



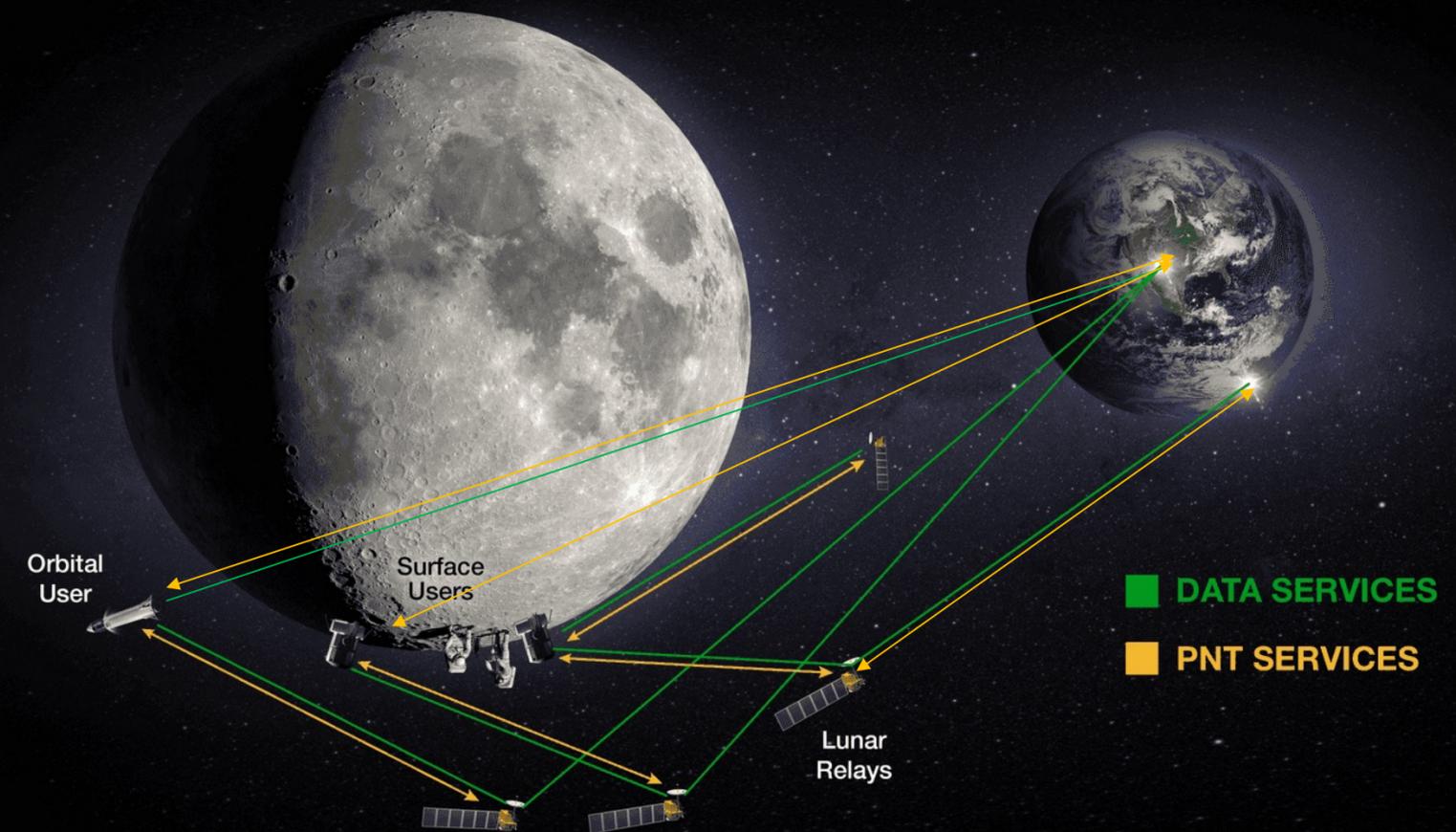
SPECTRUM USE ENABLING LUNAR PNT SERVICES

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**UNOOSA 2nd WORKSHOP ON CISLUNAR POSITIONING,
NAVIGATION, AND TIMING (PNT)
VIENNA, AUSTRIA, 10-13 FEB, 2026**

SPECTRUM UTILIZATION FOR LUNAR PNT

- Lunar PNT Services
 - Radiometrics on Point-to-Point links (Range, Doppler)
 - AFS/LANS (GNSS-Like broadcast)
 - LunaNet compliant signaling and spectrum
 - Note: IM provides services beyond the LunaNet
- Radiometrics
 - Radiometrics are supported via proximity and P2P DTE links
 - IM's implementation of LunaNet relays supports radiometrics on all service bands (S, Ka) (X for DTE)
 - 2025-2110 MHz / 2200-2290 MHz
 - 23.15-23.55 GHz / 27-27.5 GHz
 - Note: IM's LDN supports the full Ka-band from 22.55-23.55 GHz / 25.5-27.5 GHz (Beyond the scope of LunaNet) ²
 - One-way and Two-way services supported
- AFS/LANS (GNSS-Like)
 - One-way GNSS-like, PNT and data signal
 - 2483.5 – 2500 MHz
 - Provides precision position, velocity, and time (depending on user terminal capabilities)
 - Provides LANS messaging service from network->user



IM's LDN Spectrum Plan and PNT Services are based on (encompasses) the LunaNet Spectrum Plan and LunaNet Interoperability Specification (LNIS, LNIS AD 1, etc.)

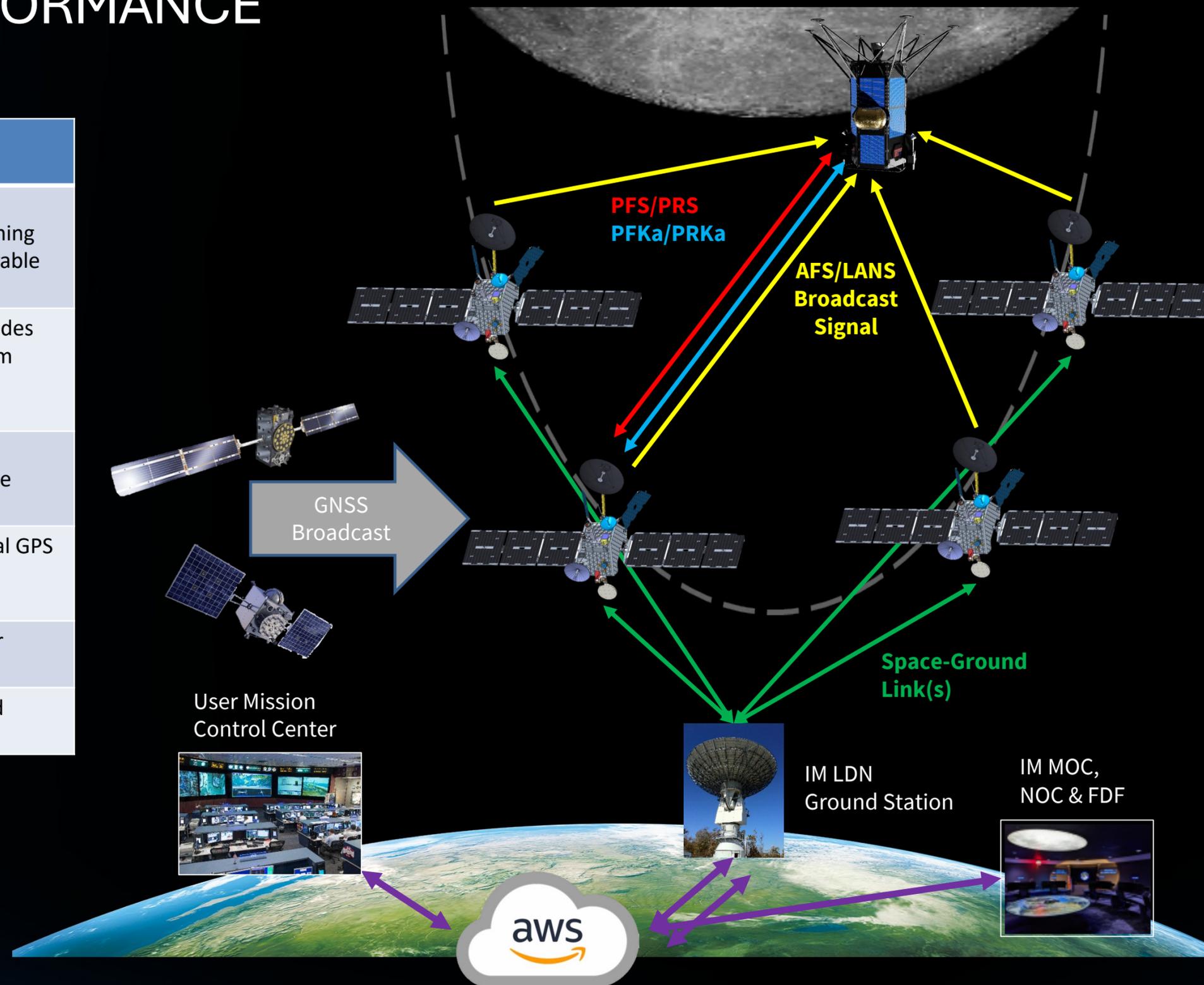
IM LUNAR PNT SERVICE ARCHITECTURE AFS/LANS & RADIOMETRIC PERFORMANCE

AFS/LANS Performance (Accuracy, SISE, GDOP, etc.)

PERFORMANCE METRIC	GPS SPS (1993)	AFS / LANS (2025)	REMARKS
Position Accuracy (95%)	≤ 100 m (95%)	≤ 100m (LLO) ± 10m (Surface)	Per LCRNS SRD. AFS SISE includes all position & timing broadcast errors; comparable metric
Velocity Accuracy (1σ)	≤ 0.3 m/s (95%)	≤ 0.01 m/s (1 cm/s)	Per LCRNS SRD. AFS provides much tighter velocity from coherent dual frequency tracking
Timing Accuracy (1σ)	≤ 340 ns (~102 m)	≤ 6 ns (~2 m)	Derived from SISE time component; LRT reference
Signal-in-Space Range / Rate Error (SISRE/SISRRE)	≤ 33 m ≤ 0.04 m/s (95%)	≤ 9 m ≤ 0.0008 m/s (95%)	AFS goal similar to original GPS SISRE threshold
User Geometry (GDOP)	4-12 Typical	3-6 in Service Volume	AFS modes positioned for regional lunar coverage
Service Availability	≥ 99.0% (Global)	≥ 98.0% (Per Service Volume)	Comparable for sustained service continuity

Radiometric Performance (Measurement in Space Error)

PERFORMANCE METRIC	VALUE	REMARK
MISE Range	0.93 m (3σ) @ 10 s	Error represented as one-way
MISE Doppler	0.33 mm/s (3σ) @ 10 s	Error represented as one-way



Illustrative concept; Conceptual system representation provided for public technical discussion; configurations may evolve.

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SPECTRUM UTILIZATION CHALLENGES

- **Radiometrics**

- Radiometric PNT services use the same spectrum allocation as the user mission TT&C and mission data links
- Spectrum bandwidth is the largest constraint
 - 5 MHz preferred channels in S, X bands
 - Ranging per LNIS uses CCSDS 414.1 – PN ranging with several Mcps chip rates.
 - PN ranging uses relatively wide bandwidths (e.g. 6 MHz for a 3 Mcps expected PN sequence)
- Shared frequency regions
 - Direct-to-Earth (DTE) links share spectrum regions with local cislunar proximity links
 - Plan does not provide for reserved space-ground “trunk links” – shared spectrum with other DTE missions
 - Can create a “near/far” interferer challenge

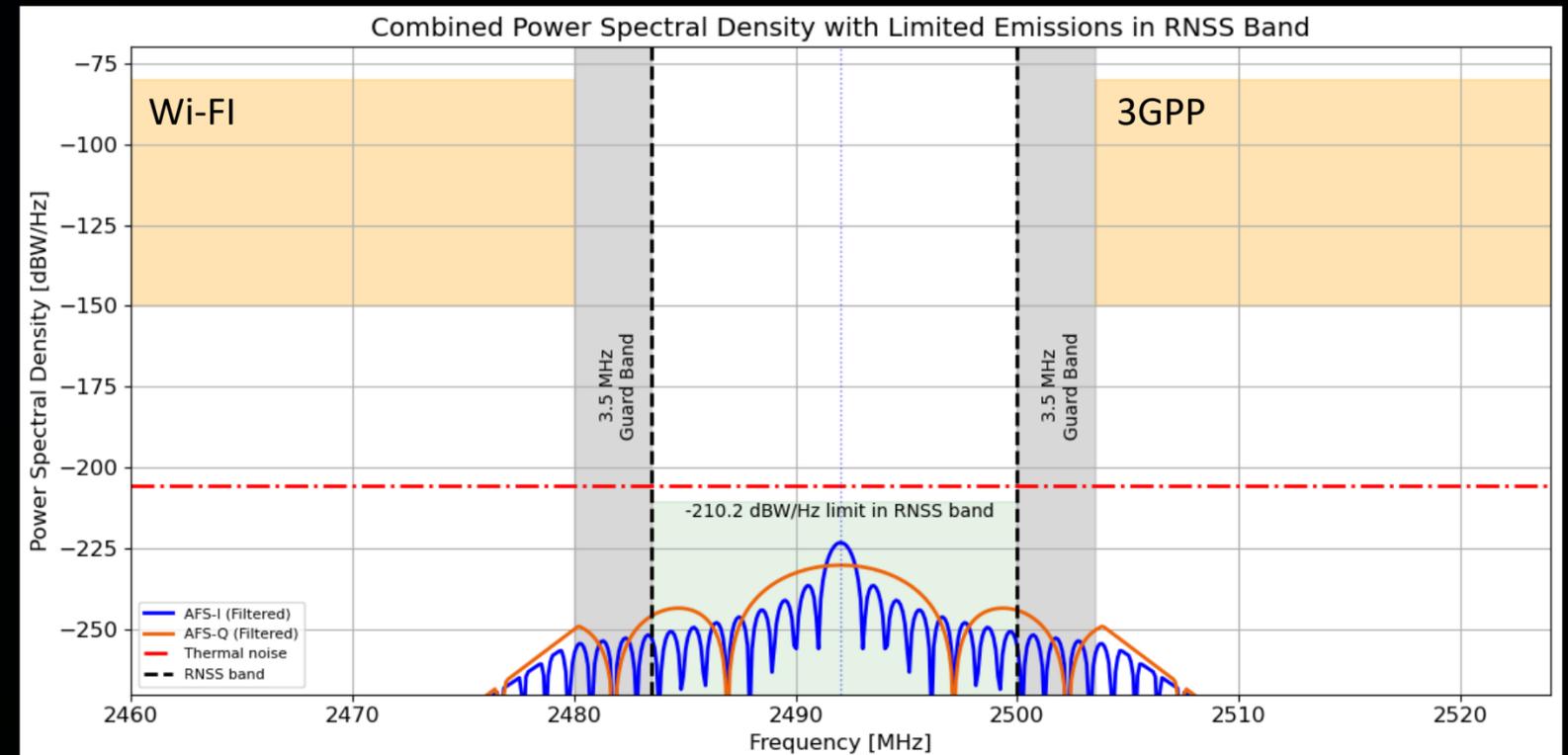
- **AFS/LANS**

- Adjacent spectrum users very close to edge of AFS/LANS band (3.5 MHz)
 - Wi-Fi (Below)
 - 3GPP (Above)
- Low signal levels for AFS/LANS at the lunar surface make the signals susceptible to interferers causing a low C/No at the receiver.
- Implementing sharp RF filters to remove interferers is complex and causes AFS receiver margin loss for practical filter designs
- Filtering and power limiting of AFS transmission must be applied to protect the radio astronomy (RAS) bands from harmonics.

IM’s LDN Spectrum Plan and PNT Services are based on (encompass) the LunaNet Spectrum Plan and LunaNet Interoperability Specification (LNIS, LNIS AD 1, etc.)

LUNAR AFS AND NEIGHBORING BANDS

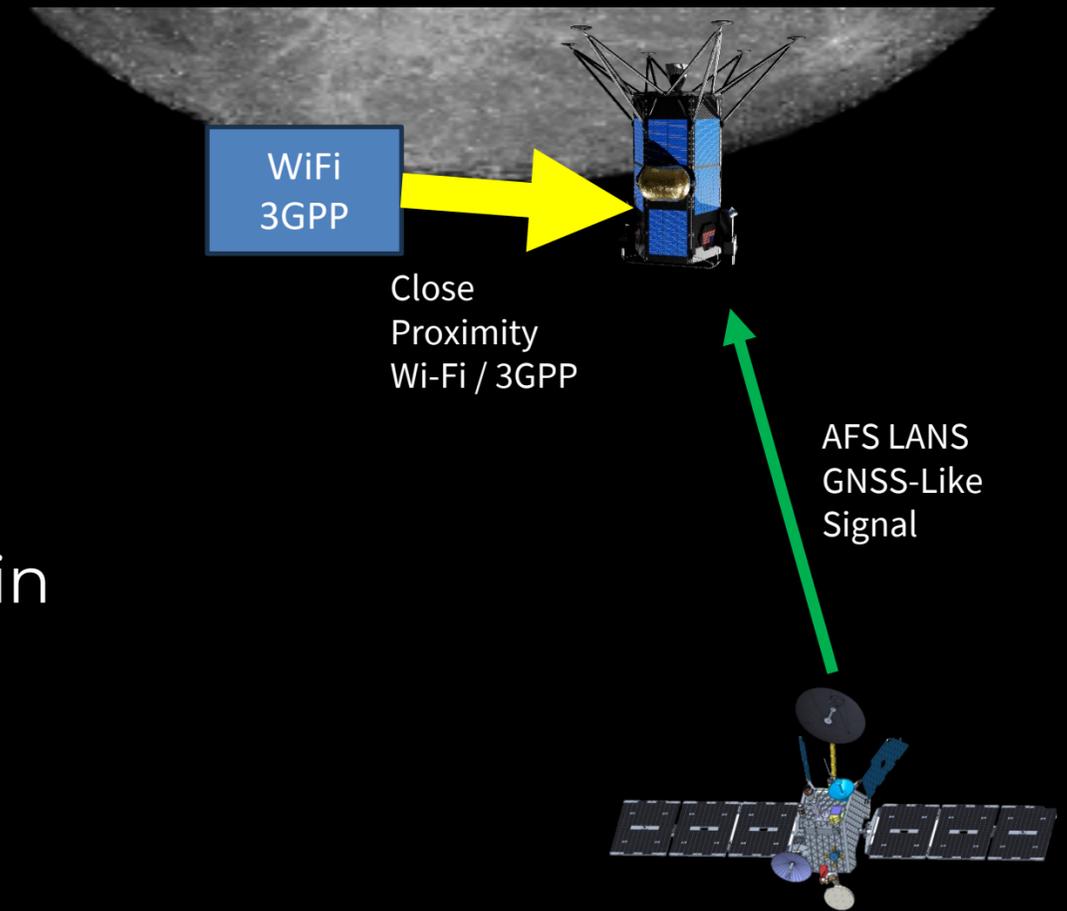
- AFS at the Lunar Surface
 - Minimum RX'd Power -160 dBW (per AD1)
 - Maximum RX'd Power -147 dBW (per AD1)
 - Center Frequency 2492.028 MHz
 - AFS Band Structure
 - 2483.5 – 2500 MHz
 - Guard Bands (3.5 MHz): 2480-2483.5 MHz, 2500-2503.5 MHz
 - Per SFCG REC 32-2R6
 - Potential Surface Wireless Interferers
 - Wi-Fi (Below): 2400-2480 MHz, +36 dBm/MHz
 - 3GPP (Above): 2503.5 – 2655.0 MHz
 - User Equipment: +10 dBm/MHz
 - Base Station: +30 dBm/MHz
- Interferers per IEEE 802.11g/n, 3GPP TS 36.101, 3GPP TS 36.104, SFCG REC 43-1



Applying in-band limits per SFCG REC 43-1

POTENTIAL INTERFERER LEVELS

- Potential interference problem
 - AFS/LANS signal is low power at the surface. (-163 dBW)
 - Receivers have ~11dB of margin (I) and ~17 dB (Q)
 - Wi-Fi and 3GPP transmitters will be in close proximity (10m's) to user AFS/LANS receivers causing interference in the PNT signal band. "Near-Far Problem"



Interferer Characterization at AFS RX Antenna

Interference Source	Distance to AFS Receiver	Max Emissions	Path Loss (FSPL)	Interference Density	I/S Ratio
3GPP BS	17 m	+30 dBm/MHz*	65.04 dB	-125.04 dBW/Hz	110.97 dB
3GPP UE	0.24 m	+10 dBm/MHz*	28.04 dB	-108.00 dBW/Hz	127.97 dB
Wi-Fi UE (US)	0.24 m	+36 dBm/MHz	27.78 dB	-81.78 dBW/Hz	154.23 dB
Wi-Fi UE (Africa, Asia, Europe)	0.24 m	+20 dBm/MHz	27.78 dB	-97.78 dBW/Hz	138.23 dB

Interferers calculated per IEEE 802.11g/n, 3GPP TS 36.101, 3GPP TS 36.104, SFCG REC 43-1

RECEIVER IMPLICATIONS

- Significant expected I/N0 levels drives practical (realizable) receiver design
- High order filters
 - Implementable filters that are sharp enough (high order) will cause passband distortions and/or passband attenuation
 - IIR – Very sharp response, but phase/amplitude “ripples” in the passband
 - FIR – Smooth filter response, but not as steep cutoff and adds loss as (implementable) filter order increases
 - Sharp filters can be implemented more easily (from a signal perspective) in waveguide... which drives SWAP much higher
- Low Noise LNAs
 - Increased cost/complexity of the receiver front end
 - Only so much additional performance available in LNAs (typical LNA already has a low NF)
- “Near-Far” problem
 - AFS signal is very weak signals at the surface user receiver
 - Wi-Fi and 3GPP are strong signals in close proximity
 - A practical RX front end that has the sensitivity required to receive the weak AFS signal can be overloaded by the strong local Wi-Fi and 3GPP signals

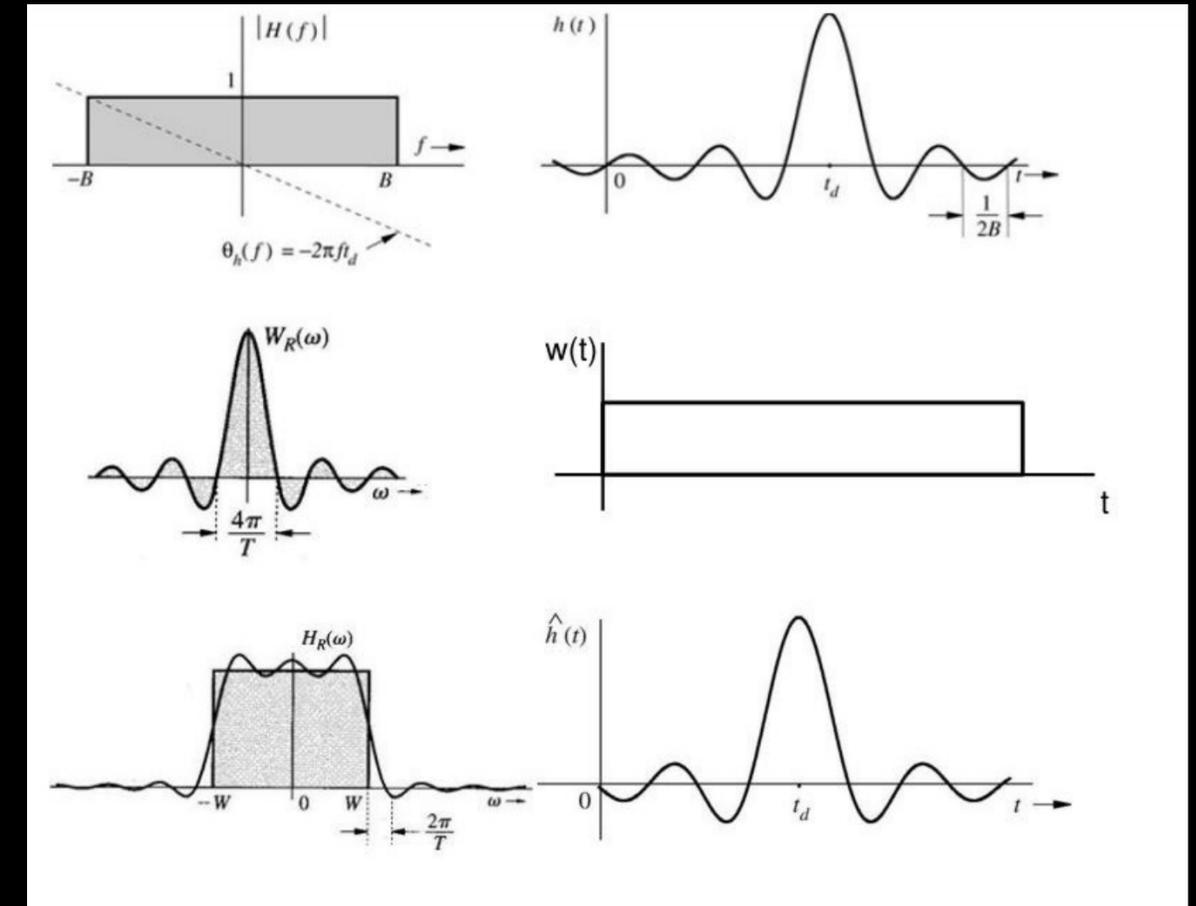
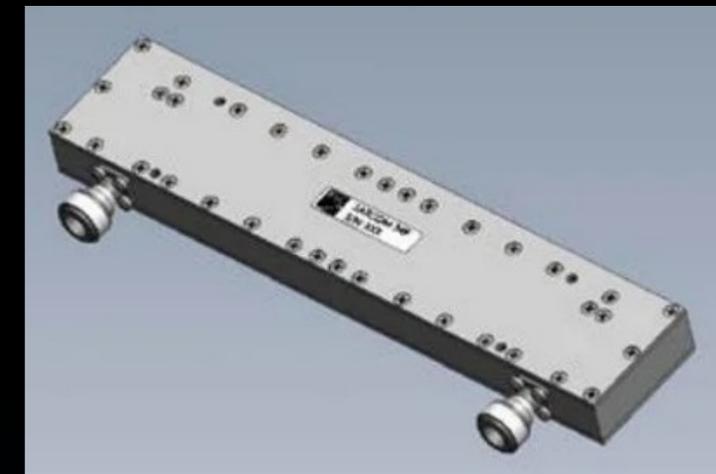


Image Credit: Bingabr, ENGR 4323/5323, Mohamed, University of Central Oklahoma



POTENTIAL MITIGATIONS

Spectrum Regulation

- Additional coordination to identify mitigations such as:
 - Increase the guard bands between AFS/LANS, Wi-Fi, and 3GPP. 20 MHz is recommended. Can be done by limiting the allowable Wi-Fi and 3GPP channels that can be used in the cislunar domain.
 - Limit the allowable transmit power for Wi-Fi and 3GPP operating in adjacent bands in lunar region
 - Require increased TX filtering of Wi-Fi and 3GPP implementations at the Moon

Receiver (User Terminal) Implementation

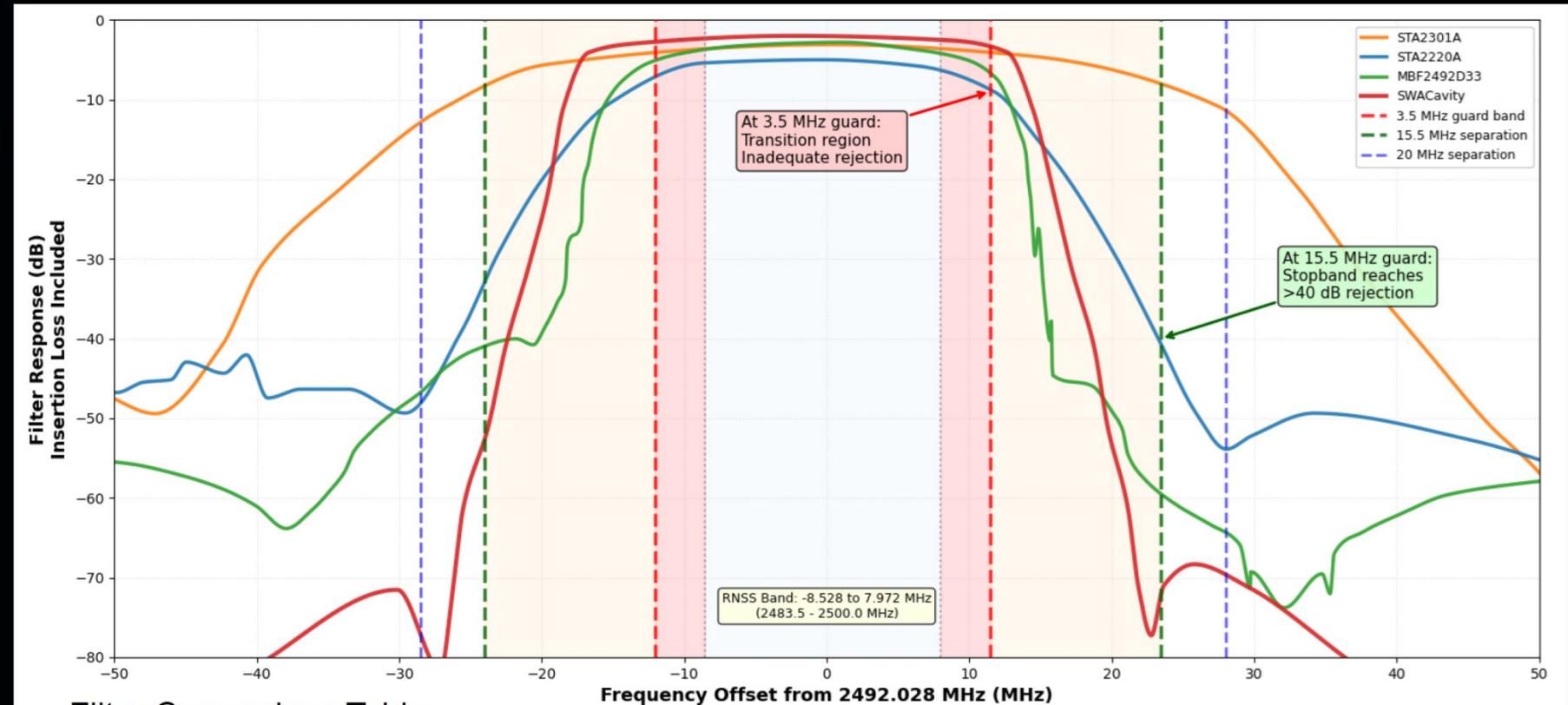
- Practical low SWAP filter designs cannot provide sufficient filtering without also causing unacceptable loss of link margin (>10 dB)

Transmitter (PNT Satellite) Implementation

- Increase required minimum PSD of AFS/LANS signal at the lunar surface.
- Will increase the margin available, decreasing the I/N_0
- Potentially significant cost (SWAP) to the PNT satellite

Note: There are currently no Wi-Fi or 3GPP users on the moon... Restrictions will not affect current users or current hardware. However, these are expected and must be planned for.

S-Band RF Bandpass Filter Comparison at 2492 MHz (w/ Insertion Loss)



Filter Comparison Table

Filter	Manufacturer	Type	BW (MHz)	IL (typ) (dB)	IL (max) (dB)	Size (cm ³)	Mass (g)	Key Trade
STA2220A	SAWTRON	SAW	8.0	5.0	8.0	0.3x0.3x0.14	< 2	High IL, small
STA2301A	SAWTRON	SAW	16.5	3.1	4.3	0.14x0.11x0.07	< 2	Low protection, small
MBF2492D33	Shenzhen Megsine Tech.	BAW	23.0	2.8	3.8	0.3x0.3x0.08	< 2	Best protection, low IL, small size
SWA-1080	Southwest Antennas	Cavity	22.0	2.0	2.0	10.8x5.6x1.0	319	Low IL, good protection, large size

Trade analysis and graphic from:

Dafesh, P., Crenshaw, J., Djuknic, G., "Lunar RNSS Out-of-Band Interference AFS Use Case", 25 JAN 2026.

SUMMARY

- Spectrum allocated above (3GPP) and below (Wi-Fi) the selected AFS/LANS band, combined with allowable out-of-band emissions causes a likely interference scenario
- Interference will be most prevalent during human operations where Wi-Fi and 3GPP can be expected to be used heavily
- Several mitigations are available to be explored
 - Regulatory – Spectrum allocation
 - Specification – LunaNet spec can specify the allowable channels, transmit power, and out-of-band emissions for Wi-Fi and 3GPP implementations by LunaNet users

Action will be required to ensure operable (and interoperable) surface wireless and GNSS capability

A photograph of a modern conference room with a large curved wall displaying a lunar data visualization. The room is dimly lit with blue ambient lighting. Several office chairs are arranged around a table. The data on the wall shows a complex network of lines and nodes, possibly representing a lunar data network.

Questions and any additional topics not covered in this presentation

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