DAS Photonics

ESA Contract No. 4000134041/21/D/MB

Electro-Photonic Transceiver Breadboarding for Ground Stations Application- KaBS

Final Presentation

17/04/2024

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AGENDA

1. Introduction & Technology review
2. Breadboard implementation
3. Breadboard Test results
4. Review of achieved performance
5. Conclusions and Recommendations

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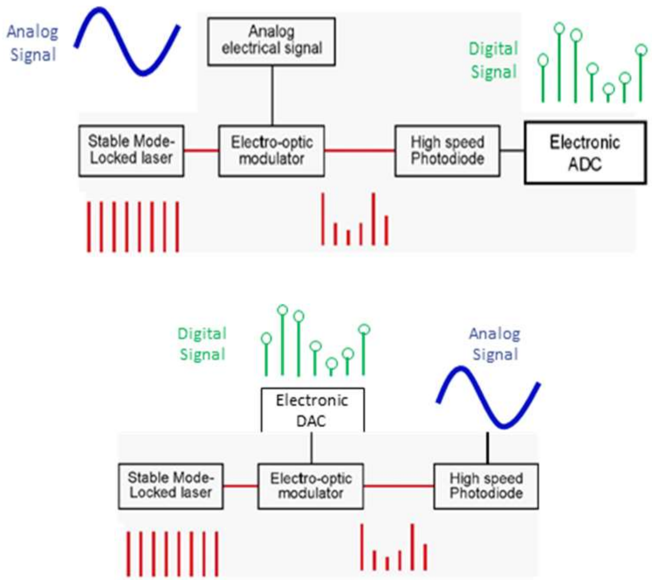
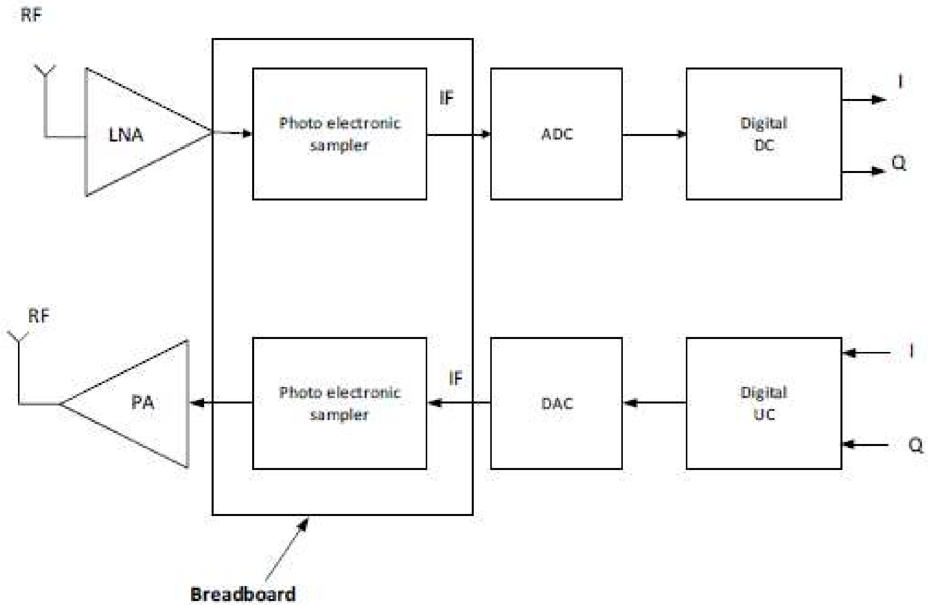
Introduction

Objectives:

- To deliver a photonic sampler able to work in both Receiver and Transmitter configurations for the sampling of Ka-band signals (Elegant Bread Board -TRL5)
- To validate its performance against tender requirements





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State-of-the-Art review of necessary technologies

Photonic clock

- Passive mode locked lasers (MLL) have been investigated as optical pulse train sources for their ability to generate much shorter pulses than their active counterparts.
  - very clean and low jitter optical pulses with a very simple configuration

Proposal: Passively MLL stabilized with and electro-optical phase-locked loop (PLL) to meet phase noise requirements

- In DAS Photonics multiple passive MLLs have been fabricated and characterized at frequencies up to 3.2 GHz with output power higher of 0dBm in the 1550 nm optical band.

State-of-the-Art review of necessary technologies

Electro-optical modulator

- There are two main technologies commercially used for the electro-optical amplitude modulation at high frequencies which are the electro-absorption modulators and the Mach-Zehnder modulators.

Proposal: Mach-Zehnder modulators,

- can manage higher power levels,
- does not consume current in the modulation process
- does not dissipate heat
- lower optical non-linearity of the material

State-of-the-Art review of necessary technologies

High-power photodiodes for RF photonic applications

Devices optimized for generating maximal RF output power and do not focus on improving the linearity nor reduce the level of spurs and harmonics. State-of-the-art reported in [1].

Highly Linear Photodiodes based on InP technology with spot size converter, MMI coupler, high-power photodiodes and electrical multiplexer [1].

[1] P. Runge et al., "Linearity of Waveguide Integrated Modified Uni-Travelling Carrier Photodiode Arrays," in IEEE Photonics Technology Letters, vol. 31, no. 3, pp. 246-249, 1 Feb.1, 2019, doi: 10.1109/LPT.2018.2890015.

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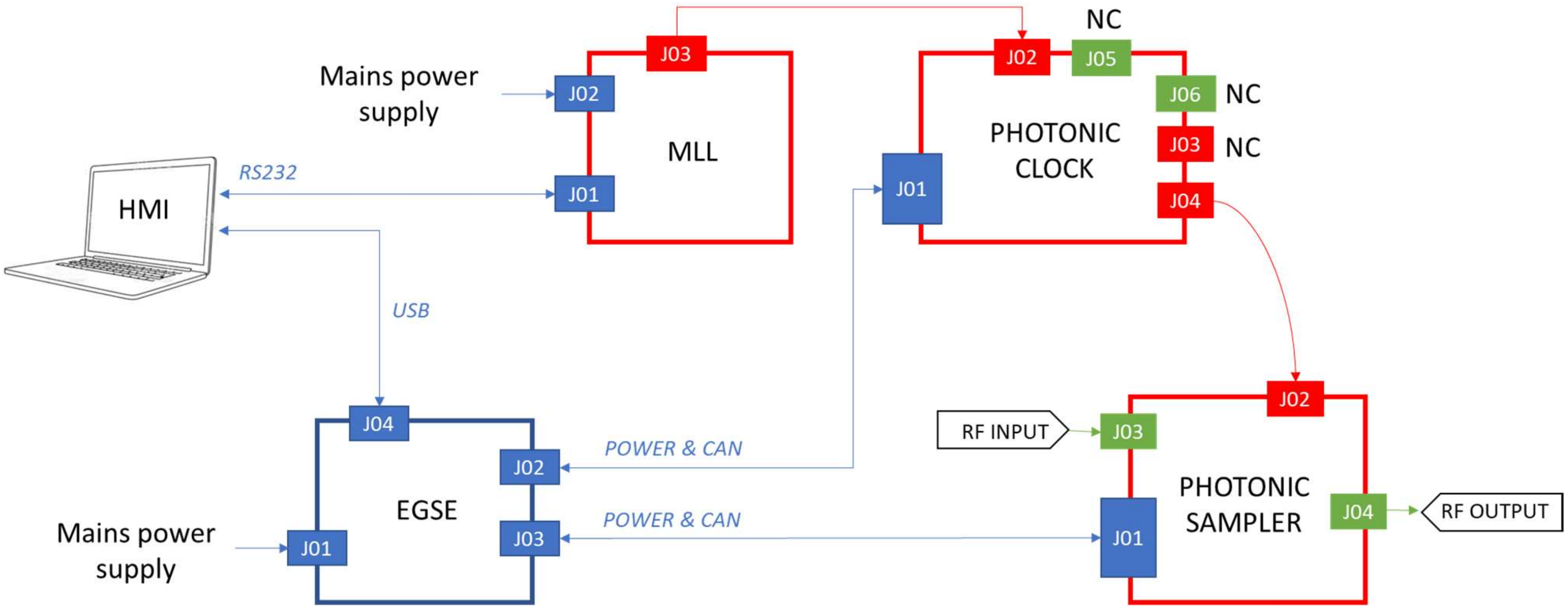
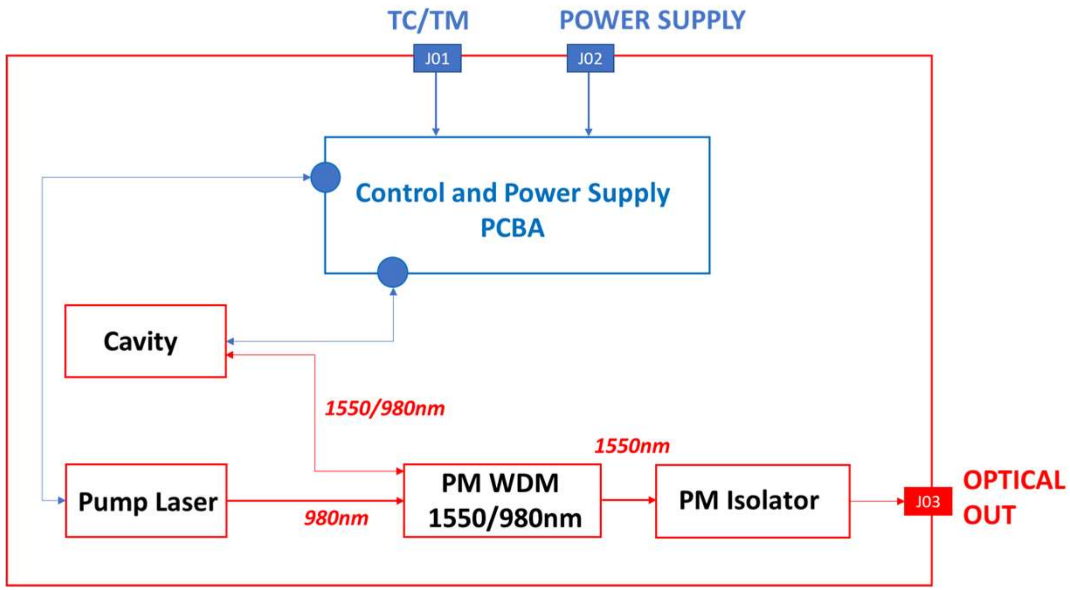
Electro-Photonic Transceiver Breadboard Architecture



RF INPUT: X/Ka band
RF OUTPUT: X/Ka band
J05 and J06 PHOTONIC CLOCK: RF clock outputs at 1.25 GHz

MLL unit – Design and manufacturing

- MLL module with MLL, power&control electronics, Firmware, mechanical interface
- MLL cavity: Optical parts, TEC and mechanical interface

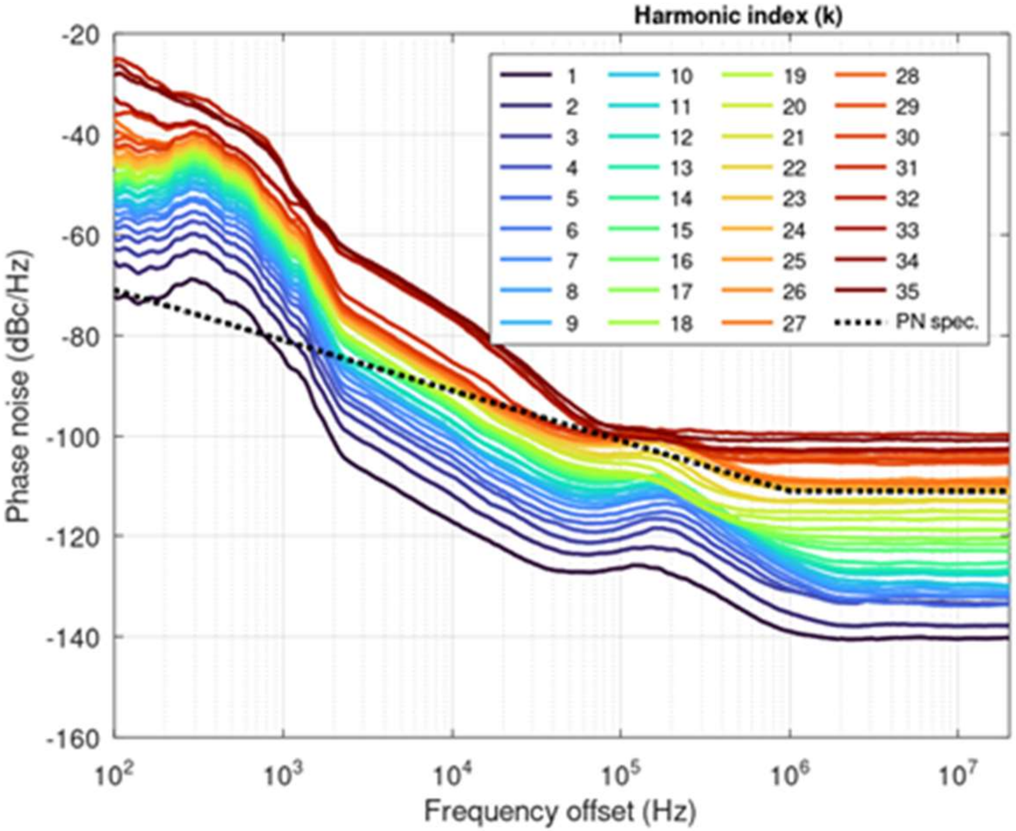


MLL unit - Review of achieved performance

ID	Parameters	Value	Units	Verification (I, R, A, T)	SoC	Comments
MLL01	Optical spectrum	1525-1565	nm	T	C	1564.18 nm [Figure 3-4]
MLL02	Pulse Repetition Frequency (Fs)	1.25	GHz	T	C	1.25724 GHz [Figure 3-4]
MLL03	Phase Noise (Deep Space) breadboard	-51-10log(f) 1Hz<f<1MHz -111 dBc/Hz f>1MHz	dBc/Hz	T	PC	Depending on number of harmonic and Frequency offset [Figure 3-11]
MLL04	Average optical output power	-5 to 8	dBm	T	C	-4.6 dBm
MLL05	Fs stability	TBD	kHz	T	NA	47.4 kHz @ 12h [Figure 3-12]
MLL06	TM/TC interface (J01)	9-pin RS-232 (f)		R	C	
MLL07	Power supply connector (J02)	IEC C14(m)		R	C	
MLL08	Optical output interface (J03)	1550nm PM fibre with FC/APC connector		R	C	

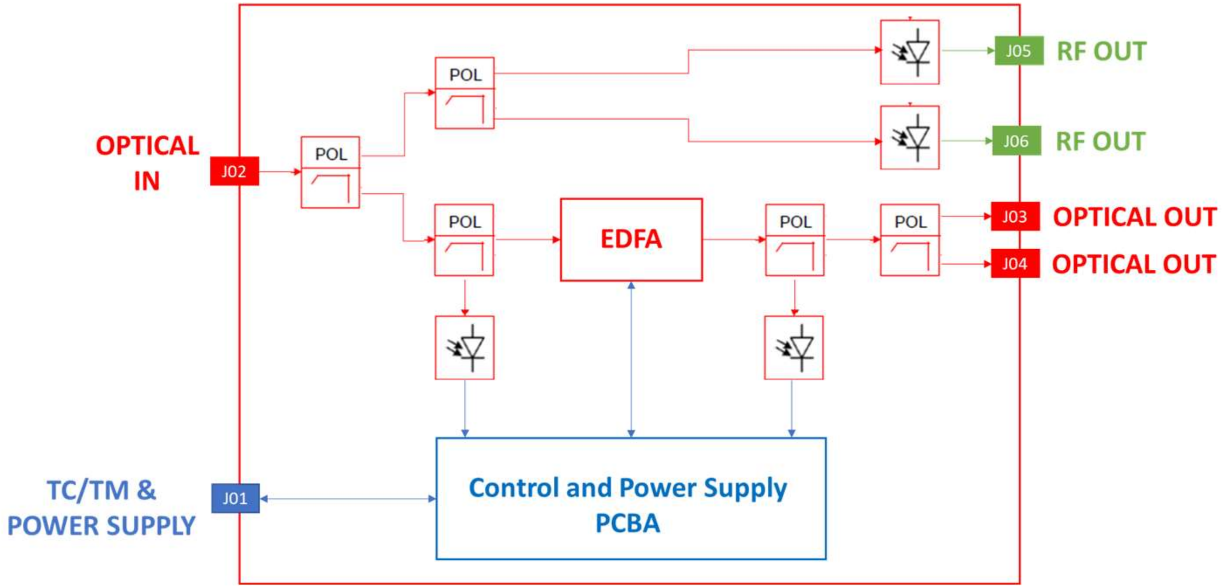
Note: Referenced Figures available in Deliverable D5

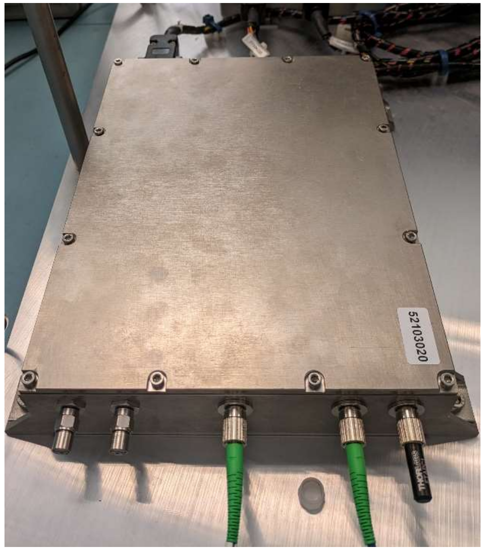
MLL unit - Phase noise of the cavity



Photonic Clock unit – Design and manufacturing

- Ready for future integration of MLL with piezo and external PLL
- Photonic parts: Erbium-Doped Fiber Amplifier (EDFA), tap monitors, splitters, RF Photodiodes
- Power&control electronics, Firmware, mechanical interface





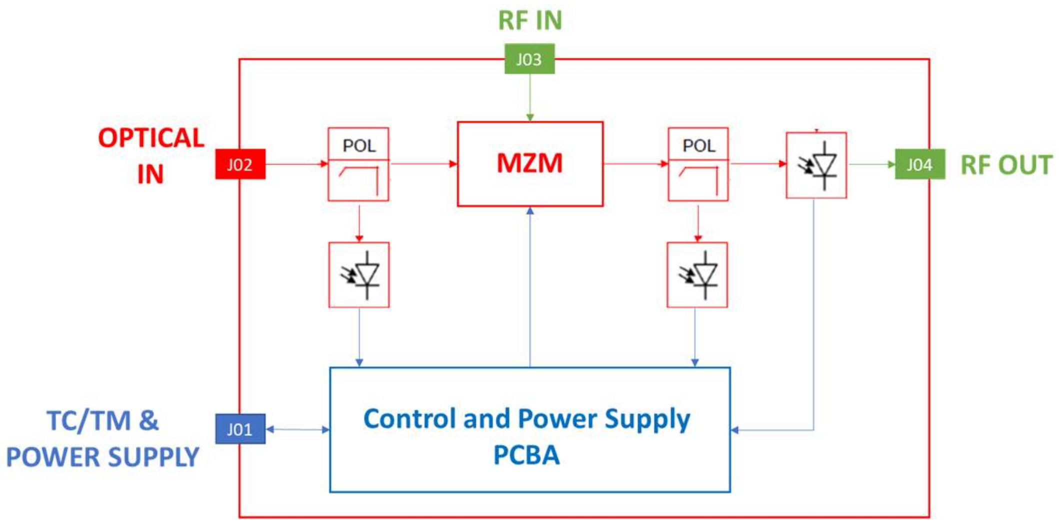
Photonic Clock unit - Review of achieved performance

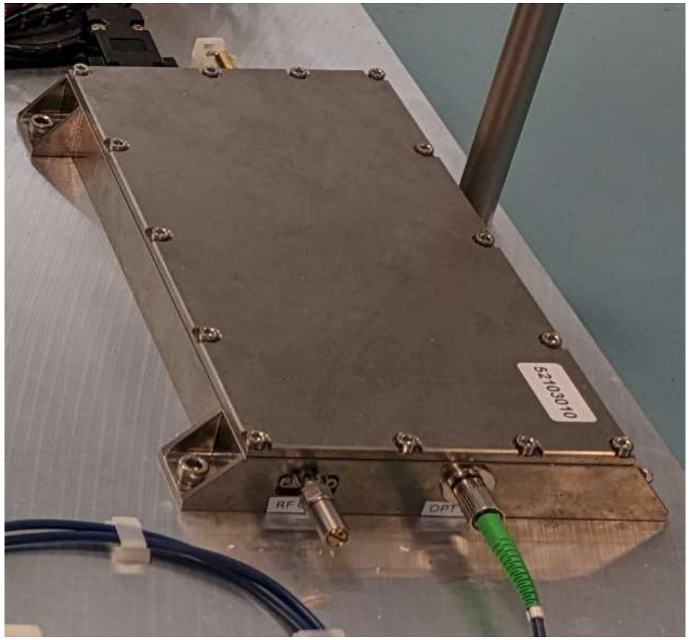
ID	Parameters	Value	Units	Verification (I, R, A, T)	SoC	Comments
PC01	Average optical input power	TBD	dBm	T	NA	-5 to 8 dBm
PC02	Average optical output power	TBD	dBm	T	NA	13.7-17.1 dBm
PC03	Gain	TBD	dB	T	NA	18.7-9.1 dB
PC04	Noise Figure	TBD	dB	T	NA	< 8 dB
PC05	DC power	6/+15/-15	V	R	C	
PC06	TM/TC	CAN bus		R	C	
PC07	Power supply & TM/TC connector (J01)	SubHD-15 (P)		R	C	
PC08	Piezo control input connector (J02)	SubD-9 (P)		R	C	
PC09	Optical input connector from MLL unit (J03)	FC/APC		R	C	
PC10	Optical output interface (J04)	1550nm PM fibre with FC/APC connector		R	C	
PC11	Optical output interface (J05)	1550nm PM fibre with FC/APC connector		R	C	
PC12	RF output connector to PLL (J06)	SMA (f)		T	C	[Figure 4-17]
PC13	RF output connector to ADC/DAC (J07)	SMA (f)		T	C	[Figure 4-17]
PC14	Size	238 x 205 x 45	mm	R	C	
PC15	Mass	1.8	kg	T	NA	Not tested
PC16	Power Consumption	8.1	W	T	C	6.3 W

Note: Referenced Figures available in Deliverable D5

Photonic Sampler unit – Design and manufacturing

- Photonic parts: 40GHz Mach-Zehnder Modulator, 50 GHz Photodetector, tap monitors
- Power&control electronics, Firmware, mechanical interface



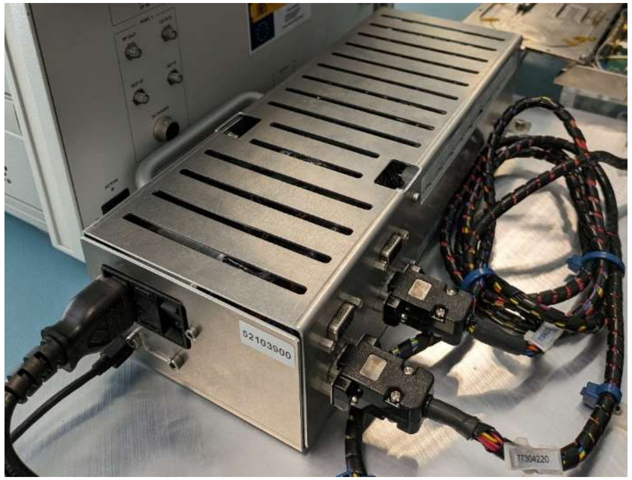


Photonic Sampler unit - Review of achieved performance

ID	Parameters	Value	Units	Verification (I, R, A, T)	SoC	Comments
PS01	Input bandwidth	40	GHz	R	C	
PS02	Output bandwidth	50	GHz	R	C	
PS03	DC power	+6/+15/-15	V	R	C	
PS04	TM/TC	CAN bus		R	C	
PS05	Power supply & TM/TC connector (J01)	SubHD-15 (P)		R	C	
PS06	Optical input interface (J02)	1550nm PM fibre with FC/APC connector		R	C	
PS07	RF input connector (J03)	K (f)		R	C	
PS08	RF output connector (J04)	V (f)		R	C	
PS09	Size	211 x 136 x 25	mm	R	C	
PS10	Mass	700	g	T	NA	Not tested
PS11	Power Consumption	0.9	W	T	C	0.45 W

EGSE - Design

- EGSE to power supply and control the PhClock and PhSampler units
  - Controller: Custom PCB and firmware
  - Power Supply Unit: Custom Power Distribution PCB, AC/DC Converter, AC switch with filter, cabling
  - Cabling
  - Mechanical interface



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Frequency plan and Sampling Frequency

- At Fs of 1.25 GHz, aliasing in the upper frequencies of the Ka band:

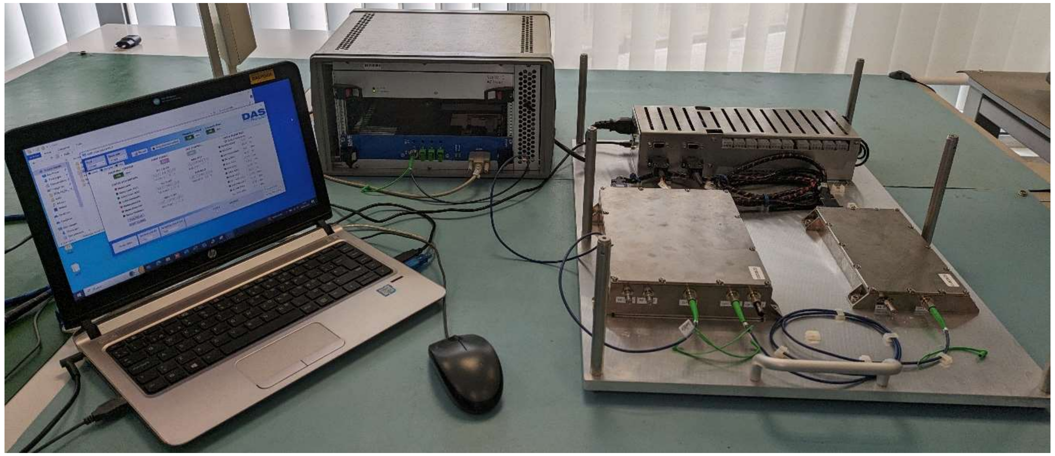
		MLL	1,25718					Nyquist							
Mission 1		fmin	fmax	BW	CLK=fs	Margin BW	N	Fmin	Margin Fmin	Fmax	Margin Fmax	Inverted	IF min	IF max	IF BW	MLL harmonic
ADC	X.DL	8,400	8,500	0,100	1,257	0,529	13	8,172	0,228	8,800	0,300	Yes	0,228	0,328	0,100	7
DAC	X-UL	7,145	7,195	0,050	1,257	0,579	11	6,914	0,231	7,543	0,348	Yes	0,231	0,281	0,050	6
ADC	Ka-DL	31,700	32,300	0,600	1,257	0,029	50	31,430	0,271	32,058	-0,242	No	0,271	0,870	0,600	25
DAC	Ka-UL	34,200	34,800	0,600	1,257	0,029	54	33,944	0,256	34,572	-0,228	No	0,256	0,856	0,600	27

- At Fs of 1.25 GHz, two different Nyquist Windows to cover the Ka band w/o aliasing:

		MLL	1,25718					Nyquist							
Mission 1		fmin	fmax	BW	CLK=fs	Margin BW	N	Fmin	Margin Fmin	Fmax	Margin Fmax	Inverted	IF min	IF max	IF BW	MLL harmonic
ADC	X.DL	8,400	8,500	0,100	1,257	0,529	13	8,172	0,228	8,800	0,300	Yes	0,300	0,400	0,100	7
DAC	X-UL	7,145	7,195	0,050	1,257	0,579	11	6,914	0,231	7,543	0,348	Yes	0,348	0,398	0,050	6
ADC	Ka-DL	31,700	32,058	0,358	1,257	0,271	50	31,430	0,271	32,058	0,000	No	0,271	0,629	0,358	25
DAC	Ka-UL	34,200	34,572	0,372	1,257	0,257	54	33,944	0,256	34,572	0,000	No	0,256	0,629	0,372	27
ADC	Ka-DL	32,058	32,300	0,242	1,257	0,387	51	32,058	0,000	32,687	0,387	Yes	0,387	0,629	0,242	26
DAC	Ka-UL	34,572	34,800	0,228	1,257	0,401	55	34,572	0,000	35,201	0,401	Yes	0,401	0,629	0,228	28

Integration and Test set-up

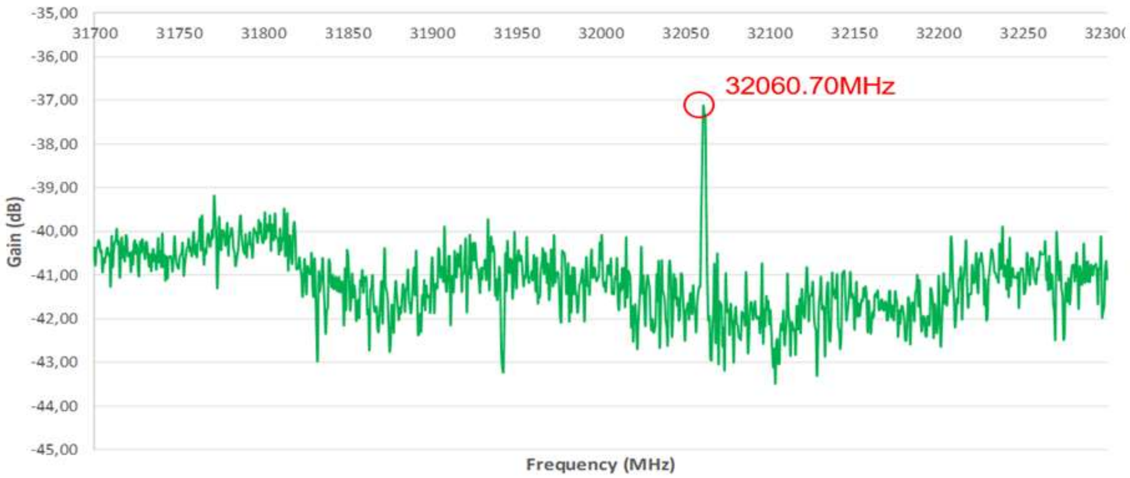
- EGSE, PhClock unit, PhSampler unit on a base plate; MLL unit on a separated rack; Human Machine Interface
- External and unit interconnection cabling

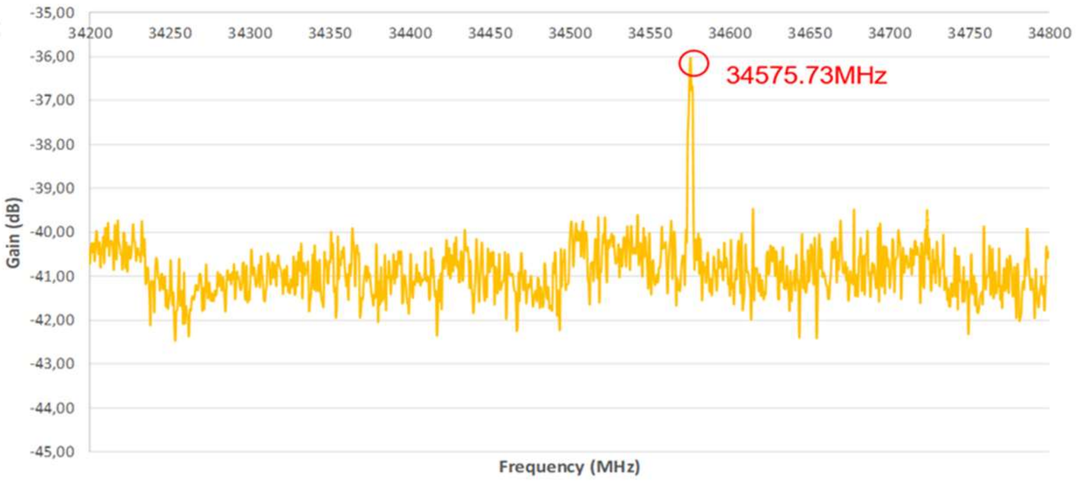


- Test performed according to the Test plan developed in the Project [Deliverable D4]

[ESPEC/GS01] Frequency bands

- Verified broadband operation from DC to 34800 MHz at the same input and output frequency
- Test with down and up conversion performed in [ESPEC/GS02] and [ESPEC/GS07]
- Verified frequency at which the Nyquist window changes in Ka band

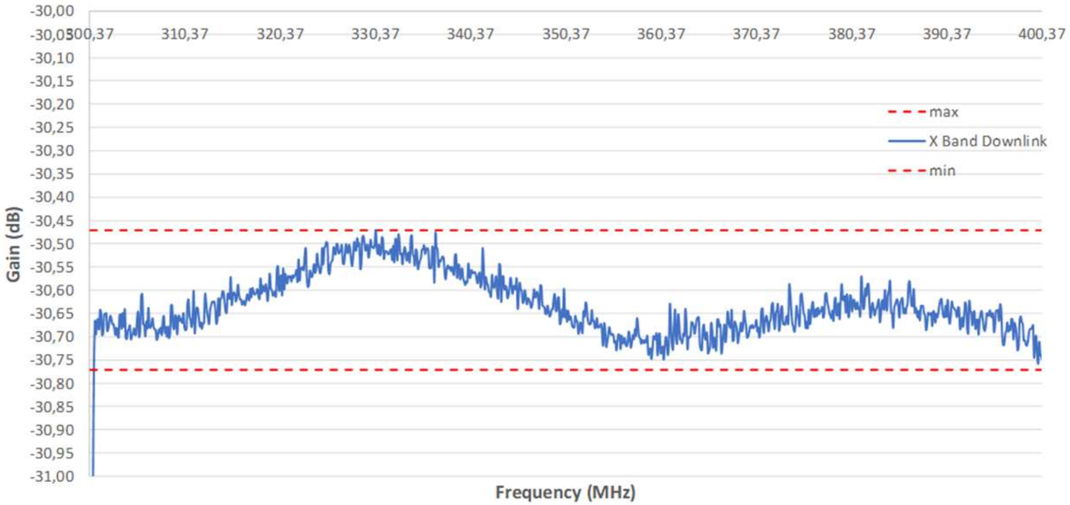




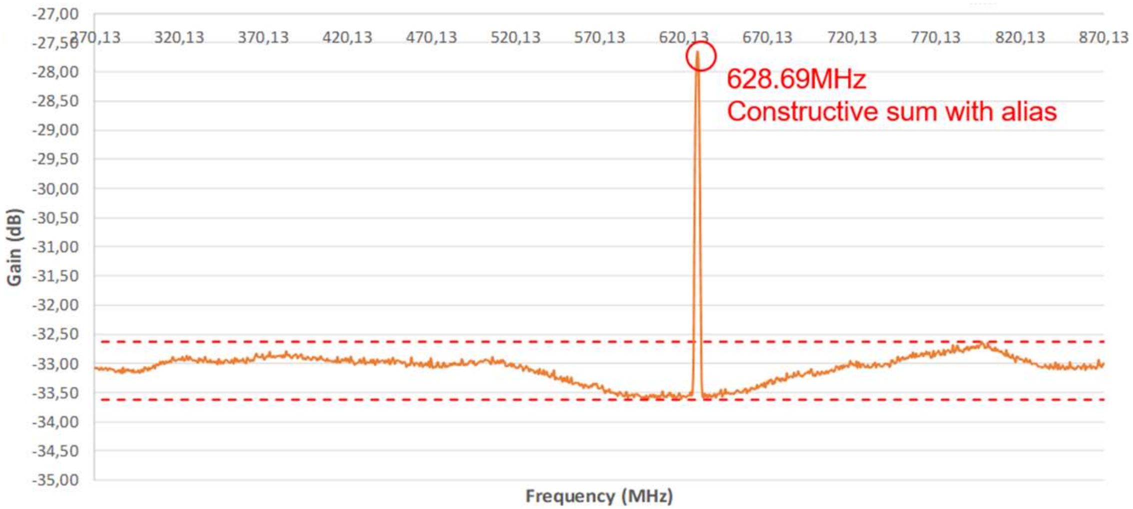
[ESPEC/GS02] IF Frequency, [ESPEC/GS03] IF Bandwidth (Receiver)

- X band: IF output 300.4-400.4MHz, 0.3dB gain flatness
- Ka band: IF output 270.1-628.7MHz (RF input 31700-32060.7MHz) w/o aliasing, 0.8dB gain flatness

X band RF input 8400-8500MHz
(Inverted Nyquist window)

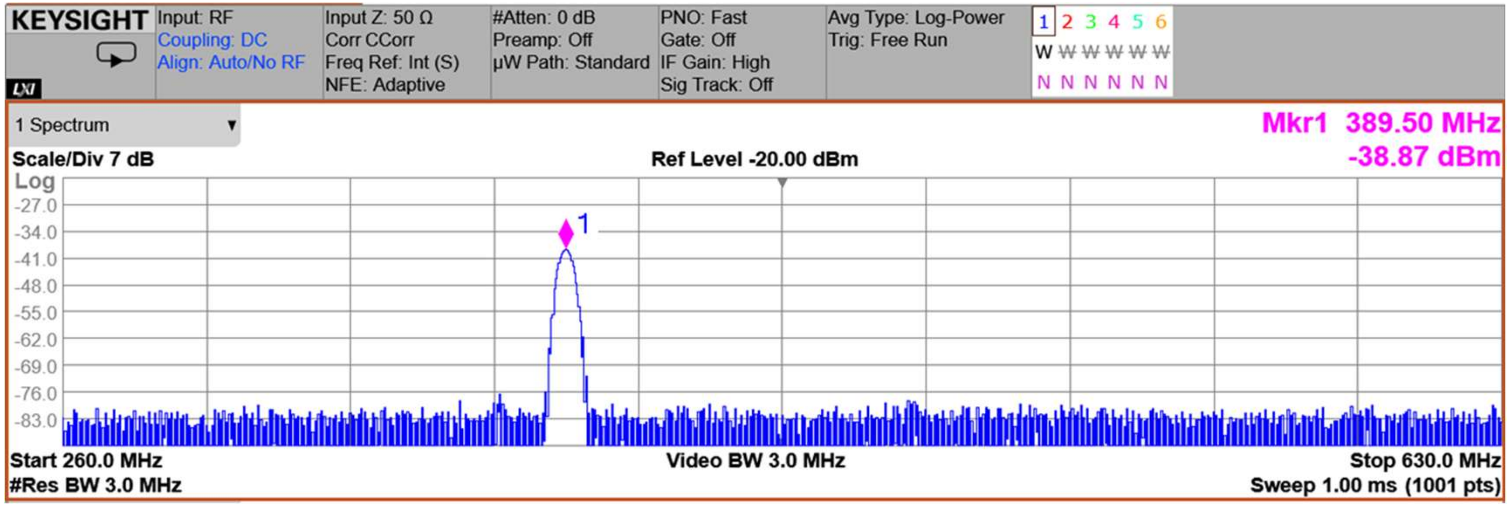


Ka band RF input 31700-32300MHz



[ESPEC/GS02] IF Frequency, [ESPEC/GS03] IF Bandwidth (Receiver)

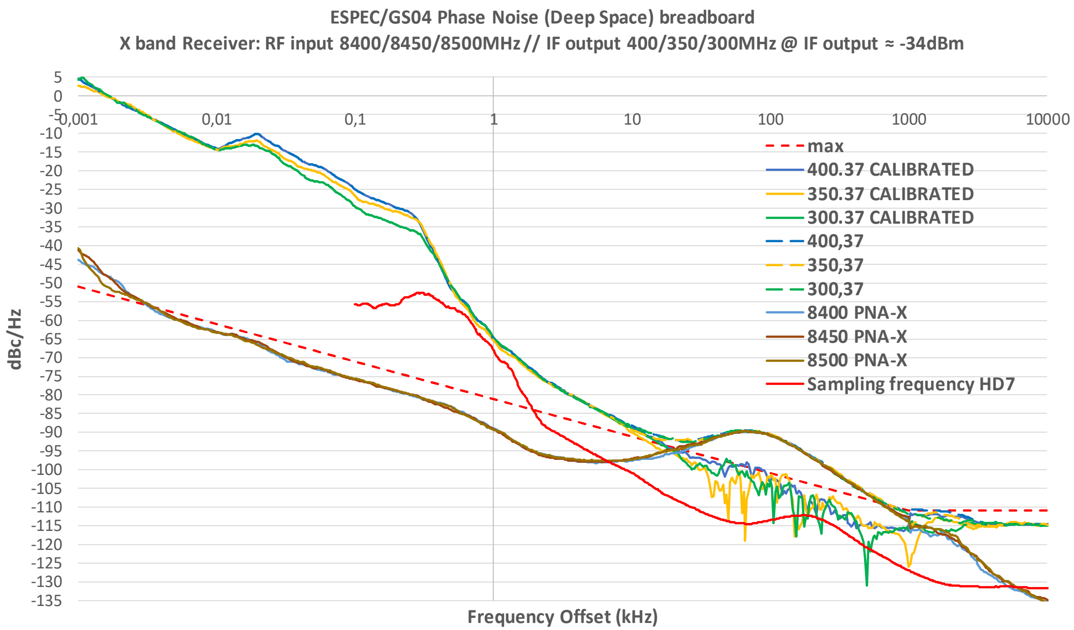
- The Ka band can be sampled without aliasing when two different Nyquist windows are employed. The IF frequency is 389.5-628.7MHz (RF input 32060.7-32300MHz).



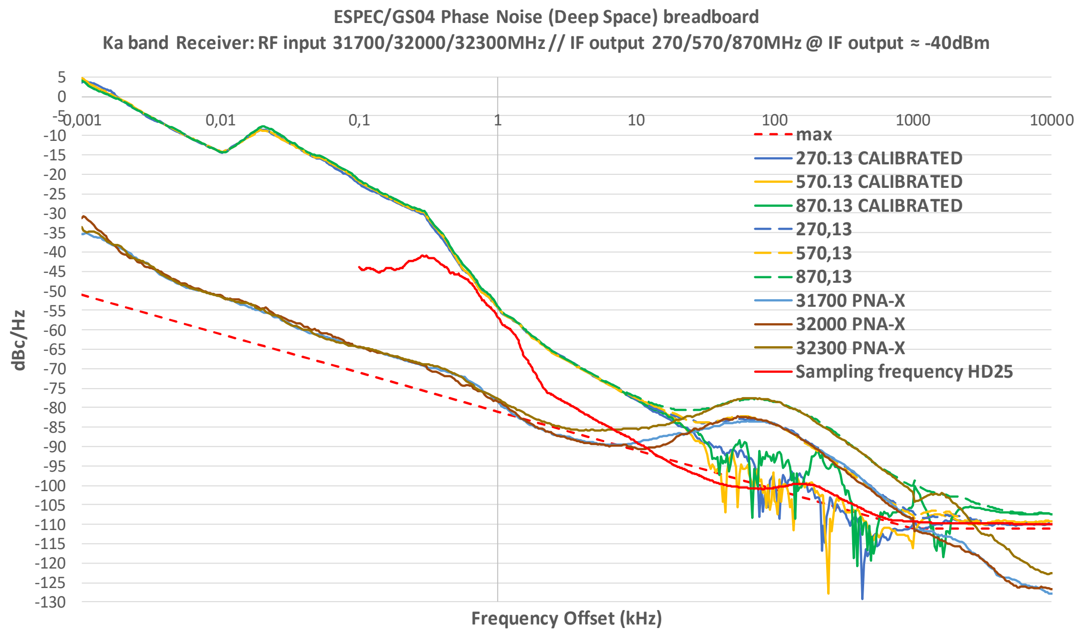
Ka band (Second Nyquist window, inverted) RF input 32300MHz

[ESPEC/GS04] Phase noise of the down converted Carrier (Receiver)

X band



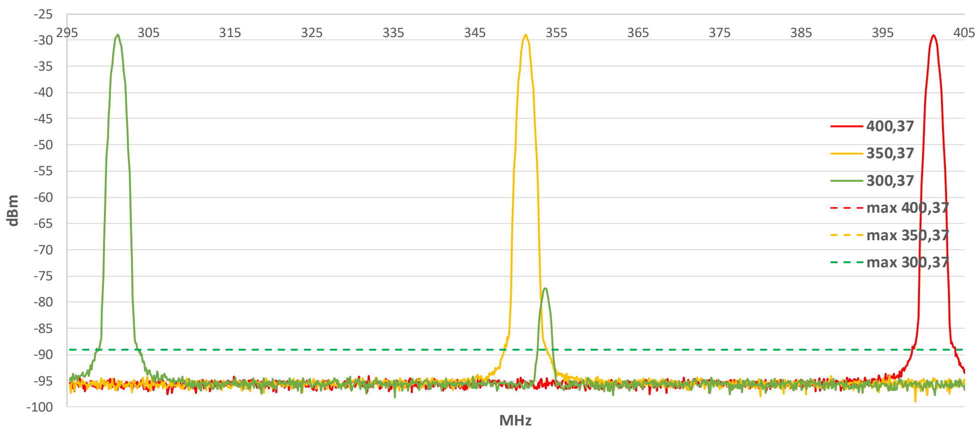
Ka band



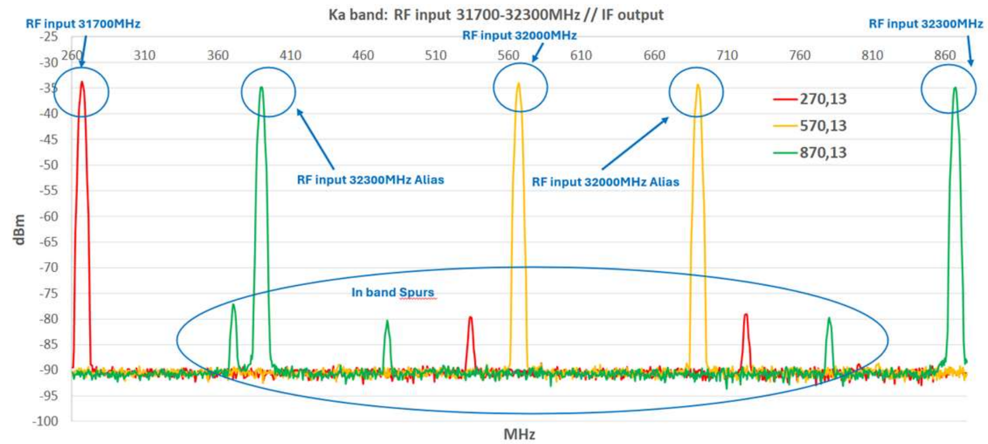
- Phase noise at low frequency offset expected to be improved when the MLL is locked to an external reference. PLL not implemented within the KaBS timeframe.

[ESPEC/GS05] Signal related In band spurious rejection @IP1dB-10 dB (Receiver)

X band RF input 8400/8450/8500MHz
(Inverted)



Ka band RF input 31700/32000/32300MHz



48.4 dBc at 8500 MHz / 300.4 MHz
IMD3 → RF in 8500MHz x3 = 25500MHz → IF out = 356MHz

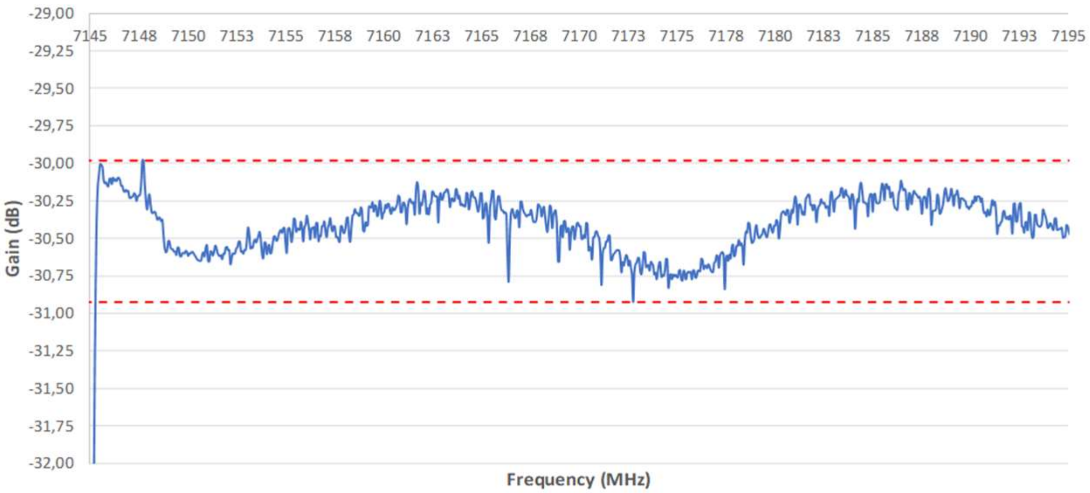
45.5 dBc at 31700 MHz / 270.1 MHz
IMD2 → RF in 31700MHz x2 = 63400MHz → IF out = 540MHz

- 32300MHz & 870.13MHz out aliasing free frequency range (31700-32058 MHz and 271-629 MHz). The alias is due to sub optimal sampling rate (it should be 2.6 GHz instead of 1.3 GHz to cover the whole Ka band 31700-32300 MHz and 271-870 MHz with the same Nyquist window).
- In-band spurious level can be reduced by reducing the RF input power
- All out of band spurious will be removed by band pass filtering (not deliverable of the project)

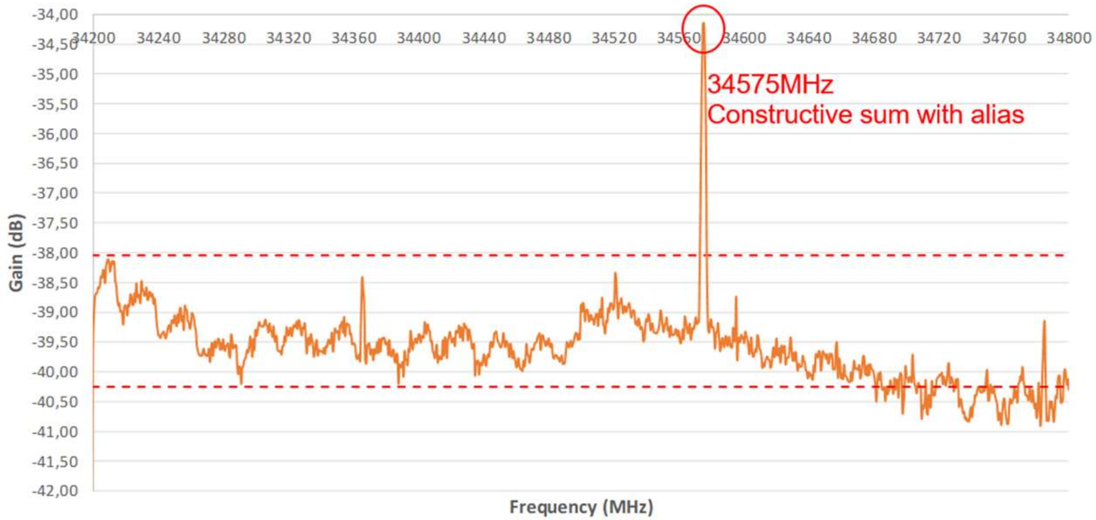
[ESPEC/GS07] IF Frequency, [ESPEC/GS08] IF Bandwidth (Transmitter)

- X band: RF output 7145-7195MHz, 0.9dB gain flatness
- Ka band: RF output 34200-34575.7MHz (IF input 255.7-628.7MHz) w/o aliasing, 2.2dB gain flatness

X band IF input 348.2-398.2MHz
(Inverted Nyquist window)

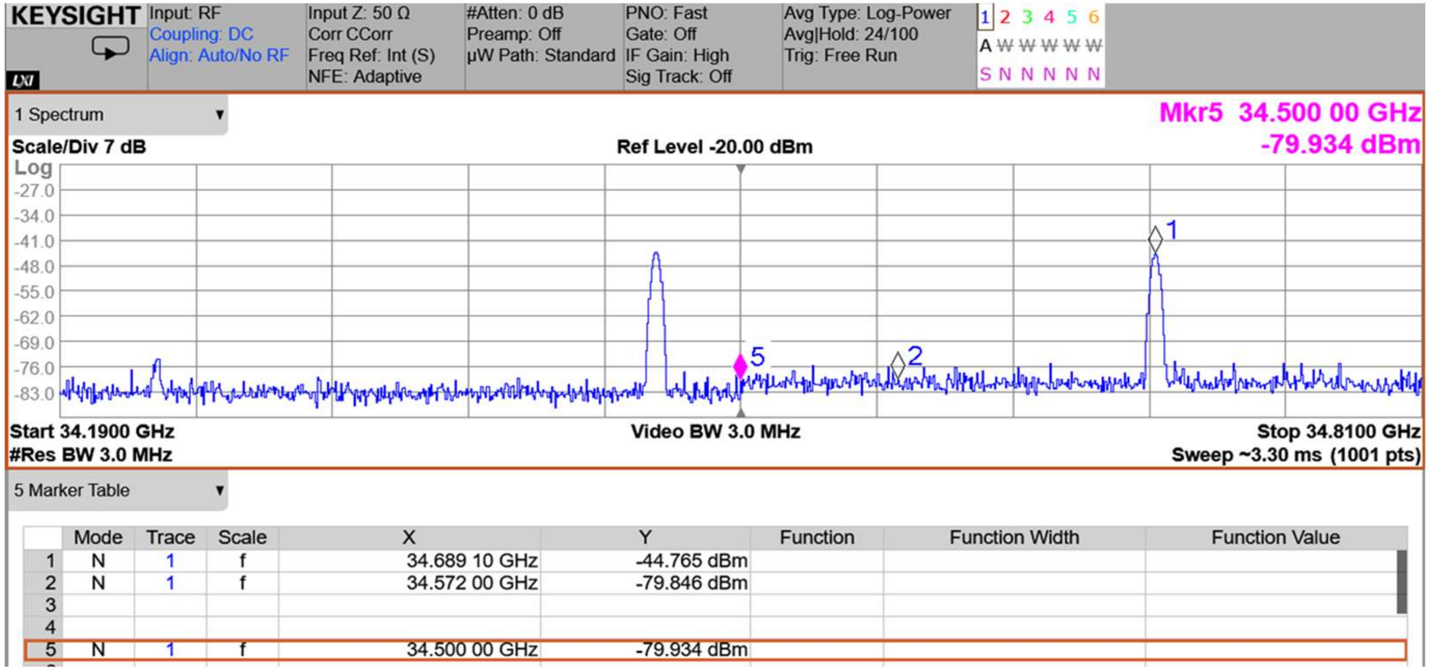


Ka band IF input 255.7-855.7MHz



[ESPEC/GS07] IF Frequency, ESPEC/GS08 IF Bandwidth (Transmitter)

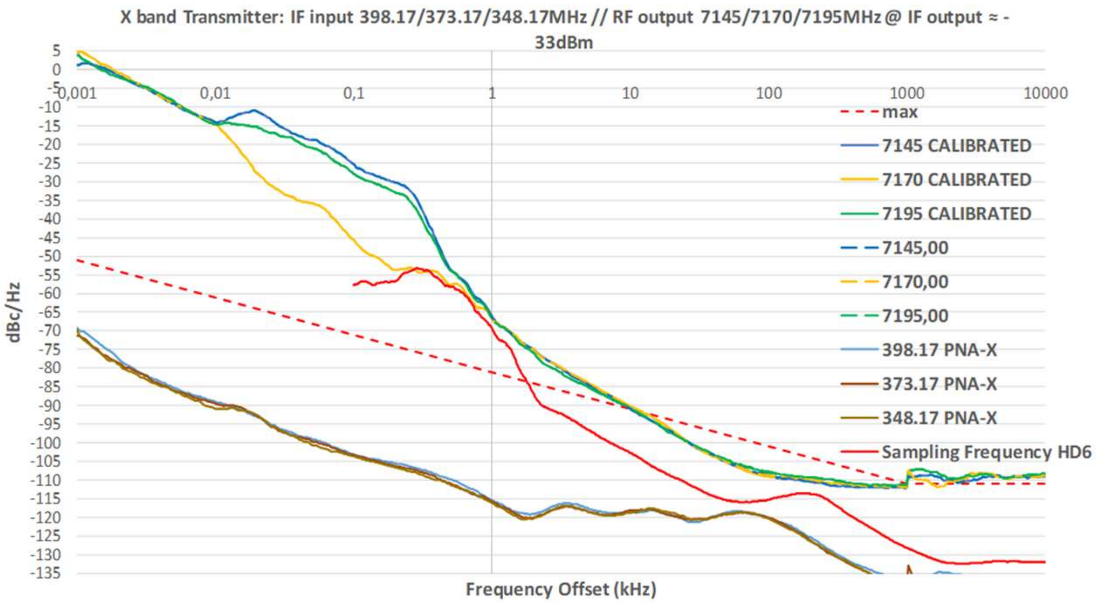
- The Ka band can be sampled without aliasing when two different Nyquist windows are employed. The RF frequency is 34575.7-34800MHz (IF input 401-628.7MHz).



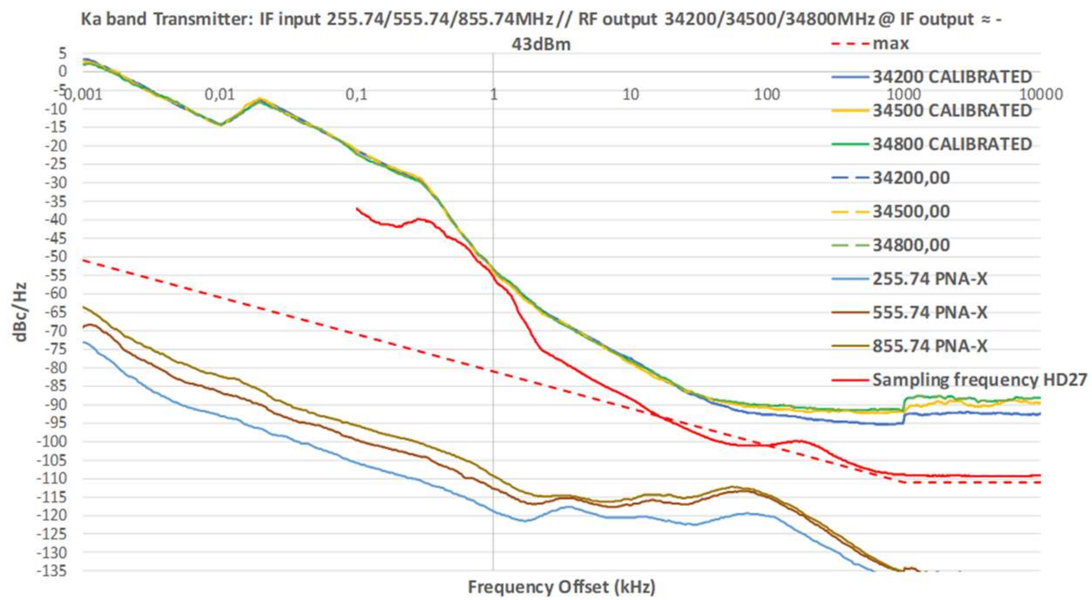
Ka band (Second Nyquist window, inverted) IF input 515MHz

[ESPEC/GS09] Phase noise of the up converted Carrier (Transmitter)

X band



Ka band

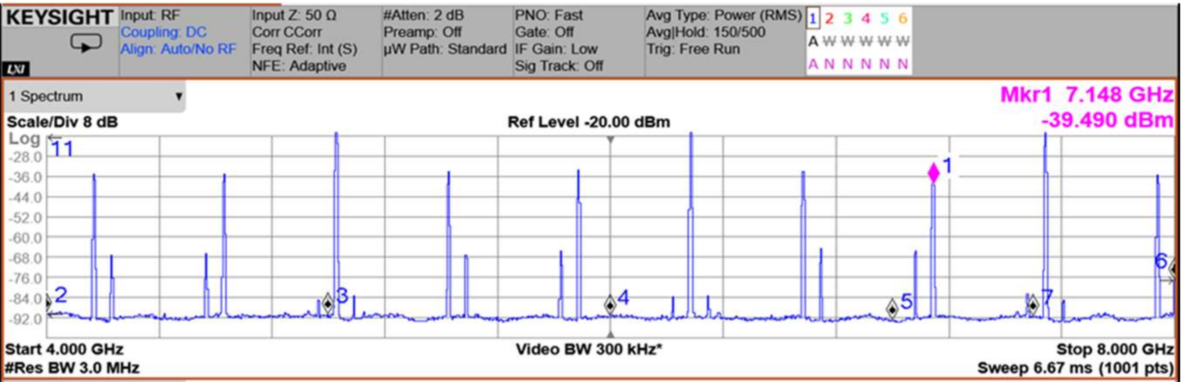


- Phase noise at low frequency offset expected to be improved when the MLL is locked to an external reference. PLL not implemented within the KaBS timeframe.

[ESPEC/GS10] Out of band output noise floor (Transmitter)

- Out of band noise floor will be improved with out of band filtering (not deliverable of KaBS).
- In-band noise floor measured at 0 dBm RF input power

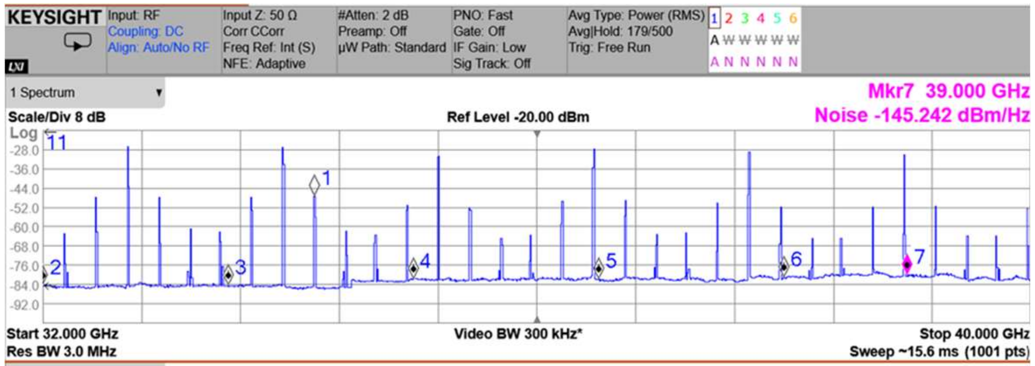
X band (IF 398.17MHz, RF 7145MHz)



5 Marker Table

	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	7.148 GHz	-39.490 dBm			
2	N	1	f	4.000 GHz	-90.726 dBm	Noise	1 Hz	-155.726 dBm/Hz
3	N	1	f	5.000 GHz	-90.884 dBm	Noise	1 Hz	-155.884 dBm/Hz
4	N	1	f	6.000 GHz	-91.687 dBm	Noise	1 Hz	-156.687 dBm/Hz
5	N	1	f	7.000 GHz	-93.333 dBm	Noise	1 Hz	-158.333 dBm/Hz

Ka band (IF 255.74MHz, RF 34200MHz)



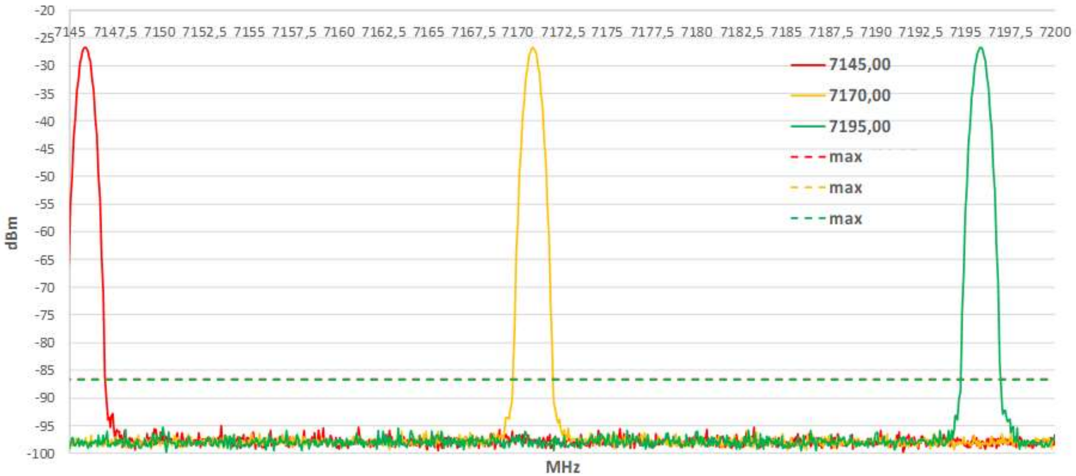
5 Marker Table

	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	34.200 GHz	-47.543 dBm			
2	N	1	f	32.000 GHz	-84.621 dBm	Noise	1 Hz	-149.621 dBm/Hz
3	N	1	f	33.500 GHz	-85.004 dBm	Noise	1 Hz	-149.630 dBm/Hz
4	N	1	f	35.000 GHz	-81.759 dBm	Noise	1 Hz	-146.758 dBm/Hz
5	N	1	f	36.500 GHz	-81.815 dBm	Noise	1 Hz	-146.809 dBm/Hz
6	N	1	f	38.000 GHz	-81.391 dBm	Noise	1 Hz	-146.391 dBm/Hz

- The signal independent noise floor is <-150 dBm/Hz depending on Resolution Bandwidth of the analyzer
- X band 7145-7195MHz: signal related noise floor is from -117.2 to -121.2 dBc/Hz
- Ka band 34200-34500MHz: signal related noise floor is from -99.3 to -99.6 dBc/Hz

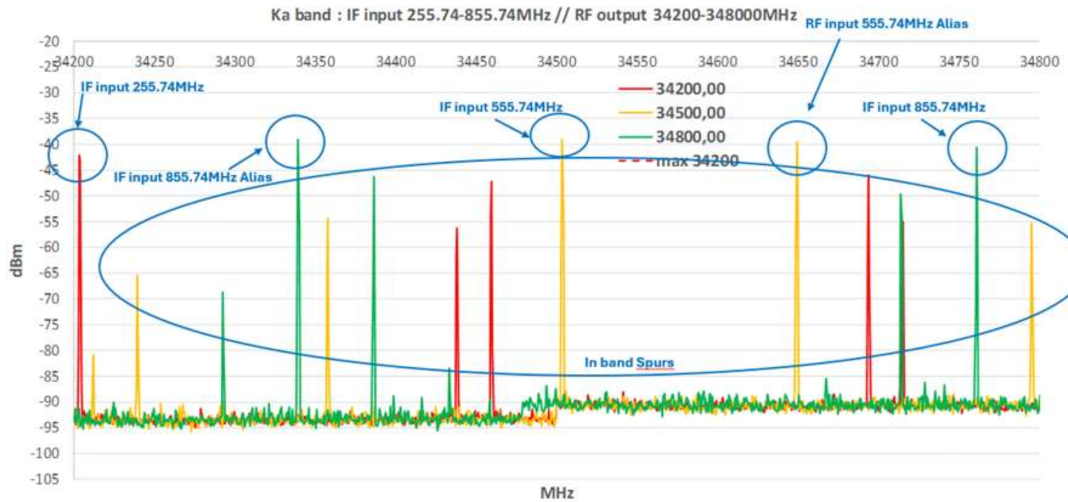
[ESPEC/GS11] Signal related In band spurious rejection @IP1dB-10 dB (Transmitter)

X band IF input 348.2/373.2/398.2MHz (Inverted)



No in-band spurious

Ka band IF input 255.7/555.7/855.7MHz

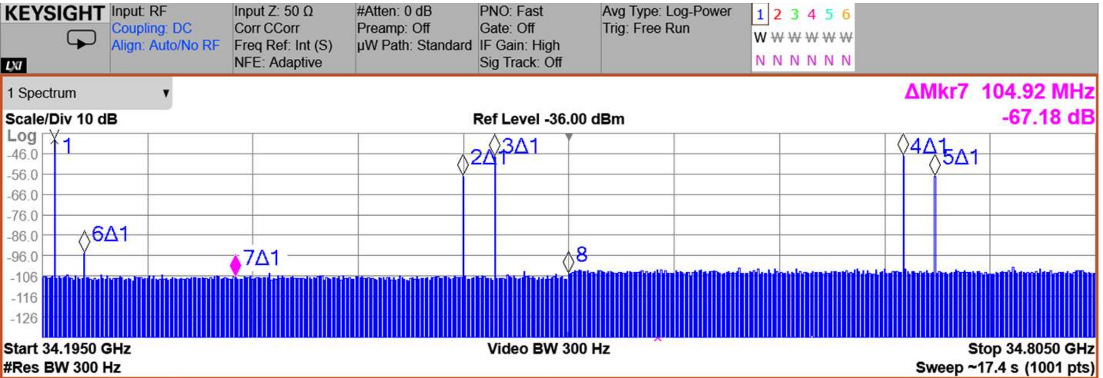


IF 255.7MHz, RF 34200MHz:
IMD2 → IF in 255.74MHz x2 = 511.48MHz → RF out = 34455.79MHz
IMD3 → IF in 255.74MHz x3 = 767.22MHz → RF out = 34434MHz

- 855.74MHz & 34800MHz & out aliasing free frequency range (256-629 MHz and 34200-34572MHz). The alias is due to sub optimal sampling rate (it should be 2.6 GHz instead of 1.3 GHz to cover the whole Ka band 256-856 MHz and 34200-34800 MHz with the same Nyquist window).
- All out of band spurious will be removed by band pass filtering (not deliverable of the project)

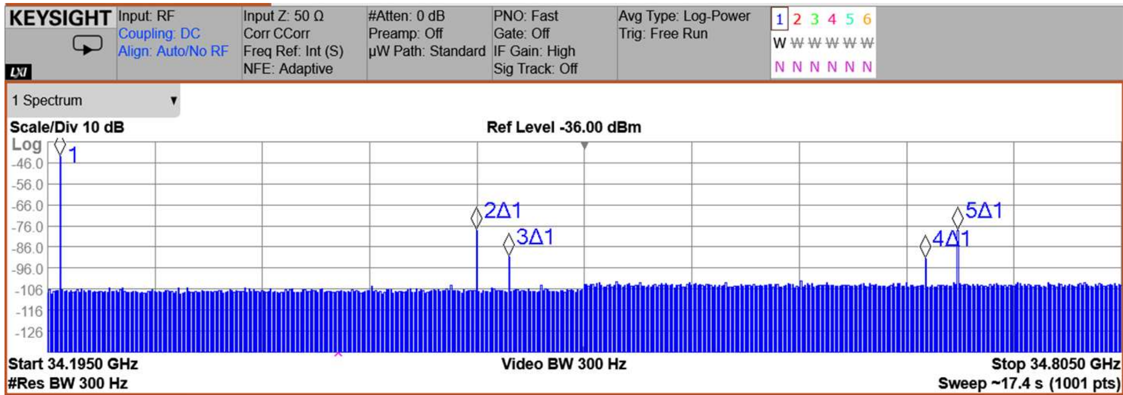
[ESPEC/GS12] Signal independent spurious level @IP1dB-15 dB (Transmitter)

- Ka band: In-band spurious level can be reduced by reducing the optical input power



	Mode	Trace	Scale		X	Y	Function	Function Width	Function Value
1	N	1	f		34.202 32 GHz	-39.42 dBm			
2	Δ1	1	f	(Δ)	236.68 MHz (Δ)	-18.06 dB			
3	Δ1	1	f	(Δ)	254.98 MHz (Δ)	-8.34 dB			
4	Δ1	1	f	(Δ)	491.66 MHz (Δ)	-8.05 dB			
5	Δ1	1	f	(Δ)	509.96 MHz (Δ)	-17.76 dB			
6	Δ1	1	f	(Δ)	17.08 MHz (Δ)	-55.70 dB			

Ka band IF input 255MHz, 7 dBm RF, 14.3 dBm optical



	Mode	Trace	Scale		X	Y	Function	Function Width	Function Value
1	N	1	f		34.202 32 GHz	-43.29 dBm			
2	Δ1	1	f	(Δ)	236.68 MHz (Δ)	-34.95 dB			
3	Δ1	1	f	(Δ)	254.98 MHz (Δ)	-47.59 dB			
4	Δ1	1	f	(Δ)	491.66 MHz (Δ)	-48.43 dB			
5	Δ1	1	f	(Δ)	509.96 MHz (Δ)	-35.14 dB			

Ka band IF input 255MHz, 7 dBm RF, 7.4 dBm optical

AGENDA

1. Introduction & Technology review
2. Breadboard implementation
3. Breadboard Test results
4. Review of achieved performance
5. Conclusions and Recommendations

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Review of achieved performance

- Frequency bands

ID	System Parameters	Value	Units	SoC	Comments
ESPEC/GS01	The design of the demonstrator shall have an input bandwidth sufficient to cover all the frequency ranges.	Band X: Service type SRS,DS. Downlink frequency 8400 – 8500 MHz Uplink frequency 7145 – 7195 MHz Band Ka: Service type SRS, DS. Downlink Frequency 31700-32300 MHz Uplink Frequency 34200-34800 MHz	MHz	C	Input bandwidth >34800 MHz Values measured at Fs = 1.25718 GHz 8400 - 8500 MHz 7145 - 7195 MHz 31700-32060.7 MHz and 32060.7-32300 MHz 34200-34575.7 MHz and 34575.7-34800 MHz

Review of achieved performance

- Receiver (Photonic ADC at Downlink Frequency)

ID	System Parameters	Value	Units	SoC	Comments
ESPEC/GS02	IF Frequency	Values calculated at Fs = 2.6 GHz: 300 - 400 (X band) 271 - 870 (Ka band)	MHz	PC	Values measured at Fs = 1.25718 GHz: 300.4-400.4 MHz (X band) 270.1-628.7 MHz and 387-629 MHz (Ka band)
ESPEC/GS03	IF Frequency BW (0.1 dB bandwidth)	Values calculated at Fs = 2.6 GHz: 100 (X band) 600 (Ka band)	MHz	PC	Values measured at Fs = 1.25718 GHz: 100 MHz at 0.3 dB (X band) 358.6 MHz at 0.8 dB and 242 MHz at TBC dB (Ka band)
ESPEC/GS04	Phase Noise (Deep Space) breadboard	-51-10log(f) 1Hz<f<1MHz -111 dBc/Hz f>1MHz	dBc/Hz	PC	X band: NC at Freq. offset< 10 kHz C at Freq. offset >10 kHz Ka band: NC
ESPEC/GS05	Signal related In band spurious rejection (Contribution of the breadboard)	60	dBc	PC	X band @2.3 dBm RF input power: C at 8400 and 8450 MHz NC at 8500 MHz Ka band @-1 dBm RF input power: NC at 31700 MHz C at 32000 MHz
ESPEC/GS06	Signal independent spurious level	<-90	dBm	PC	X band @-2.6 dBm RF input power: C In-band Ka band @-6 dBm RF input power: C In-band at 32000MHz, NC In-band at 31700MHz

Review of achieved performance

- Transmitter (Photonic DAC at Uplink Frequency)

ID	System Parameters	Value	Units	SoC	Comments
ESPEC/GS07	IF Frequency	Values calculated at Fs = 2.6 GHz: 231 - 281 (X band) 256 - 856 (Ka band)	MHz	PC	Values measured at Fs = 1.25718 GHz: 348.2-398.2 MHz (X band) 255.7-628.7 MHz and 401-629 MHz (Ka band)
ESPEC/GS08	Minimum BW (0.1 dB)	Values calculated at Fs = 2.6 GHz: 50 (X band) 600 (Ka band)	MHz	PC	Values measured at Fs = 1.25718 GHz: 50 MHz at 0.9 dB (X band) 375 MHz at 2.2 dB and 228 MHz at TBC dB (Ka band)
ESPEC/GS09	Phase Noise (Deep Space)	-51-10log(f) 1Hz<f<1MHz -111 dBc/Hz f>1MHz	dBc/Hz	PC	X band: NC at Freq. offset< 10 kHz C at Freq. offset >10 kHz Ka band: NC
ESPEC/GS10	Out of band output noise floor	< -150 dBm/Hz < -143 dBc/Hz (Both conditions)	dBm/Hz dBc/Hz	PC	@0 dBm RF input power < -150 dBm/Hz In-band X band: -121.2 to -117.2 dBc/Hz In-band Ka band: -99.3 to -99.6 dBc/Hz In-band
ESPEC/GS11	Signal related In-band spurious rejection	60	dBc	PC	@4.5 dBm RF input power X band: C Ka band: NC
ESPEC/GS12	Signal independent spurious level	<-90	dBm	PC	@0 dBm RF input power X band: C In-band Ka band: NC In-band

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Conclusions

- An electro-photonic transceiver architecture for Ground Station systems has been designed, manufactured and experimentally demonstrated.
- The feasibility of the system for down and up conversion up to the Ka band has been demonstrated based on photonic sampling with a mode-locked laser.
- For a Sampling frequency of 1.257 GHz,
  - Receiver: X band (RF input 8400-8500 MHz, IF output 300.4 400.4 MHz), Ka band (RF input 31700-32060.7 MHz and 32060.7-32300 MHz, IF output 270.1-628.7 MHz and 387-629 MHz)
  - Transmitter: X band (IF input 348.2-398.2 MHz, RF output 7145-7195 MHz), Ka band (IF input 255.7-628.7 MHz and 401-629 MHz, RF output 34200-34575.7 MHz and 34575.7-34800 MHz).
- The feasibility in other frequency bands in particular Q/V bands together with wider bandwidths has not been studied but the same concept can apply as well.
- These features make it a unique device enabling software-defined transceivers without multiple frequency conversions, fully reprogrammable and easily scalable to any frequency band.
- Further optimization of phase noise due to laser stability and in-band spurious due to intermodulation and aliasing will be required to be full in line with the specifications.
- The technology can have different applications from wideband communication or electronic warfare and frequency distribution, which is considered strategic for non-European dependence on third parties.

Recommendations

The phase noise and in-band spurious could be improved with the following actions:

1. Phase noise is not compliant with specifications at low frequency offset due to stability of the mode-locked laser cavity. This is expected to be improved by implementation of a phase-locked loop locked to a reference for phase and frequency stability improvement.
2. In-band spurious in the Ka band have been measured out of specifications and are due to intermodulation. The level of the spurious can be reduced by reducing the optical input power. The spurious could be further improved by improving the linearity of the photodetector.
3. Spurious due to aliasing are observed in the Ka band (at downlink >32060.7MHz and uplink >34575.7MHz when employing the same Nyquist repetition) and can be avoided by increasing the sampling frequency.
4. Optimization of the mode-locked laser technology to improve cavity stability.
5. Noise figure can be improved by adding antialiasing filtering at the RF input.
6. The frequency plan and sampling frequency should be designed considering the in-band intermodulation to minimize the in-band spurious.

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Thank you for your attention!

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