MHz

Quality of Signal and RF performance

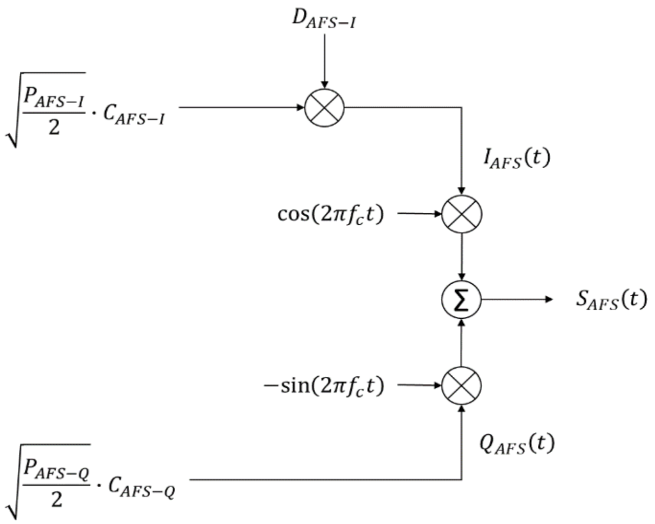
KPI	Requirement
Correlation Loss	< 0,6 dB
Code-Code-Coherency	< 500 ps
Code-Carrier-Coherencies	< 130 ps
IBUS	< 35 dBc

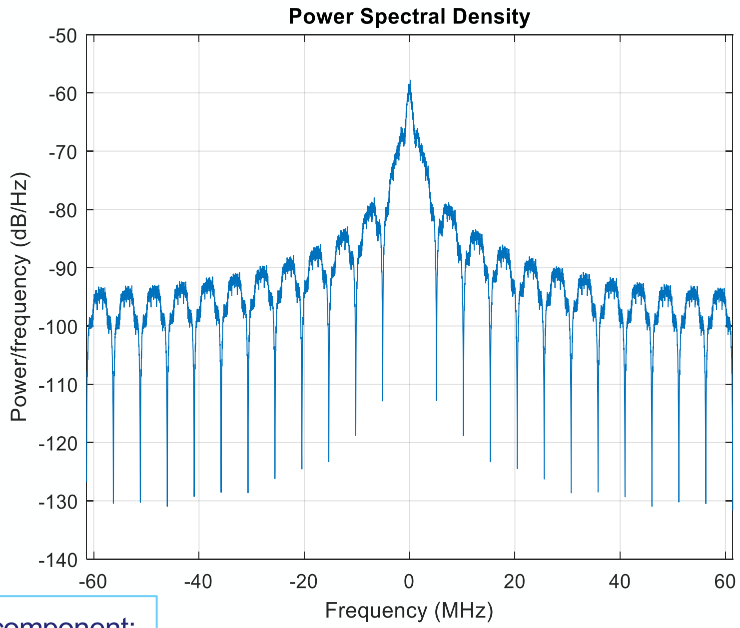
Navigation Signal Characteristics

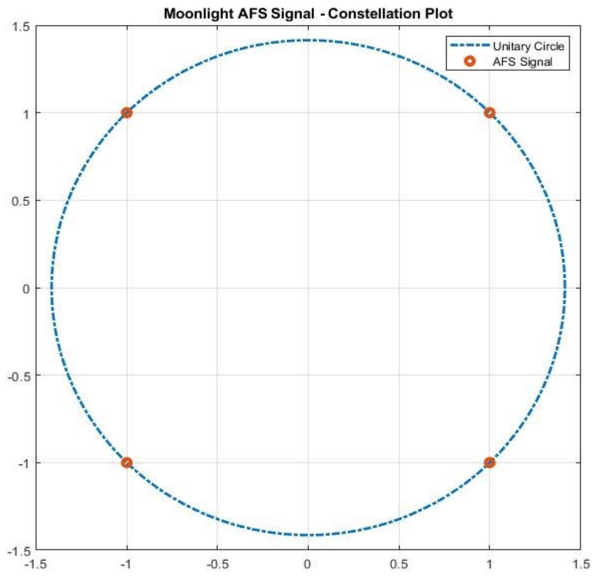
One-way Ranging AFS		
Parameter	Data	Pilot
Initial Phase	0 deg	90 deg
Waveform	BPSK (1)	BPSK (5)
Chip-rate	1.023 Mchip/s	5.115 Mchip/s
Symbol Rate	500 Sps	N/A
Relative power	50%	50%

(a) Moonlight Navigation Signal Modulation

- The Navigation Signal in generation stage is obtained by two BPSK (one in phase and one in quadrature) with the same power level;
- Looking at the constellation plot it is possible to perceive as (at infinite bandwidth) the signal has a constant envelope and it is equivalent to a QPSK;







- P_{AFS-I} and P_{AFS-Q} are respectively the power of the I and Q component;
- C_{AFS-I} and C_{AFS-Q} are respectively the codes of the I and Q component;
- D_{AFS-I} is the navigation data on the data channel
- f_c is the carrier frequency

(a) Moonlight IBUS Mask derivation approach

- **LSIS-070: Maximum In-Band Spurious Transmissions**
  The aggregate EIRP of all unwanted emissions (including discrete emissions and parasitic emissions) integrated over the transmit bandwidth of each signal shall not exceed -35 dB {LSIS-TBC-2007} relative to the total power emitted in the bandwidth specified in 2.3.1.5.

- As concern for the performance in terms of IBUS, the requirement has been flowed down at Payload Level reporting that the aggregate EIRP of all unwanted emissions (including discrete emissions and parasitic emissions) integrated over the transmit bandwidth of each signal shall not exceed -35 dBc relative to the total power emitted in the bandwidth specified.

- The expected IBUS has been is below the specification

Unit	Requirement IBUS
LCNS-REQ-NAVPL-104020	-35 dBc

(a) Moonlight OBUS mask derivation approach

/// The OBUS masks have been derived starting from:

/// **ECSS-E-ST-50-05C (Space Engineering - Radio frequency and modulation)**

/// Where indications on spurious emissions to protection of Radio astronomy (section 5.5.1.2) and Deep space frequencies (section 5.5.1.3)

/// The OBUS mask is designed to limit these spurious emissions due to HPA non-linear behaviour, ensuring the correct transmission frequency, while protecting Radio Astronomy services.

$$EIRP_{req} = PFD_f \; - 13dB + 10\log_{10}(4\,\pi l^2)$$

$$l = 341792\ km$$

- $EIRP_{req}$: Calculated requirements
- PFD_f: Power Flux Density values provided for several frequencies on Earth surface
- $-13dB$: Margin indication provided in the ECSS document
- $10\log_{10}(4\,\pi l^2)$: Minimum slant range to evaluate the spherical correction to be applied

(a) Moonlight Protection of Radio astronomy bands

/// OBUS masks for RFI protection:

Centre frequency [MHz]	Assumed Observation Bandwidth [kHz]	EIRP requirement [dBW]
327	10	-22,33
1420	20	-14,33
1612	20	-12,33
1665	20	-12,33
4830	50	-1,33
14488	150	12,67
22200	250	19,67
23700	250	20,67

Centre frequency [MHz]	Assumed Observation Bandwidth [MHz]	EIRP Requirement [dBW]
13,385	0,05	-19,33
25,61	0,12	-30,33
73,8	1,6	-27,33
151,525	2,95	-25,33
325,3	6,6	-20,33
408,05	3,9	-20,33
611	6	-16,33
1413,5	27	-11,33
1665	10	-12,33
2695	10	-8,33
4995	10	-2,33
10650	100	8,67
15375	50	12,67
22355	290	22,67
23800	400	21,67
31550	500	27,67

(b) Nav Observables: pseudoranges

Pseudoranges are obtained considering the true geometric range between satellites and users and adding the error contributions associated to:

$$\rho_i = d_i + \epsilon_{clk,sat} + \epsilon_{clk,rx} + \epsilon_{mp} + \epsilon_{DLL}$$

- d_i: *True geometric range*
- $\epsilon_{clk,sat}$: *Satellite clock offset*
- $\epsilon_{clk,rx}$: *Receiver clock offset*
- ϵ_{mp}: *Multipath error*
- ϵ_{DLL}: *DLL error*

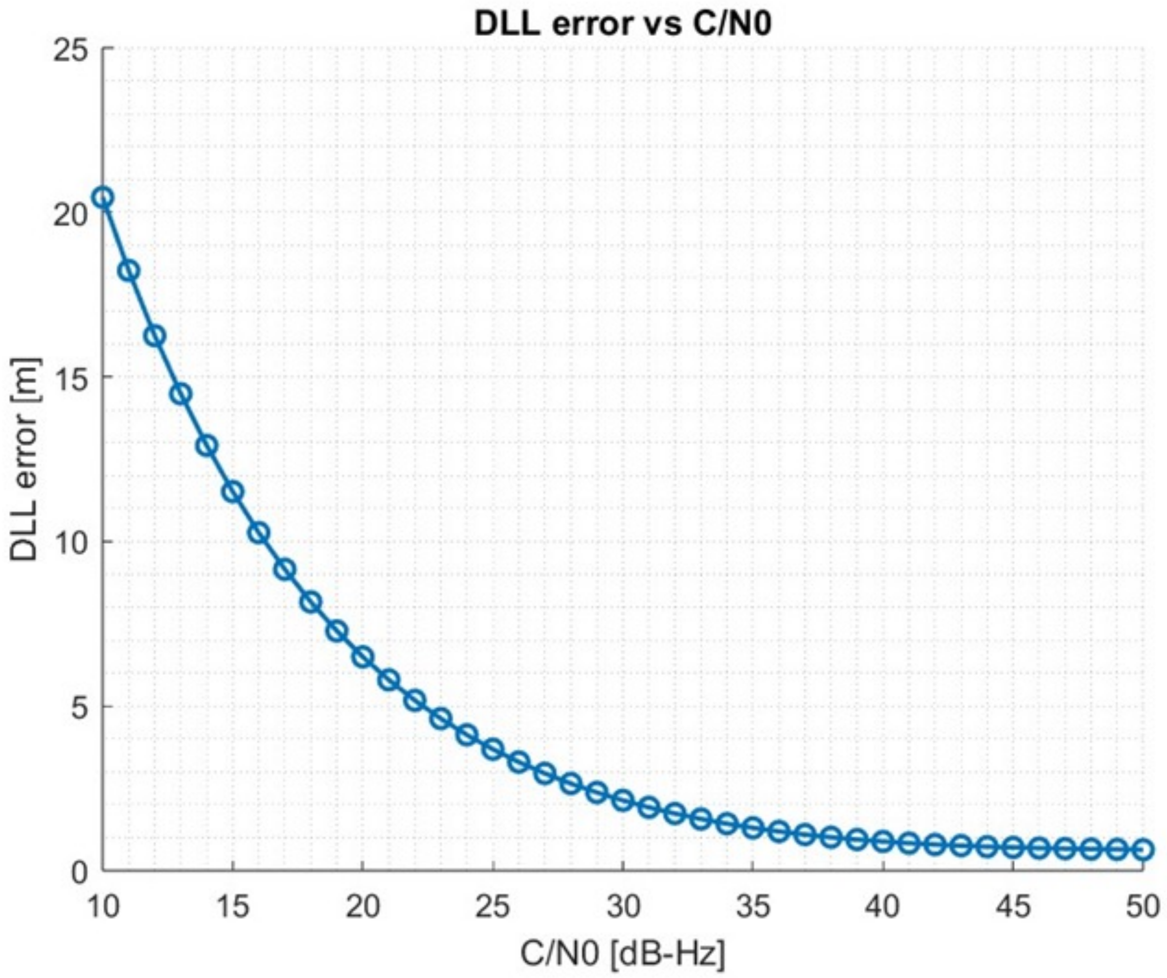
/// The DLL error is modelled as AWGN with a 1-σ computed through the following expression:

$$\sigma_{DLL} = \sqrt{L_{SC\,bias}^2 + \sigma_{TN}^2}$$

$$\sigma_{TN} = c_0 \sqrt{B_n\left(1 - \frac{B_n T}{2}\right) \frac{\int_{-\frac{B_{FE}}{2}}^{\frac{B_{FE}}{2}} S_s(f)\ \sin(\pi\ f\ D\ T_C)\ df}{(2\pi)^2 \frac{C}{N_0}\left(\int_{-\frac{B_{FE}}{2}}^{\frac{B_{FE}}{2}} f\ S_s(f)\ \sin(\pi\ f\ D\ T_C)\ df\right)^2}}$$

- $L_{SC\,bias}$: *S-Curve bias losses*
- c_0: *Speed of light*
- B_n: *DLL noise bandwidth*
- T: *Coherent integration time*
- $\frac{C}{N_0}$: *Signal-to-noise ratio*
- B_{FE}: *Front-end bandwidth*
- $S_s(f)$: *BPSK-R normalized PSD*
- D: *Early – late spacing*
- T_C: *Modulation chip period*

(b) Nav Observables: DLL versus C/n0



$1\sigma_{DLL}$ (total) as function of the C/N0 for various satellite contributions

(b) Nav Observables: Carrier Phase

/// PLL tracking loop error modelled using the 1-sigma rule-of-thumb from Kaplan [RD.1] plus the satellite contribution to phase noise

$$\sigma_{PLL_P} = \sqrt{\sigma^2_{tPLL_P} + \sigma^2_v + \theta^2_A} + \frac{\theta_e}{3} \leq 30\,\text{deg}$$

$$\sigma_{PLL_D} = \sqrt{\sigma^2_{tPLL_D} + \sigma^2_v + \theta^2_A} + \frac{\theta_e}{3} \leq 15\,\text{deg}$$

Dynamic stress error

$$\theta_{e2} = \frac{d^2R/dt^2}{\omega_0^2} = \frac{d^2R/dt^2}{\left(\frac{B_n}{0.53}\right)^2} = 0.2809\frac{d^2R/dt^2}{B_n^2}\ (\text{deg})$$

$$\theta_{e3} = \frac{d^3R/dt^3}{\omega_0^3} = \frac{d^3R/dt^3}{\left(\frac{B_n}{0.7845}\right)^3} = 0.4828\frac{d^3R/dt^3}{B_n^3}\ (\text{deg})$$

27/10/2025

$$\sigma_{tPLL_P} = \frac{360}{2\pi}\sqrt{\frac{B_n}{C/N_0}}$$

$$\sigma_{tPLL_D} = \frac{360}{2\pi}\sqrt{\frac{B_n}{C/N_0}\left(1+\frac{1}{2T\,C/N_0}\right)}\ (\text{deg})$$

Thermal Noise

$$\sigma_v = \frac{360 f_L S_v}{2\pi}\sqrt{\int_{f_{min}}^{f_{max}} \frac{P(f_m)}{f_m^2}\,df_m}\ (\text{deg})$$

Vibration

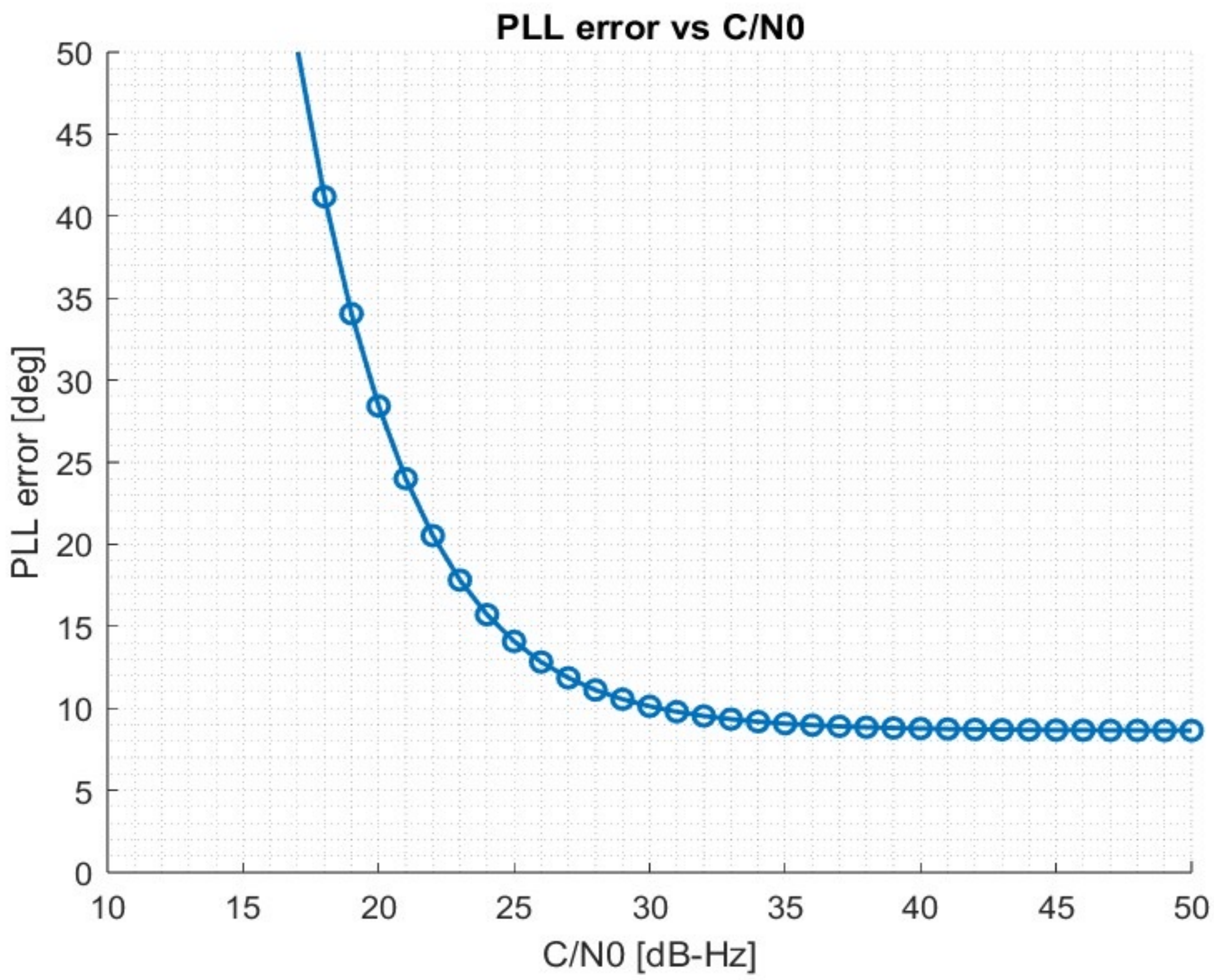
$$\theta_{A2} = 144\frac{\sigma_A(\tau) f_L}{B_n}\ (\text{deg}) \qquad \sigma_A(\tau) = 2.5\frac{\Delta\theta}{\omega_L \tau}$$

$$\theta_{A3} = 160\frac{\sigma_A(\tau) f_L}{B_n}\ (\text{deg}) \qquad \sigma_A(\tau) = 2.25\frac{\Delta\theta}{\omega_L \tau}$$

Allan DevOscillator Phase Noise

[RD.1] E. D. Kaplan, "Understanding GPS: Principles and Applications''

(b) Nav Observables: PLL error versus C/n0



$1\sigma_{PLL}$ (total) as function of the C/N0 for various satellite contributions

(c) ITU Frequency Filing (NAV mission)

Telespazio Italy as system design authority is also responsible for the relevant activities to obtain all necessary licenses to deploy, operate the LCNS system and provide LCNS services.

This includes but is not limited to defining the LCNS system and segments, frequency plan for all the envisaged NAV/COM links in line with the mission applicable documents/standards(a partial list is here below provided for info):

CCSDS 350.1-G-3	SECURITY THREATS AGAINST SPACE MISSIONS
CCSDS 350 .4-G-2	CCSDS Guide for SECURE SYSTEM INTERCONNECTION
CCSDS 350 .7-G-2	CCSDS SECURITY Guide for MISSION PLANNERS
LN-IS	LunaNet Interoperability Specifications
ITU-R RA.479-5	Protection of frequencies for radio astronomical measurements in the SZM
ITU-RR22	Article 22 of the Radio Regulation); Section V; Radio Astronomy in the Shielded Zone of the Moon
ITU-R RA.314-10	Preferred Frequency Bands for Radio Astronomical Measurements
https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf	NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts
SFCG 32-2	COMMUNICATION AND POSITIONING, NAVIGATION, AND TIMING FREQUENCY ALLOCATIONS AND SHARING IN THE LUNAR REGION
SFCG 41-1	Efficient Spectrum Utilization for Space Research Systems in the Lunar Region
SFCG 42-1	Frequency Channel Plan for In-situ Lunar Data Relay Satellites
SFCG 23-5	Protection of Radio Astronomy Observations in the Shielded Zone of the Moon

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System Design drivers (NAV)

- Elliptical Frozen Lunar Orbit (**ELFO**)
- Orbital period **24h**
- **4** Orbital Planes / **1** Satellite per Orbit
- **3** Earth Ground Station (120° long. Spaced)
- **1** Earth Ground AFS Monitoring Station

- **Frequency Bands/BW:**
  - Trunk Link **(X-Band):**
    - Uplink **-** 7190 - 7235 MHz
    - Downlink - 8450 - 8500 MHz
    - UL/DL Bandwidth < 6 MHz(99% Energy)
  - User Link (**S-Band**):
    - AFS - 2483.5 MHz - 2500 MHz
    - DL Bandwidth < 16.5 MHz

Parameter		Value
I Channel	Data Format/Modulation	NRZ-L/PSK/DSSS/UQPSK
	PN Code Type	Standard Gold Codes
	PN Code Length	$(2^{10} - 1)$ chips
Q Channel	Data Format/Modulation	NRZ-L/DSSS/UQPSK
	PN Code Type	Truncated Maximum Length
	PN Code Length	$256 * (2^{10} - 1)$ chips
I/Q Power Ratio		10 dB ± 0.5 dB

Parameter		Coherent Mode	Non-Coherent Mode
Data Format/Modulation		OQPSK	OQPSK
I Channel	SS Code Length	Truncated Max Length $256 * (2^{10} - 1)$ chips	$(2^{11} - 1)$ chips Gold Code
Q Channel	Data Format/Modulation	Truncated Max Length $256 * (2^{10} - 1)$ chips $256 * (2^{10} - 1)$ chips	$(2^{11} - 1)$ chips Gold Code
	Code Epoch Reference	$x + \frac{1}{2}$ chips delay w.r.t. SS Code on I Channel (with $x \geq 20000$ chips)	$\frac{1}{2}$ chip delay w.r.t. SS Code on I Channel
I/Q Power Ratio		0 dB $\pm$ 0.5 dB	0 dB $\pm$ 0.5 dB
Ranging Service Possible		Yes	No

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DATE LIMITE POUR LA RÉCEPTION DES COMMENTAIRES EXPIRY DATE FOR THE RECEIPT OF COMMENTS FECHA LÍMITE PARA LA RECEPTIÓN DE LOS COMENTARIOS	19.12.2025

(c) Spreading Codes Features: Primary Code

Primary Code: Weil codes and spreading sequences

- A set of **210 spreading codes** is currently proposed for Lunanet (AD.1).
  - The pilot channel (AFS-Q) primary codes are **Weil sequences** of length 10230;
  - The codes are derived from a **Legendre sequence** *L(t)* of length 10247 from which 17 bits are deleted.

- The KPI assessing the performance of a spreading-code set are:
  - Cross-correlation Function (CCF) maximum, RMS, 99% and 99.9% percentile;
  - Amplitude of the highest Auto-correlation Function (ACF) side peaks.

	ACF side-peak (dB)	CCF Max (dB)	CCF RMS (dB)	CCF 99% (dB)	CCF 99.9% (dB)
Lunanet Codes (AD.1)	-31.08	-26.39	-40.10	-32.38	-30.37

RD[1] LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal, Version 1, 2025

(c) Secondary and tertiary Spreading Codes

The pilot channel (AFS-Q) **secondary code** shall be one of these four sequences:

Secondary code ID	Secondary code
S_0	**1110**
S_1	**0111**
S_2	**1011**
S_3	**1101**

Similarly to the primary codes, the **tertiary codes** are based on **Weil sequences** (1500 bits):

- Tertiary codes are generated by a **Legendre sequence** *L(t)* of length 1499;
- Codes of 1500 bits are obtained appending a 0 at the end of the 1499-bit sequences.

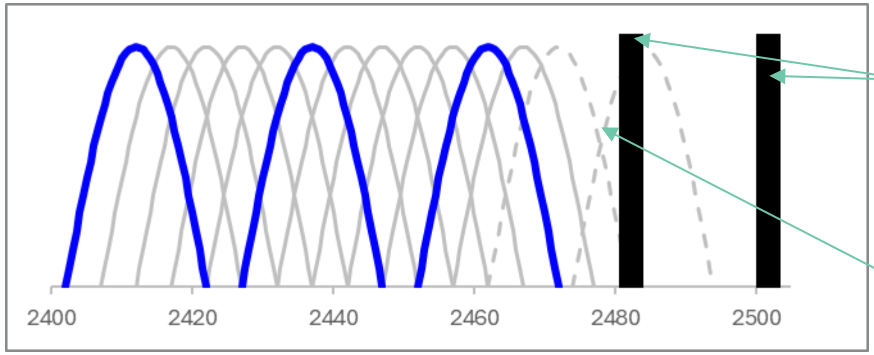
RD[1] LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal, Version 1, 2025

(d) Potential interferers - other S-band Signals

Band (MHz)	use	Name	Comment
2025-2110	Orbit – surface	Com FWD	P2P Proximity links, residual or suppressed carrier
2200-2290	Surface – Orbit	Com RTN	
2400-2480	Surface Wireless	Wifi	Assume 802.11b/g/n
2503.5-2690	Surface Wireless	3GPP	Assume LTE band 41

3 other S-band systems are defined in the LNIS:

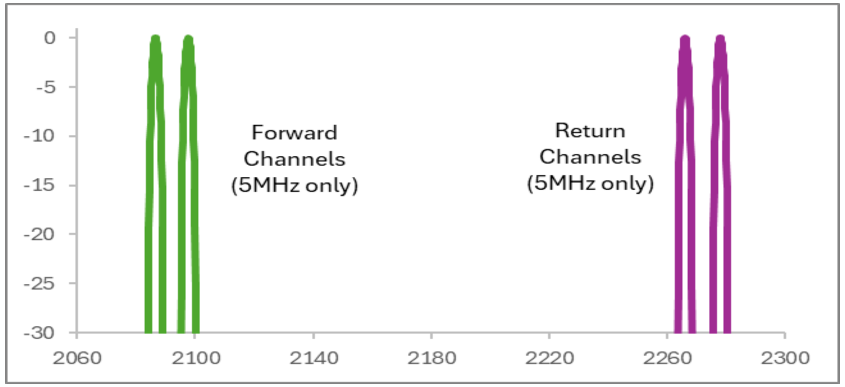
Wifi band (with non overlapping 20MHz channels in blue)



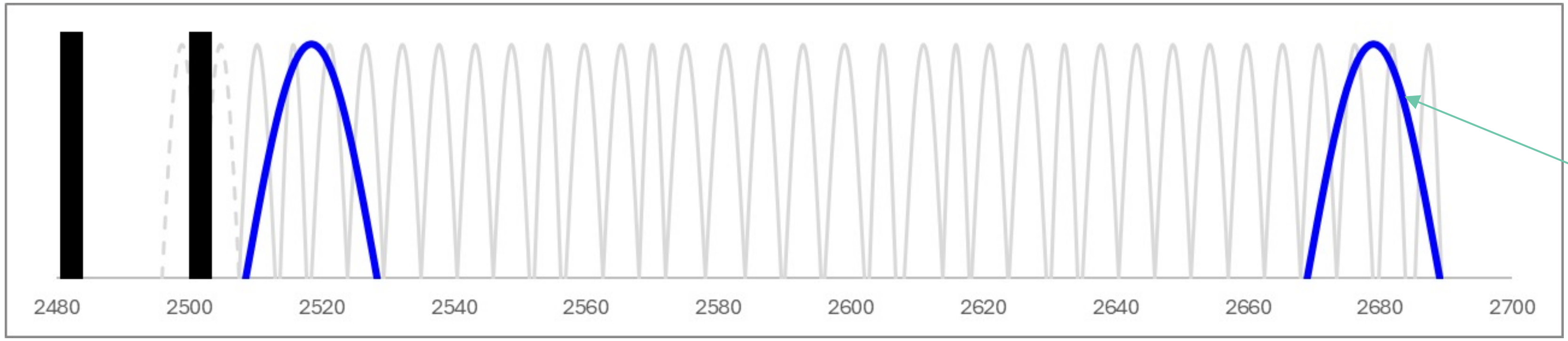
Guard bands incorporated into frequency allocation for wifi and 3GPP

Dotted lines indicate terrestrial channels that cannot be used according to SFCG 43-1

S-band Proximity Communication



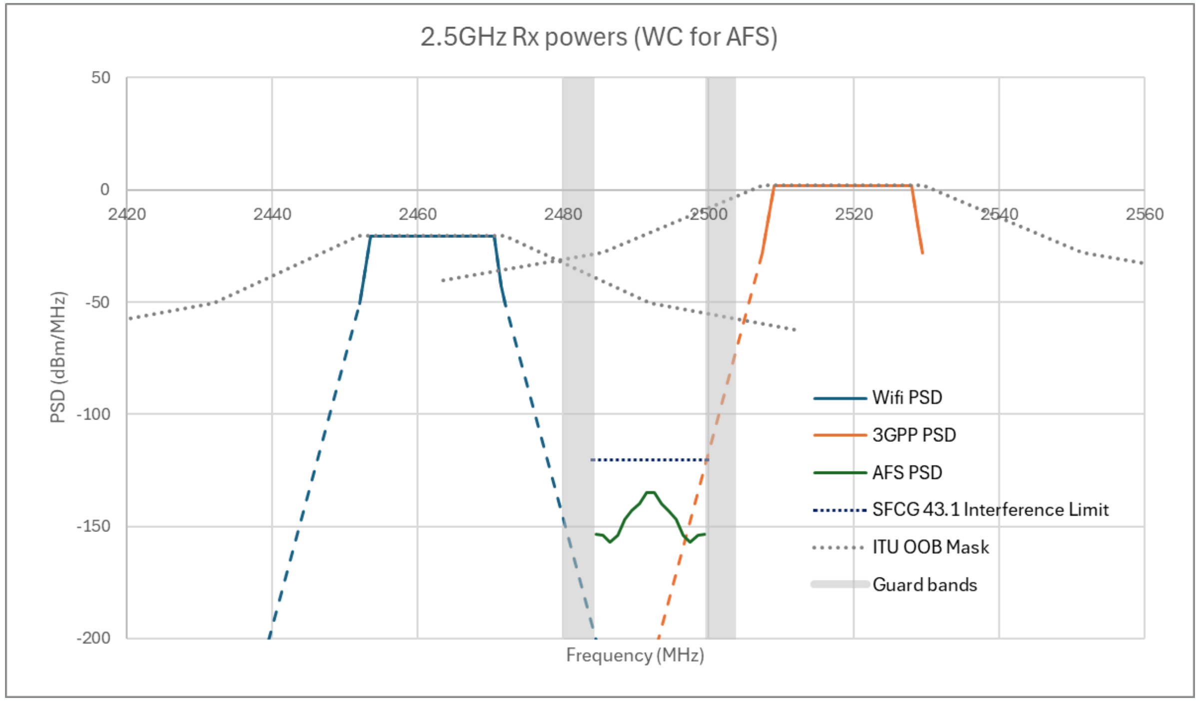
3GPP band (with lowest and highest 20MHz bands in blue)

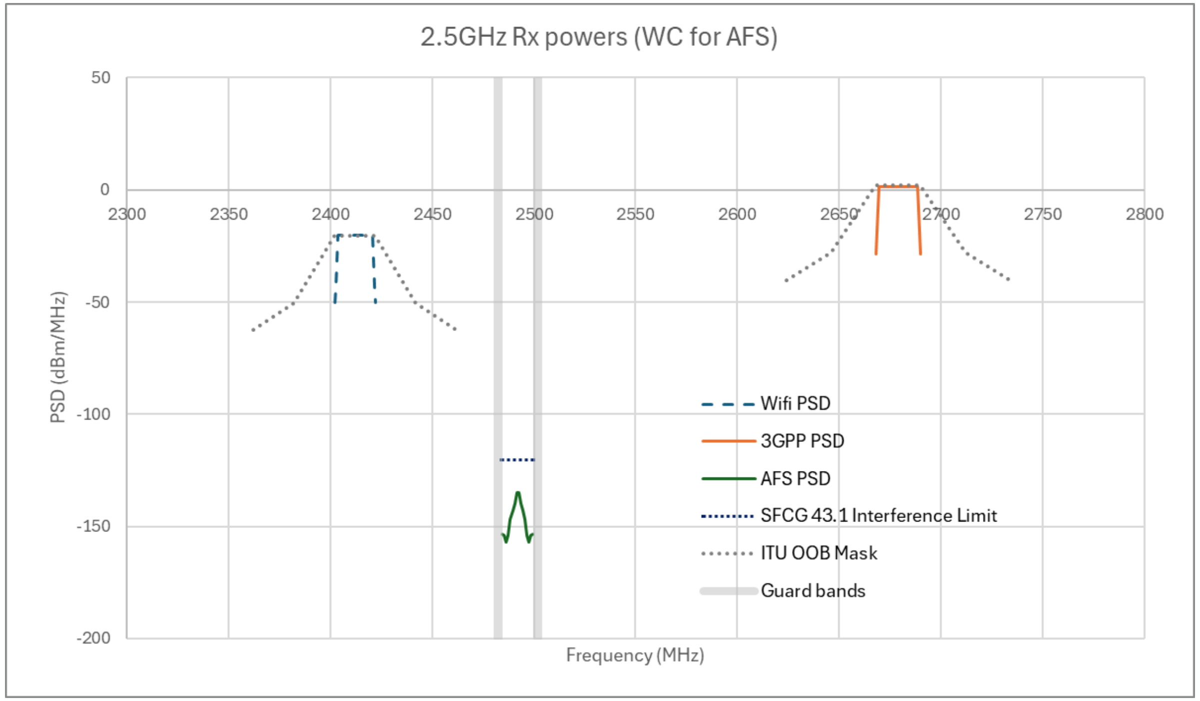


20MHz bands assumed to be formed by aggregating existing 5.5MHz channel allocations (in grey)

(d) Interference from other S-band Systems

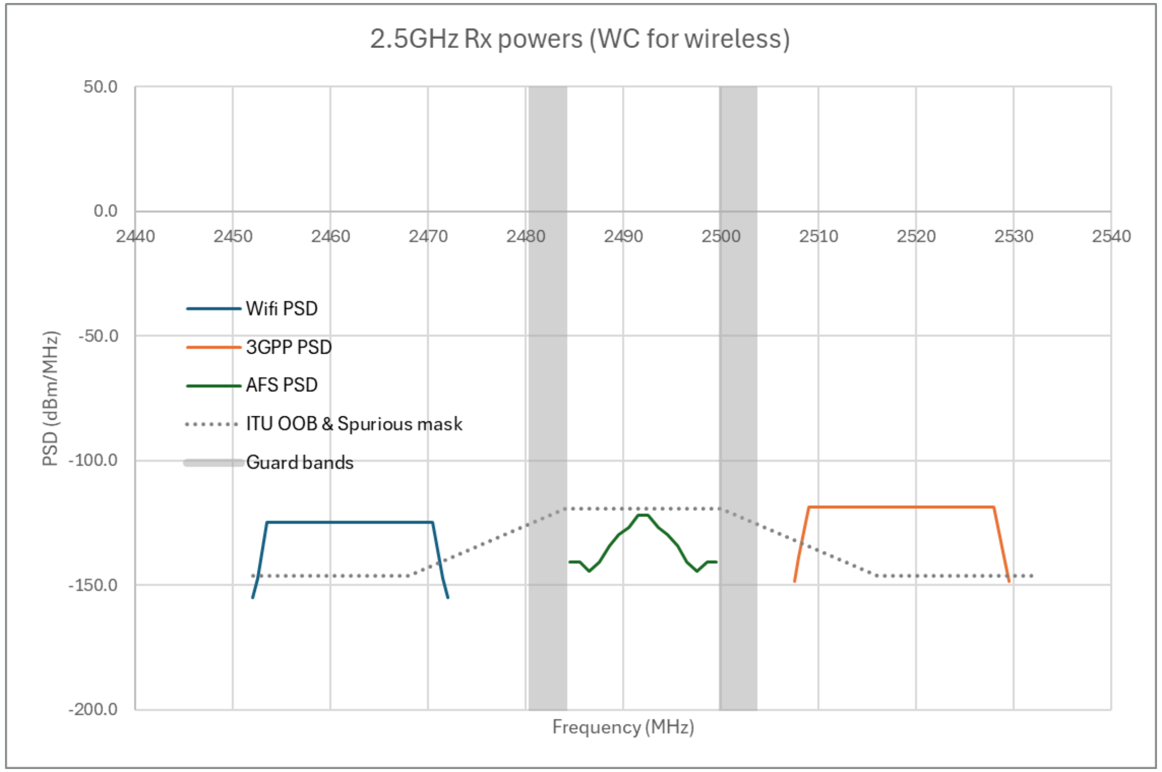
- The plots below show the WC interference scenario for the AFS signal (as defined in SFCG 43-1 – 0.24m separation of AFS and surface wireless antennas), assuming the surface wireless networks use existing terrestrial channel allocations.
- For the 3GPP the SFGC43-1 interference limit is met only with **12dB/MHz roll-off**.
  - ❑ Hence **it is recommended for this WC scenario system designers who require their astronaut to be able to receive both AFS and access surface wireless networks ease the interference problem by choosing a more appropriate channel as shown bottom right**
  - ❑ It is expected that **AFS receivers implement strong out of band filtering to avoid LNA saturation** from the surface wireless signals.

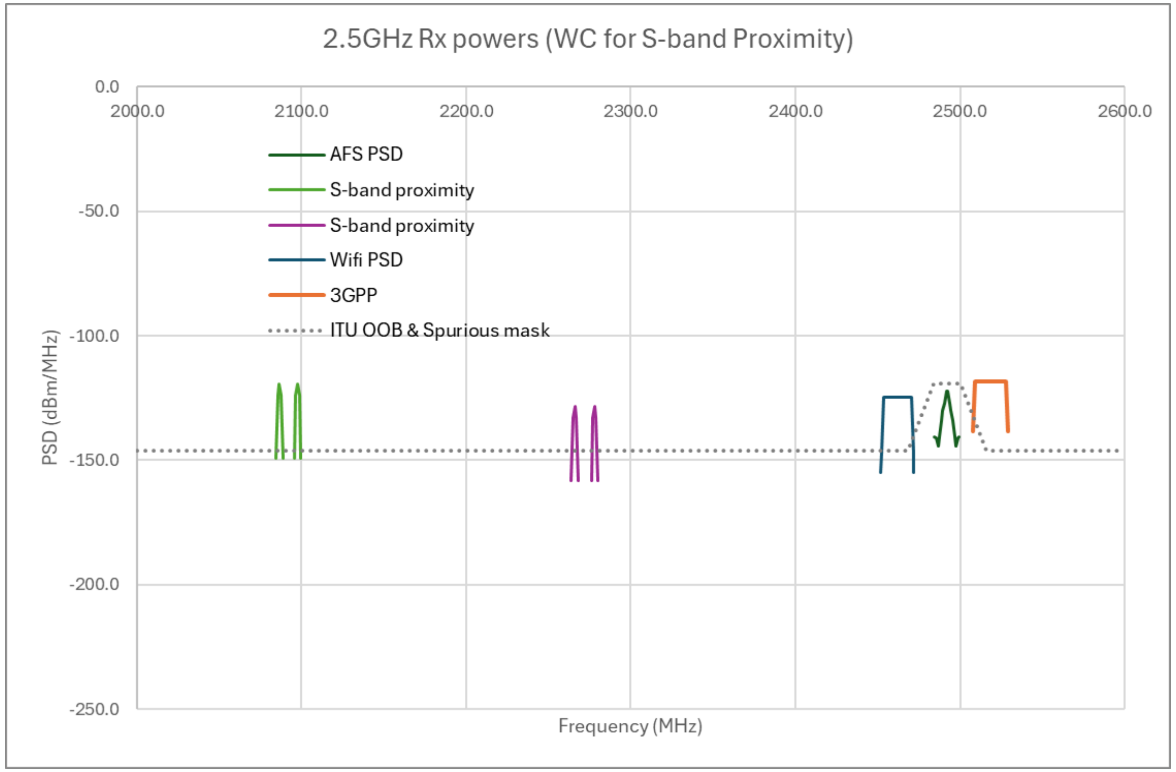




(d) Interference onto other S-band systems

- The plots below show the WC interference scenario for other S-band signals defined in the LNIS
- For other systems the maximum AFS received power is at a similar level to the minimum received power for all other S-band signals.
  - ❑ Hence **no need for specific requirements are foreseen on the AFS signal to control outgoing interference beyond the generic ITU OOB and spurious emissions requirements.**





Thank you!