Amplitude and Phase Imbalance Calibration for Space-Based Precision Direction Finding Systems

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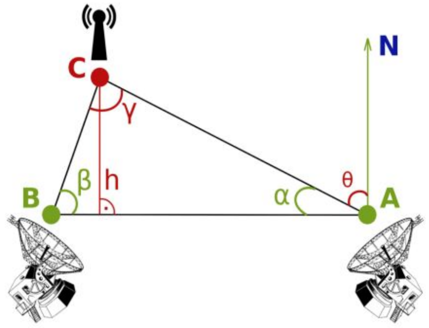
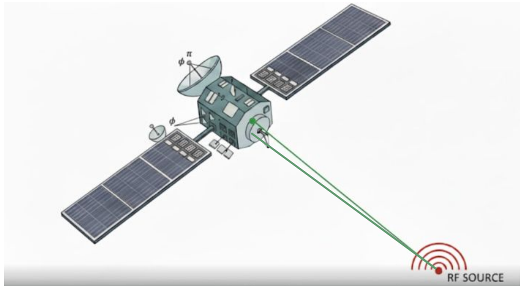
Stockholm - 10/14/2025

Outline

Introduction

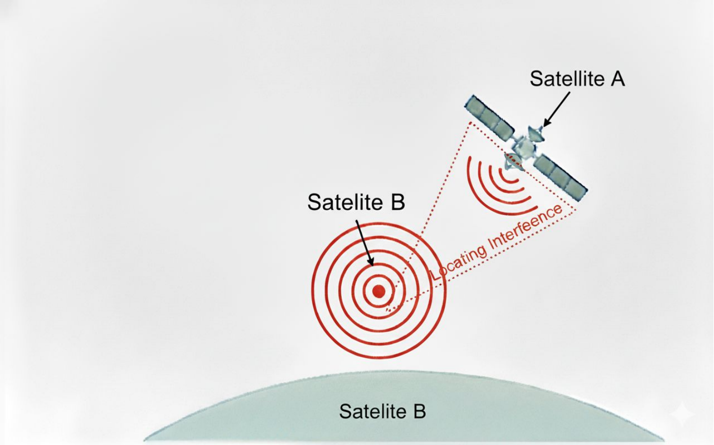
- Direction Finding - DF;
- Uses Triangulation and other techniques to find the location of radio sources;
- One of the most used solution is based on using two receiving antennas;
- Very used in radio navigation for ships, aircraft, search and rescue (emergency transmitters), **space systems**, illegal interference and etc.

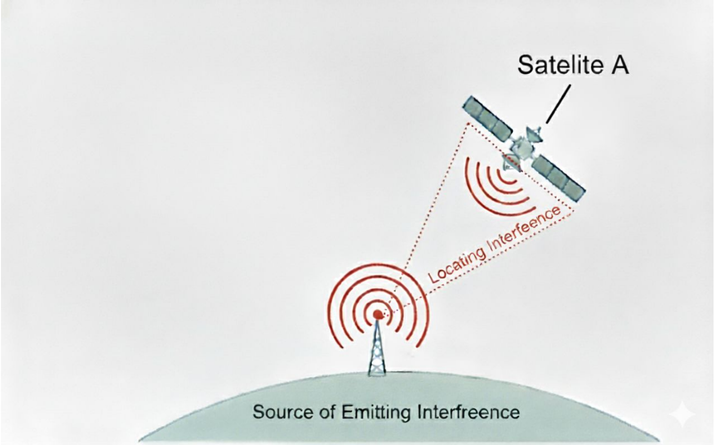




Introduction

- DF application in earth orbit.





The front-end is used to properly conditioning the signal for a Software defined Radio (SDR).

Its calibration is necessary due to:

- Electrical and physical length variability;
- Active device variability as gain and time degradation;
- Temperature.

} **Dynamical Variability**

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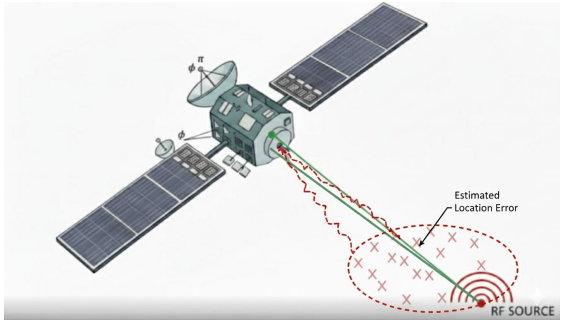
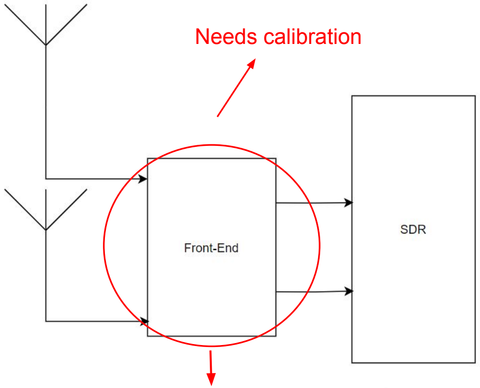
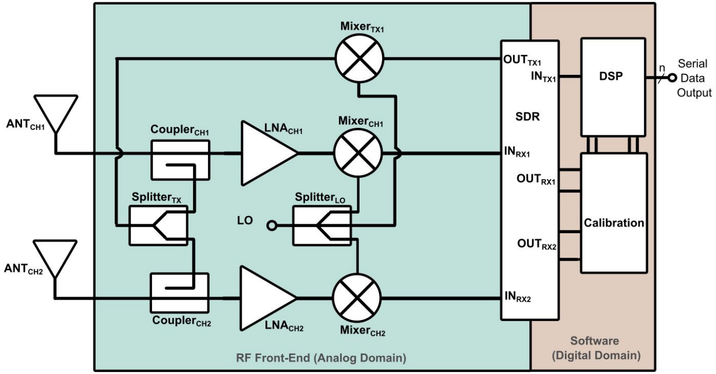
If not calibrated it introduces error in the DF algorithm due to channel imbalance.





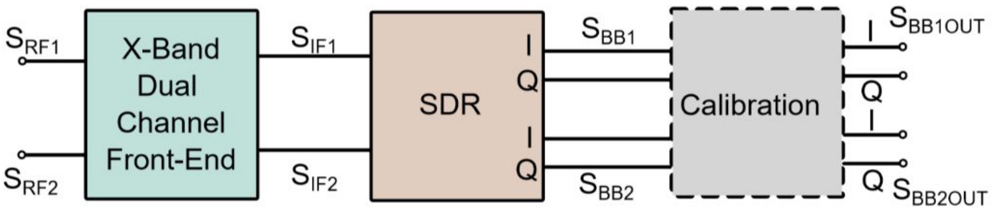


Objective

- To apply the calibration technique in a real system;
- To discuss calibration for low cost learning SDRs like ADALM PLUTO;
- To Propose and compare online and offline calibration.

Calibration System Description

- RF Receiver Block at X-Band
- 8.5 to 9.5 GHz



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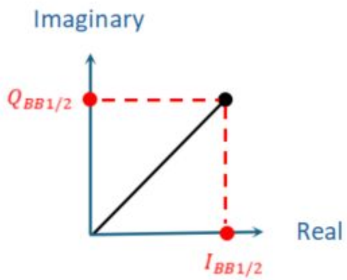
$$S_{BB1/2} = I_{BB1/2} + jQ_{BB1/2} = |A_{BB1/2}|\angle\emptyset_{BB1/2}$$

$$|A_{BB1}| = \sqrt{{I_{BB1/2}}^2 + {Q_{BB1/2}}^2}$$

$$\emptyset_{BB1/2} = \tan^{-1}\left(\frac{Q_{BB1/2}}{I_{BB1/2}}\right)$$



Calibration System Description

- Calibration methodology

$$\alpha_{BB12} = \frac{|A_{BB1}|}{|A_{BB2}|}$$

Amplitude Compensation

$$\Delta_{\phi BB12} = \emptyset_{BB1} - \emptyset_{BB2}$$

Phase Compensation

$$S^*_{BB1} = |A_{BB1}| e^{j(\phi_{BB1})}$$ CH1

$$S^*_{BB2} = \alpha_{BB12} |A_{BB2}| e^{j(\phi_{BB2} + \Delta\phi_{BB12})}$$ CH2

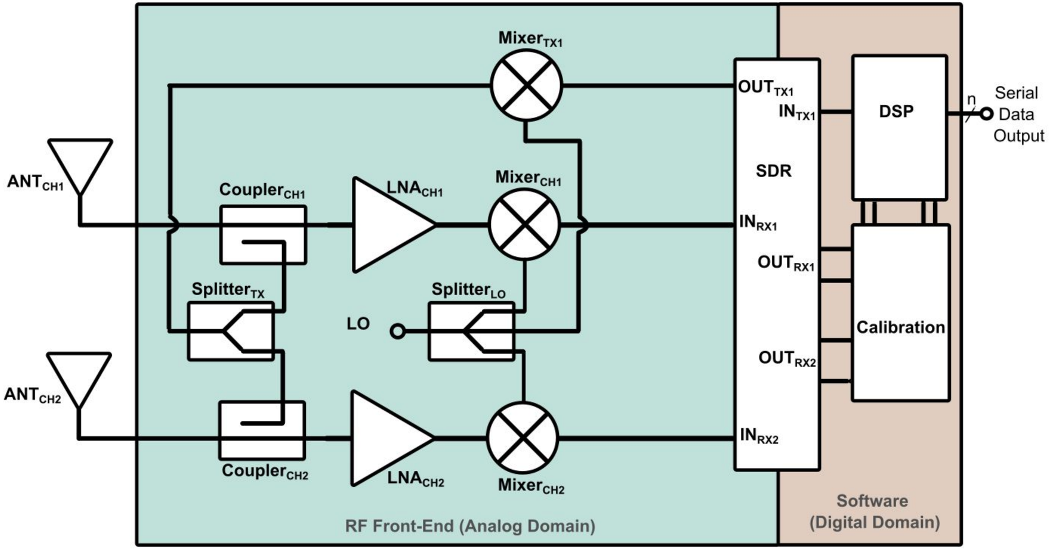
Calibrated Signal

$$S^*_{BB1} = |A_{BB1}| \underline{/\phi_{BB1}}$$

Reference Channel

$$S^*_{BB2} = |\alpha_{BB12}| \underline{/\Delta\phi_{BB12}} |A_{BB2}| \underline{/\phi_{BB2}} = \alpha_{BB12} |A_{BB2}| \underline{/\phi_{BB2} + \Delta\phi_{BB12}} = \frac{|A_{BB1}|}{|A_{BB2}|} |A_{BB2}| \underline{/\phi_{BB2} + \phi_{BB1} - \phi_{BB2}} = |A_{BB1}| \underline{/\phi_{BB1}}$$

Proof of concept: X-band Front-end Local oscillator

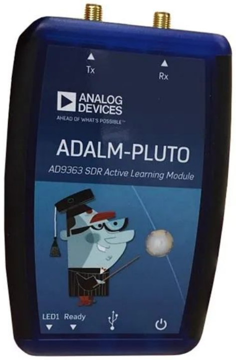


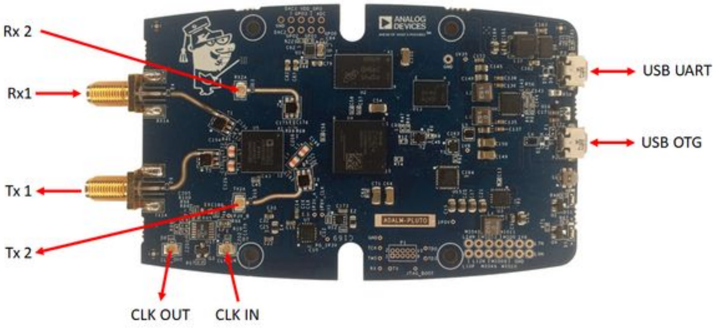
Gain: 24 dB
NF: 0.8 dB

Calibration System Description

SDR

- ADALM-PLUTO (Revision C) - RF learning module;
- Based on the Analog Devices AD9363 - RF Agile Transceiver;
- 12-bit ADC and DAC;
- 15.72MS/s for two channel operation;
- RF coverage from 325 MHz to 3.8 GHz.

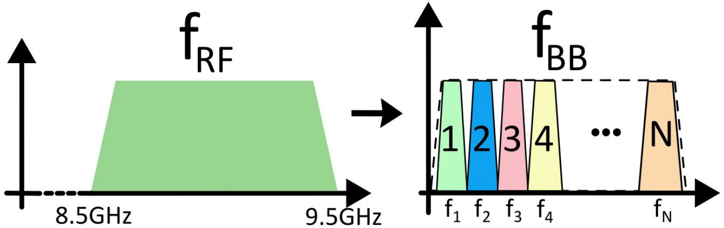




REF: [Adalm Pluto - Overview]

Calibration System Description

- The SDR is not able to receive all the signal bandwidth (8.5 to 9.5 GHz implies 1 GHz bandwidth) at once.
- So the bandwidth will be split in N time multiplexed narrow-band channels according to the SDR limitations.
- IF bandwidth of 200 MHz (400 MHz up to 600 MHz)
- A baseband of 10 MHz was assumed so the RF receiving system should select 100 channels to accommodate the 1 GHz RF bandwidth.



$$\begin{bmatrix} |S^*_{BB2_1}| \\ |S^*_{BB2_2}| \\ \cdots \\ |S^*_{BB2_n}| \end{bmatrix} = [|\alpha_{BB2_1}|] \cdot \begin{bmatrix} |A_{BB2_1}| \\ |A_{BB2_2}| \\ \cdots \\ |A_{BB2_n}| \end{bmatrix}$$

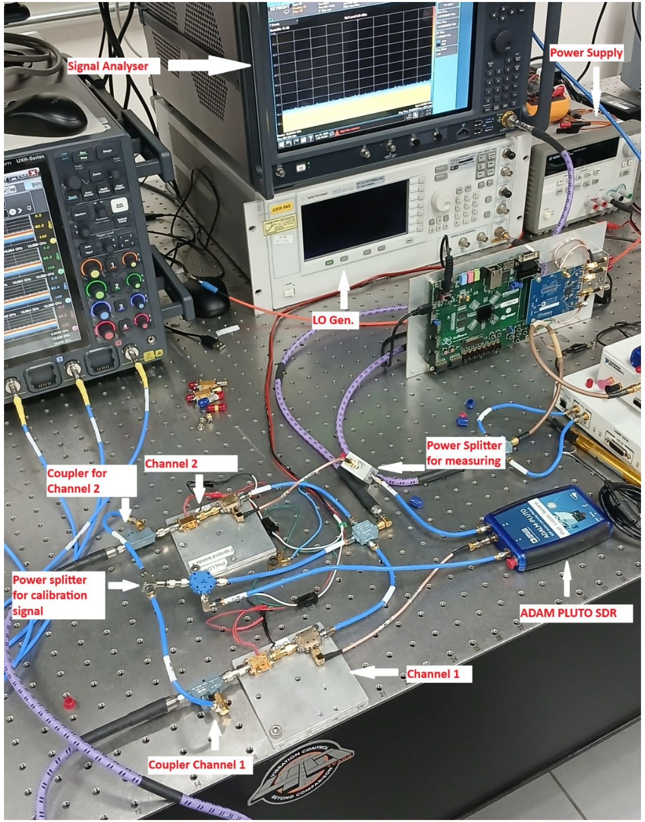
$$\begin{bmatrix} \phi^*_{BB2_1} \\ \phi^*_{BB2_2} \\ \cdots \\ \phi^*_{BB2_n} \end{bmatrix} = [\phi_{BB2_1}] + \begin{bmatrix} \Delta\phi_{BB12_1} \\ \Delta\phi_{BB12_2} \\ \cdots \\ \Delta\phi_{BB12_n} \end{bmatrix}$$

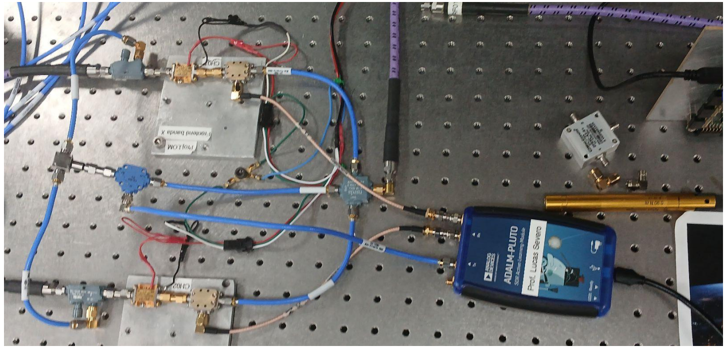
LO Frequency (GHz)	RF bandwidth (GHz)
8.1	8.5 - 8.7
8.3	8.7 - 8.9
8.5	8.9 - 9.1
8.7	9.1 - 9.3
8.9	9.3 - 9.5

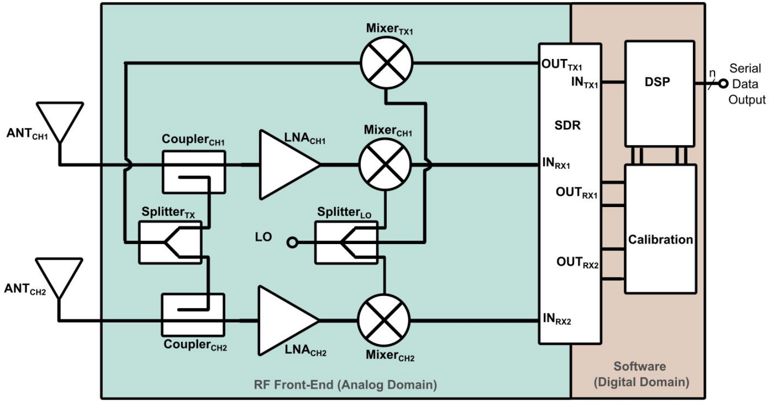
IF bandwidth of 200 MHz (400 MHz up to 600 MHz) - ADALM PLUTO

Experimental Results

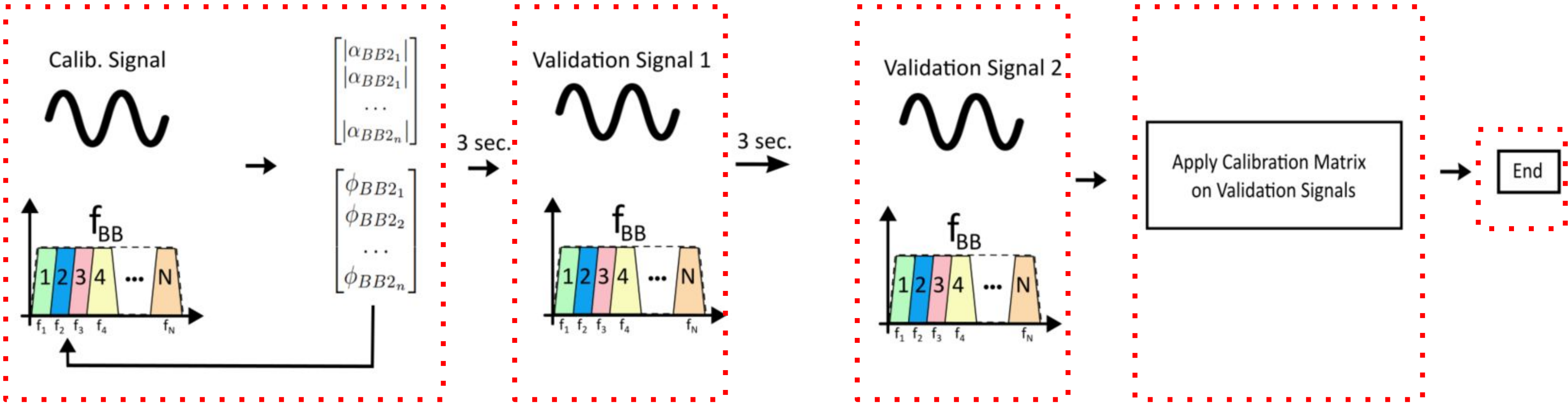
Laboratorial Setup





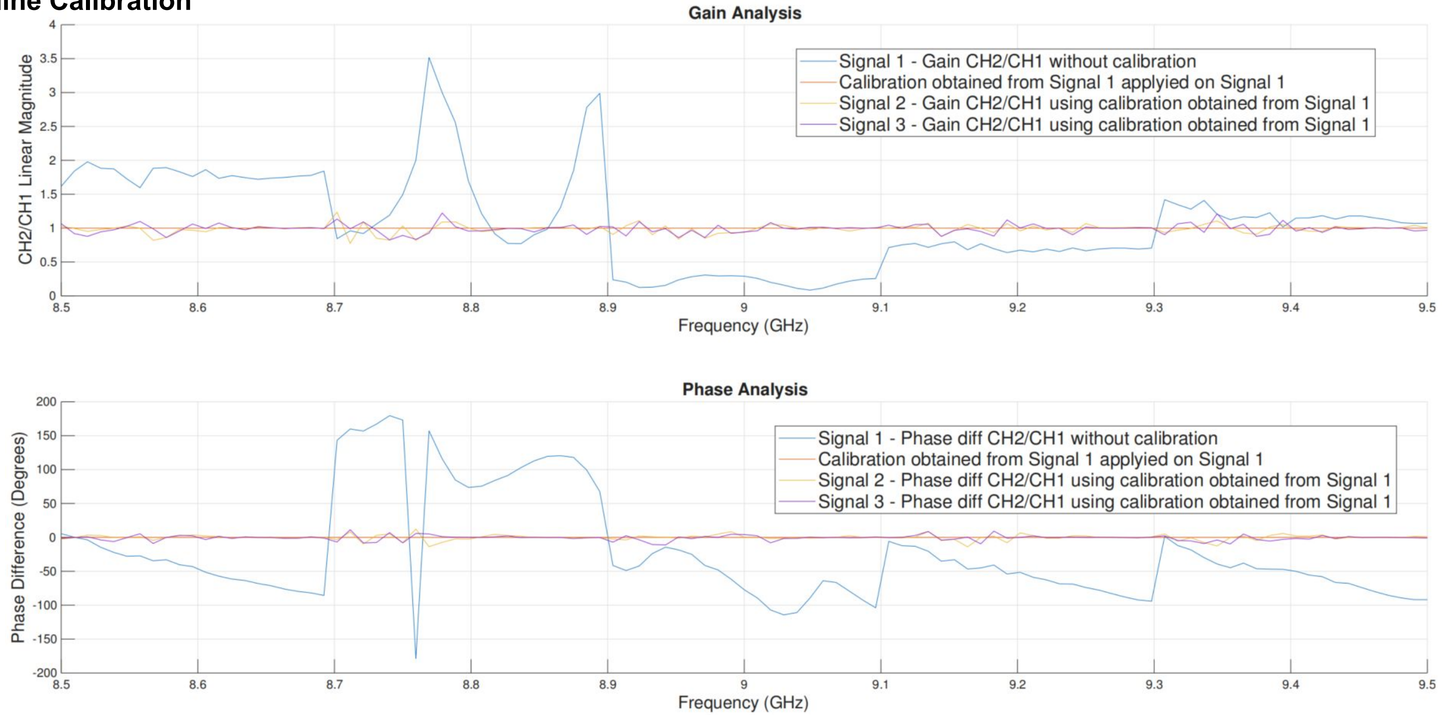


- **Offline Calibration**



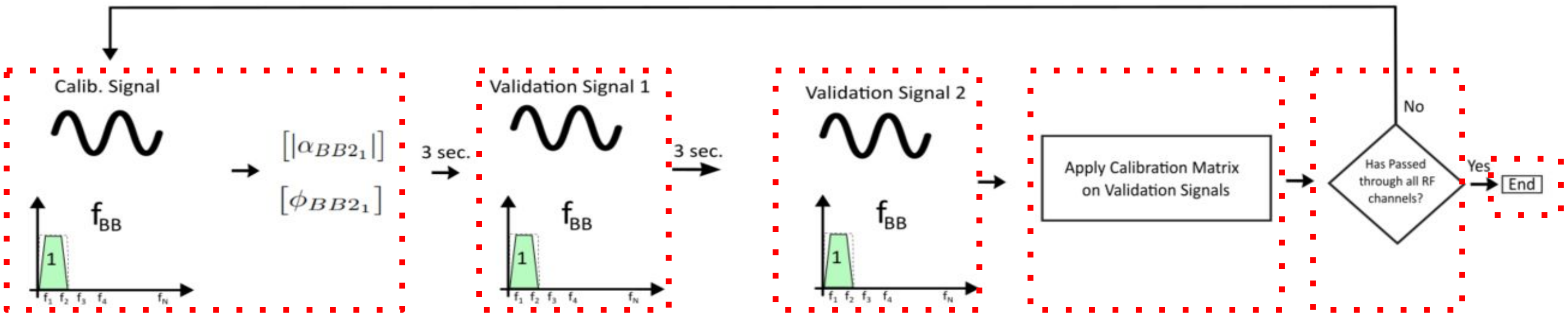
Experimental Results

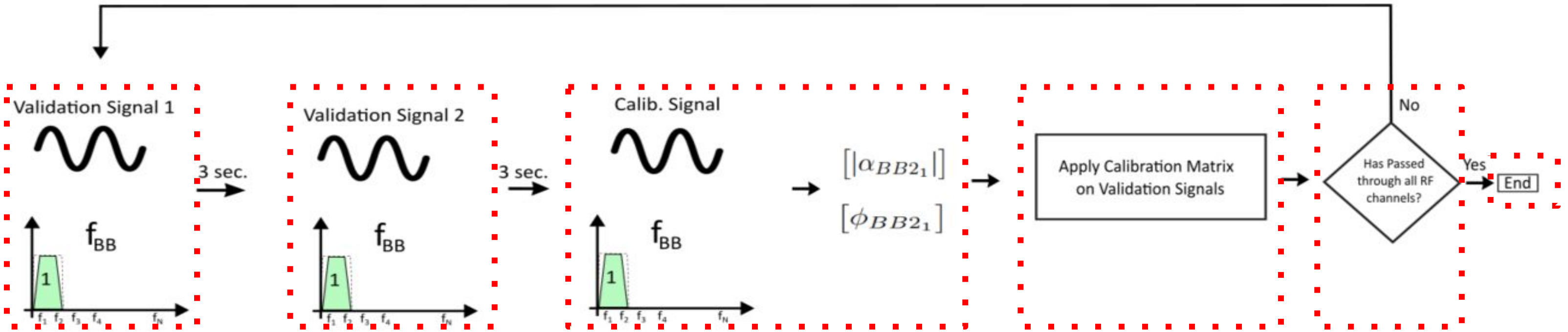
- **Offline Calibration**



However, the ADALM-PLUTO radio has demonstrated a lack of repeatability when the frequency of the internal LO is changed, so this calibration has led to some errors.

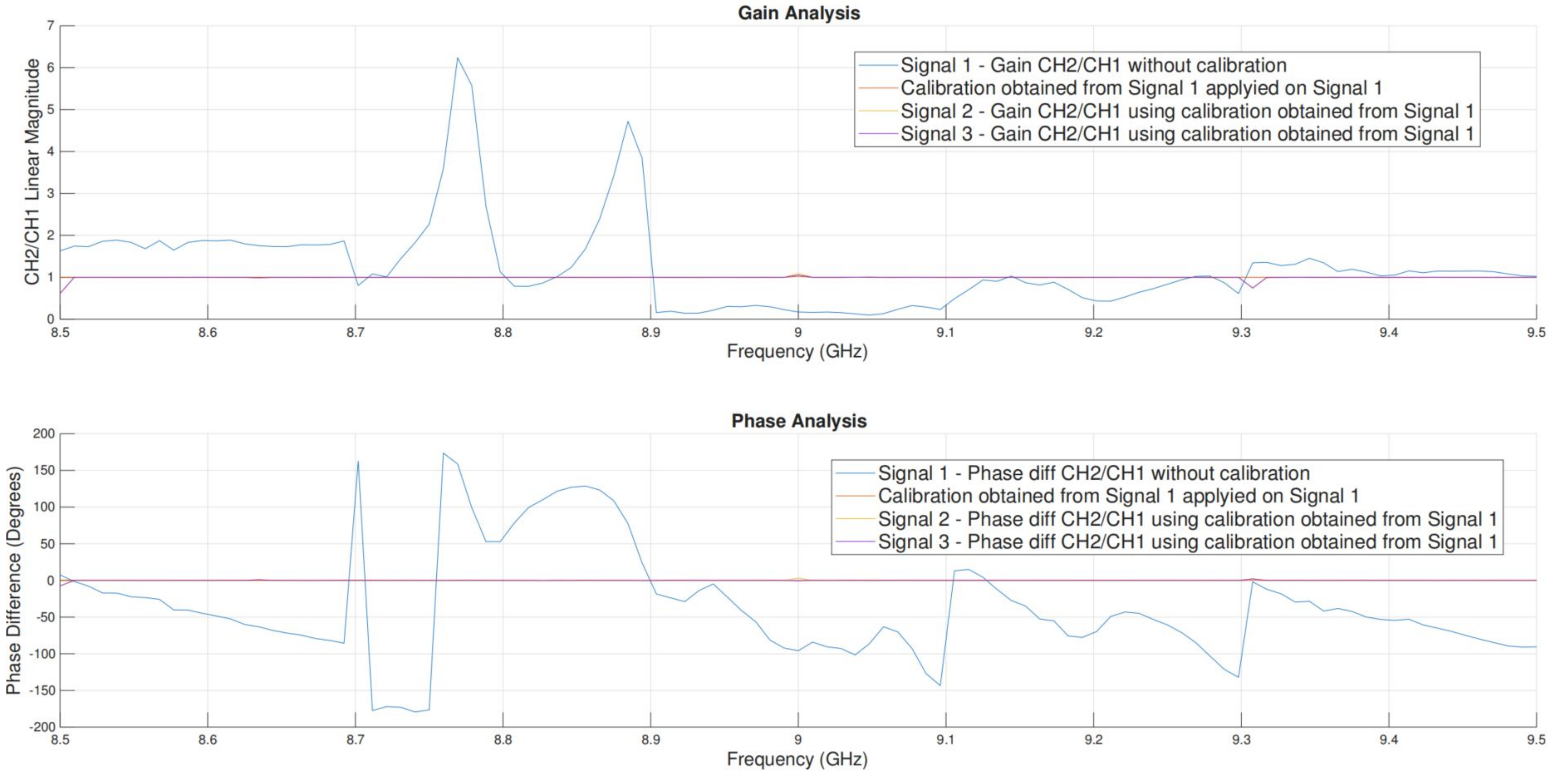
Proposed method - Real Time Calibration (Online)





Experimental Results

- **Online Calibration**



Experimental Results

Online Calibration

Offline Calibration

Amplitude

Online Calibration:

Measurement Step	Max	Min	Mean	Std. Dev.
Initial (Uncalib.)	6.238	0.096	1.248	1.046
2nd Reading	1.026	0.997	1.000	0.003
3rd Reading	1.092	0.614	0.994	0.046

Offline Calibration:

Measurement Step	Max	Min	Mean	Std. Dev.
Initial (Uncalib.)	3.518	0.085	1.099	0.700
Calibrated Data 2	1.238	0.774	0.989	0.067
Calibrated Data 3	1.223	0.826	0.991	0.070

Phase

Online Calibration:

Measurement Step	Max	Min	Mean	Std. Dev.
Initial (Uncalib.)	173.59	-179.34	-36.15	74.32
2nd Reading	0.33	-0.32	0.00	0.06
3rd Reading	3.12	-7.47	0.01	0.83

Offline Calibration:

Measurement Step	Max	Min	Mean	Std. Dev.
Initial (Uncalib.)	179.50	-178.97	-22.24	76.54
Calibrated Data 2	12.25	-13.99	-0.13	4.06
Calibrated Data 3	11.22	-11.26	-0.81	4.01

Conclusion

Conventional offline calibration methods are insufficient for wideband SDRs ,like ADALM-PLUTO, that require frequency agility over a 1 GHz bandwidth.

Proposed Solution: A real-time, "in-place" calibration methodology was successfully implemented to overcome the limitations of traditional approaches.

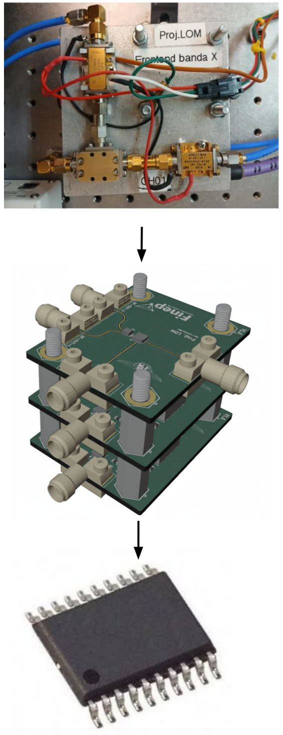
Validation: The technique effectively corrected significant gain and phase imbalances across various frequencies, proving its suitability for frequency-agile systems.

Future Work:

- Miniaturize the hardware to fit a 1U CubeSat standard.

- Integrate additional antennas to evaluate Angle of Arrival (AoA) estimation performance.

Miniaturize the circuit



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Acknowledgment

The authors would like to thank the Brazilian Air Force and the research agencies FINEP (ref 01.22.0581.00) and CNPq (grant 303609/2023-0) for partial support of this work

Thanks for your attention!
Obrigado!

Any Questions?

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