Preliminary Design of Compatible and Interoperable Lunar Navigation Signals

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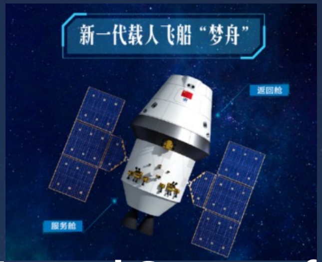
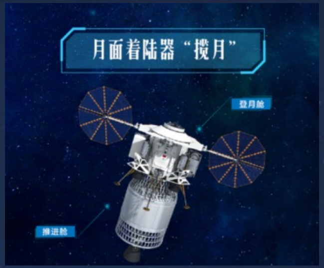
Topics

Introduction

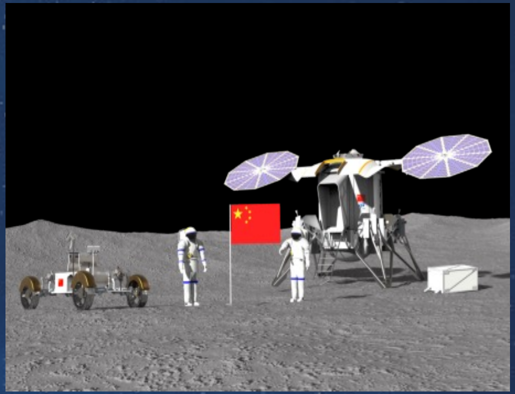
- Lunar exploration and resource development involve complex task forms such as sustained presence and interactive collaboration, which impose higher requirements on the accuracy, reliability, and more convenient access to spatiotemporal information. This has made the demand for lunar Positioning, Navigation, and Timing (PNT) space infrastructure increasingly urgent.
- To ensure better coordination among different lunar PNT systems, compatibility and interoperability are essential.
  - **Compatibility** refers to the ability of global and regional navigation satellite systems and augmentations to be used separately or together without causing unacceptable interference and/or other harm to an individual system and/or service. (from ICG)
  - **Interoperability** refers to the ability of global and regional navigation satellite systems and augmentations and the services they provide to be used together to provide better capabilities at the user level than would be achieved by relying solely on the open signals of one system. (from ICG)



Manned Spacecraft "Mengzhou"



Lunar Lander "Lanyue"


Manned lunar exploration


International Lunar Research Station

Design Concepts

- The design of lunar PNT signals requires a comprehensive consideration of frequency selection, transmission power, modulation schemes, ranging codes, navigation messages and so on.
- In terms of frequency selection:
  - The recommendation **ITU RA.479-5** proposes that all frequencies below 2 GHz in the Shielded Zone of the Moon (SZM) should be reserved for radio astronomy.
  - According to the recommendation **SFCG REC 32-2R5** from Space Spectrum Coordination Group (SFCG), lunar navigation signals are suggested to be broadcast in the 2483.5-2500 MHz band (S-band).
  - The **BeiDou Navigation Satellite System** (BDS) broadcasts S-band navigation signals in the Earth region, and relevant experience in the design of payloads and receivers can be used.
  - Consideration should be given to interoperability with other lunar PNT systems, such as the **Augmented Forward Signal (AFS) of LunaNet**, to enhance the performance of receivers.

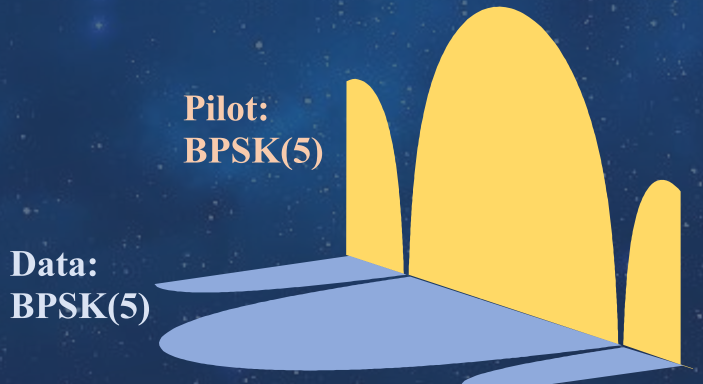
Based on the above considerations, it is recommended that the lunar navigation signals be broadcast in the 2483.5-2500 MHz band, with a center frequency of 2492.028 MHz.

In the future, the feasibility of other frequency bands for lunar navigation will also be assessed, such as L-band (outside the SZM), C-band and so on.

Design Concepts

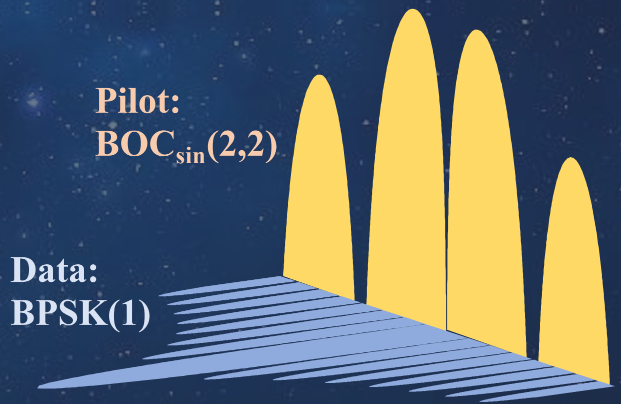
- The design of lunar navigation signals can draw on the mature experience in GNSS, balancing the performance of data transmission, measurement accuracy, implementation complexity, as well as compatibility and interoperability in the lunar application environment.
- Based on the preliminaries, the following three lunar navigation signal candidates are recommended:

Scheme	Key Features	Carrier Frequency	Modulation	Ranging Code
1	Precision Priority	2492.028 MHz	Data (in-phase): BPSK(5) Pilot (quadrature-phase): BPSK(5)	Weil/Gold
2	Interoperability Priority	2492.028 MHz	Data (in-phase): BPSK(1) Pilot (quadrature-phase): BPSK(5)	Weil/Gold
3	Compatibility Priority	2492.028 MHz	Data (in-phase): BPSK(1) Pilot (quadrature-phase): $BOC_{sin}(2,2)$	Weil/Gold



Precision Priority Scheme

Interoperability Priority Scheme

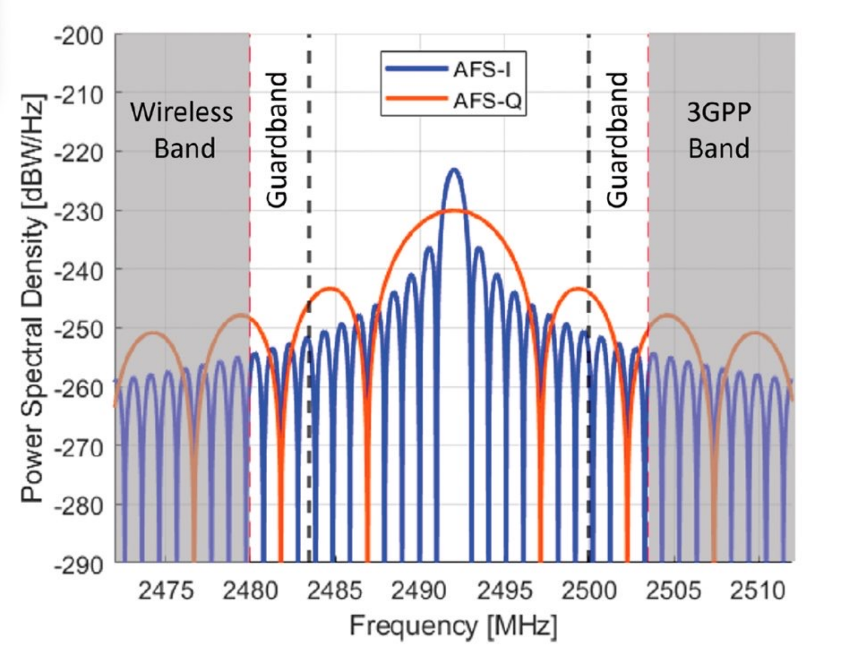


Compatibility Priority Scheme

Compatibility Analysis

- To avoid harmful interference between lunar PNT systems, signal compatibility analysis needs to be conducted to support the selection of signal modulation schemes and power levels.
- LunaNet broadcast Augmented Forward Signal (AFS) to provide GNSS-like lunar augmented navigation service. The AFS uses a Code Division Multiple Access (CDMA) signal structure in the 2483.5-2500 MHz band with a center frequency of 2492.028 MHz.

Frequency Band	2483.5-2500 MHz
Carrier Frequency	2492.028 MHz
Modulation	AFS-I (Data): BPSK(1) AFS-Q (Pilot): BPSK(5)
Power Allocation	AFS-I: 50%, AFS-Q: 50%
Received Minimum Power at the Lunar Geoid within the Service Volume	-160 dBW
Received Maximum Power at the Lunar Geoid within the Service Volume	-147 dBW
Received Maximum Power at the Lunar Geoid outside the Service Volume	-141 dBW



[1] LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal (LSIS-AFS), Version 1, January 29, 2025.
[2] LunaNet AFS Properties and Signal Band, ICG-IOAG Cislunar PNT Workshop, February 11-13, 2025.

Compatibility Analysis

- The compatibility is assessed from four dimensions: spectral separation coefficient, effective carrier-to-noise density ratio, code tracking error, and out-of-band power spectral density.

(1) Spectral separation coefficient

Spectral separation coefficient reflects the spectral overlap between the target signal and the interference. The smaller the spectral separation coefficient, the higher the degree of spectral separation between signals, and the less interference there is between the signals.

$$SSC = \int_{-\beta_r/2}^{\beta_r/2} G_l(f) G_s(f) df$$

β_r: double-sided reception bandwidth of the receiver

$G_s(f)$: normalized power spectral density of the target signal

$G_l(f)$: normalized power spectral density of the interference

Compatibility Analysis

- The compatibility is assessed from four dimensions: spectral separation coefficient, effective carrier-to-noise density ratio, code tracking error, and out-of-band power spectral density.

(2) Effective carrier-to-noise density ratio

The effective carrier-to-noise density ratio is the ratio of the carrier power of the target signal to the power spectral density of the equivalent white noise caused by both interference and noise. It serves as a measure of signal quality under the combined effects of interference and white noise.

$$\left(\frac{C_s}{N_0}\right)_{eff} = \frac{\frac{C_s}{N_0}\int_{-\beta_r/2}^{\beta_r/2} G_s(f)df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f)df + \frac{C_l}{N_0}\int_{-\beta_r/2}^{\beta_r/2} G_l(f)G_s(f)df}$$

C_s: received carrier power of the target signal

$G_s(f)$: normalized power spectral density of the target signal

N_0: power spectral density of the white noise

β_r: double-sided reception bandwidth of the receiver

C_l: received carrier power of the interference

$G_l(f)$: normalized power spectral density of the interference

Compatibility Analysis

- The compatibility is assessed from four dimensions: spectral separation coefficient, effective carrier-to-noise density ratio, code tracking error, and out-of-band power spectral density.

(3) Code tracking error

The variance of the code tracking error (in units of seconds squared) for coherent early-late processing (CELP) is

$$\sigma^2_{CELP} = \frac{B_L(1-0.5B_L T)\int_{-\beta_r/2}^{\beta_r/2} G_s(f)\sin^2(\pi f \Delta)df}{(2\pi)^2 C_s\left(\int_{-\beta_r/2}^{\beta_r/2} f G_s(f)\sin(\pi f \Delta)df\right)^2}\left(N_0 + \frac{C_l\int_{-\beta_r/2}^{\beta_r/2} G_l(f)G_s(f)\sin^2(\pi f \Delta)df}{\int_{-\beta_r/2}^{\beta_r/2} G_s(f)\sin^2(\pi f \Delta)df}\right)$$

B_L: one-sided equivalent rectangular bandwidth of the code tracking loop
T: integration time used in the discriminator
Δ: two-sided early-to-late spacing of the correlator taps in seconds
C_s: received carrier power of the target signal
$G_s(f)$: normalized power spectral density of the target signal
N_0: power spectral density of the white noise
β_r: double-sided reception bandwidth of the receiver
C_l: received carrier power of the interference
$G_l(f)$: normalized power spectral density of the interference

Compatibility Analysis

- The compatibility is assessed from four dimensions: spectral separation coefficient, effective carrier-to-noise density ratio, code tracking error, and out-of-band power spectral density.

(4) Out-of-band power spectral density

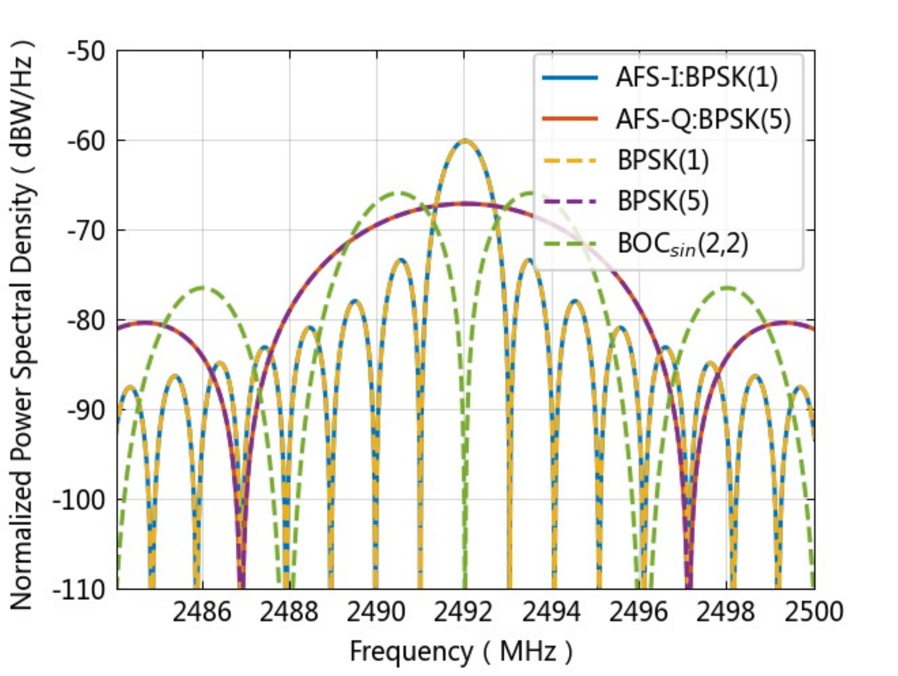
The out-of-band power spectral density measures the interference from the lunar navigation signals to the out-of-band signals.

Compatibility Analysis

- The in-phase data component is denoted as s_{data}, and the quadrature-phase pilot component is denoted as s_{pilot}. The modulation of s_{data} is either BPSK(1) or BPSK(5). The modulation of s_{pilot} is either BPSK(5) or $BOC_{sin}(2,2)$.

(1) Spectral separation coefficient (SSC)

In the simulation, the double-sided reception bandwidth denoted as β_r is set to 16 MHz.



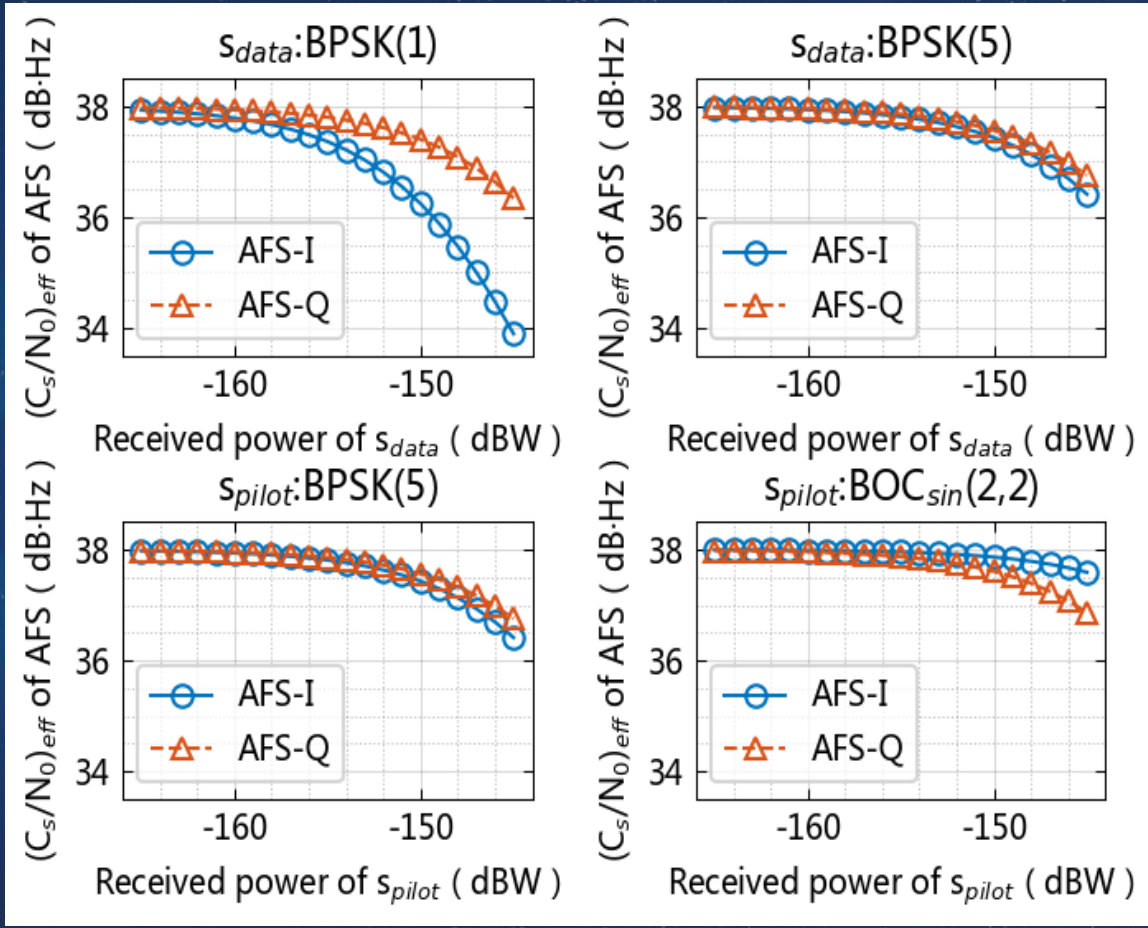
Normalized Power Spectral Density of AFS and candidate modulation schemes

SSC（dB）		Target Signal				
		AFS-I	AFS-Q	BPSK(1)	BPSK(5)	$BOC_{sin}(2,2)$
Interference Signal	AFS-I	-61.86	-67.39	-61.86	-67.39	-73.90
	AFS-Q	-67.39	-68.85	-67.39	-68.85	-69.31
	BPSK(1)	-61.86	-67.39	-61.86	-67.39	-73.90
	BPSK(5)	-67.39	-68.85	-67.39	-68.85	-69.31
	$BOC_{sin}(2,2)$	-73.90	-69.31	-73.90	-69.31	-67.89

Compatibility Analysis

(2) Effective carrier-to-noise density ratio ($(C_s/N_0)_{eff}$)

The simulation result of the interference from s_{data} and s_{pilot} to AFS is as follows.



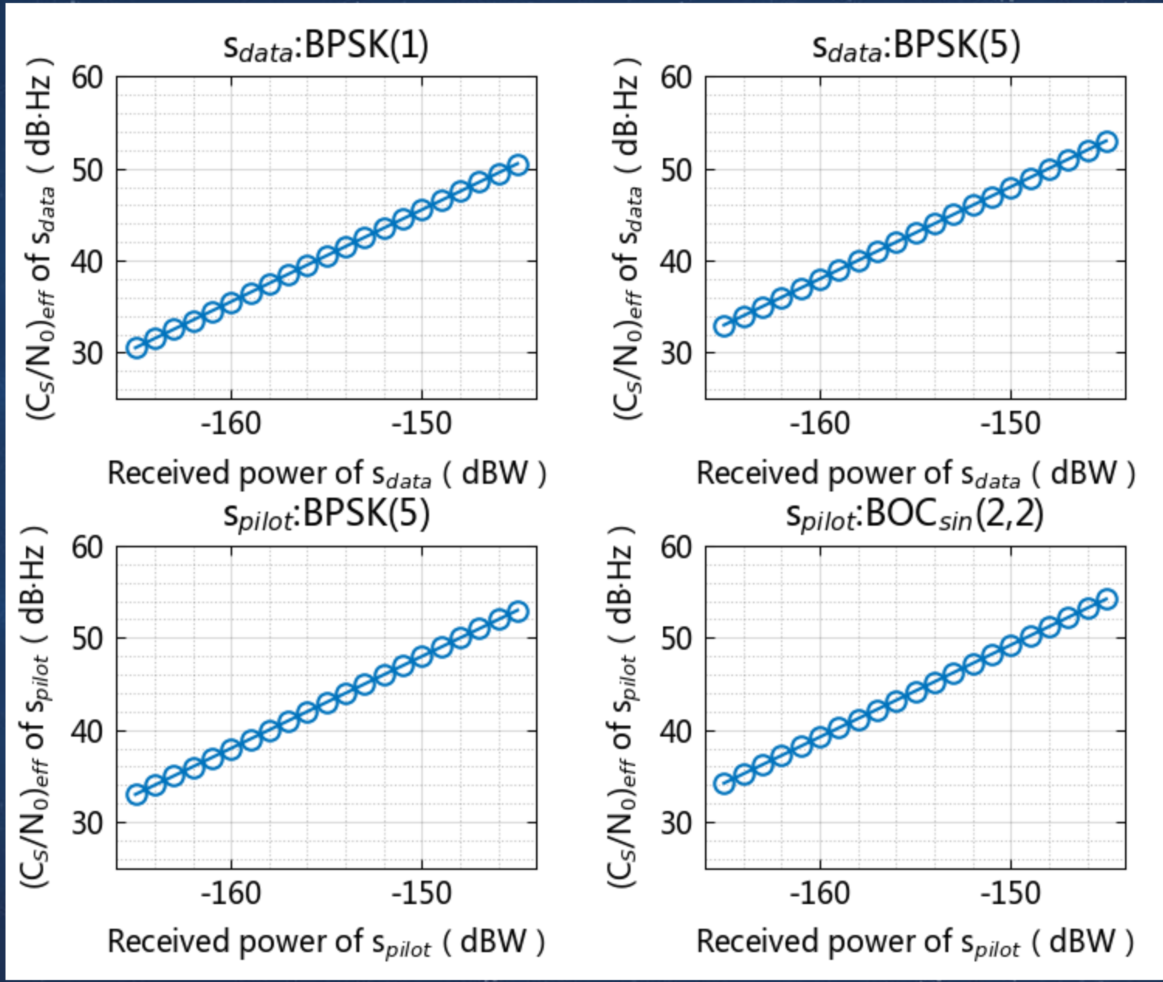
- The received power of AFS composite signal is set to -160 dBW.
- The double-sided reception bandwidth is set to 16 MHz.
- The power spectral density of the white noise is set to -201 dBW/Hz.
- The coverage multiplicity of the signal is set to 6.

Minimum $(C_s/N_0)_{eff}$ of AFS-I and AFS-Q (dB ■ Hz)		Received Signal Power（dBW）			
		-160	-155	-150	-145
Modulation	BPSK(1)	37.79	37.36	36.24	33.89
	BPSK(5)	37.94	37.81	37.43	36.41
	$\mathrm{BOC_{sin}}(2,2)$	37.96	37.87	37.61	36.86

Compatibility Analysis

(2) Effective carrier-to-noise density ratio ($(C_s/N_0)_{eff}$)

The simulation result of the interference from AFS to s_{data} and s_{pilot} is as follows.



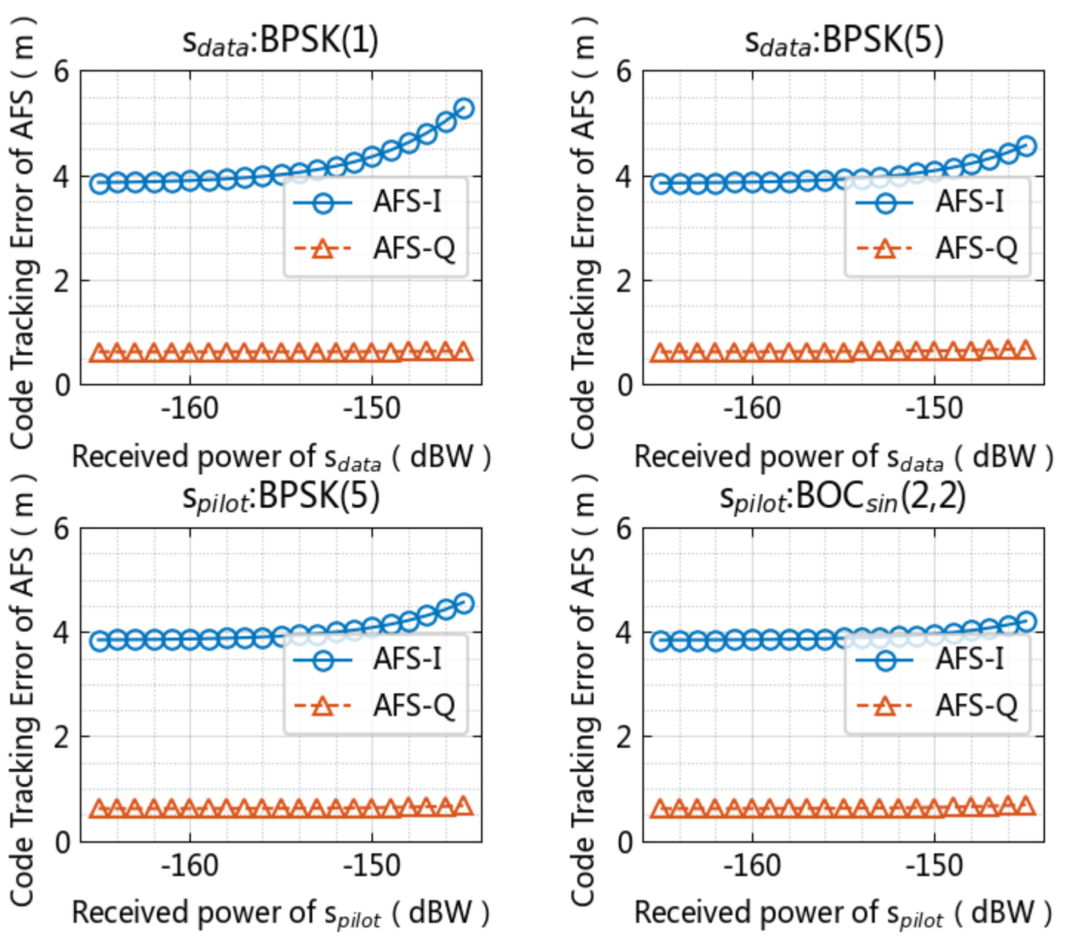
- The received power of the AFS composite signal is set to -141 dBW.
- The double-sided reception bandwidth is set to 16 MHz.
- The power spectral density of the white noise is set to -201 dBW/Hz.
- The coverage multiplicity of AFS is set to 6.

➢ If the effective carrier-to-noise density ratio of the new signal is constrained to be no less than 35 dB·Hz, the received power of the new signal should not be less than -160 dBW, -162 dBW and -164 dBW for BPSK(1), BPSK(5) and $BOC_{sin}(2,2)$ modulation respectively.

Compatibility Analysis

(3) Code Tracking Error

The simulation result of the interference from s_{data} and s_{pilot} to AFS is as follows.



- The one-sided equivalent rectangular bandwidth of the code tracking loop is set to 4 Hz.
- The integration time used in the discriminator is set to 2 ms.
- The two-sided early-to-late spacing of the correlator taps is set to 488.76 ns for AFS-I and 97.75 ns for AFS-Q.
- Other parameters are the same as the simulation settings of the effective carrier-to-noise ratio.

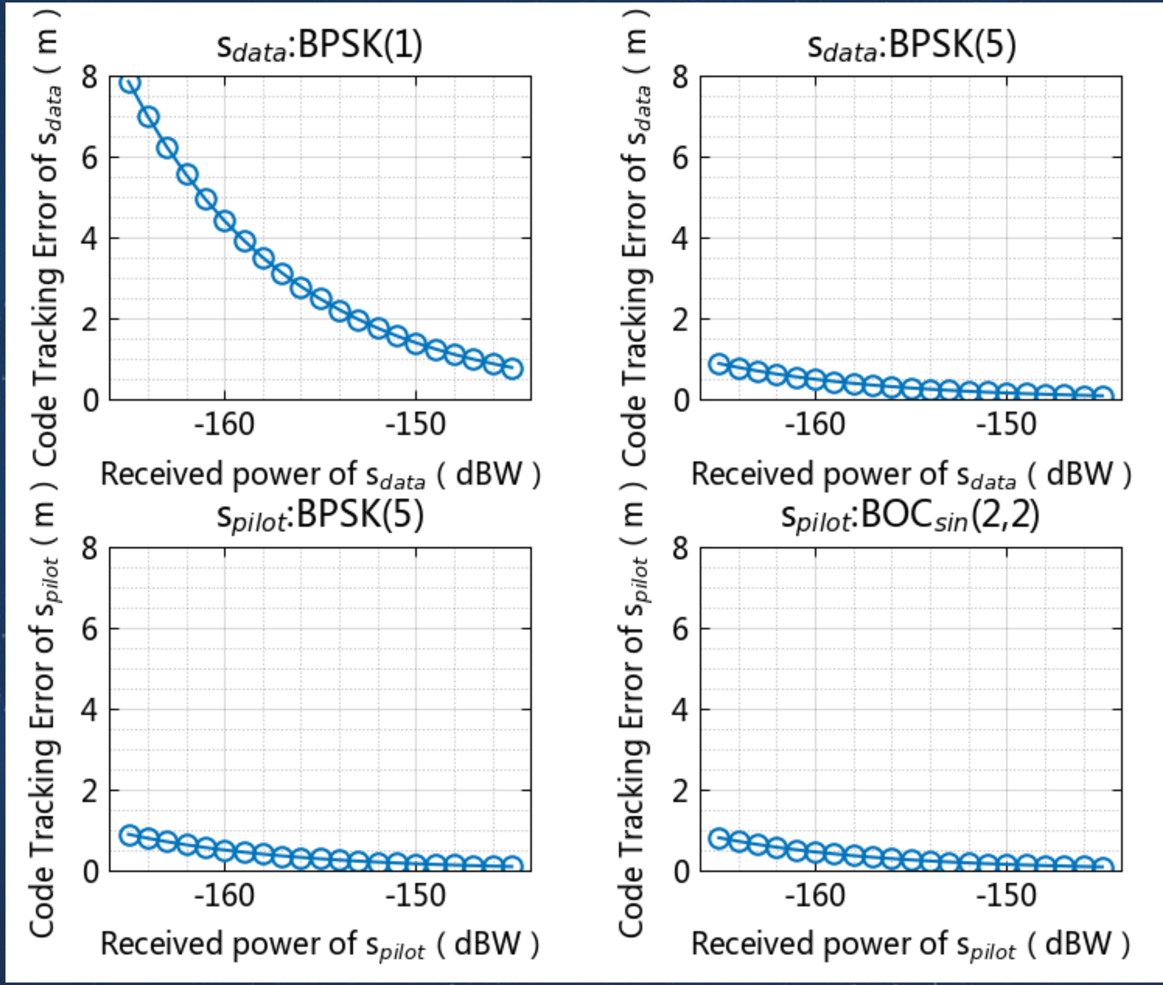
➢ When the modulation of the signal is BPSK(1), the code tracking error of AFS-I is most affected. Therefore, the signal transmission power should not be too high.

➢ When the modulation of the signal is BPSK(5) or BOC$_{sin}$(2,2), the code tracking error of AFS is less affected, and the compatibility is better.

Compatibility Analysis

(3) Code Tracking Error

The simulation result of the interference from AFS to s_{data} and s_{pilot} is as follows.



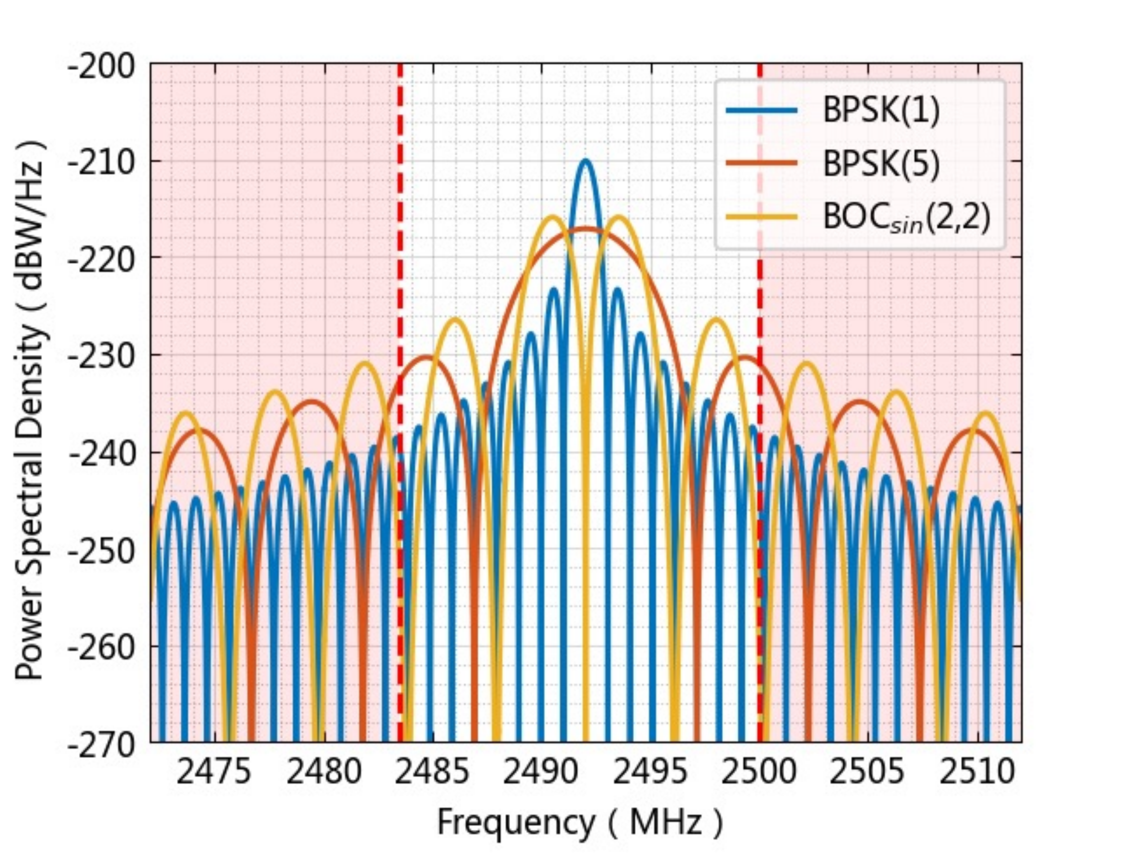
- The one-sided equivalent rectangular bandwidth of the code tracking loop is set to 4 Hz.
- The integration time used in the discriminator is set to 2 ms.
- The two-sided early-to-late spacing of the correlator taps is set to 488.76 ns for BPSK(1) and 97.75 ns for BPSK(5) and $BOC_{sin}(2,2)$.
- Other parameters are the same as the simulation settings of the effective carrier-to-noise ratio.

➢ The code tracking error of the signal employing BPSK(5) and $BOC_{sin}(2,2)$ modulation is much better than that of the signal employing BPSK(1).

Compatibility Analysis

(4) Out-of-band power spectral density

The out-of-band power spectral density measures the interference from the lunar navigation signals to the out-of-band signals.



- If we assume the received power of the lunar navigation signal is **-150 dBW**, the power spectral density of the signal is shown in the figure on the left. The out-of-band power spectral density is below **-230 dBW/Hz** for all modulation candidates.
- Because the out-of-band power spectral density is extremely low, the interference from the lunar navigation signals to the out-of-band signals is acceptable.

Conclusions

- If relevant agencies plan to broadcast GNSS-like lunar navigation signals, it is recommended to deploy the signals in the 2483.5-2500 MHz band to achieve better interoperability.
- This presentation provides a preliminary analysis of the compatibility of lunar navigation signals from four aspects: spectral separation coefficient, effective carrier-to-noise density ratio, code tracking error, and out-of-band power spectral density. The analysis results indicate that:
    - By controlling the transmission power of the lunar navigation signals within a reasonable range, good compatibility can be achieved.
    - Due to the extremely low out-of-band power spectral density of lunar navigation signals, the interference to the out-of-band signals is acceptable.
- We present the recommendations from the China Academy of Space Technology on the design of lunar navigation signals. The presentation focuses on theoretical analysis, and will be continuously refined and adjusted based on engineering practice in subsequent stages.

Thanks!