Software-Defined Radio System for Tracking Application

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Background

Proposed solution

Used signal processing

Simulation in GNU Radio

Measurement Results

Conclusion and Outlooks

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STC group in charge of telemetry and bi-directional links with flying projectiles

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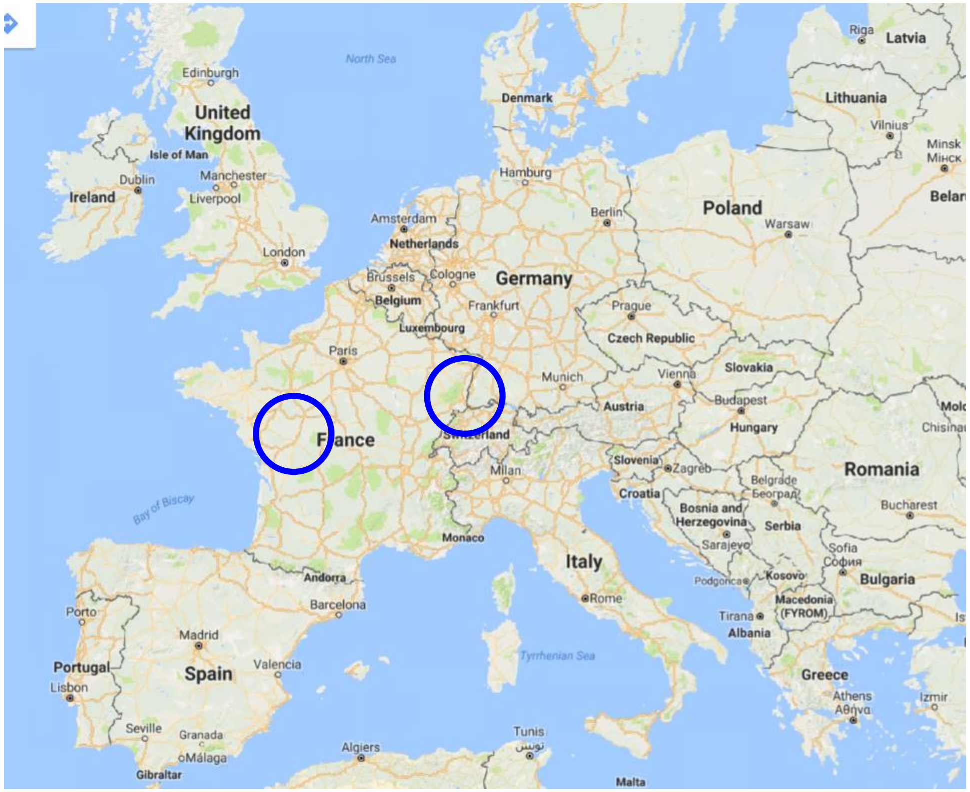
Work developed within a PhD funded by ISL, supervised by ISL and XLIM

XLIM: A multidisciplinary Research Institute located on several geographical sites, mainly in Limoges but also in Poitiers



Background

Many Software Defined Radio (SDR) tracking applications in research focus on tracking mobile phones, vehicles, satellites, etc [1-2] with various difficulties to overcome (indoor localization, multi-path).

[1]: V. Nambiar et al., "SDR based indoor localization using ambient WiFi and GSM signals," *2017 ICNC*.
[2]: V. Y. Vu and A. B. Delai, "Digital Solution for inter-vehicle localisation system by means of Direction-Of-Arrival," *2006 ISISPC*
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➡ Our project:

develop a passive high-speed projectile tracking system based on commercial SDR and antenna arrays

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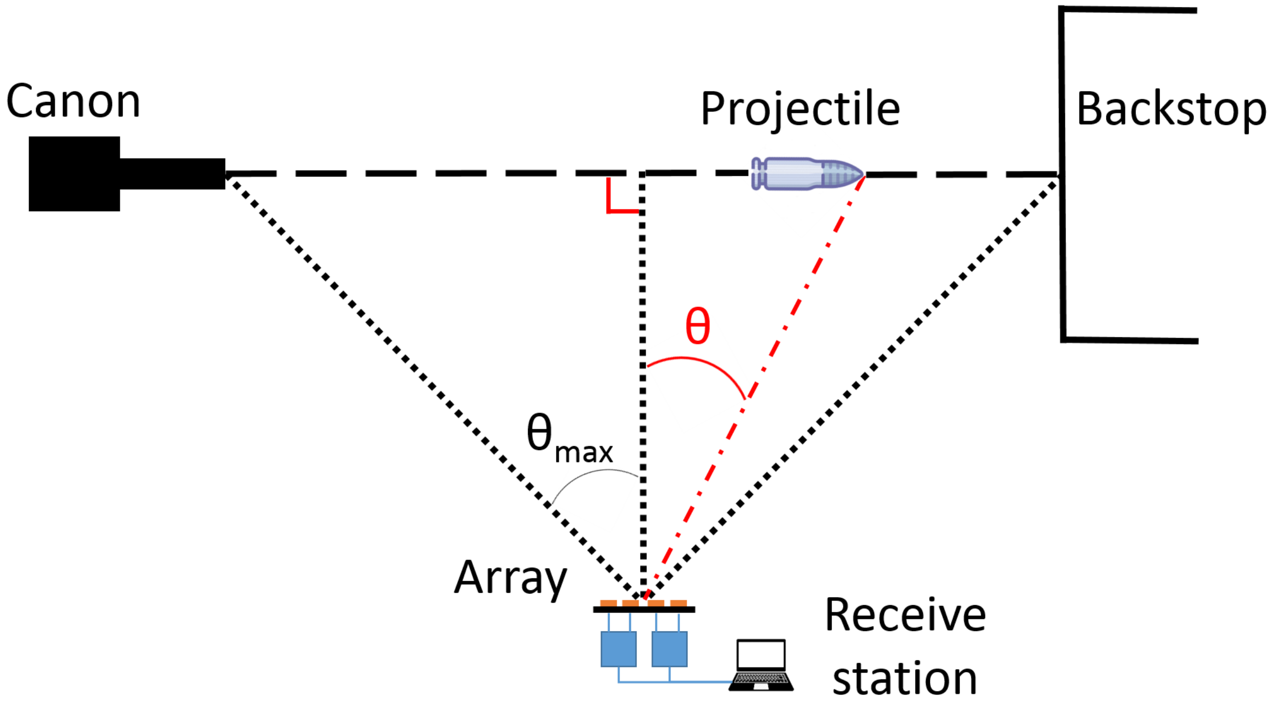

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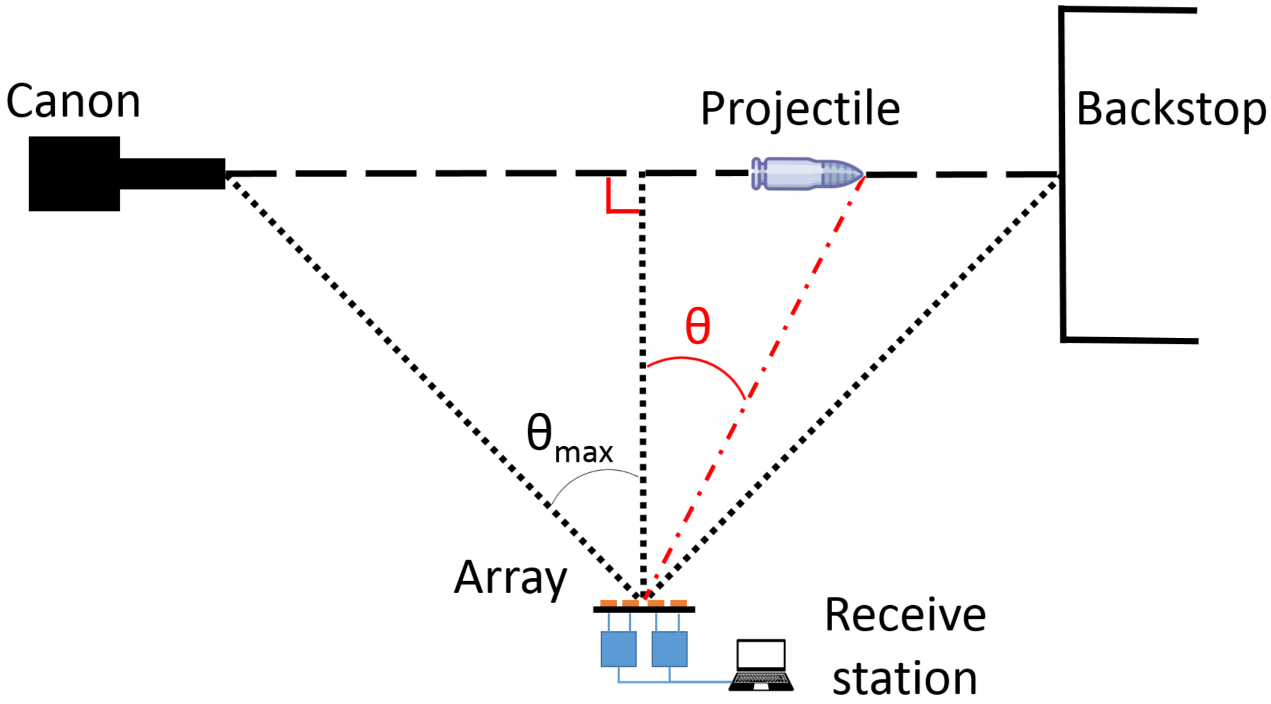

Steered antenna array electronically follows projectile (no mechanical displacement)

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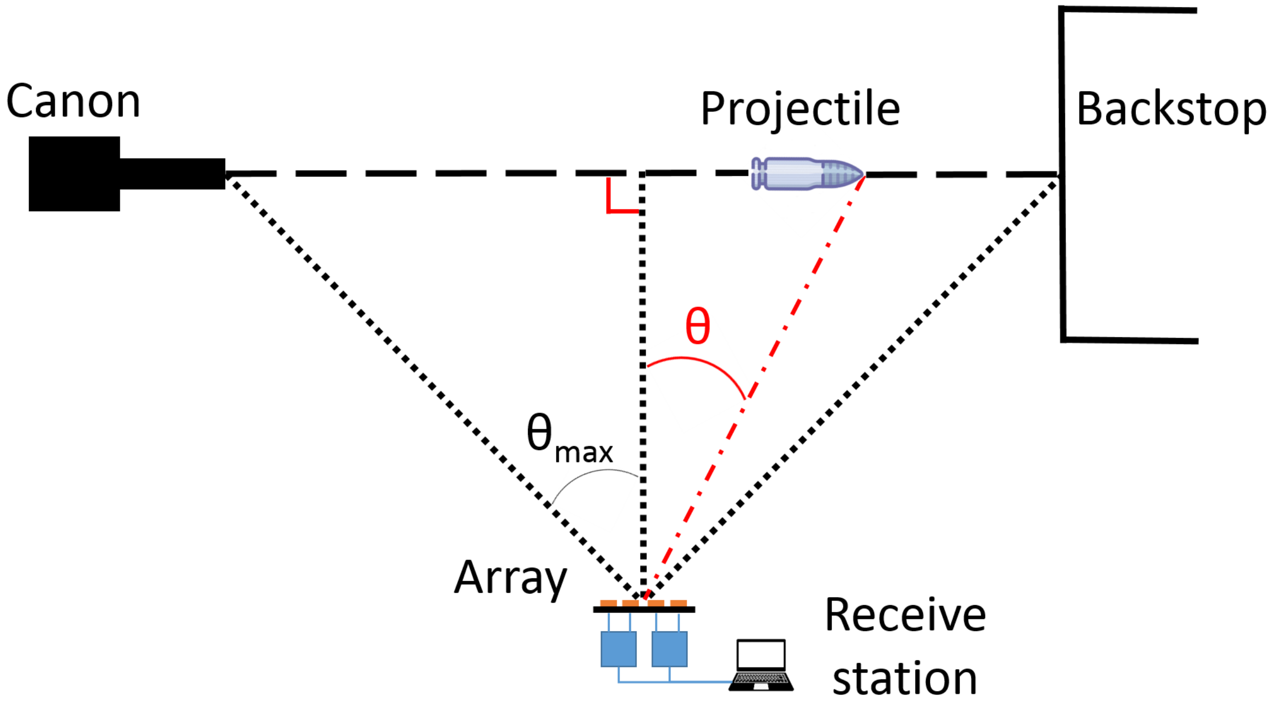

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Direction of the projectile computed from received signals (DOA)

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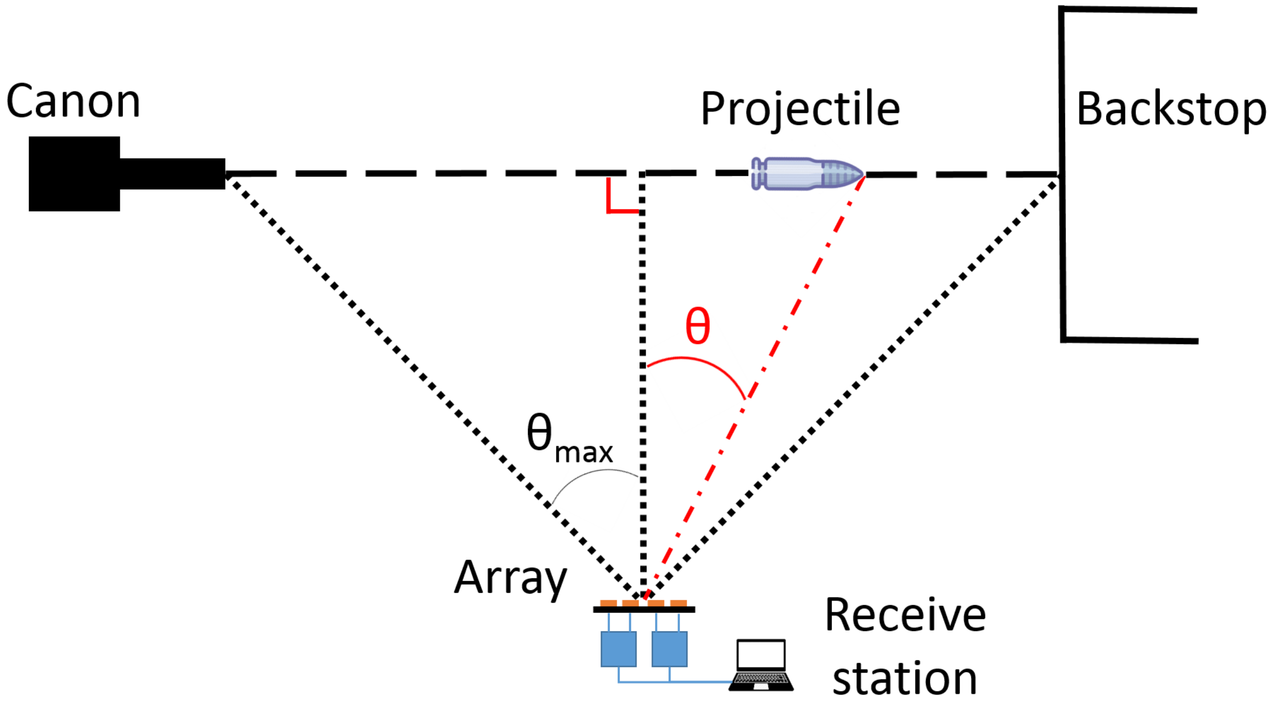

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Direction of the projectile computed from received signals (DOA)

Array main lobe steered towards estimated direction of the transmitter

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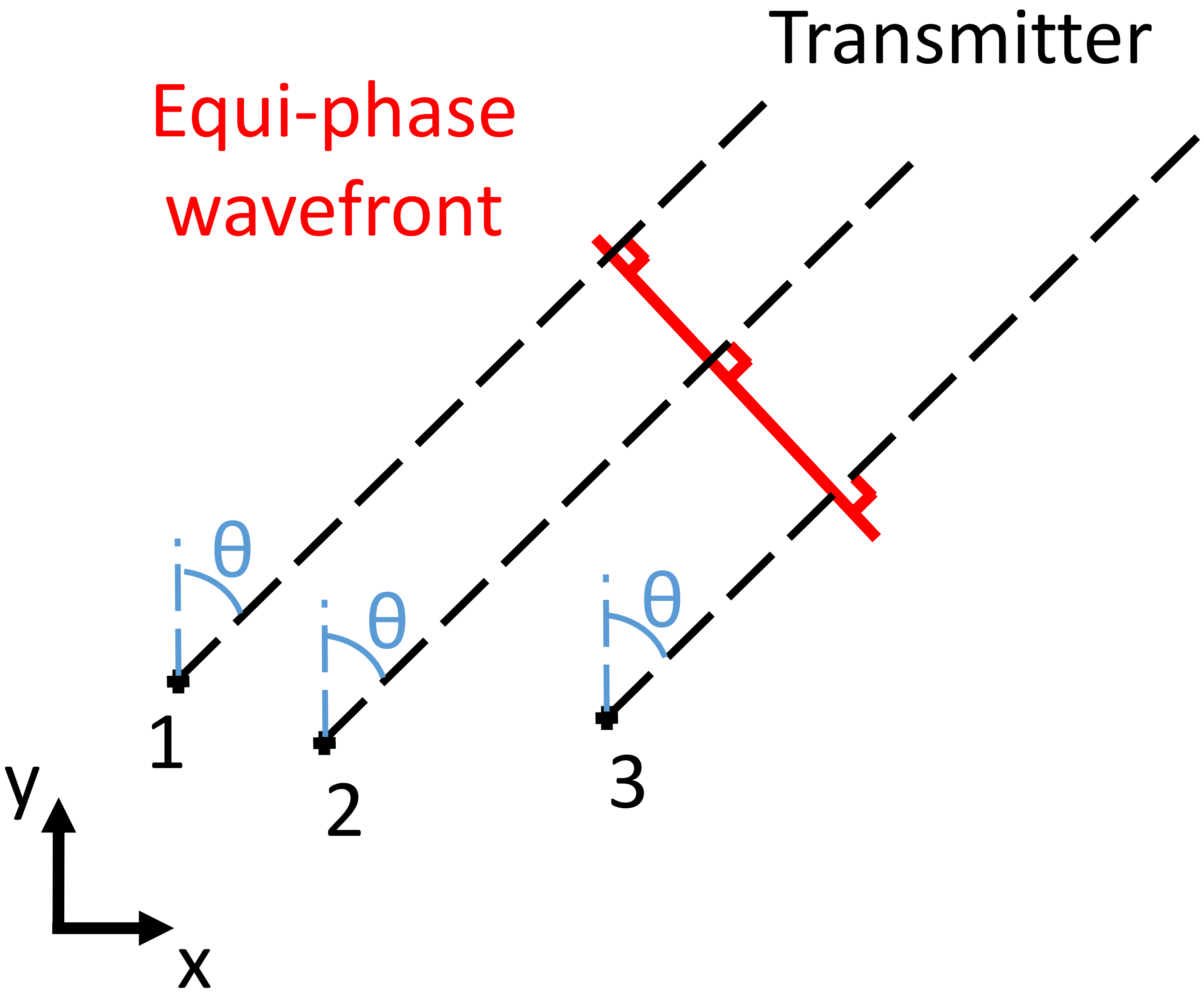

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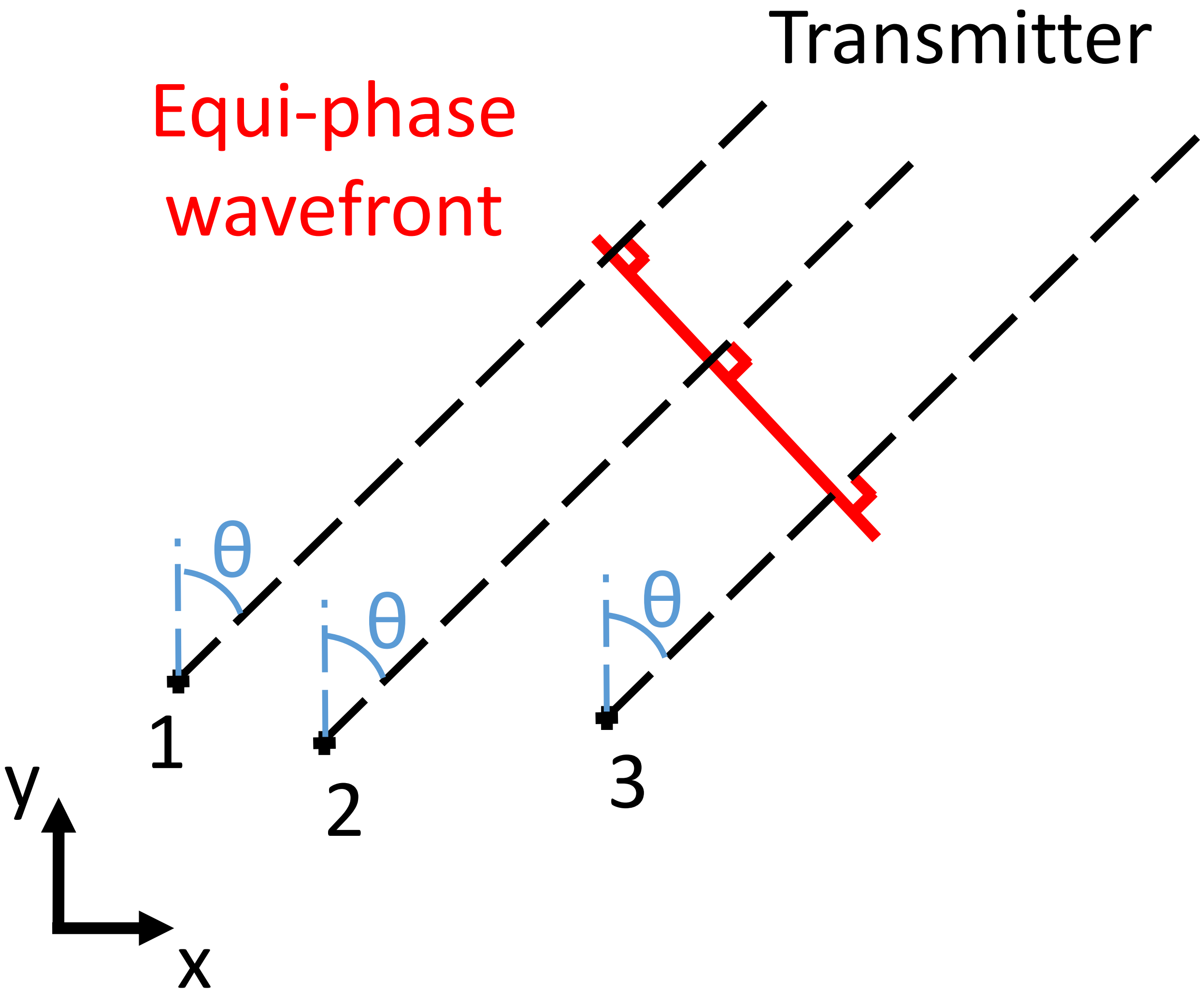
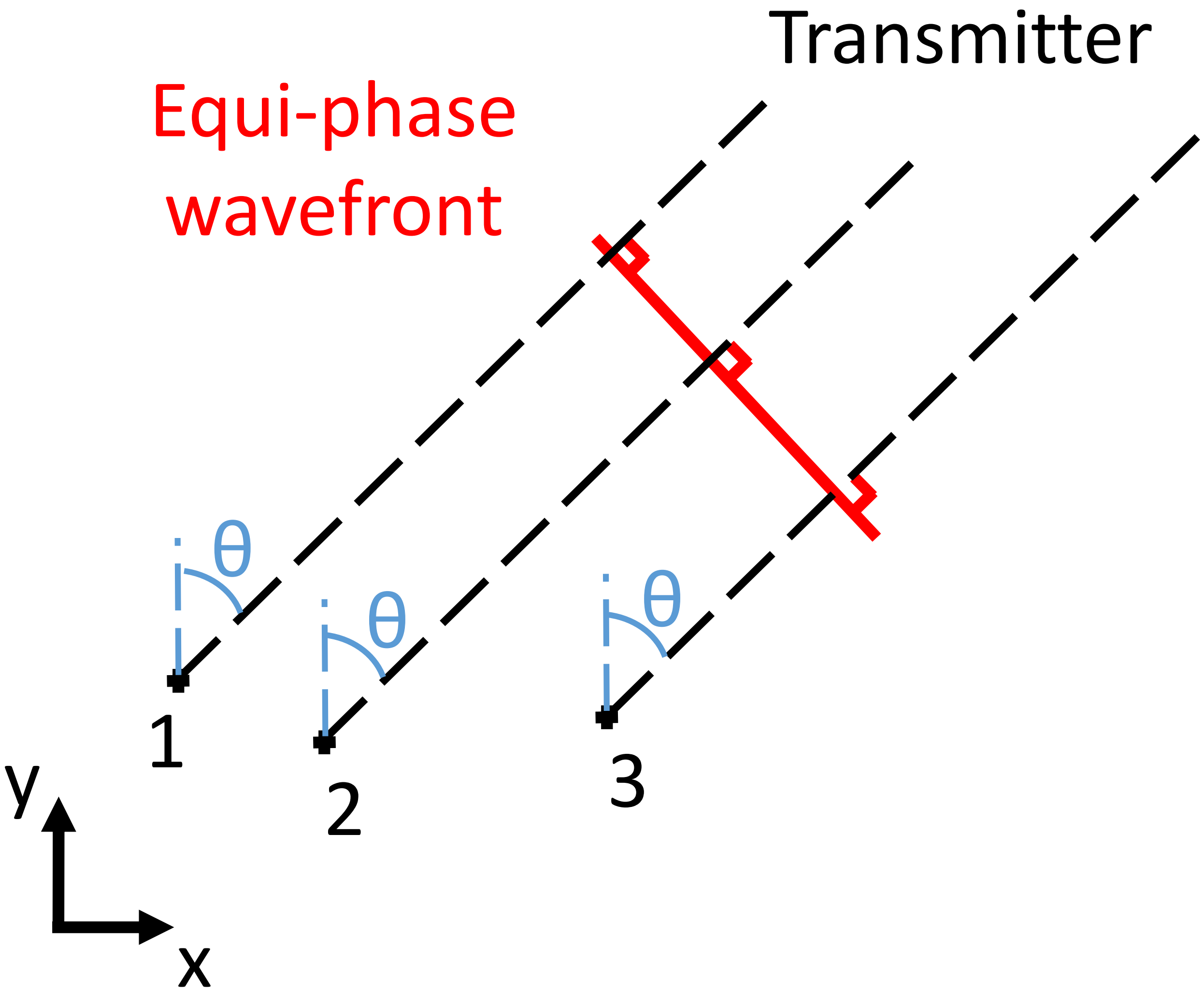


Transmitted signal:

$$s_{TX} = e^{j\omega t}$$

Used signal processing



Transmitted signal:

$$s_{TX} = e^{j\omega t}$$

Received signals:

$$s_1 = e^{j\,(\omega t + \varphi_1)}$$

$$s_2 = e^{j\,(\omega t + \varphi_2)}$$

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By influencing on the phase shifts between signals:

favor constructive interference for chosen particular θ (DOA).

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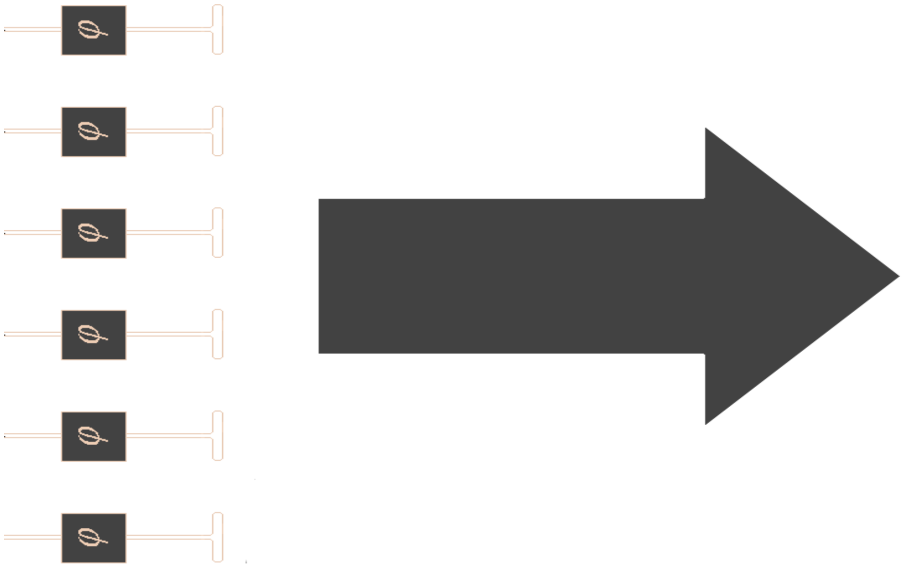

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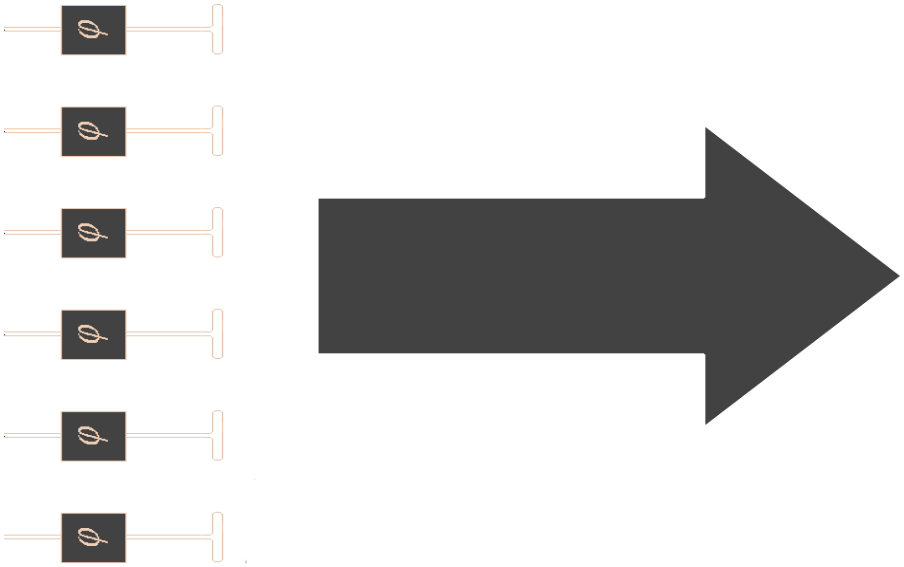
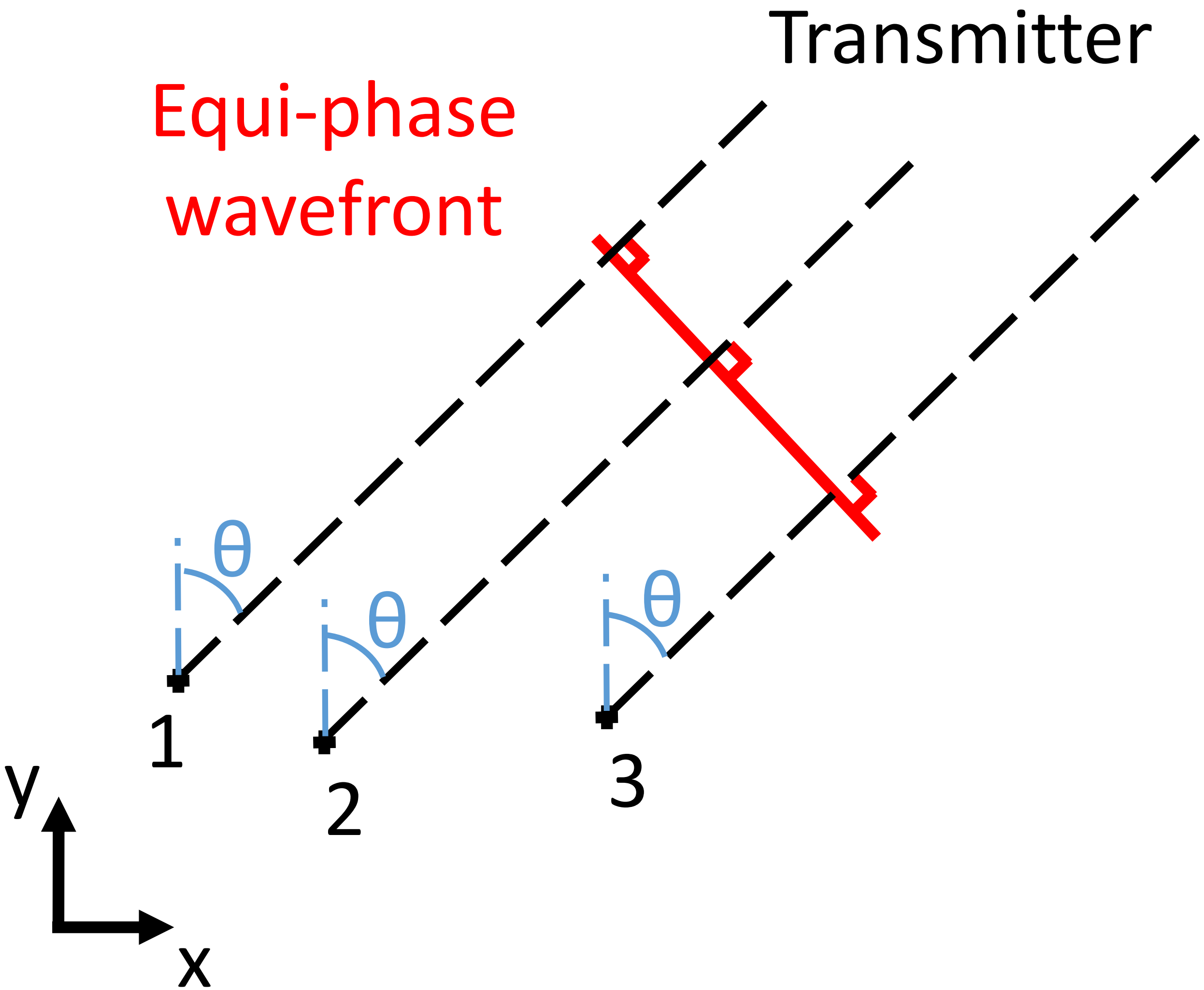


For a Uniform Linear Array (ULA), phase shifts between adjacing elements φ:

$$\varphi = \frac{2\pi}{\lambda}\, d\, sin\theta$$

λ: wavelength
d: inter-element spacing

Used signal processing



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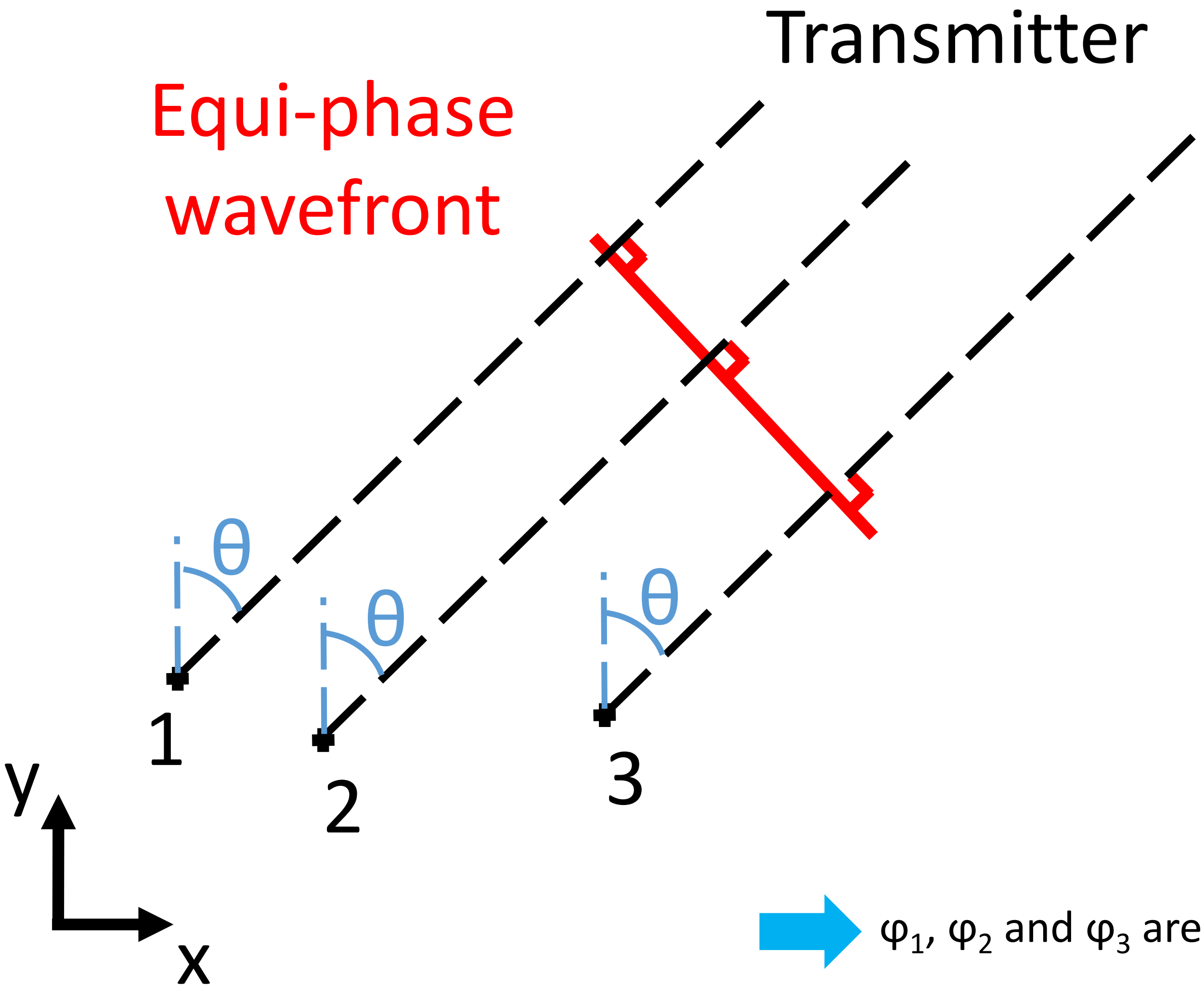

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φ_1, φ_2 and φ_3 are used to estimate θ (DOA)

Used signal processing

DOA computed using conventional beamformer algorithm (Bartlett)

- Only one transmitting source

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- Easy and fast to implement

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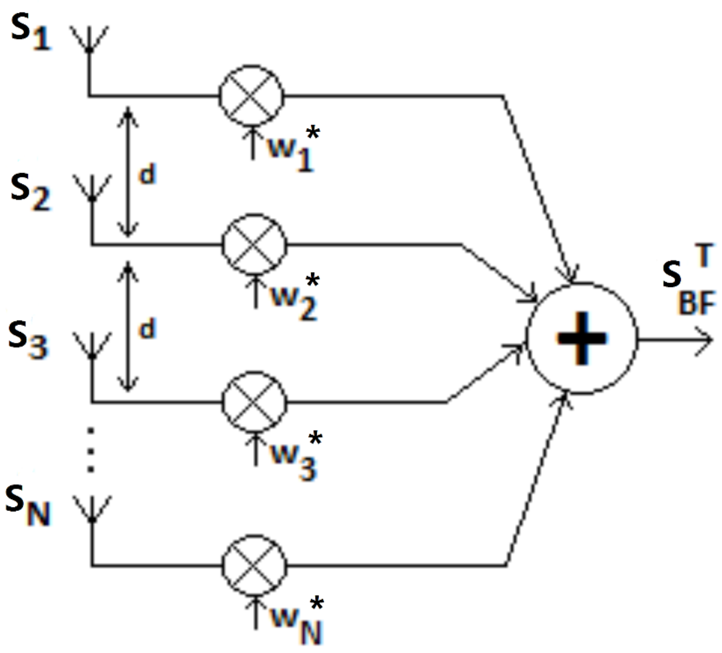

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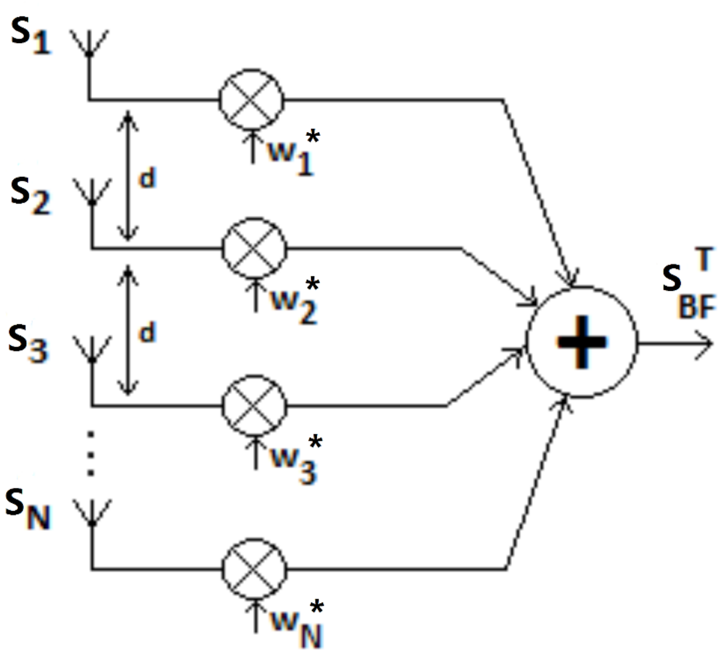

$$s = \begin{pmatrix} s_1 \\ \cdots \\ s_N \end{pmatrix} \qquad w = \begin{pmatrix} w_1 \\ \cdots \\ w_N \end{pmatrix}$$

$$s_{BF}^{T} = w_1^* \, s_1 + \cdots + w_N^* \, s_N = w^H \, s$$

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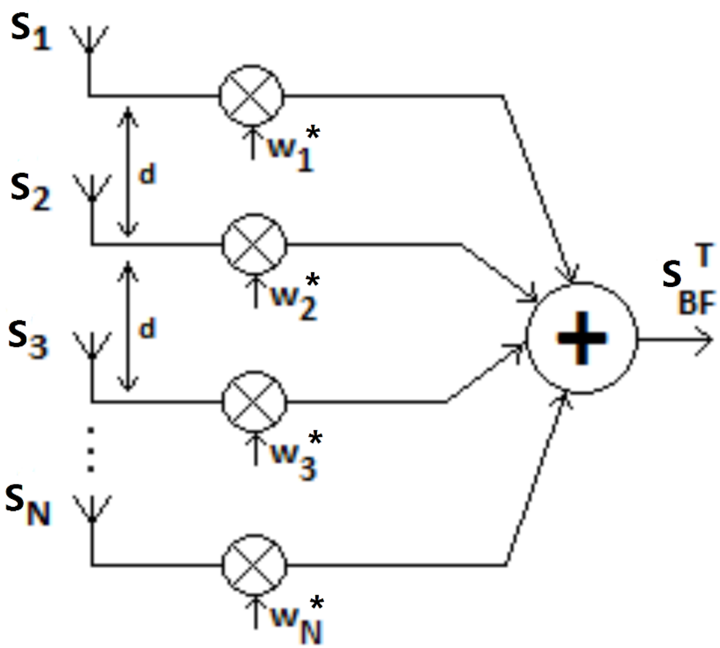

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➡ Optimize w in order to maximize s_{BF}^T

Used signal processing

Work presented here focuses on reception mode.

Commercial UBX-160 & Octoclock

➡ frequency and sampling time synchronization between channels

➡ NO phase synchronization between channels

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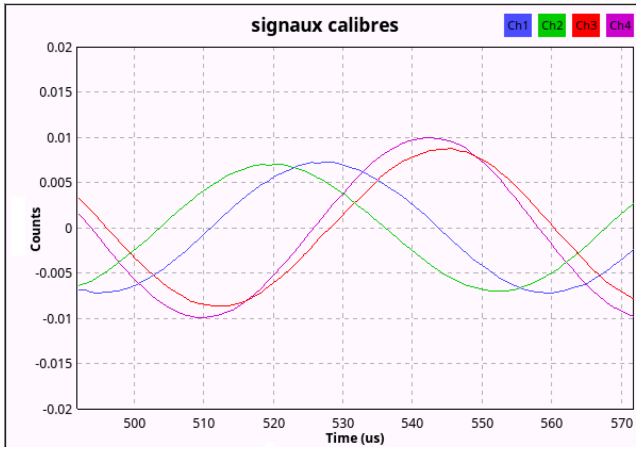

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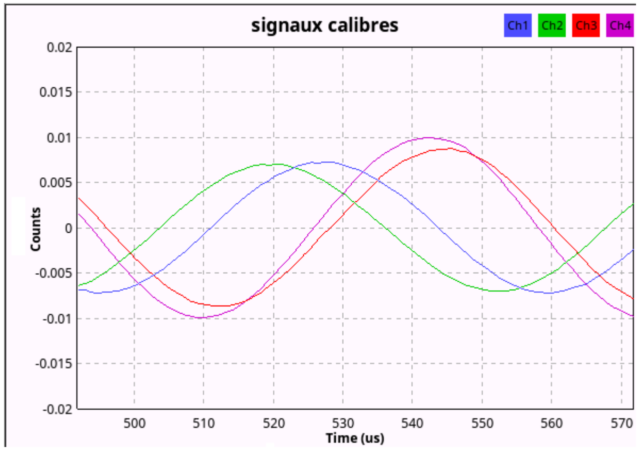

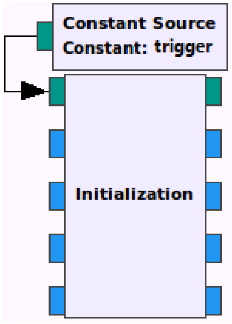

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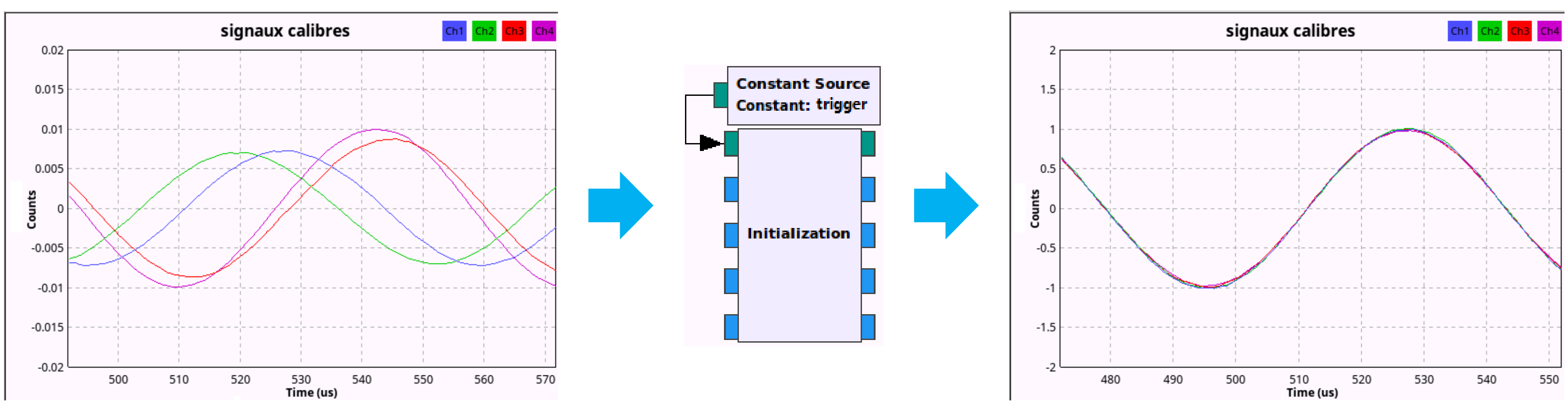

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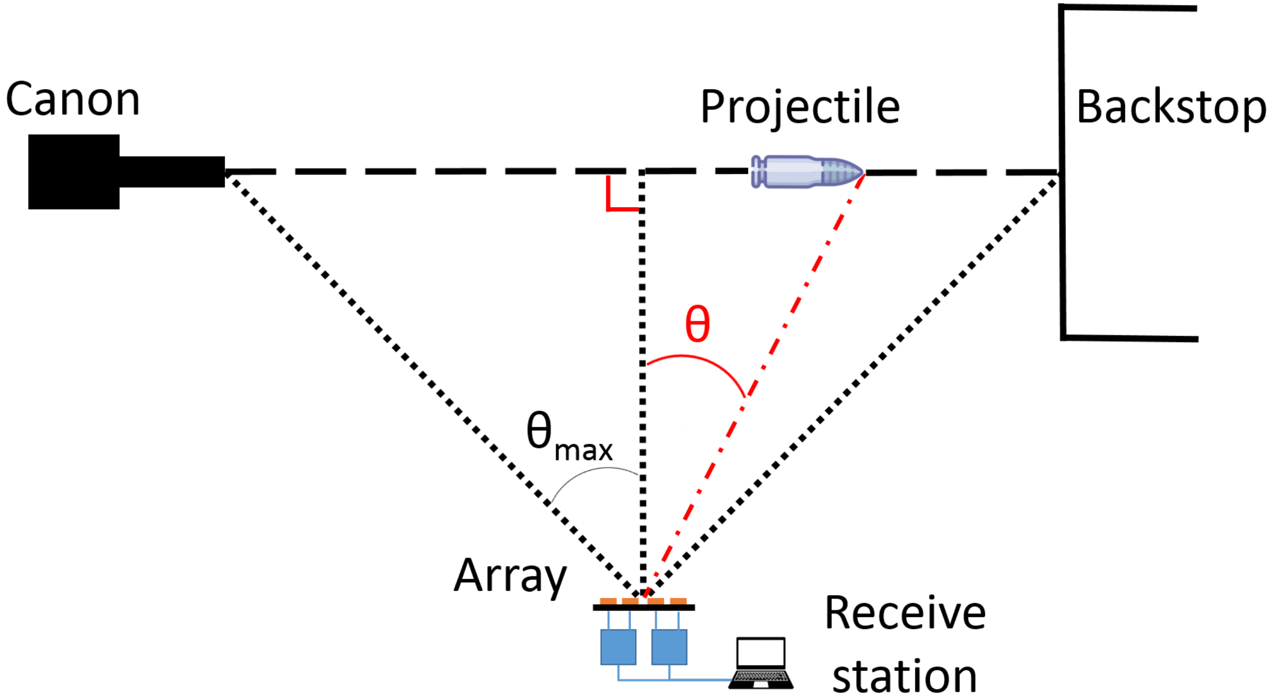
Aimed application: passive solution for projectile following



Simulation in GNU Radio

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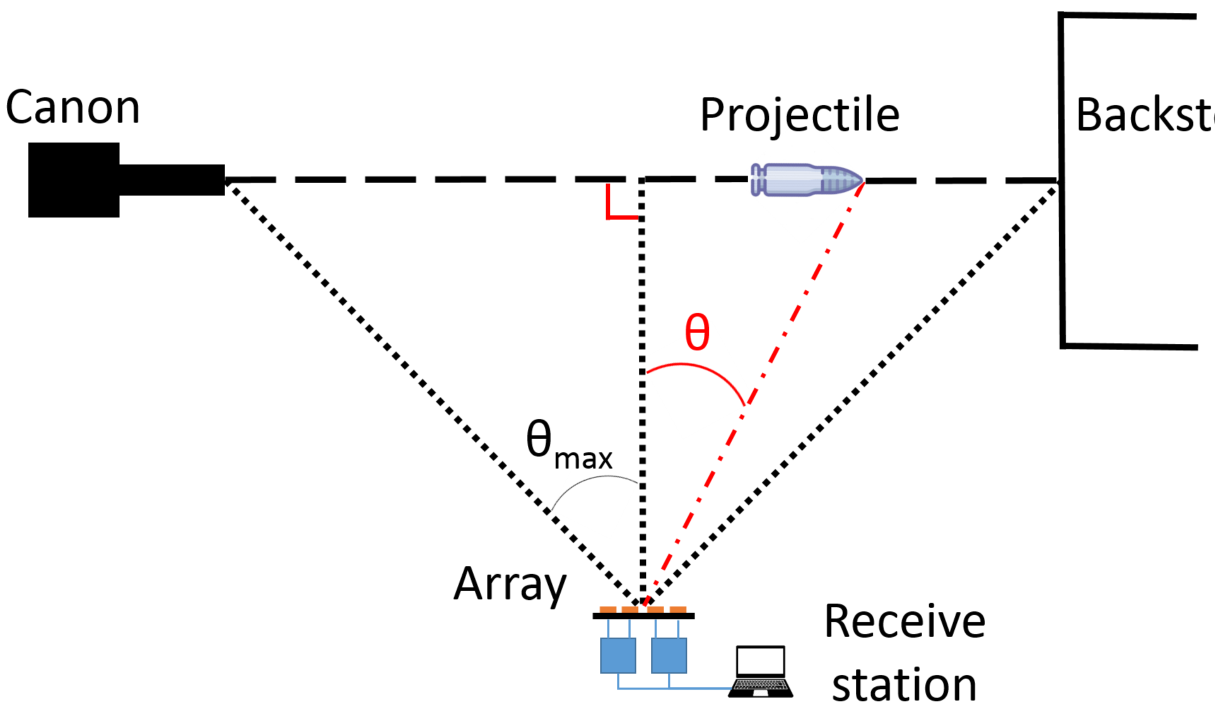

Estimated DOA used to steer array main lobe in projectile direction in real-time

Simulation in GNU Radio

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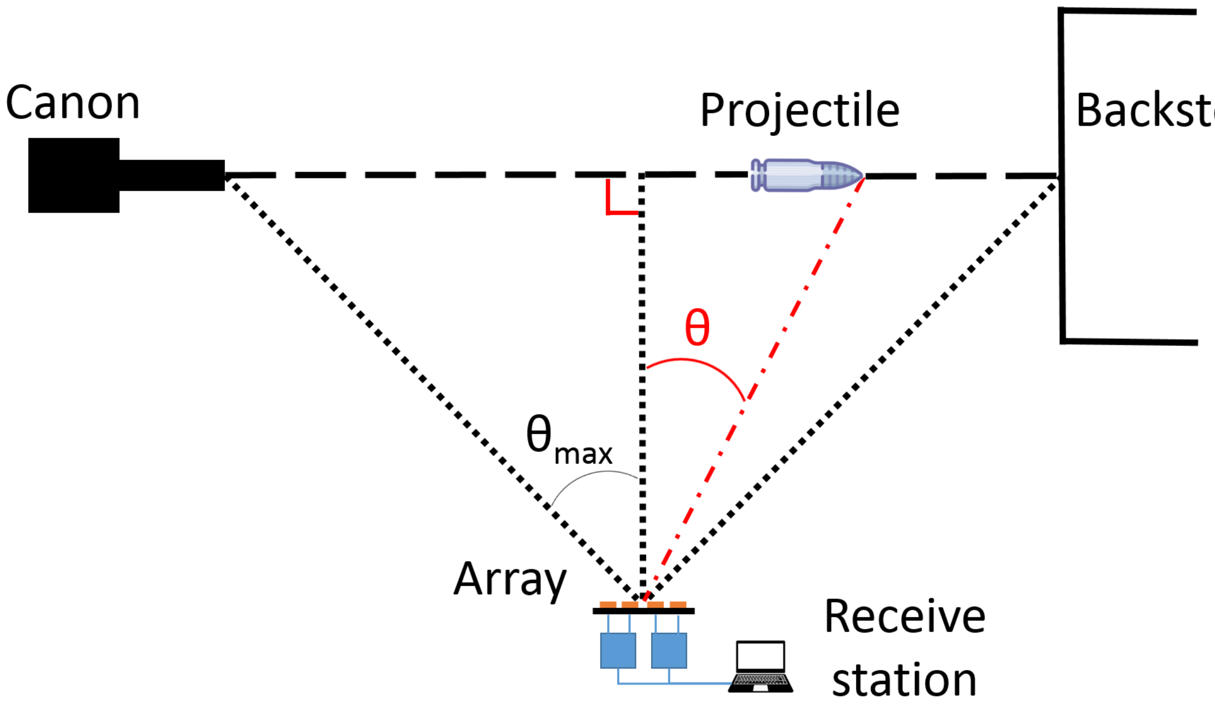
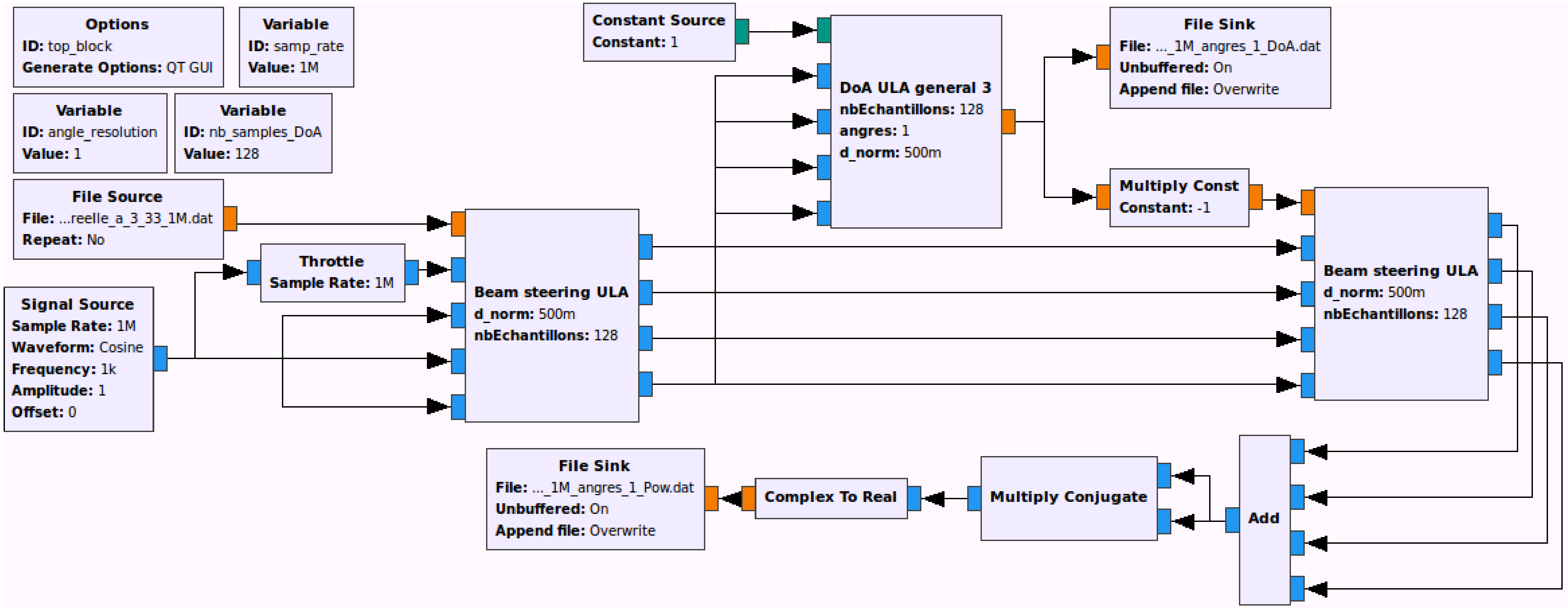


Estimated DOA used to steer array main lobe in projectile direction in real-time

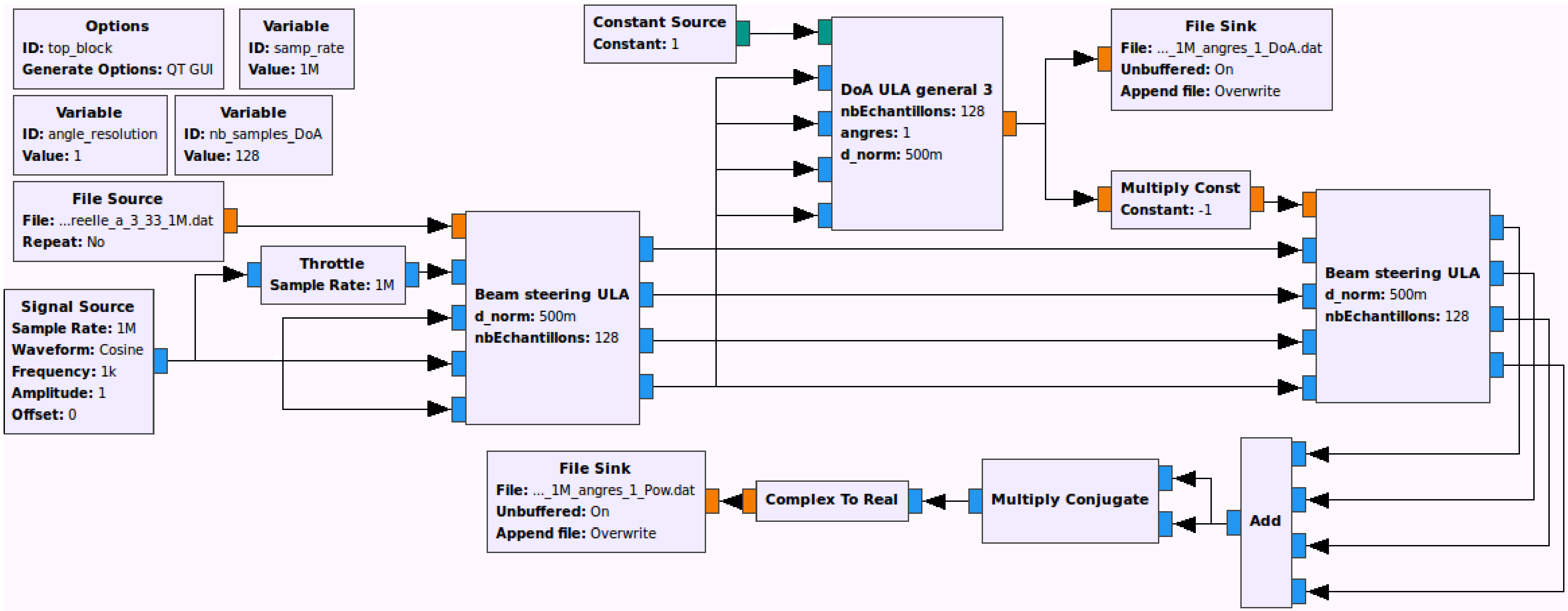
θ values were generated from a previous firing to run simulations in GNU Radio

Simulation in GNU Radio



Expected performance for a particular setup

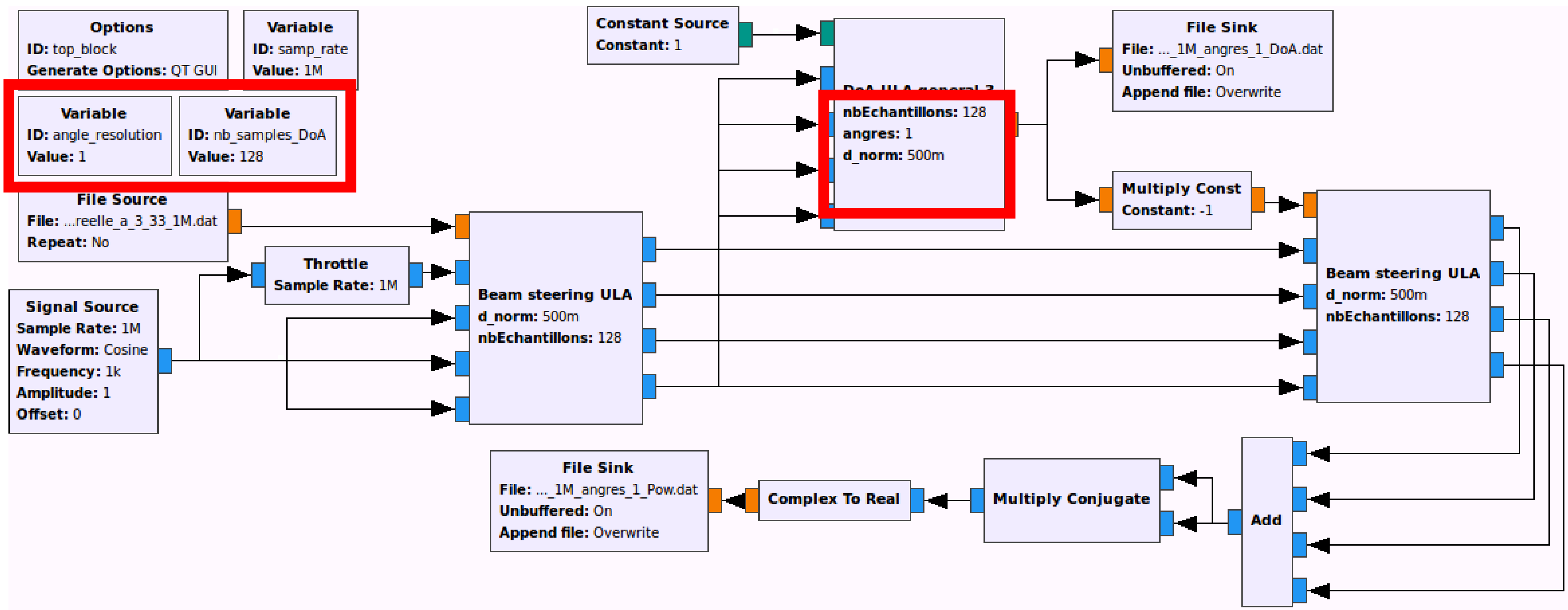
Simulation in GNU Radio



Expected performance for a particular setup

θ values simulate sampling for projectiles of different speeds and for different sampling rates

Simulation in GNU Radio

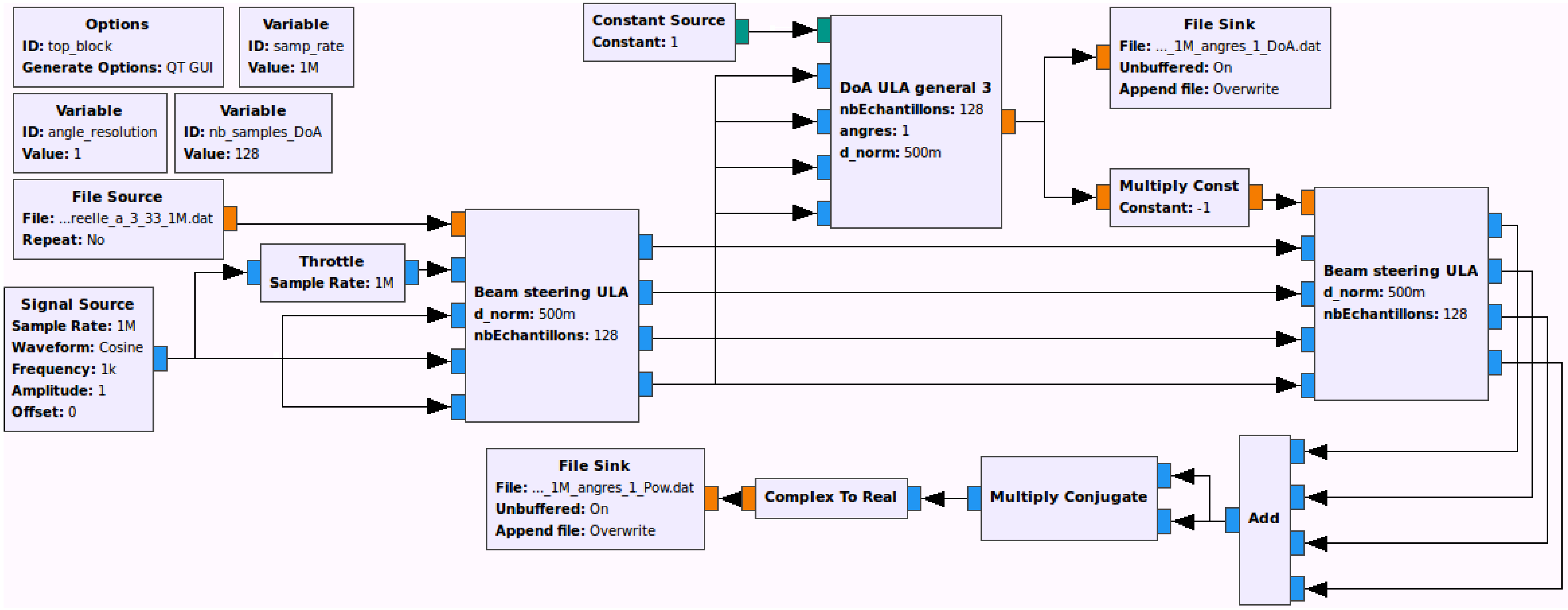


Expected performance for a particular setup

θ values simulate sampling for projectiles of different speeds and for different sampling rates

DOA estimation performance can be adjusted by setting DOA search angular resolution and number of samples per estimation.

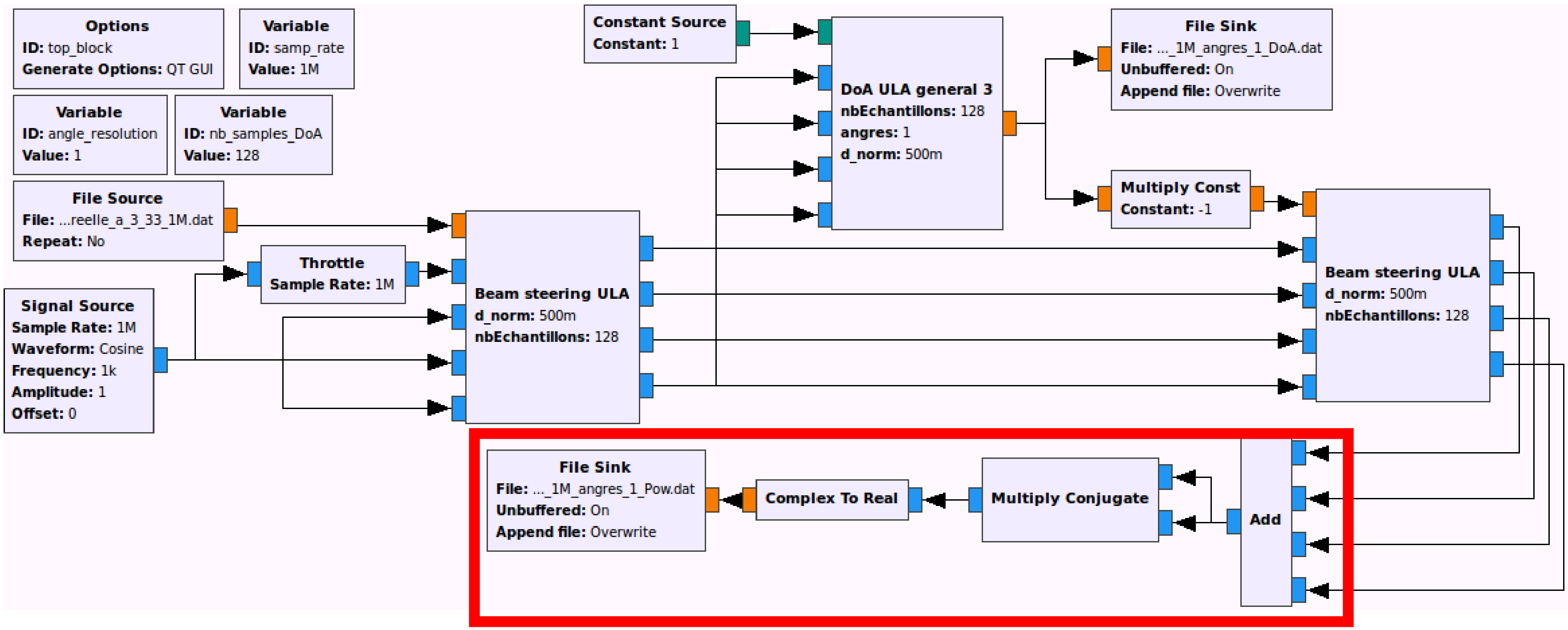
Simulation in GNU Radio



Expected performance for a particular setup

Signal amplitudes normalized to unit

Simulation in GNU Radio

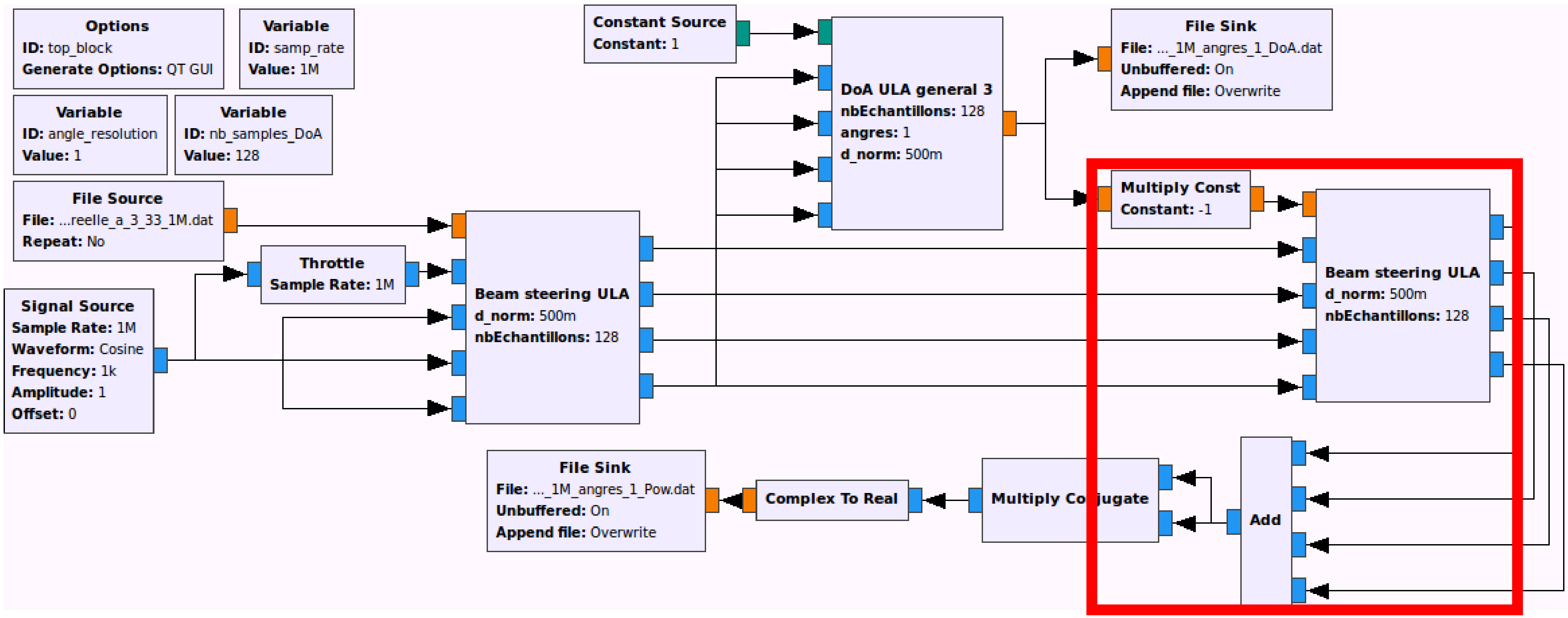


Expected performance for a particular setup

Signal amplitudes normalized to unit

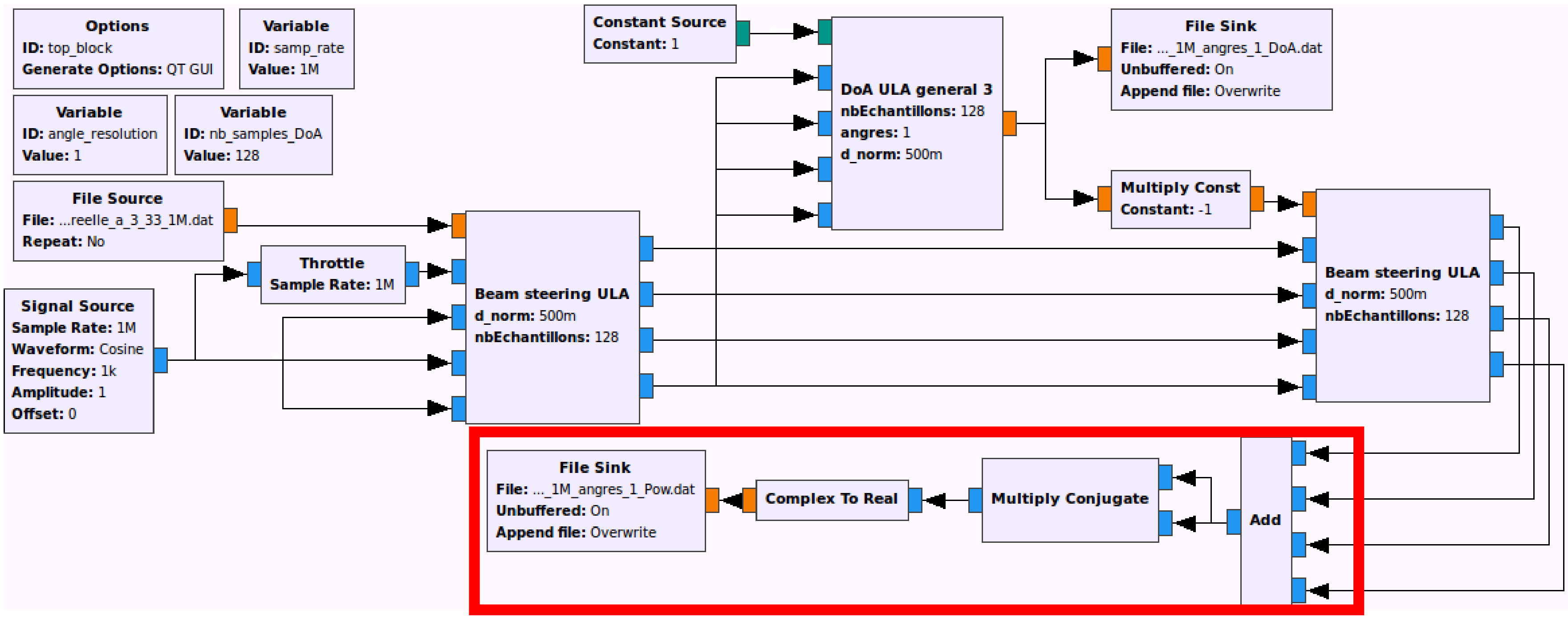
Program ability to maintain phase alignement between channels assessed by computing $|s_{BF}^T|^2$

Simulation in GNU Radio



$$Sum\ signal(\theta, \theta_{DOA}) = \sum_{n=1}^{4} e^{j(n-1)\frac{2\pi}{\lambda} d(sin\theta\ - sin\theta_{DOA})}$$

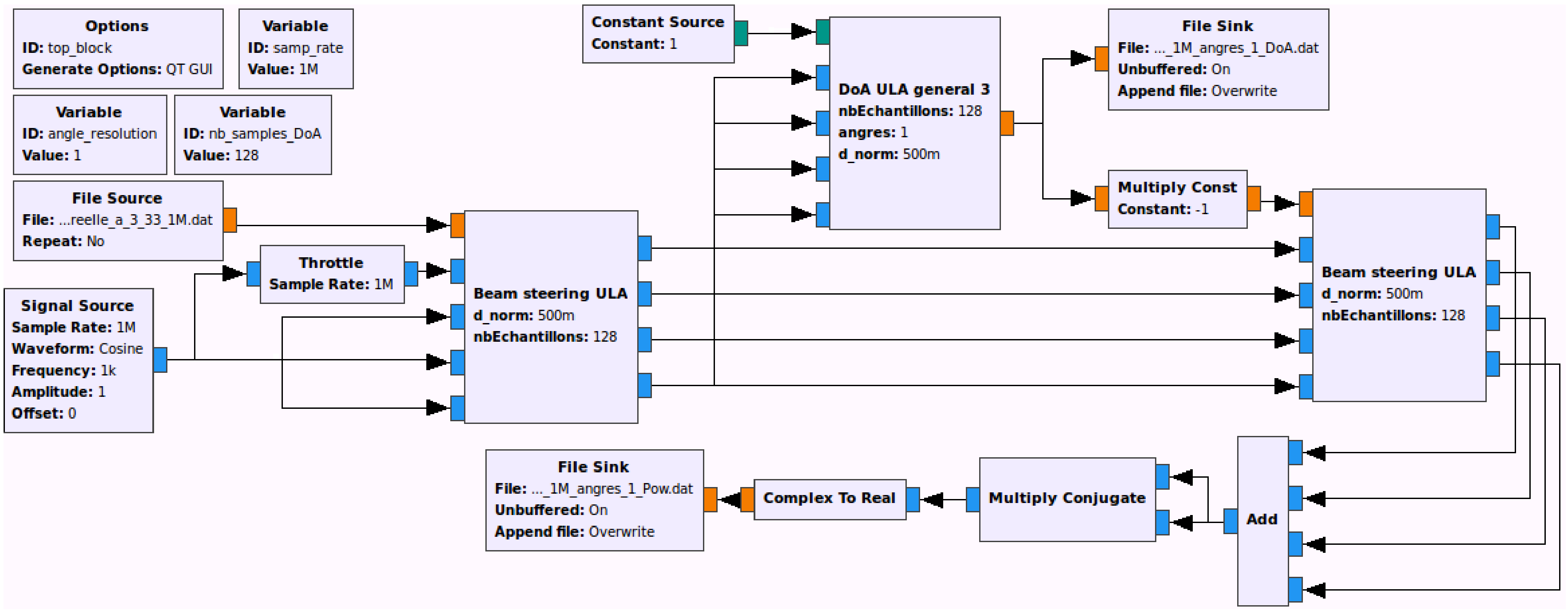
Simulation in GNU Radio



$$Sum\ signal(\theta, \theta_{DOA}) = \sum_{n=1}^{4} e^{j(n-1)\frac{2\pi}{\lambda} d(sin\theta - sin\theta_{DOA})}$$

$$G_{reception\ simulation}(\theta, \theta_{DOA}) = \left| \sum_{n=1}^{4} e^{j(n-1)\frac{2\pi}{\lambda} d(sin\theta - sin\theta_{DOA})} \right|^2$$

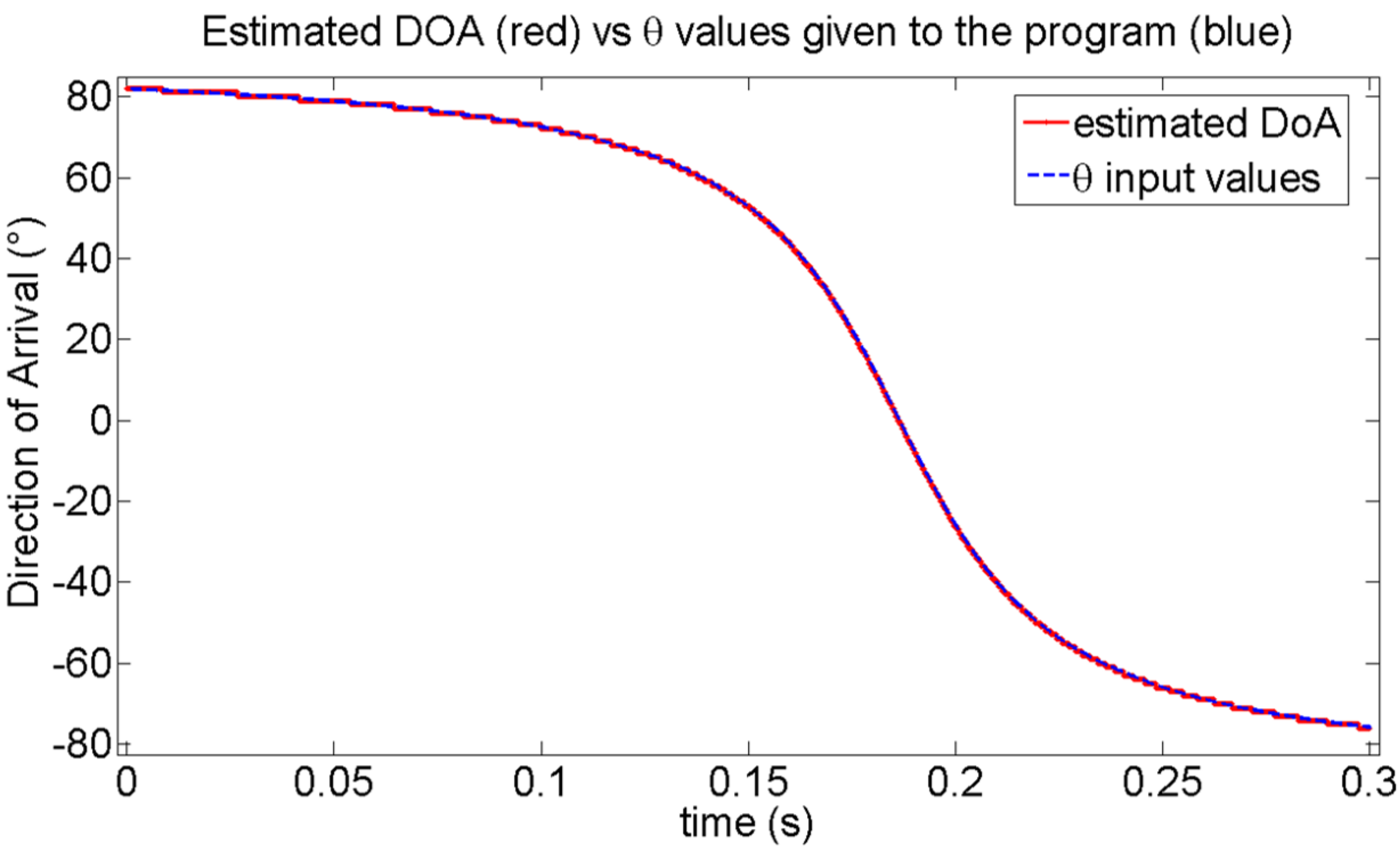
Simulation in GNU Radio



Presented simulation is for a projectile flying at Mach 4,9 (≈ 1670 m/s)

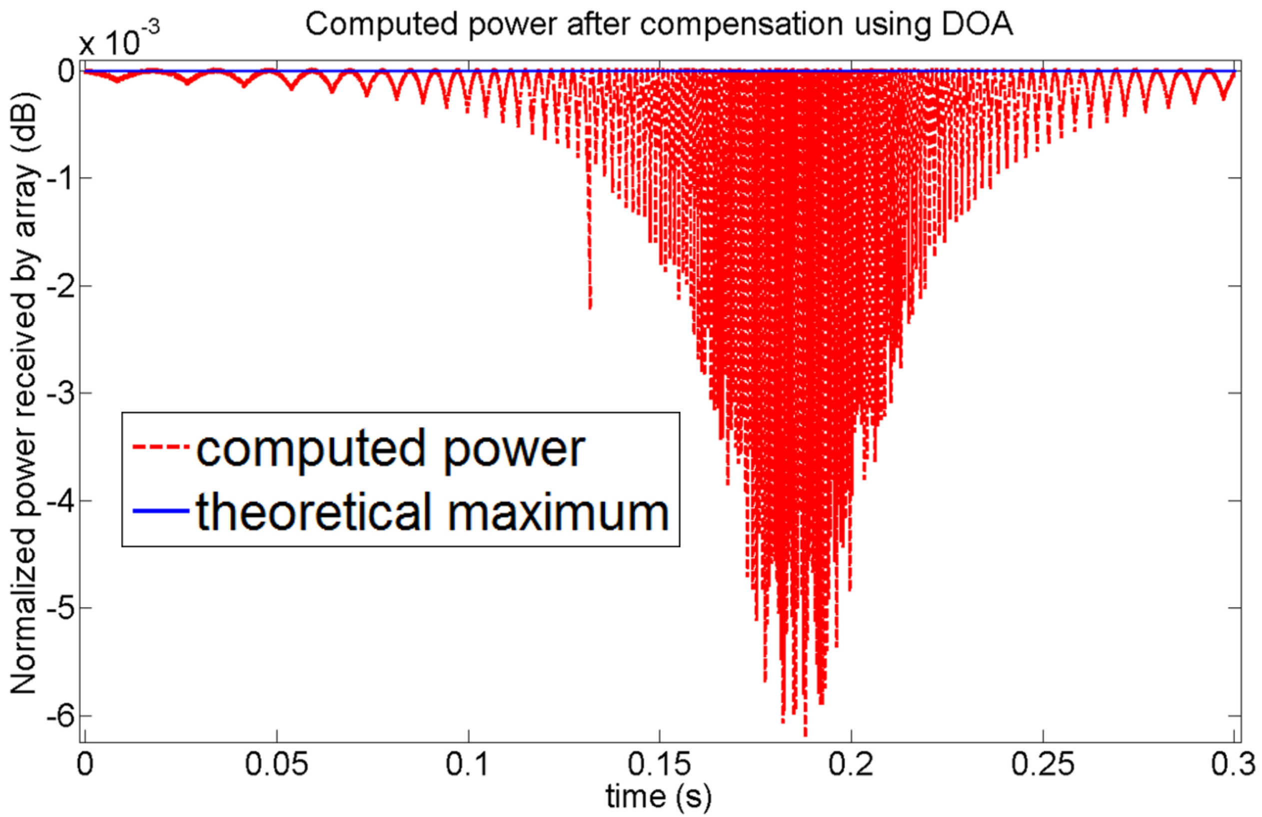
Sampling rate 1MS/s, DOA search 1° precise with 128 samples per DOA estimation

Simulation in GNU Radio



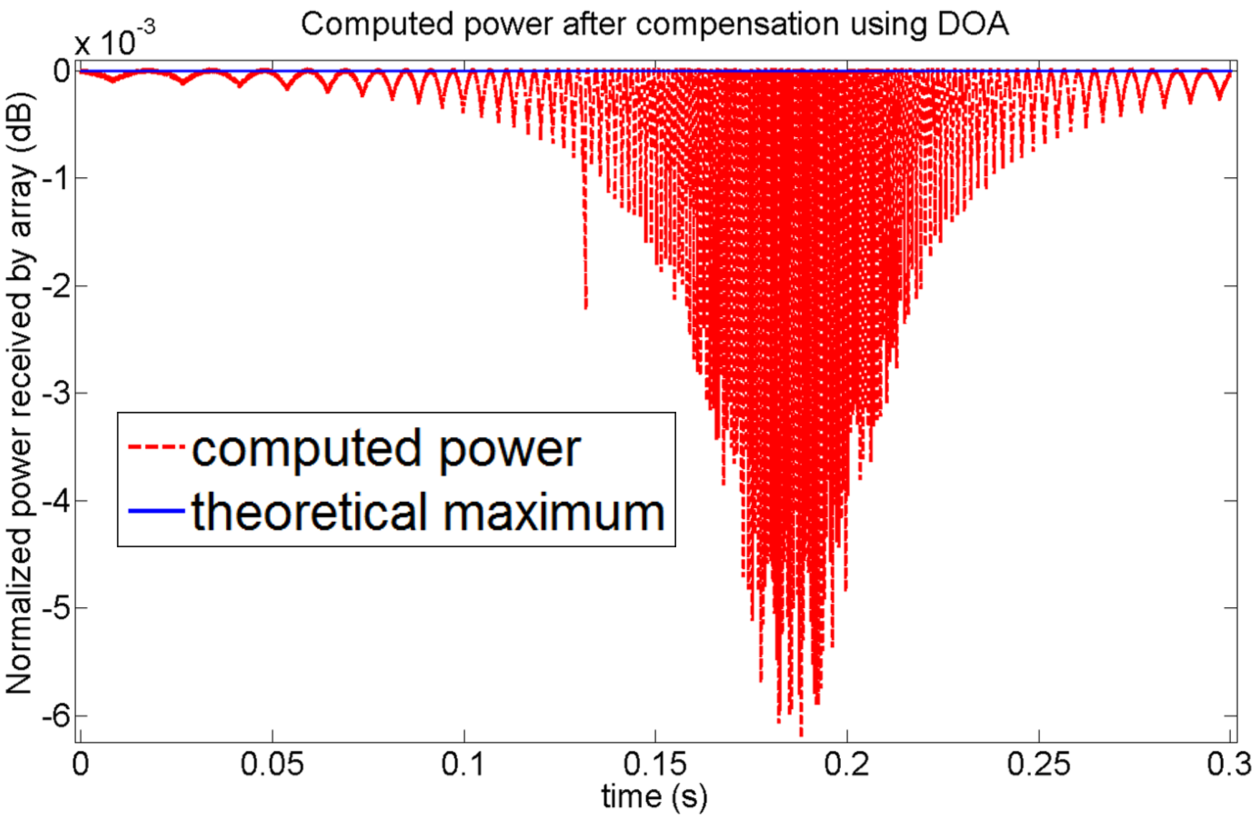
Simulation shows the program can accurately follow the projectile at Mach 4,9 (faster than real fired projectiles)

Simulation in GNU Radio



Reception gain variations below $10^{-2} dB$

Simulation in GNU Radio



Reception gain variations below $10^{-2} dB$

➡ successfully maintained constant over projectile trajectory by accurately steering array main lobe in projectile direction.

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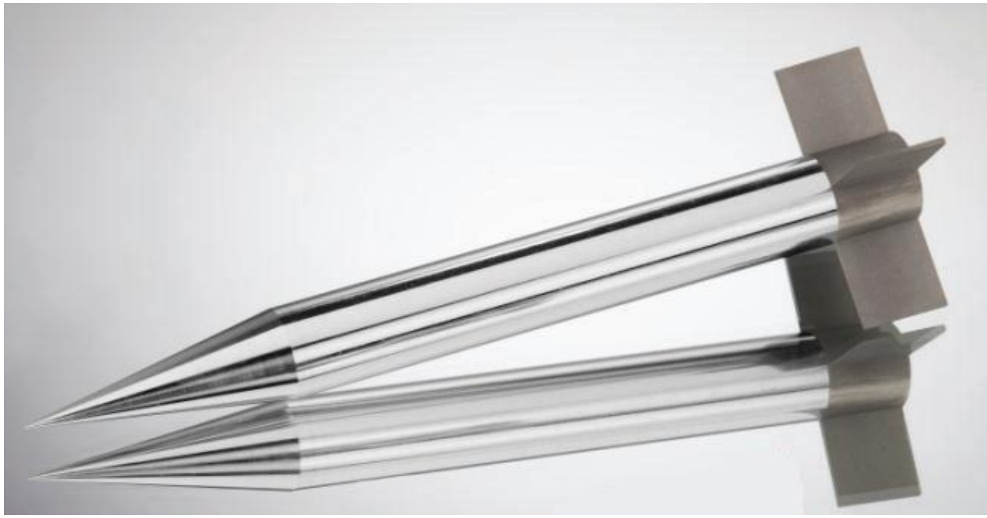
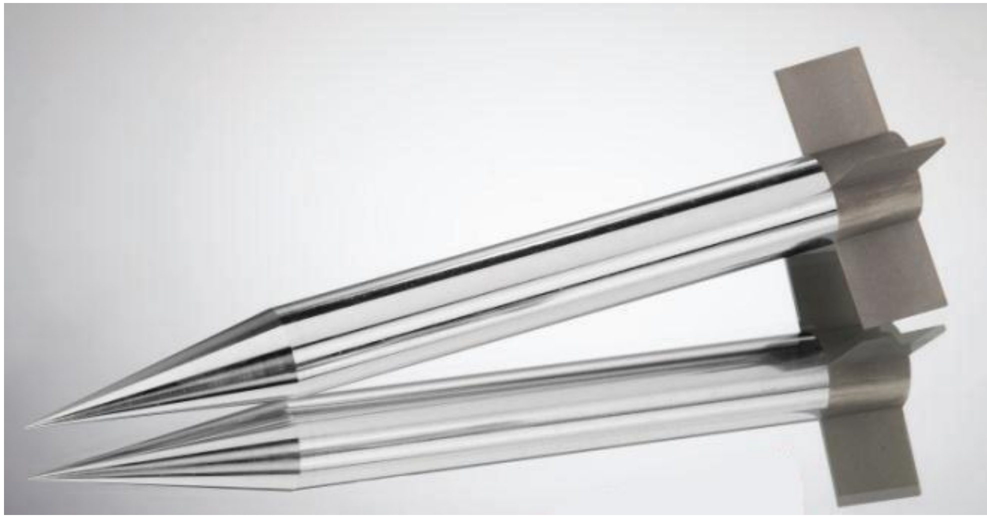
Measurement results



Fired projectiles

Measurement results



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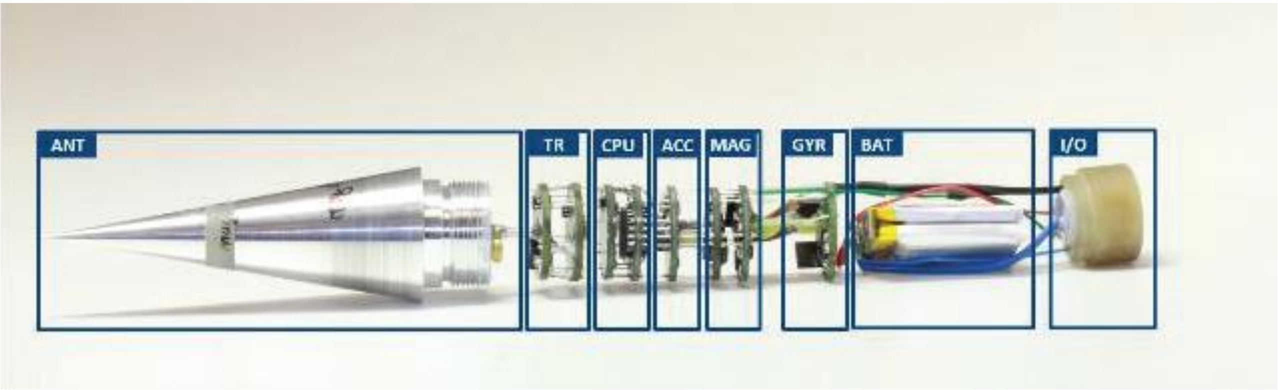
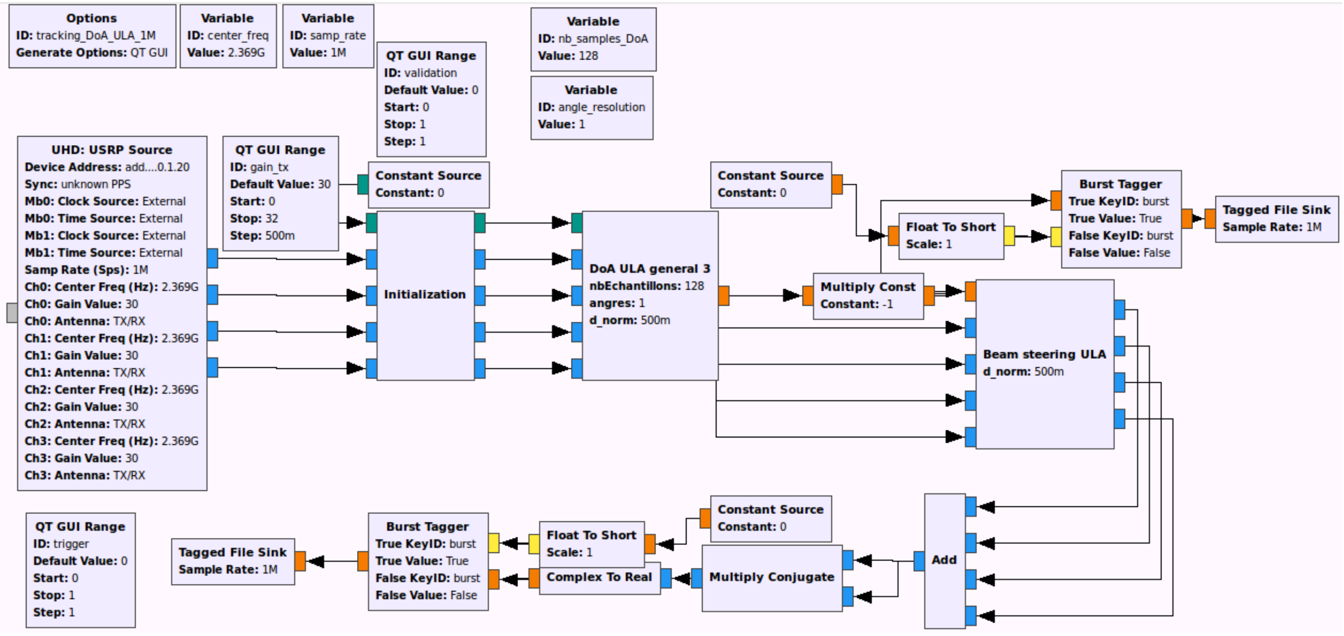


Embedded electronics

Measurement results



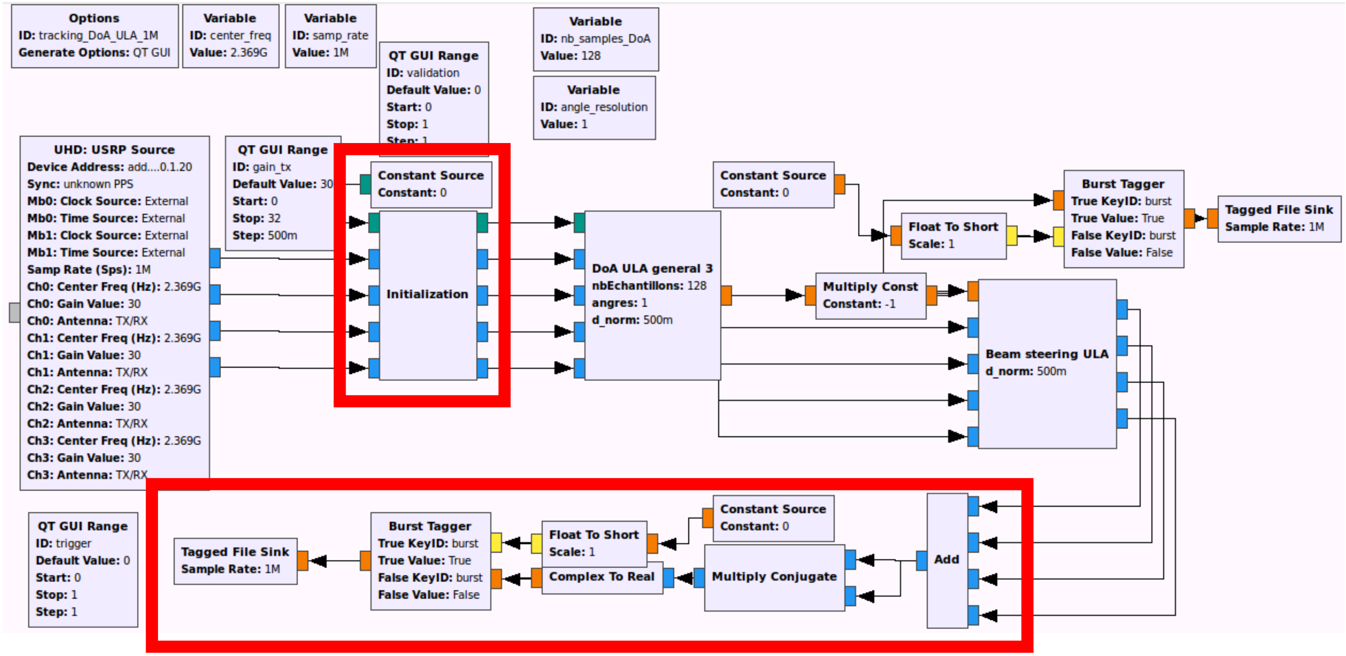
Projectiles fired at Mach 1,3 in June

Transmitter onboard projectile GFSK 2Mbits/s @ 2,369 GHz

Projectile directly visible by antenna array in the [-60°; +50°] angular range

Conventional beamformer (Bartlett) algorithm
1MS/s sampling rate
128 samples per DOA estimation with 1° of angular resolution

Measurement results

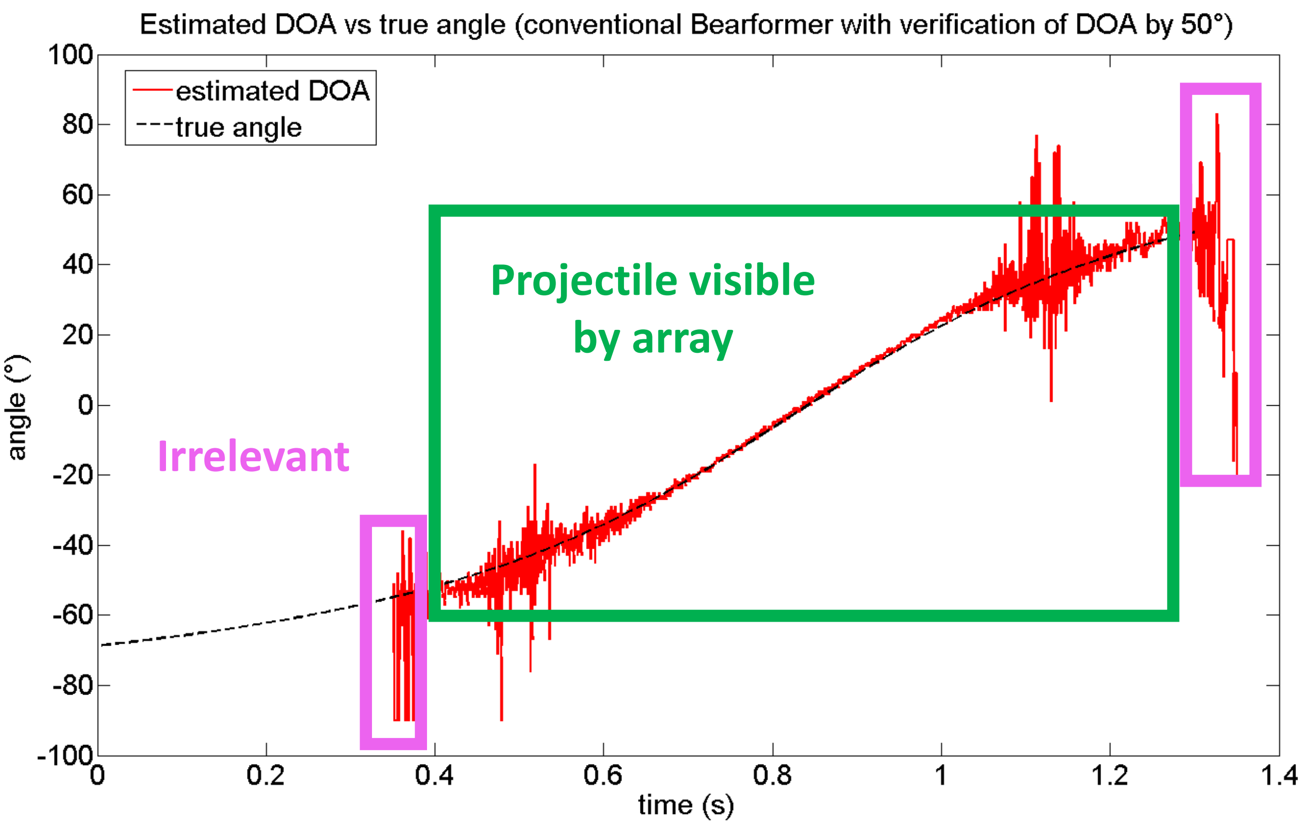


Compensation of phase-shifts created by hardware and antennas

$$G_{reception\ measurement}(\theta, \theta_{DOA}) = \left| \sum_{n=1}^{4} e^{j(\varphi_{ant\ n}(\theta) - \varphi_{ant\ n}(\theta=0^\circ))} \ e^{j(n-1)\frac{2\pi}{\lambda}(\sin\theta - \sin\theta_{DOA})} \right|^2$$

Measurement results

1^{st} projectile

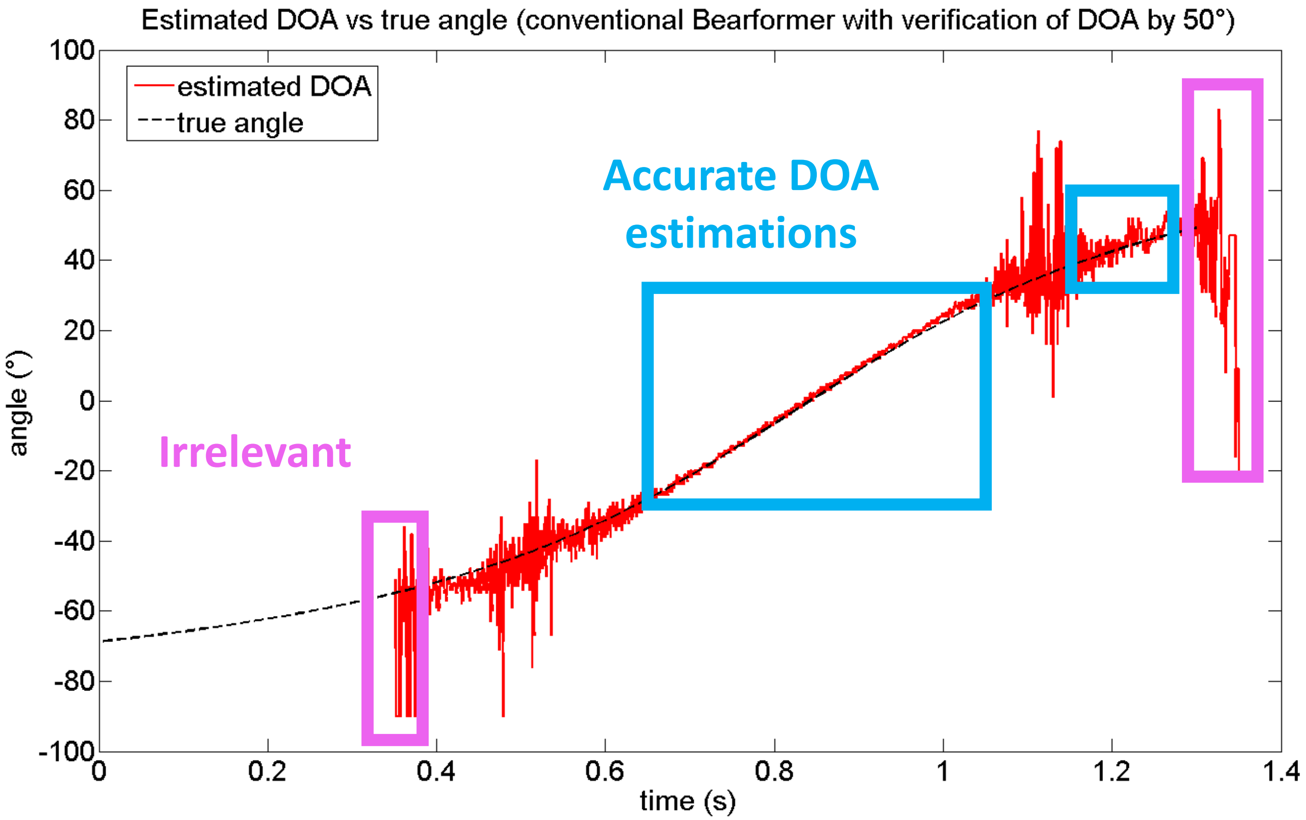


Projectile visible by array when in [-60°; +50°]

Measurements outside [-60°; +50°] irrelevant

Measurement results

1st projectile

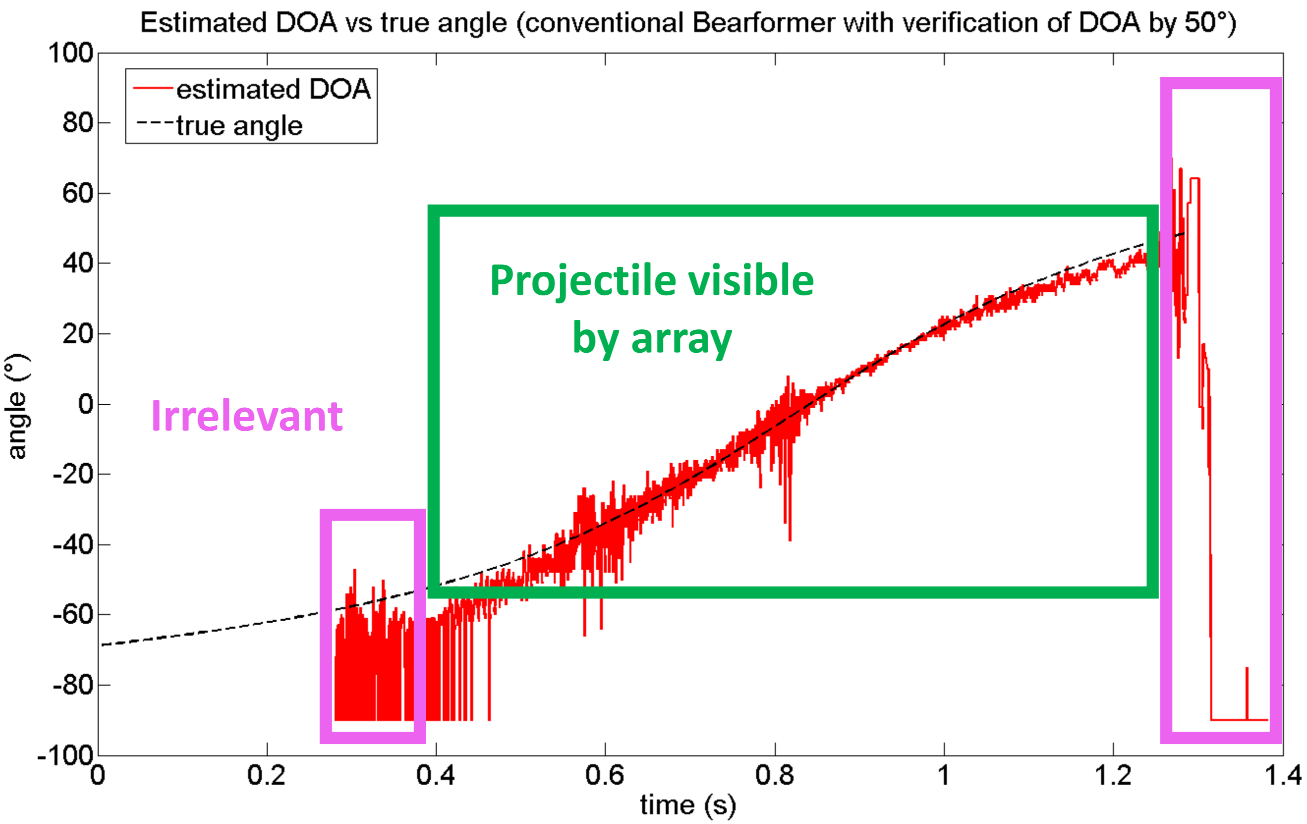


Accurate DOA acquisition in [-30°; +30°]

Noise peaks between 0,5 and 0,6s, and between 1,1 and 1,2s.

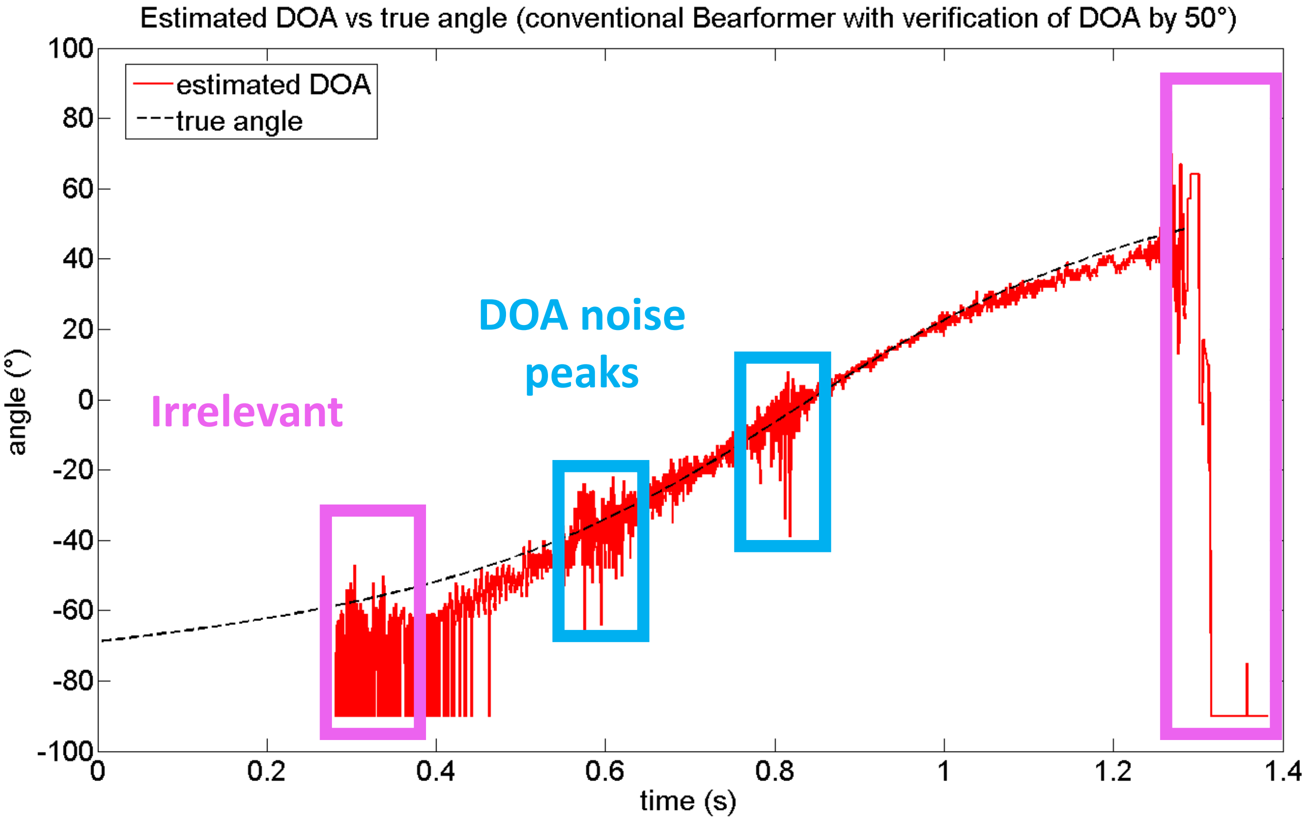
Measurement results

2nd projectile



Measurement results

2nd projectile

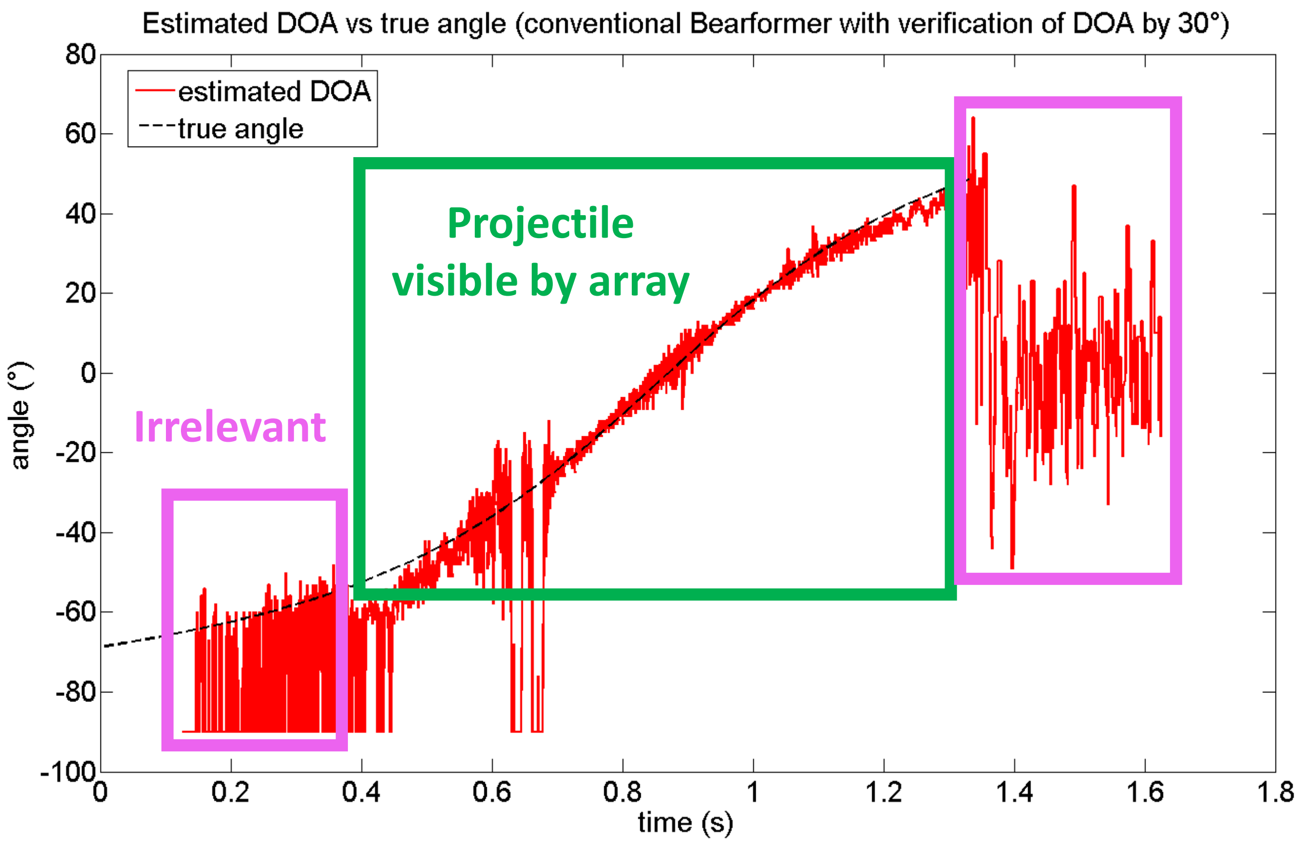


DOA acquisition noisier than with the 1st projectile

Noise peaks between 0,5 and 0,6s, and between 0,8 and 0,9s

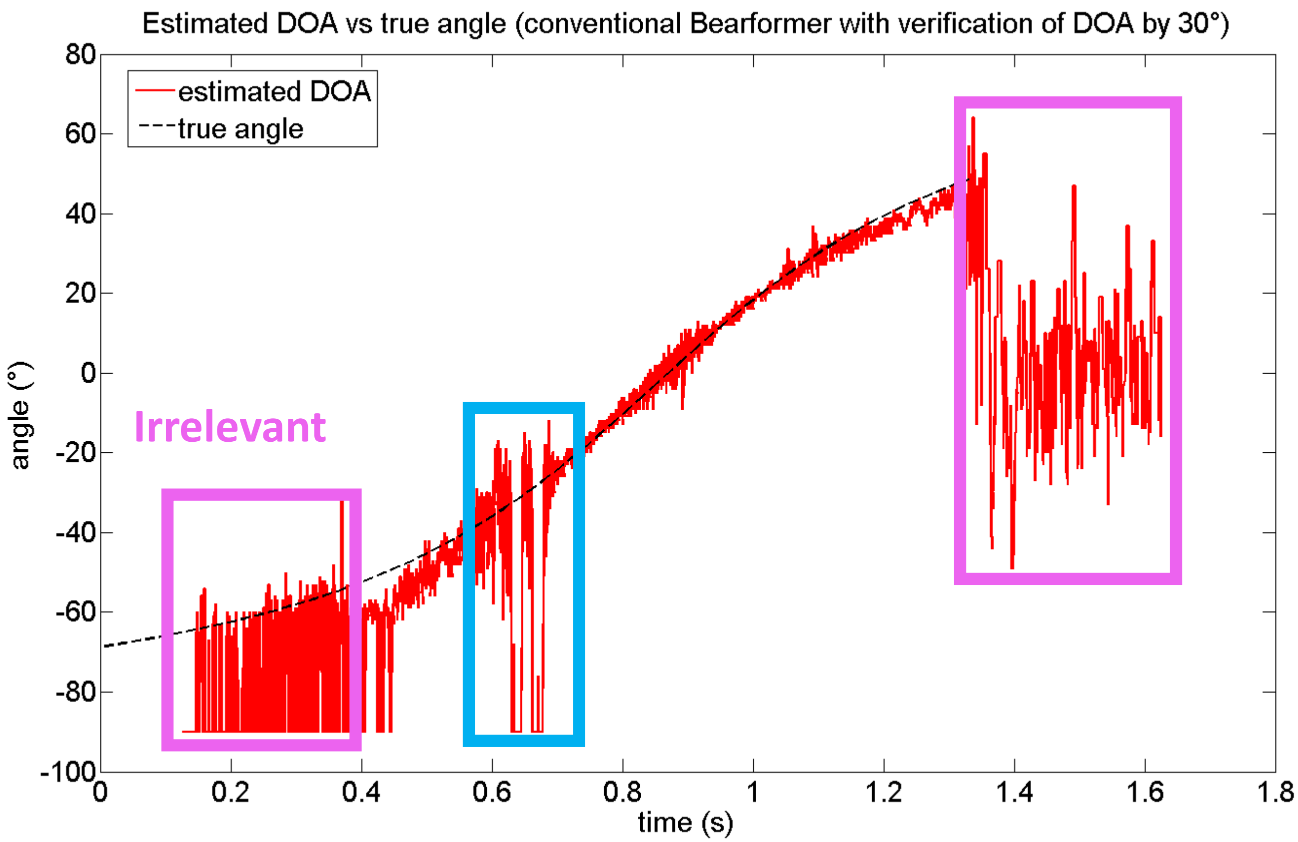
Measurement results

3rd projectile



Measurement results

3rd projectile

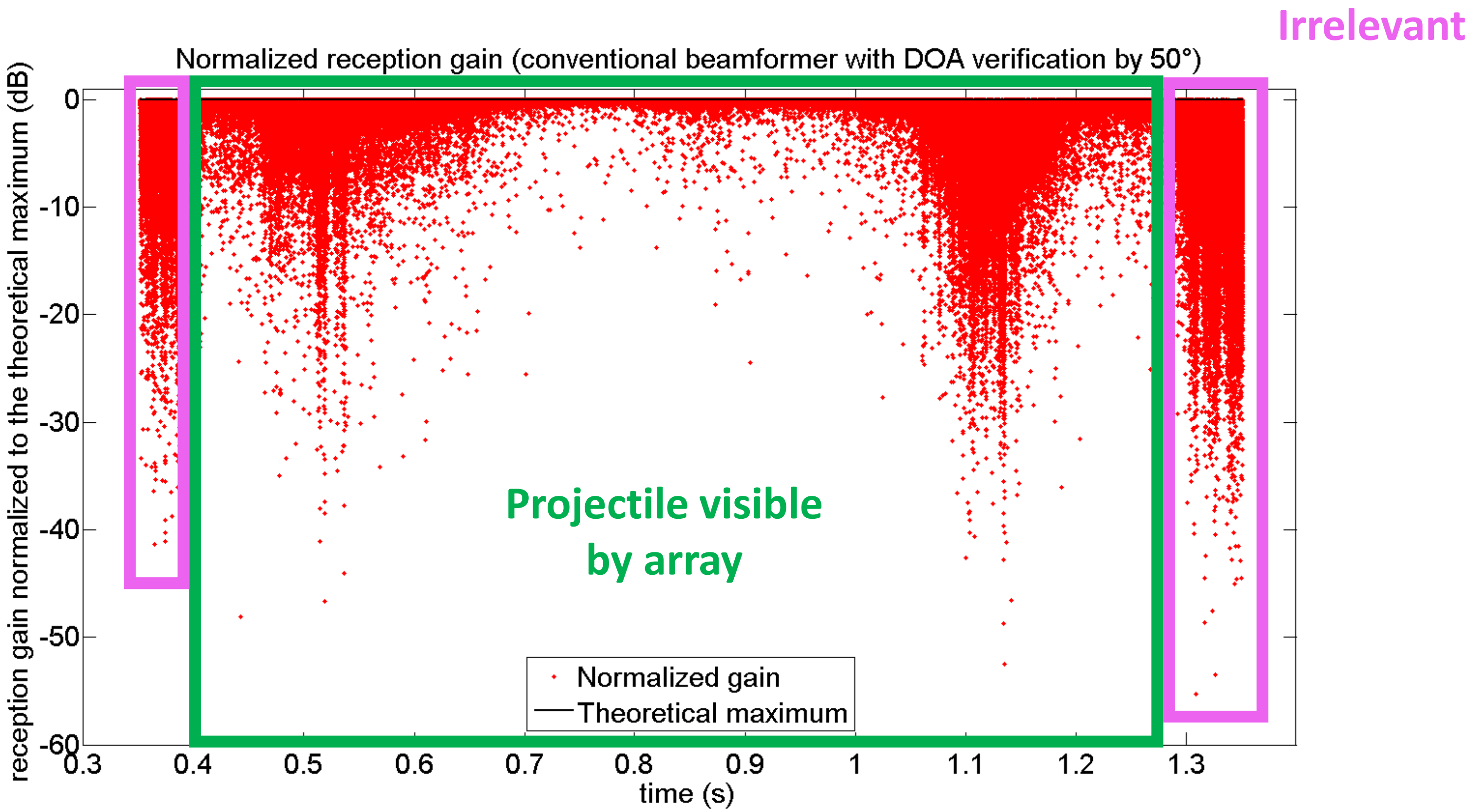


DOA verification loop blocked DOA at -90° between 0,7 and 0,8s

➡ wrong estimates over 0,05s

Measurement results

1st projectile

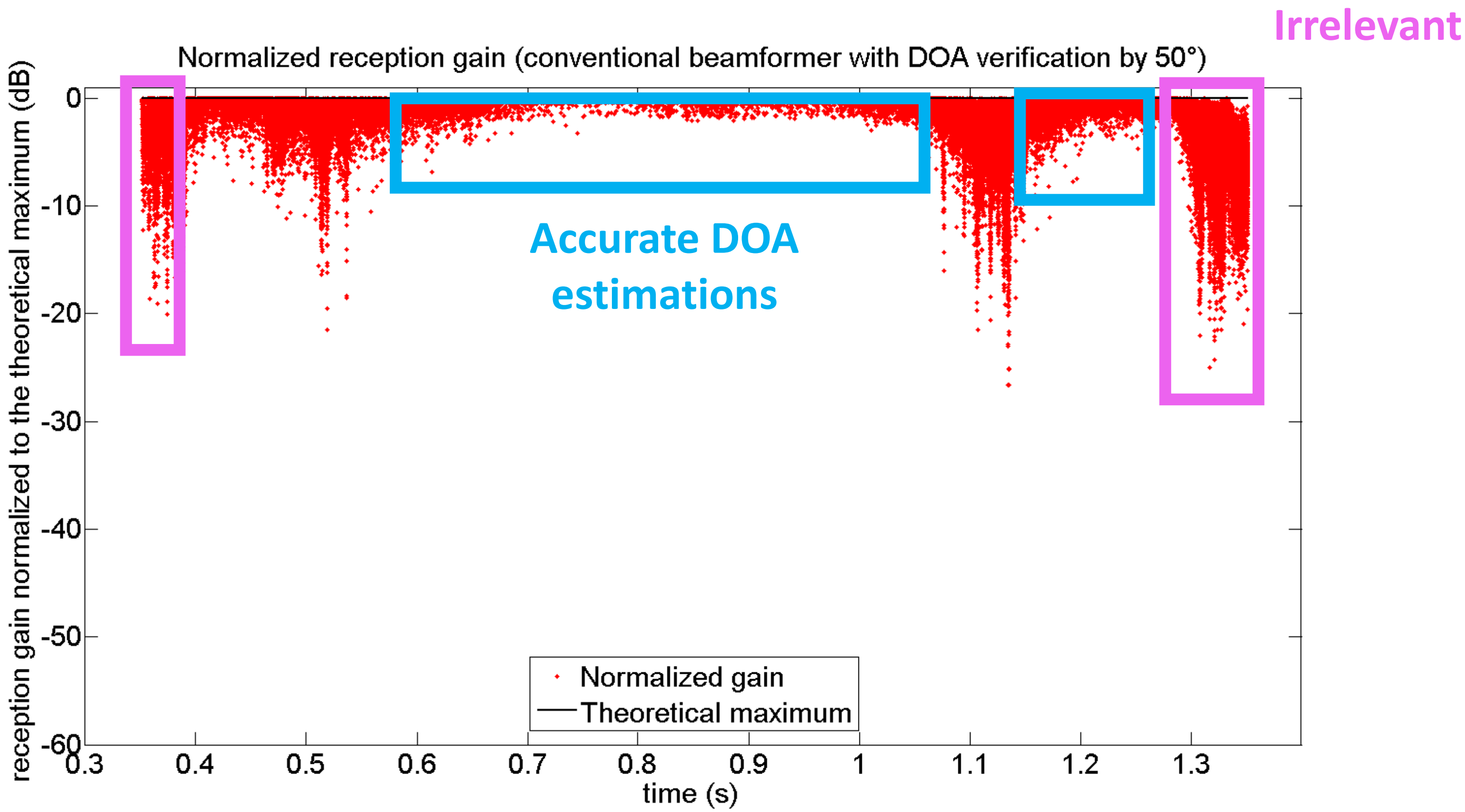


Some points indicate gain losses

Measurement results

3 point averaging

1st projectile



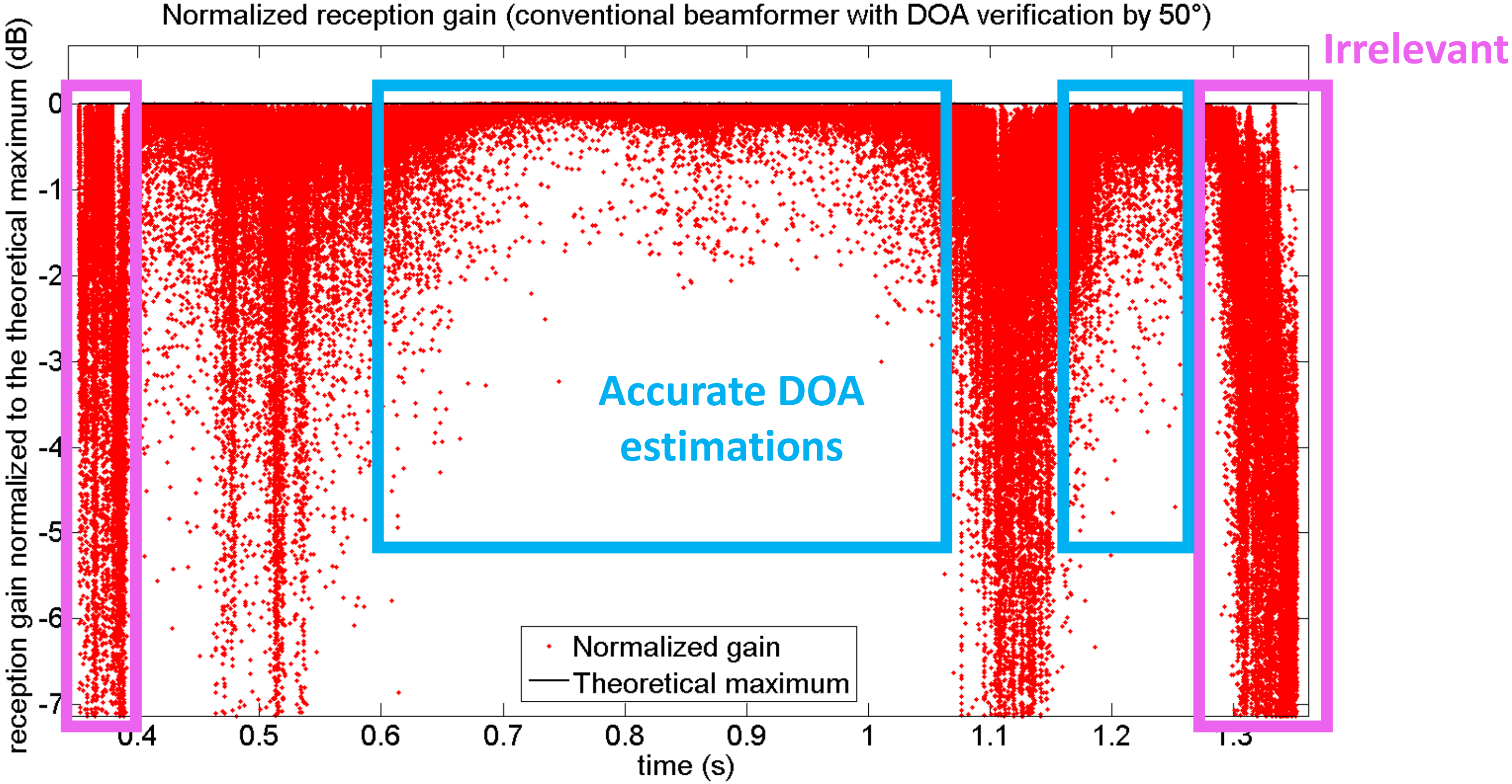
Gain losses represent a minority of points

Besides noise peaks, reception gain is constant within 5dB

Measurement results

3 point averaging (Zoom)

1st projectile



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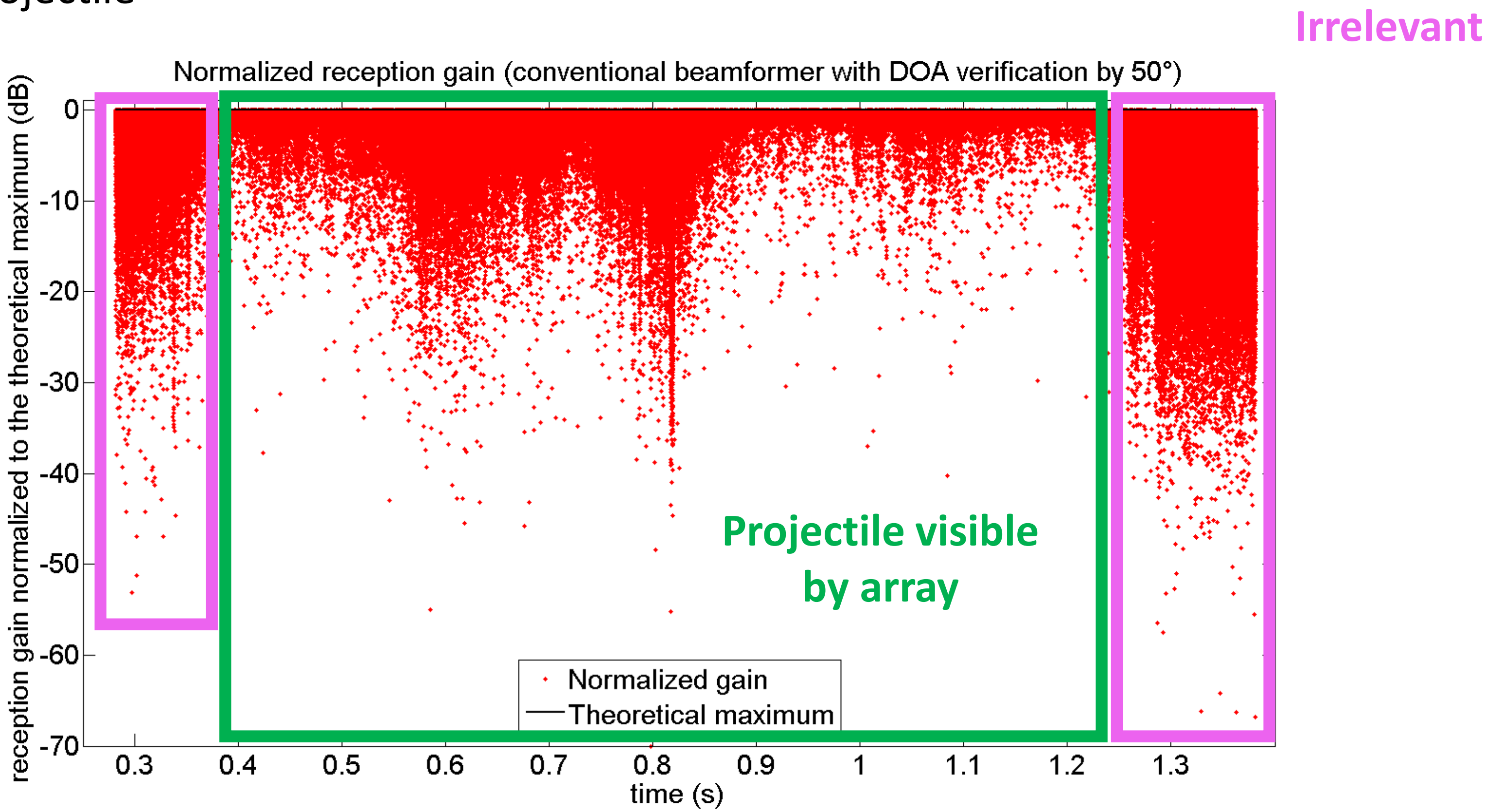
Besides noise peaks, reception gain is constant within 5dB

Measurement results

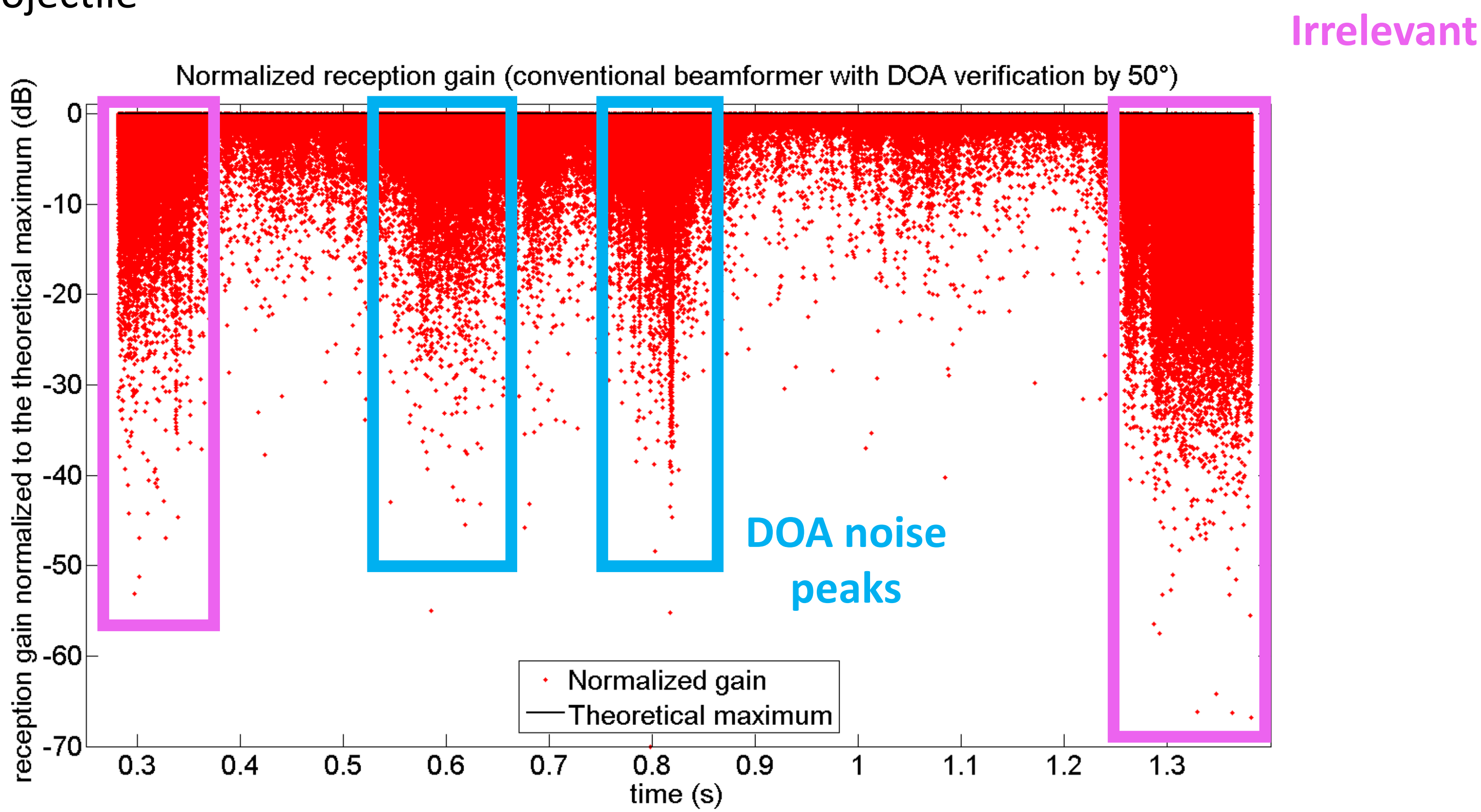
2nd projectile



Noise peaks on DOA estimations induce more gain losses

Measurement results

2nd projectile

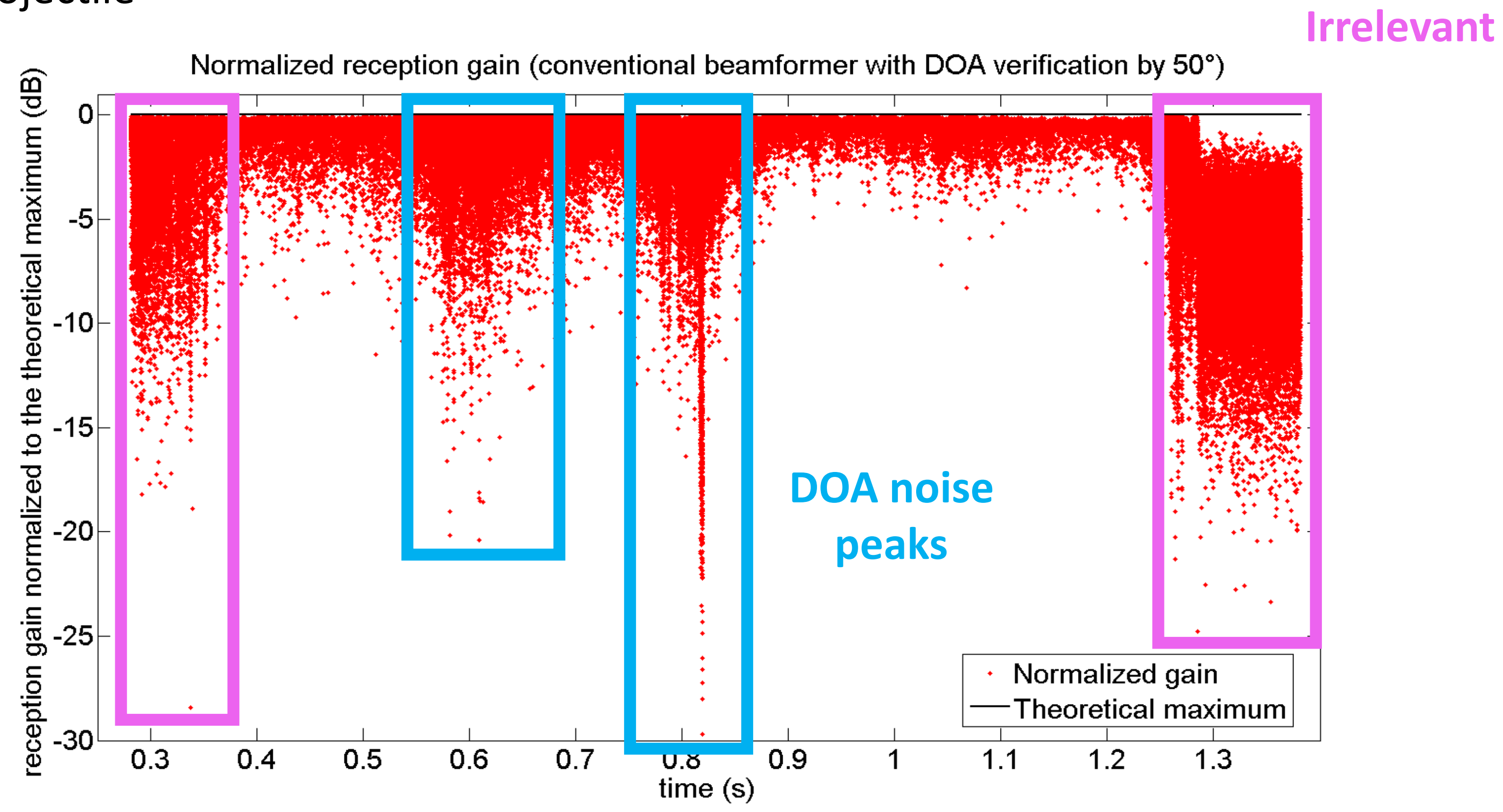


Noise peaks on DOA estimations induce more gain losses

Measurement results

3 point averaging

2nd projectile

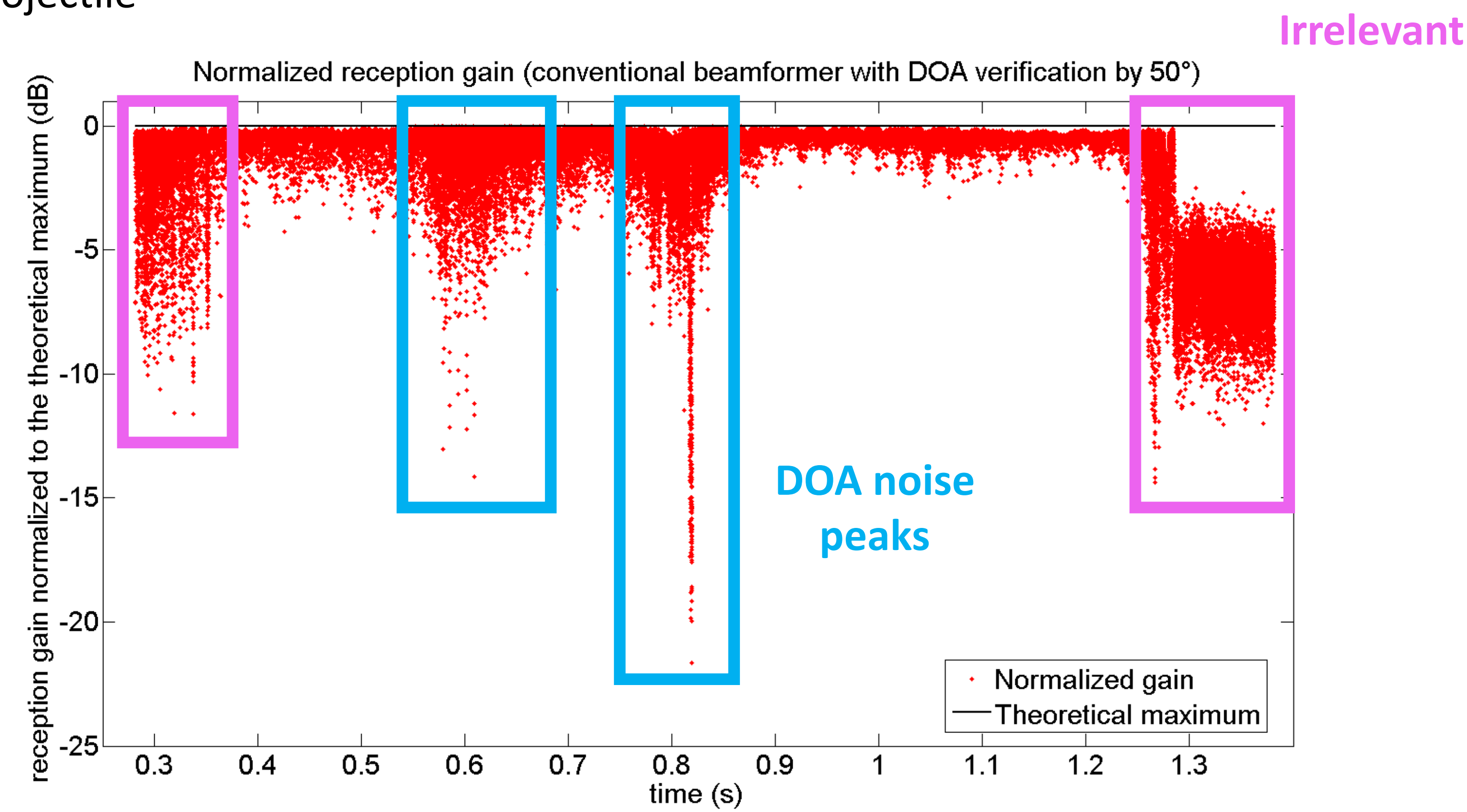


Majority of points remain above -5dB when correct DOA estimation

Measurement results

10 point averaging

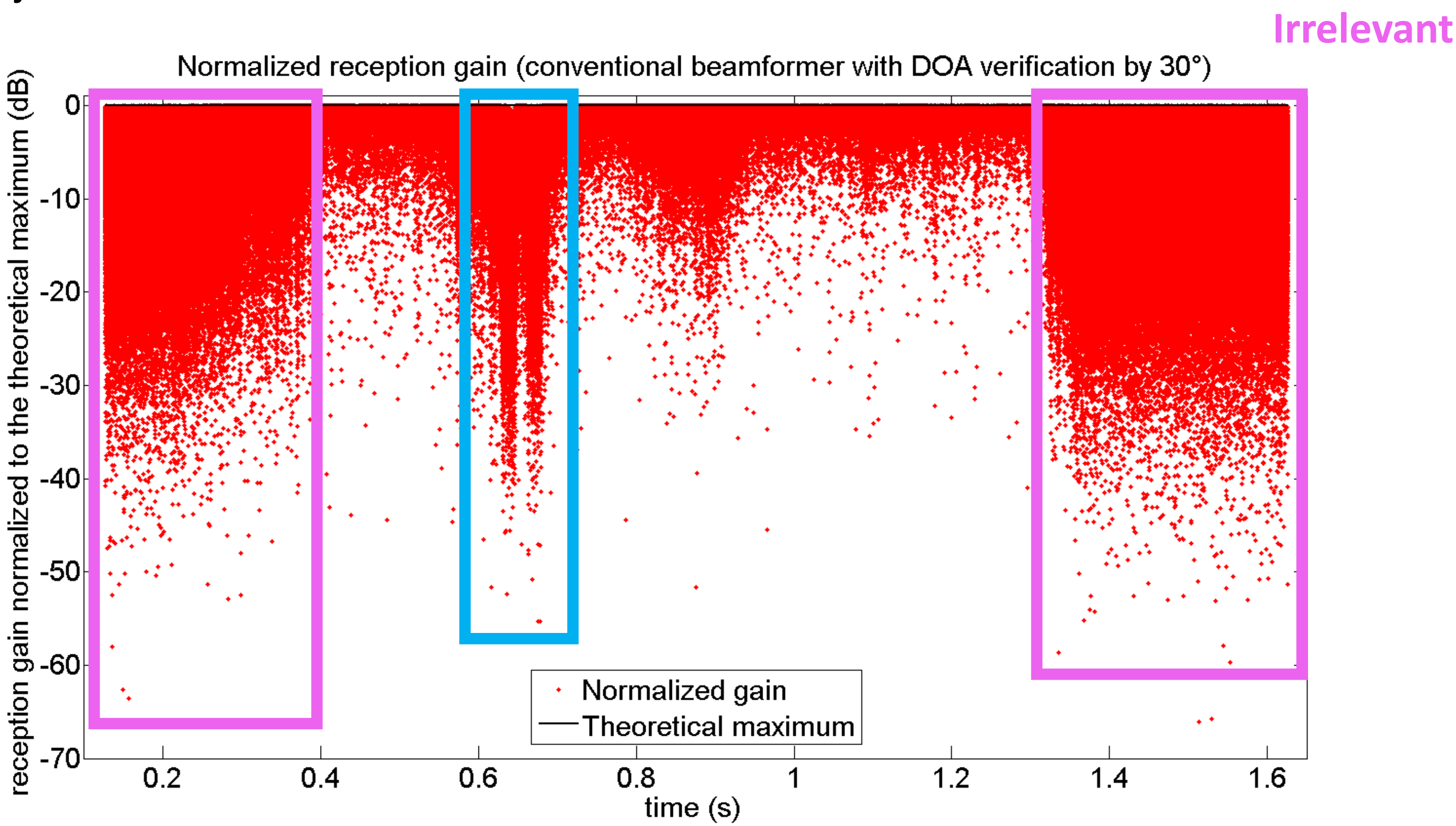
2nd projectile



Majority of points remain above -5dB when correct DOA estimation

Measurement results

3rd projectile



DOA verification loop blocked DOA at -90° between 0,7 and 0,8s

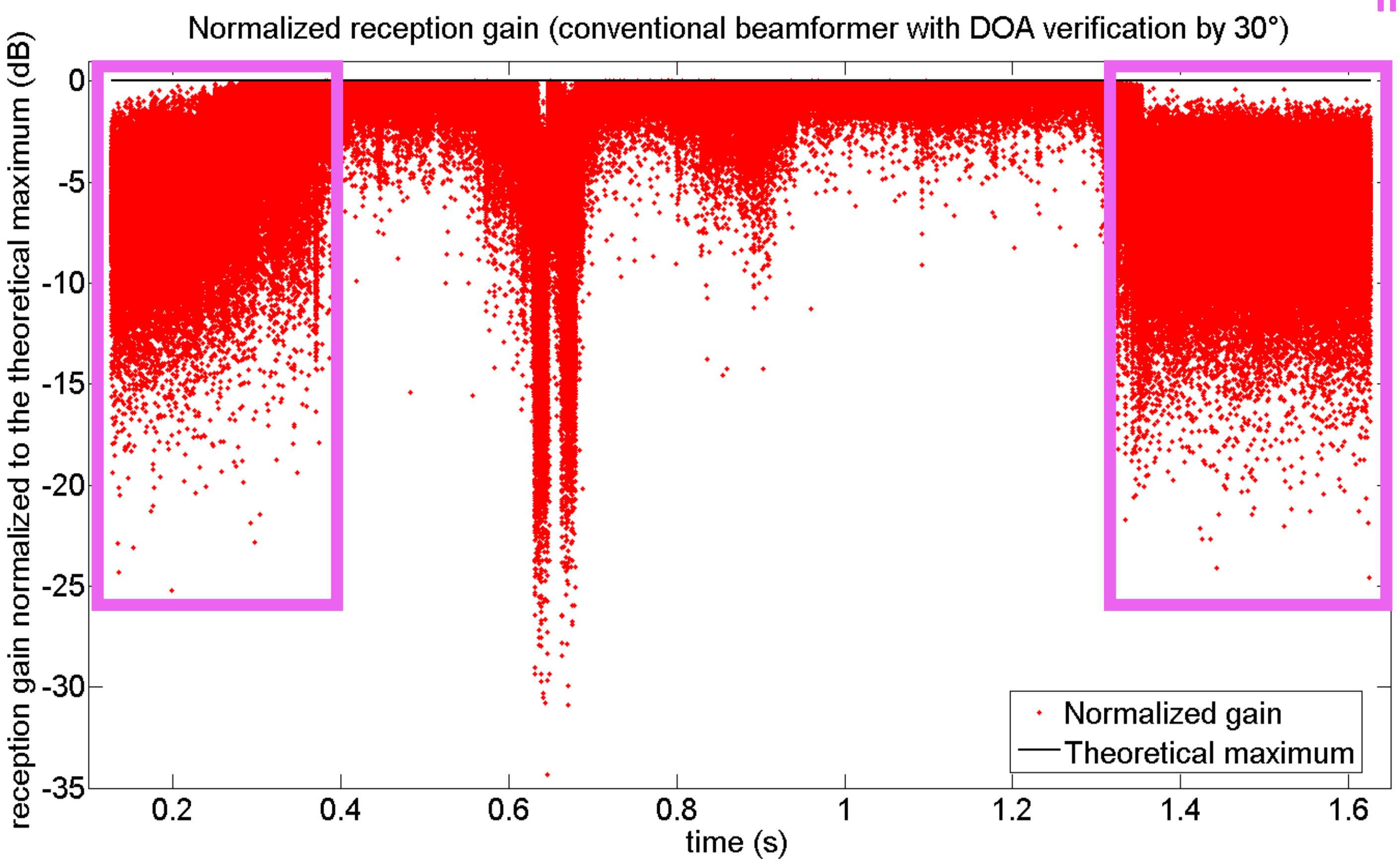
wrong estimates over 0,05s

Measurement results

3 point averaging

3rd projectile

Irrelevant

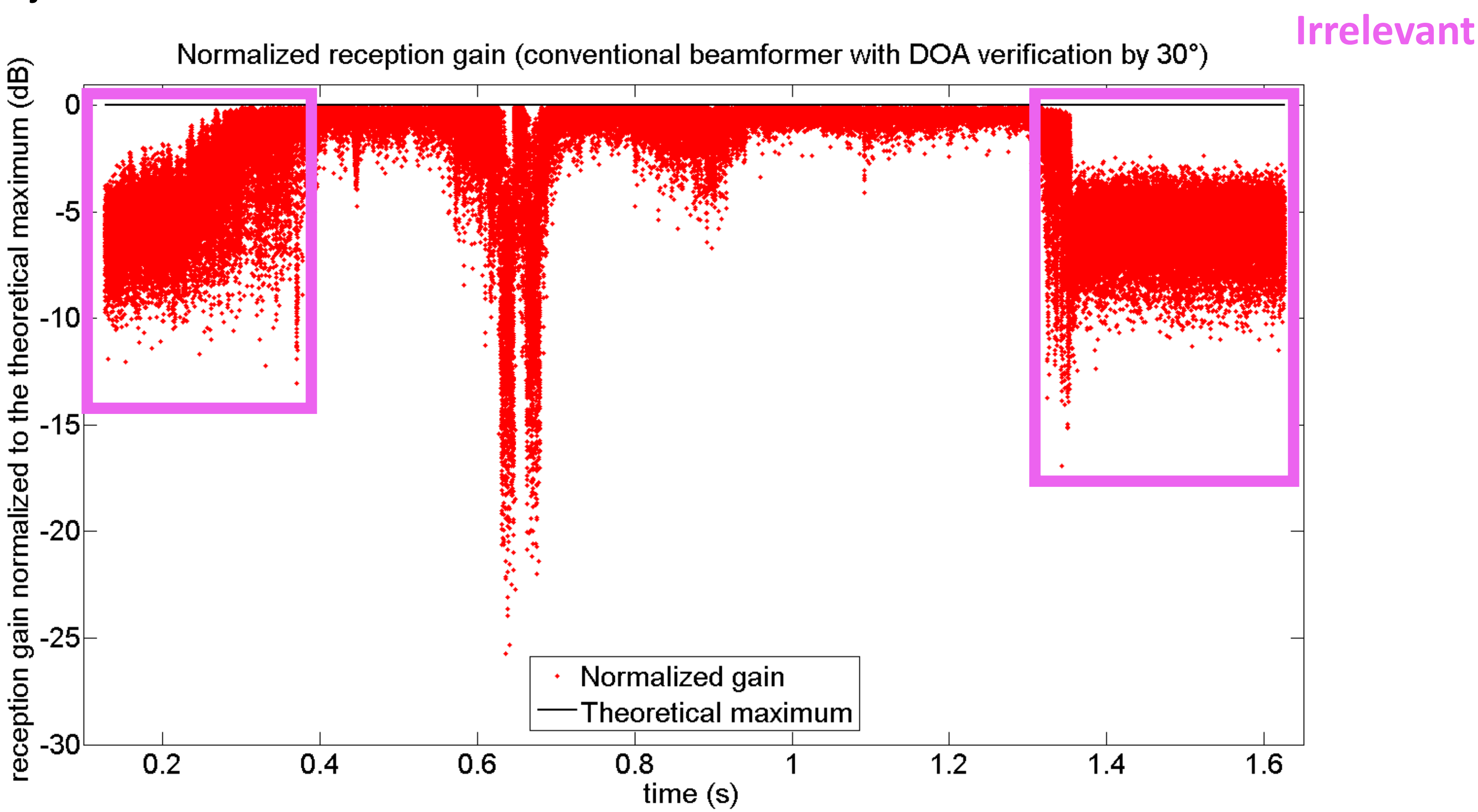


DOA errors aside, the averaged reception gain remains over -5dB over the projectile trajectory

Measurement results

10 point averaging

3rd projectile



DOA errors aside, the averaged reception gain remains over -5dB over the projectile trajectory

Overview

Background

Proposed solution

Used signal processing

Simulation in GNU Radio

Measurement Results

Conclusion and Outlooks

Conclusion

A passive solution for high-speed projectile tracking using commercial UBX-160 and GNU Radio is proposed

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First measurements have been performed with real projectiles and have demonstrated the system ability to follow projectiles in real conditions

Errors in DOA have been found, but the reception gain has been shown to remain constant within 5dB for the projectile trajectory with accurate estimation

Outlooks

Measurements using other DOA algorithms (Capon)

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Hardware update for remote measurement triggering

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Increase of the sampling rate to 25MS/s to run while performing telemetry reception measurements

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Research on embedding SDR components in gyrostabilized projectiles