ICG-IOAG Workshop on Cislunar Positioning, Navigation, and Timing

Spectrum Factors for Lunar In-Situ PNT Service Design in the Lunar Environment

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Lunar PNT Spectrum Overview

- The S-band PNT frequencies (2 483.5 – 2 500 MHz) sits in the middle of a busy portion of the lunar spectrum
  - Separated by only 3.5 MHz from adjacent frequency bands planned for lunar surface wireless communications
- Other PNT bands have their own drawbacks in the lunar region
  - L-band PNT frequencies could cause harmful interference to radio astronomy observations in the Shielded Zone of the Moon (SZM), which are protected by Articles 22.22-22.25 of the Radio Regulations
  - Similarly, C-band PNT frequencies (5 010 - 5 030 MHz) could interfere with the near adjacent 4 990 - 5 000 MHz RAS allocation in the SZM

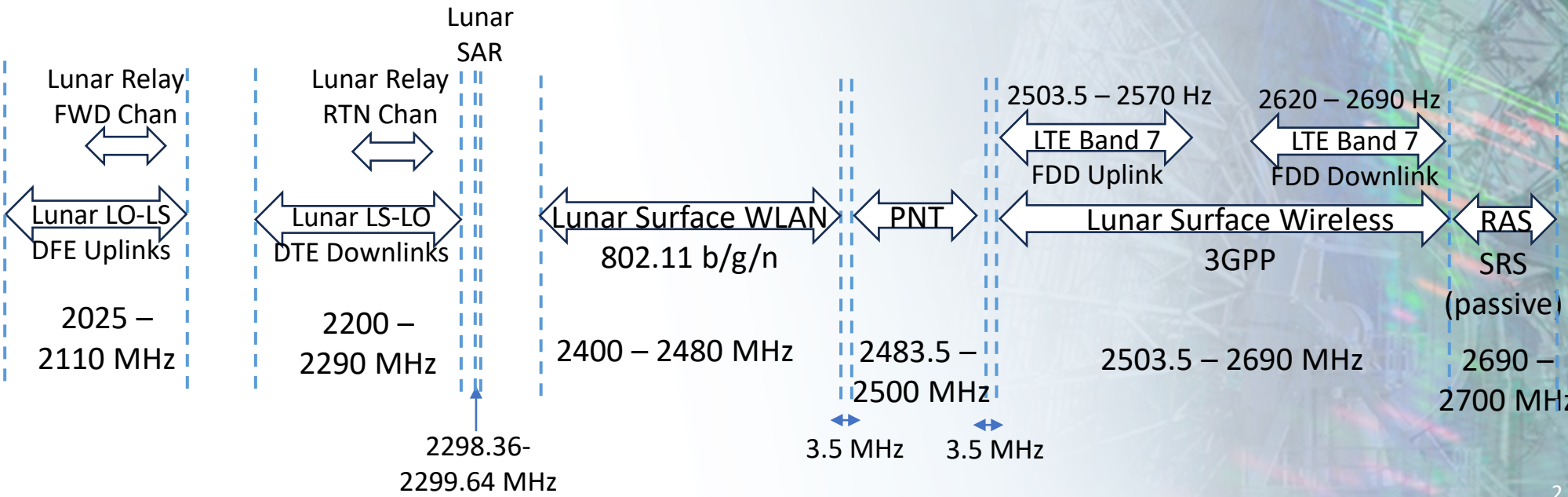


Figure 1. Lunar S-band Spectrum

Potential RFI to S-band Lunar PNT Receivers

- EVA Suit-to-Suit PNT Receiver Interference Scenarios
  - Adjacent band interference from WiFi transmitter (2 400 – 2 480 GHz) on own suit (self-interference) or adjacent EVA suit
  - Adjacent band interference from 3GPP transmitter (2 503.5 – 2 570 GHz FDD uplink) on own suit or adjacent EVA suit
  - Aggregate interference from both EVA suit WiFi and 3GPP transmitters
- Types of Interference
  - PNT receiver saturation due to strong adjacent band WiFi or 3GPP signal transmitted by same suit or nearby unit
  - In-band interference to S-band PNT receiver due to out-of-band emissions from adjacent band WiFi or 3GPP transmitters
  - In-band interference from other lunar Sb-and PNT satellites

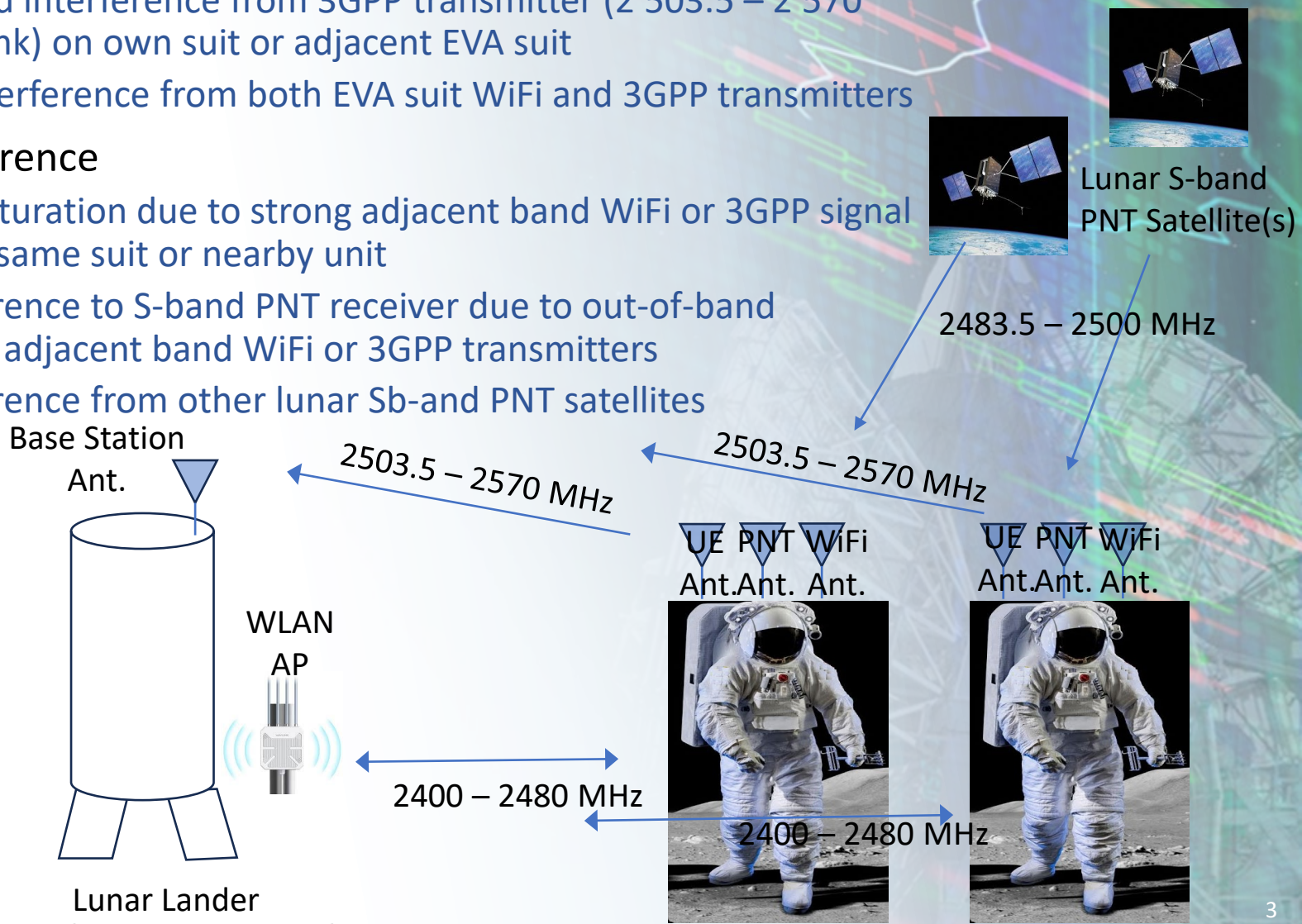


Figure 2. Lunar Surface PNT Interference Example

S-band PNT Interference Protection Criterion

- Currently there are no ITU-R Recommendations defining the interference protection criterion (IPC) for S-band PNT receivers in the 2483.5 – 2500 MHz band
- Recommendation ITU-R M.1903 provides the aggregate interference threshold power density levels for L-band PNT receivers in the 1 559 -1 610 MHz band on Earth
  - Different thresholds are defined for different types of PNT receivers, including general purpose and high precision, and for acquisition vs. tracking mode
  - There is uncertainty as to how well these values will translate to S-band PNT receivers used in space. This will likely need to be resolved with S-band PNT receiver testing

Table 1. L-band PNT Receiver Aggregate Interference Protection Criteria (Rec ITU-R M.1903)

	General Purpose #1 Receiver	High Precision Receiver
Acquisition mode, narrow-band interference	-158 dBW	-157.4 dBW
Tracking mode, narrowband interference	-152 dBW	-157.4 dBW
Acquisition mode, wideband interference	-142 dB(W/MHz)	-147.4 dB(W/MHz)
Tracking mode, wideband interference	-136 dB(W/MHz)	-147.4 dB(W/MHz)
Max Receiver Antenna Gain	6 dBi	3 dBi

Provisional SFCG Recommendation 43-1

- Prov SFCG REC 43-1 provides a PFD limit of -121 dB(W/m^2/MHz) for aggregate unwanted emissions into the 2483.5 – 2500 MHz PNT band at the input of the receive antenna
- The PFD limit is derived directly from the IPC and receive antenna gain for the high precision receiver in Rec ITU-R M.1903

$$PFD\ Limit = IPC - 10\log_{10}\frac{\lambda^2}{4\pi} - G_{rx}$$

- Alternative approach is to specify unwanted emissions mask or limits for the adjacent band transmitters
  - Ultimately both approaches may be needed, after the PNT system parameters and receiver sensitivity has been more well defined.

Comparison of PFD Limits vs. Unwanted Emissions Mask

Method	Pros	Cons
Interference PFD limits	Takes into account aggregate interference	Verification has to been done at system level
Unwanted Emissions Mask	Easy for transmitter equipment maker to build to Verification can be done by ground test	Aggregate interference from unwanted emissions could exceed IPC Allowable unwanted emission levels dependent on assumptions about geometry and antenna coupling loss

PNT Receiver Saturation due to RFI

- Receiver saturation due to adjacent band signals is dealt with differently than unwanted emissions
  - PNT receiver filtering
  - EIRP limits on signals in adjacent bands
- Prov SFCG Rec 43-1 recommends that the lunar surface PNT receiver front end have sufficient filtering of signals in adjacent bands to avoid saturation
  - Depends on antenna coupling between interferer and victim receiver, interferer transmit power, and saturation level of PNT receiver
  - Rec ITU-R M.1903 provides saturation levels for different types of L-band PNT receivers on Earth; similar measurements for S-band PNT receivers to be used on the Moon are needed.

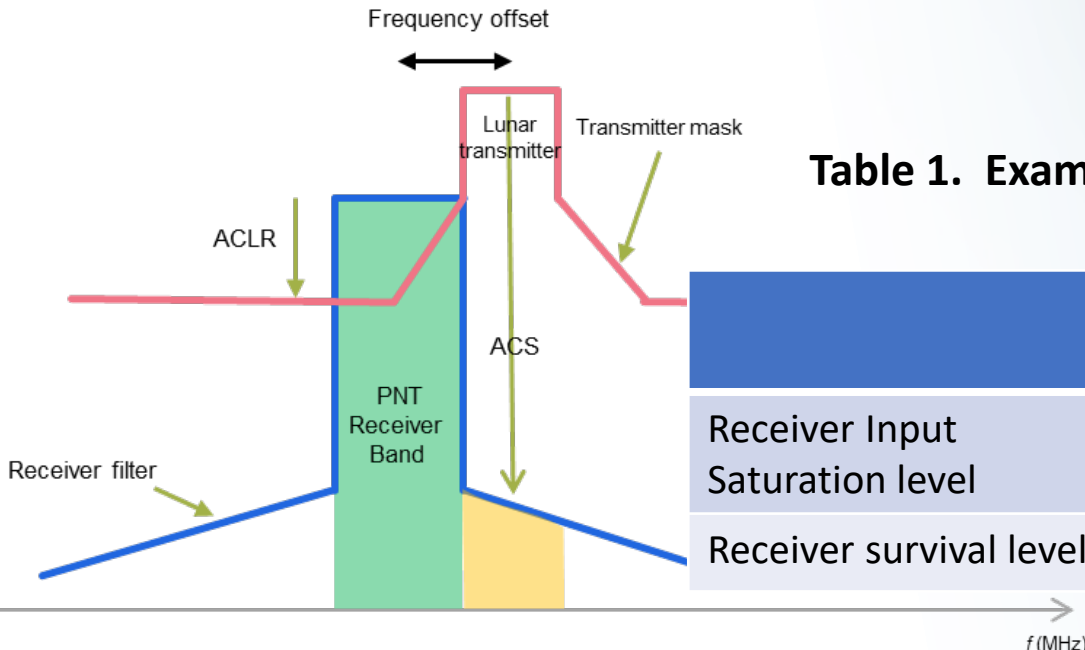
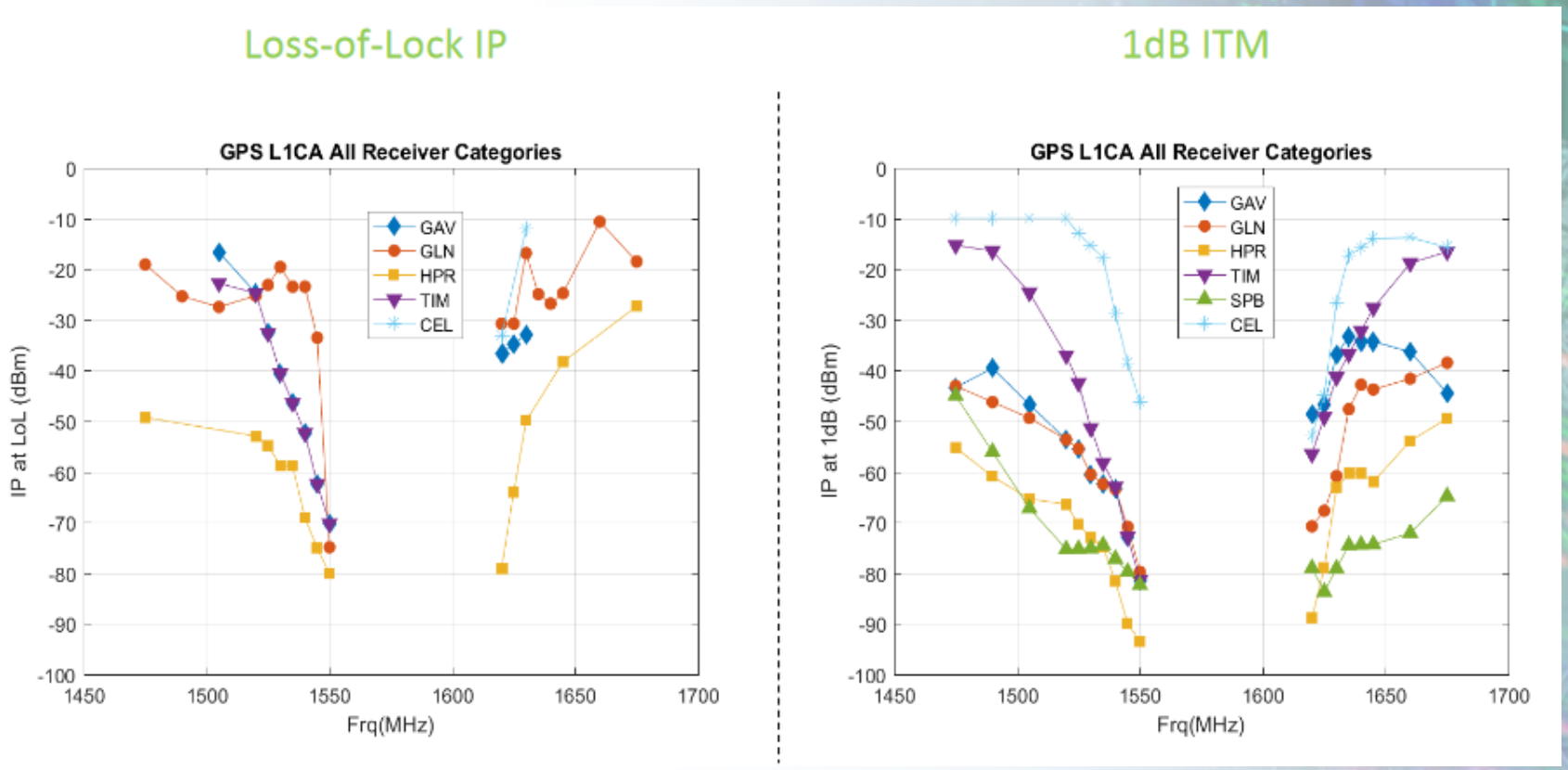


Table 1. Examples of L-band PNT Receiver Saturation Levels (from Rec ITU-R M.1903)

	General Purpose #1 Receiver	High Precision Receiver
Receiver Input Saturation level	-70 dBW	-120 dBW
Receiver survival level	-20 dBW	-20 dBW

Example of PNT Receiver IPC Measurements

- The interference to the PNT receiver due to adjacent bands can be measured based on loss-of-lock vs. 1 dB interference tolerance masks (ITM)
  - ITM is based on 1 dB C/N_0 degradation to the receiver
- An example of IPC measurements from a L-band PNT study is shown for a 10 MHz LTE signal in the adjacent band



Source: C. Hegarty and A. Odeh, The MITRE Corporation, Loss of Lock Analysis presentation, GPS-ABS Workshop VI, Washington, D.C., March 2017

Interference Mitigation Strategies

- Appropriate selection of channels for lunar surface wireless systems in adjacent bands
  - In cases where PNT and wireless receivers will be in close proximity, choose wireless channels with sufficient frequency separation from PNT band
- PNT receiver RF and pre-correlation filter design
  - Tradeoff between PNT signal distortion and adjacent channel selectivity
  - Temperature variation on the lunar surface can change RF filter characteristics, which is another challenge
- Minimize antenna coupling between PNT receiver and lunar surface wireless transmitters
  - Possible when the location of PNT and wireless antennas are known beforehand
- For devices on the same EVA suit, time multiplexing between PNT and lunar surface wireless radios to avoid self-interference is also possible

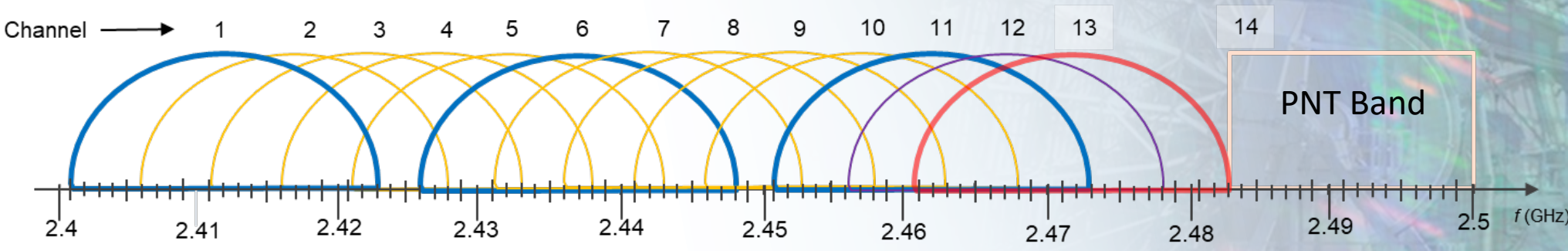


Figure 3. IEEE 802.11 Channels in 2.4 – 2.48 GHz

Summary

- Due to adjacent lunar surface wireless frequency bands, lunar S-band PNT receivers in the 2483.5 – 2500 MHz will face challenges with interference when the systems are in close range of each other
  - Lunar spectrum architecture driven in part by the need to protect of radio astronomy observations in the SZM
- Provisional SFCG Rec 43-1 provides an aggregate unwanted emissions PFD limit at the input to the S-band PNT receiver, but this can be difficult to compute and verify without knowledge of the system configuration and adjacent systems
- Measurements of lunar S-band PNT receiver characteristics (e.g., IPC, adjacent channel selection, saturation levels, noise figure) and impact of adjacent band wireless systems are needed
  - Test, test, and more test
- Work in the SFCG to develop additional recommendations to protect PNT receivers on the Moon is on-going

Thank you for listening

Comments or questions?