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Interference Detection, Classification and Cancellation from Space

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Contents

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Contents

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Harp Technologies Ltd

- An SME established in 2007, located in Espoo, Finland
- Contract based R&D services in RF, micro- and millimetrewave technologies
- 15 employees
- Co-operates with leading players in the field (inc., e.g., the three LSIs)

Business Lines

Microwave Sensors

- Radars, radiometer systems
- Subsystems, TX & RX modules
- Component modules

WG ferrite components

- WG isolators, switches, circulators
- WG switches up to W-band
- High power components

RF, micro-, and mm-waves

Signal Processing

- Technology and algorithms for emitter detection and counteraction
- Real time signal processing
- Resource-friendly sensors

Electromagnetics

- EM modeling and simulations
- Antenna design
- RCS simulations

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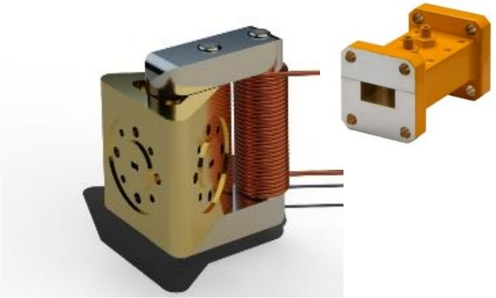
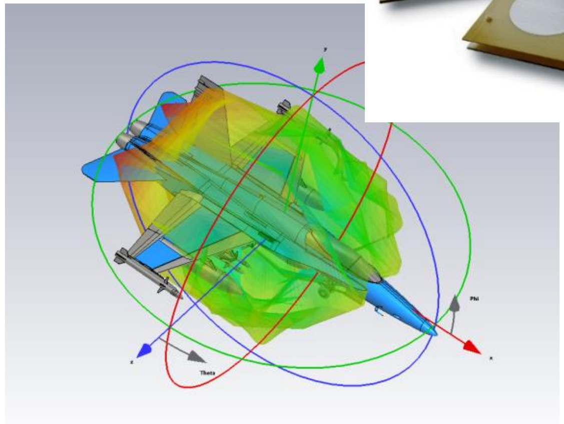
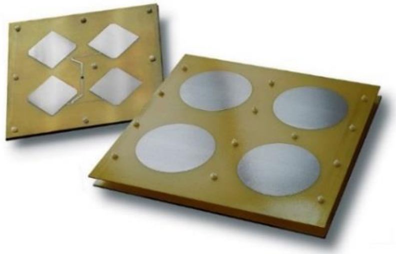
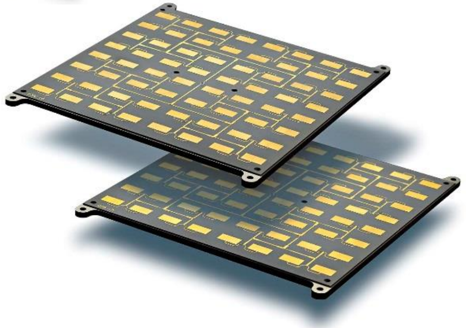
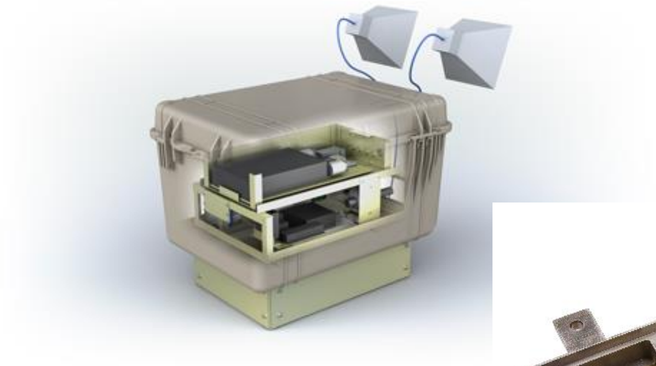
R&D examples

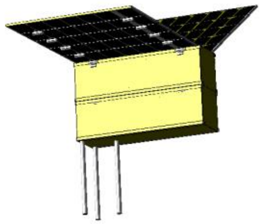


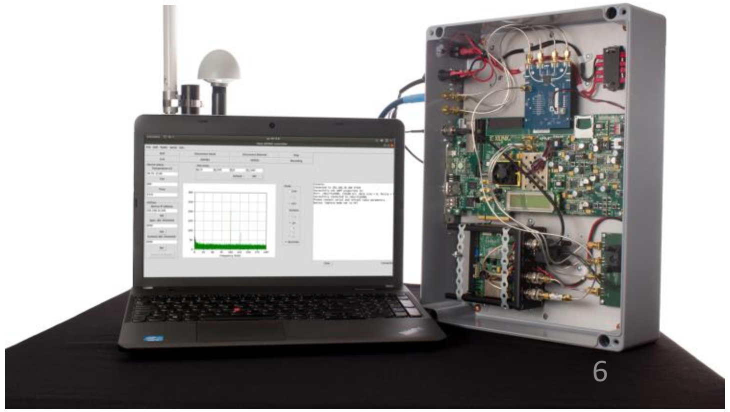








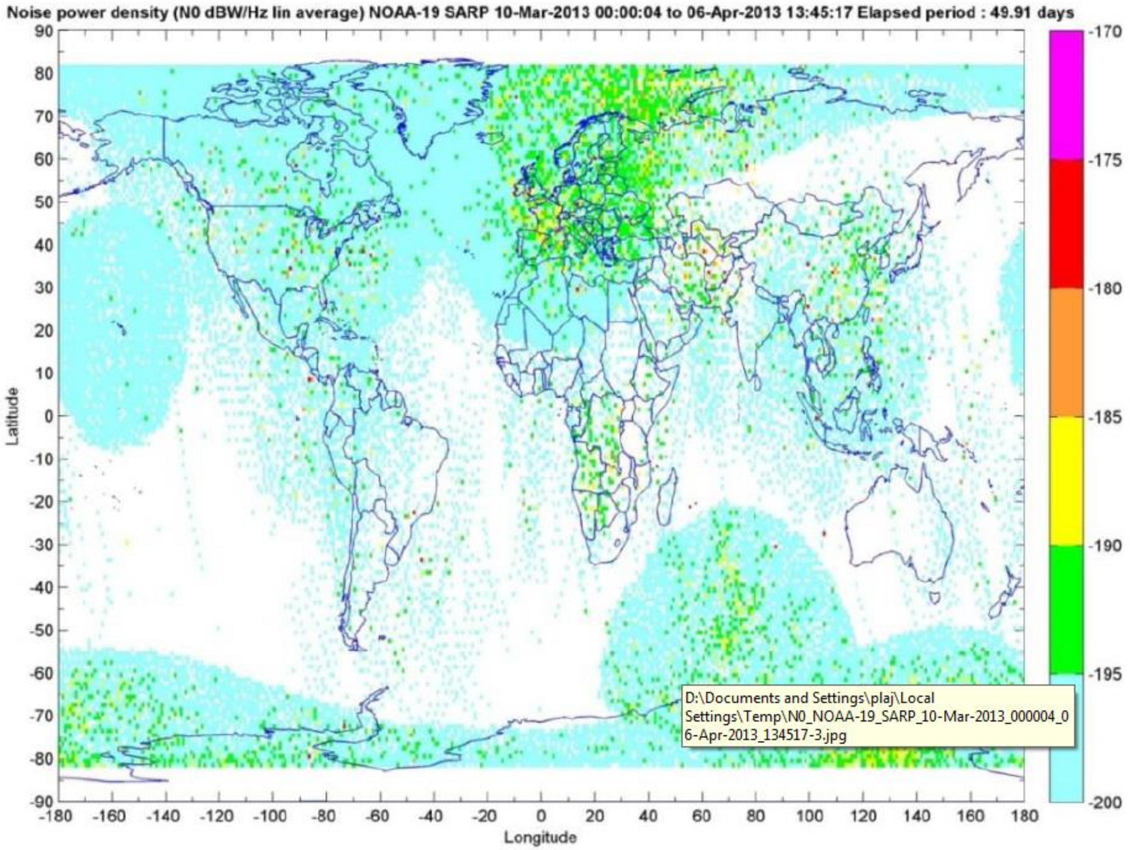




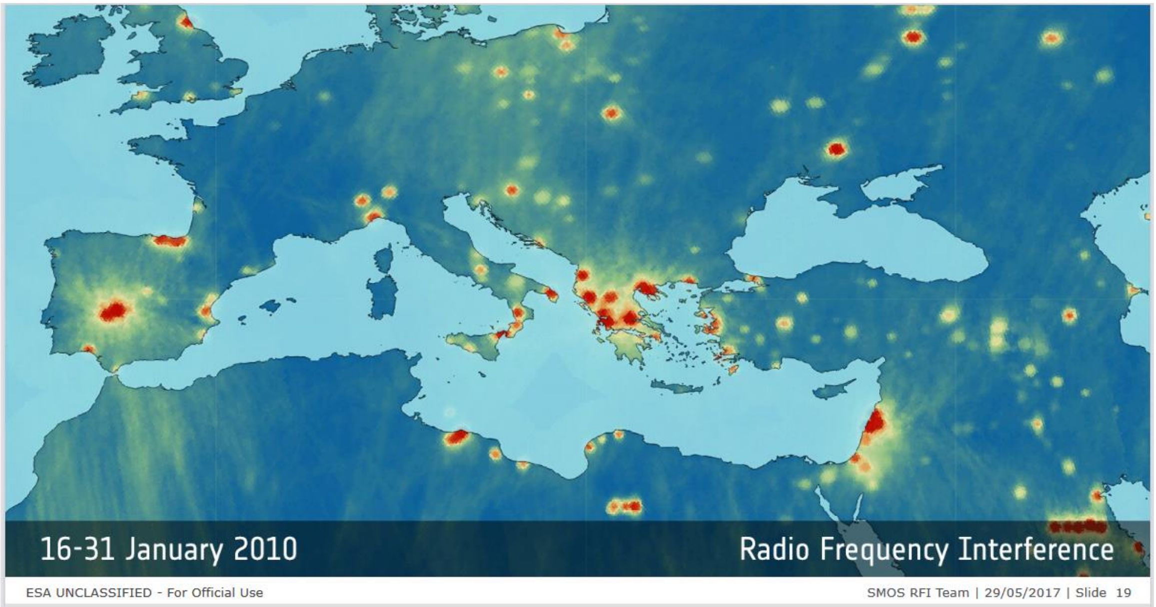
Contents

Motivation of the Activity

SAR service interferences at UHF

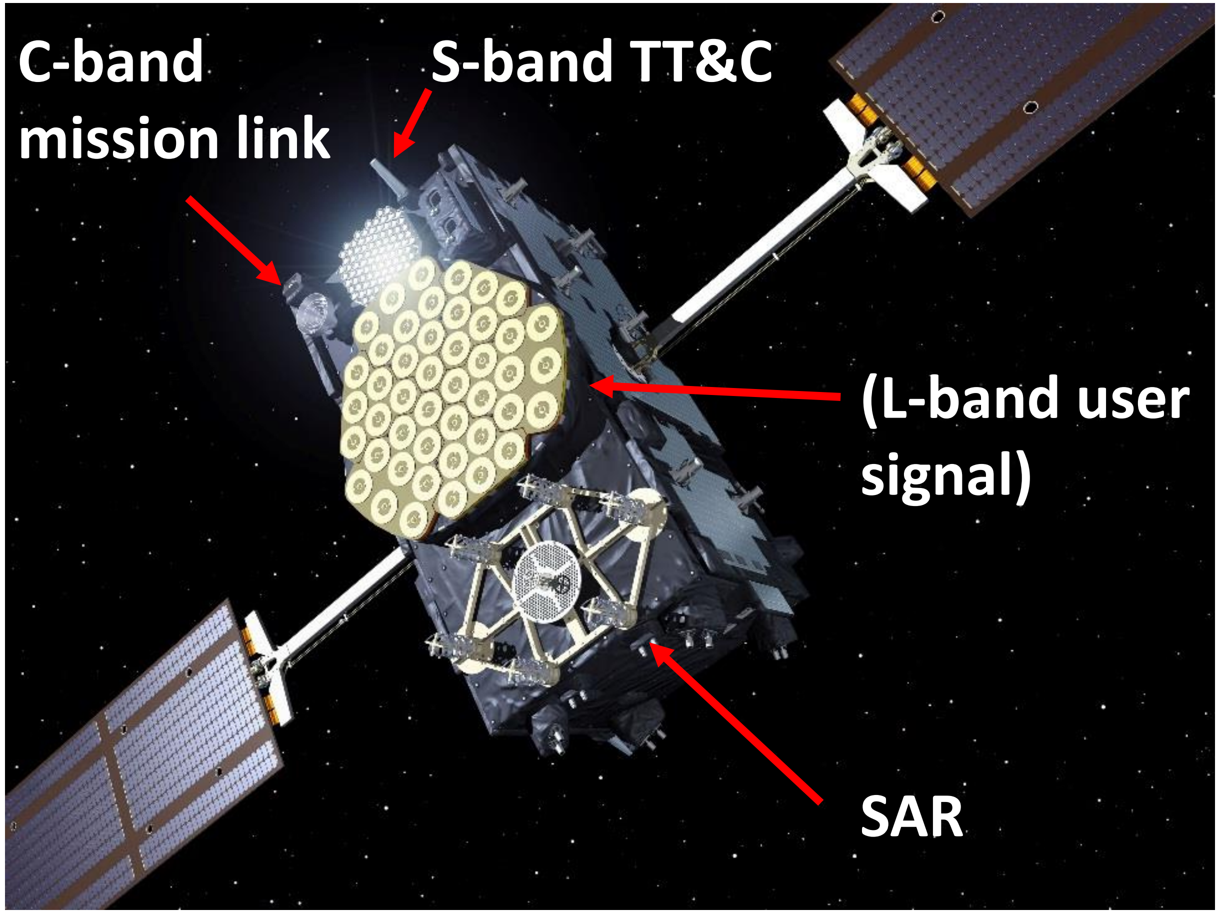


Un-allowed emitters at L-band



Motivation of the Activity

- RF emitters interfere with many societal services across the application domains. Reports of RFI from all sectors (E.g., EO, Telecom, Navigation, Satcom, Science)
- Specific considerations for Galileo uplink (receiver) operations:
  - UHF-receiver for SAR service
  - S-band receiver for TT&C
  - C-band receiver for mission data link



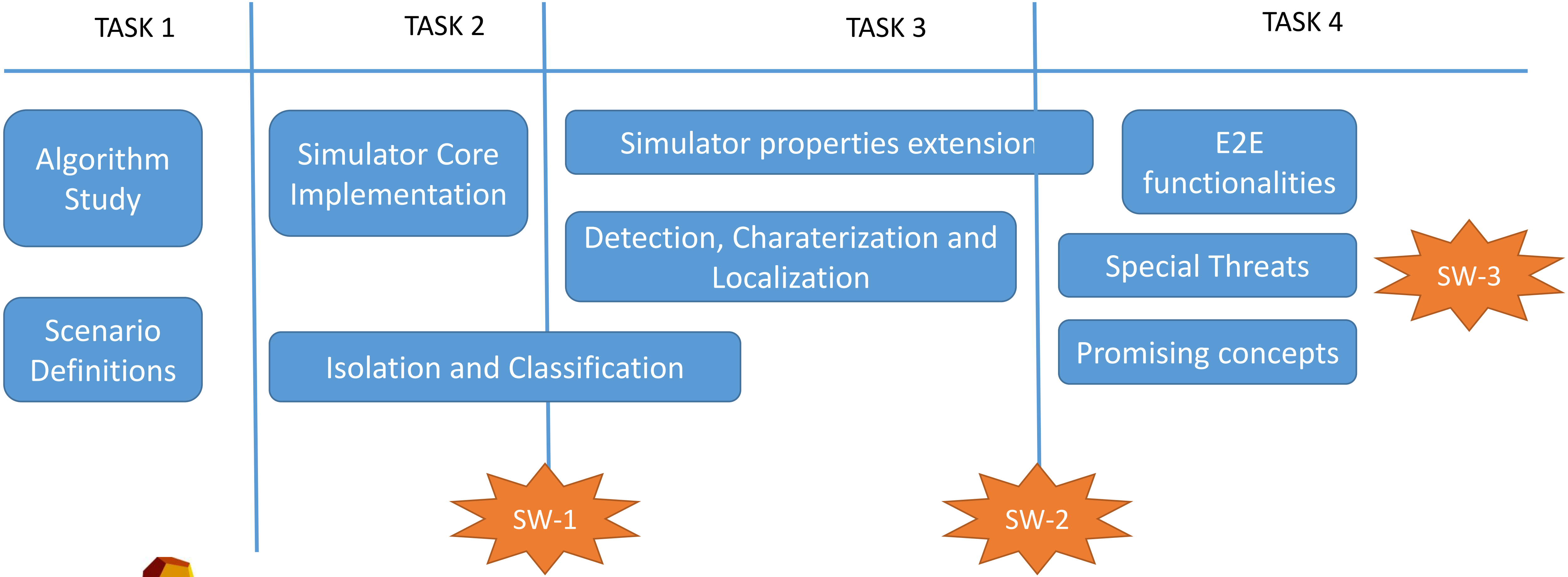
Goals of the Activity

1) To **study the performance** of RFI detection, isolation, classification and characterization and localization techniques in the presence of Radio Frequency Interference signals
2) To **develop an End-to-End software simulator tool** for the simulation-based performance assessment of the above-mentioned techniques
3) To **identify the most promising techniques**

Project Facts

- Name: Interference Detection, classification and cancellation from Space (IDS)
- ESA budget: TDE Program
- Duration: 3/2019 → 6/2022
- Consortium: Harp Technologies, no sub Co's
  Team of three persons
- Project Budget: 300 k€

Project Structure

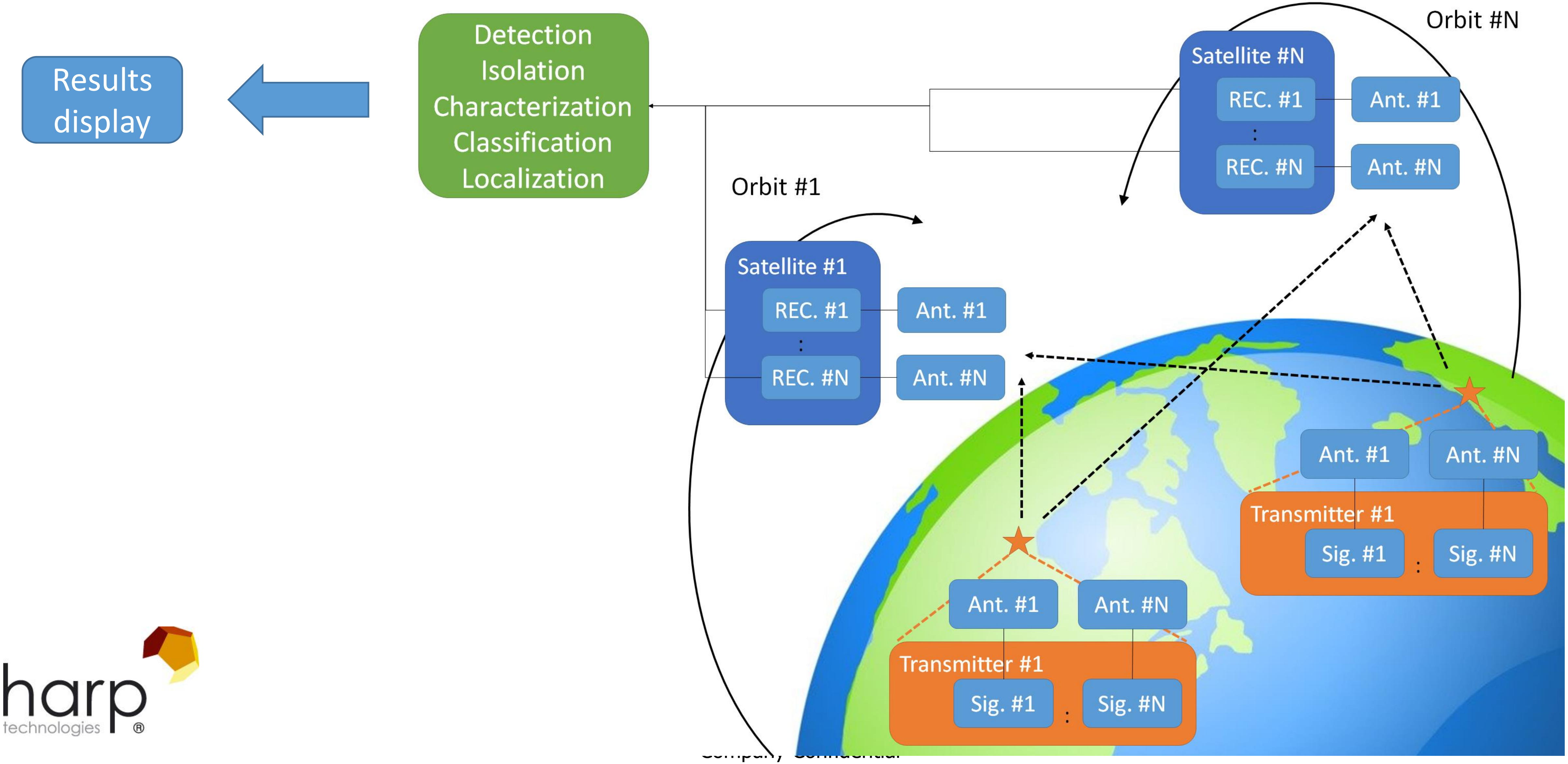


Contents

IDS Simulator - General

- Tool programmed and used in MATLAB-environment
- Allows generic setup of
  - RFI transmitters on ground with various chars
  - Satellites at orbits, equipped with antenna-receiving system with detailed hardware models
  - RFI counteraction algorithms, with tunable details
  - Viewing the main results, access to numerical results
  - Graphical User Interfaces

IDS Simulator – Overall Setup



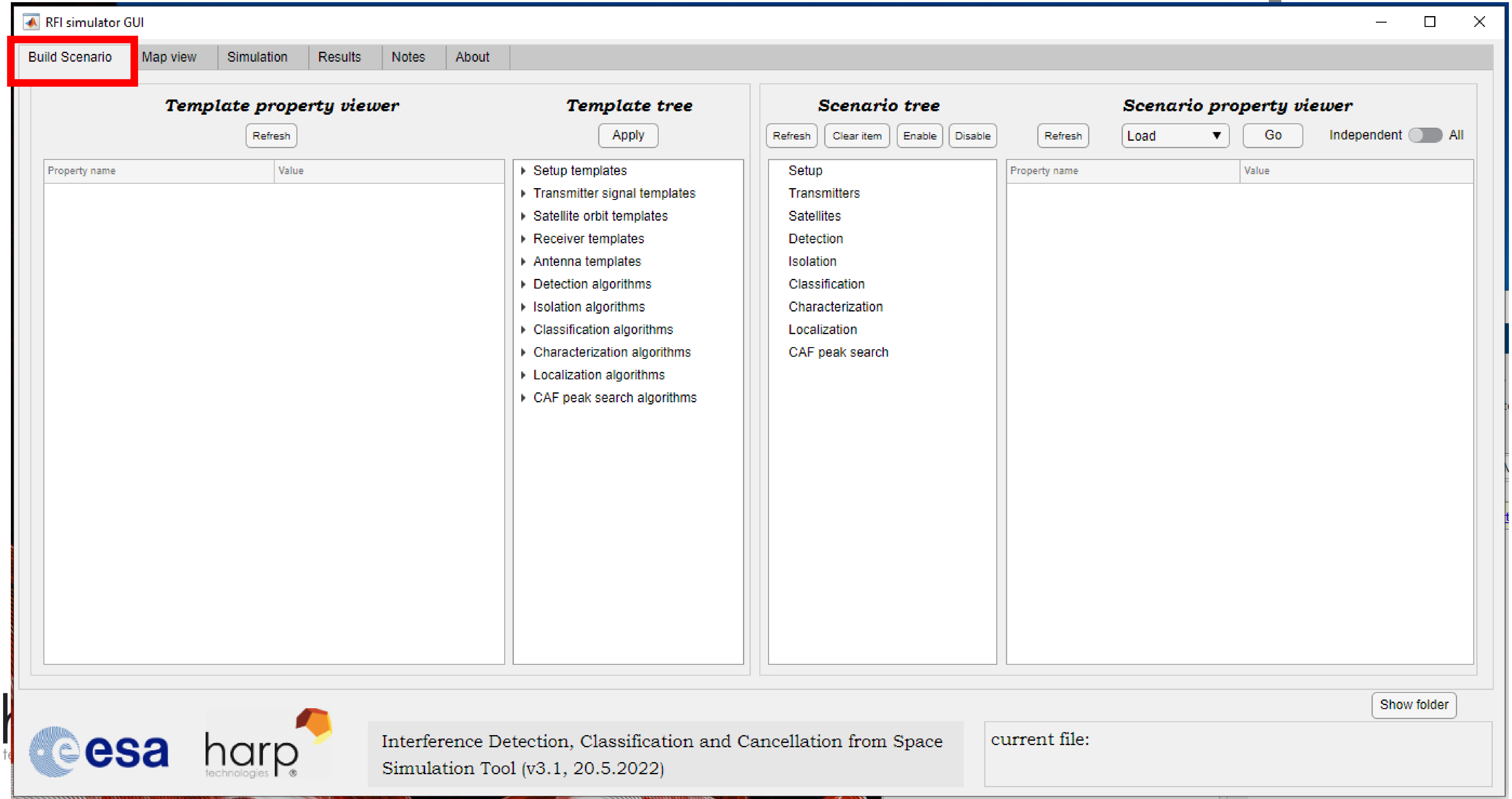
IDS Simulator – Operation Modes

- Activated algorithms applied to
  - Sum of the signal from all transmitters
  - Each transmitter signal individually
- Activated algorithms applied
  - In parallel to the raw signal from transmitter
  - Concatenated using the signal from another algorithm as input (e.g., Detection → Isolation → Classification)
- Power-sweep mode
  - TX power of transmitter is swept over a range to determine algorithm's performance wrt. transmitted power

IDS Simulator – Algorithms

Algorithm class	Technique	
Detection	Energy detector	Gaussianity detector
	Power Spectral Density detector	Space-domain detector
Isolation	Short-Time Fourier Transform (STFT)	
	Fourier Synchro-Squeezed Transform (FSST)	
	Single-channel Quadratic Time-Frequency Domain (SQTFD)	
	Multi-channel Quadratic Time-Frequency Domain (MQTFD)	
	Independent Component Analysis (ICA)	
	Convolutive ICA (CICA)	
Characterization	Mean frequency	Pulse width
	Occupied bandwidth	Duty cycle
	Spectral kurtosis	
Classification	Feature based pattern recognition by State Vector Machine (SVM) classification	
	Recurrent Neural Network (RNN) (using Matlab's Deep Learning Toolbox)	
	Convolutive Neural Network (CNN) (using Matlab's Deep Learning Toolbox)	
Localization	Time-Difference of Arrival (TDOA) using Cross Ambiguity Function (CAF)	TDOA & FDOA (Frequency Difference of Arrival) using CAF
	MUSIC (Multiple Signal Characterization)	

IDS Simulator – Overall Setup



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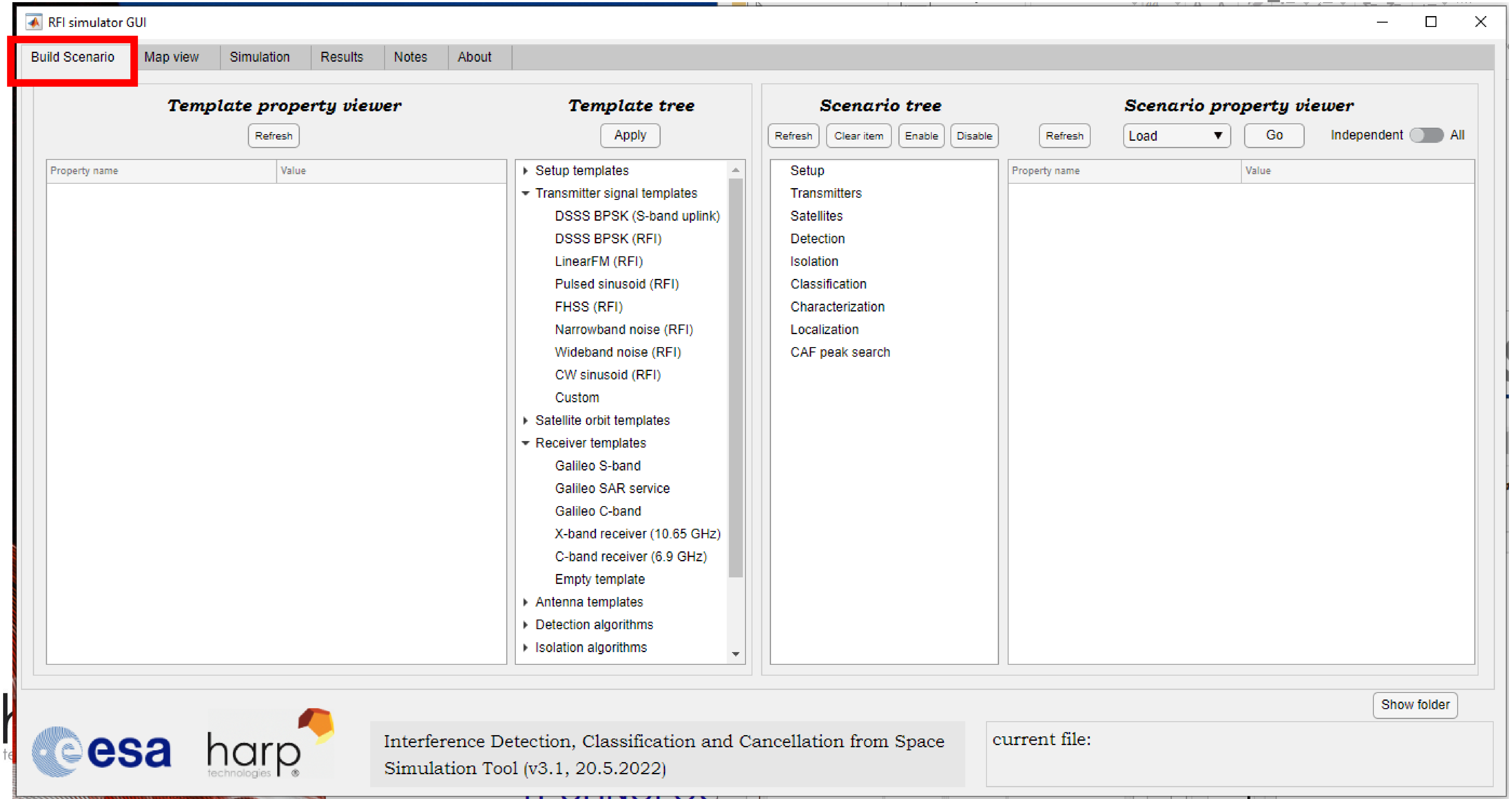

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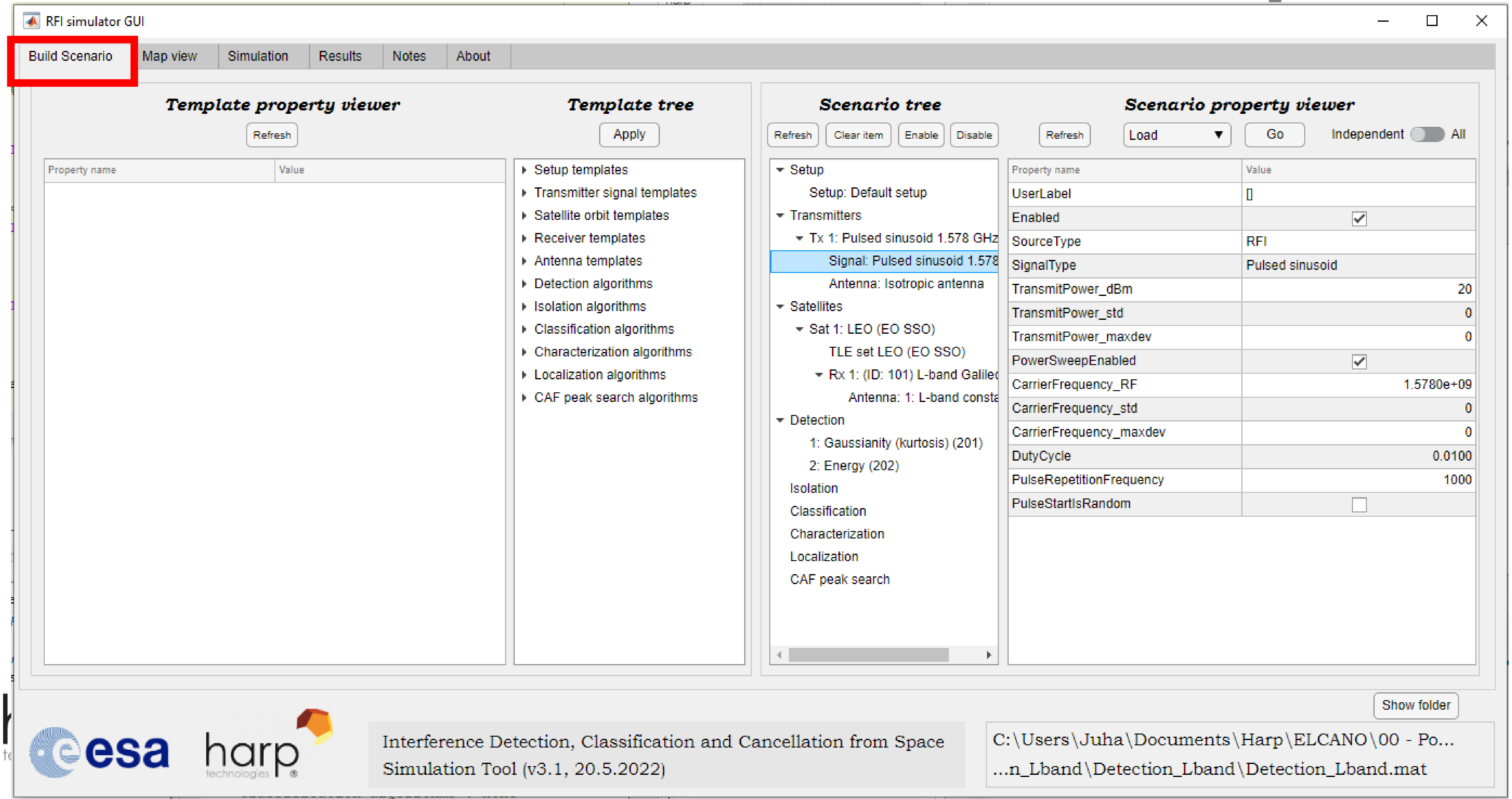

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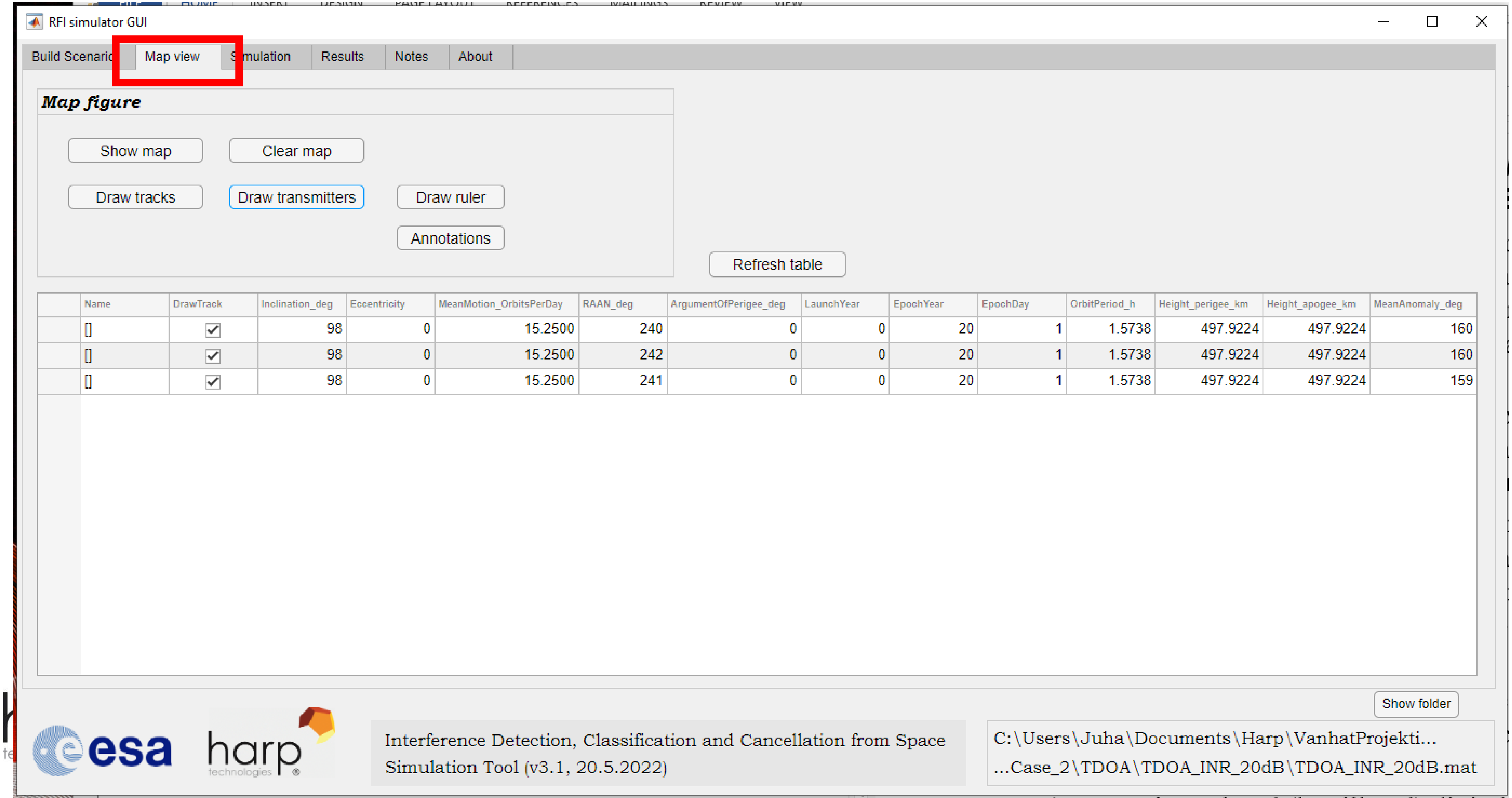

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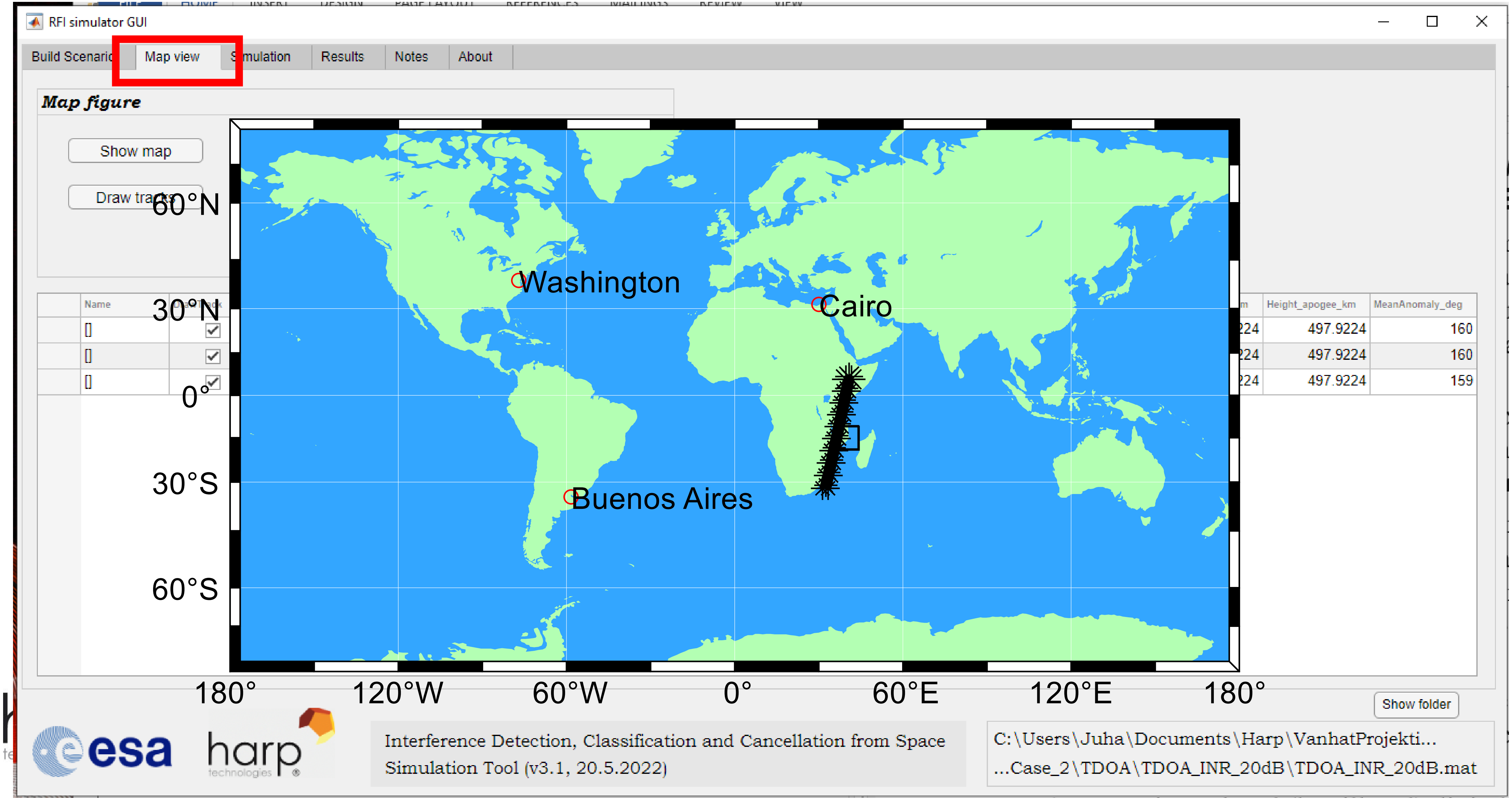

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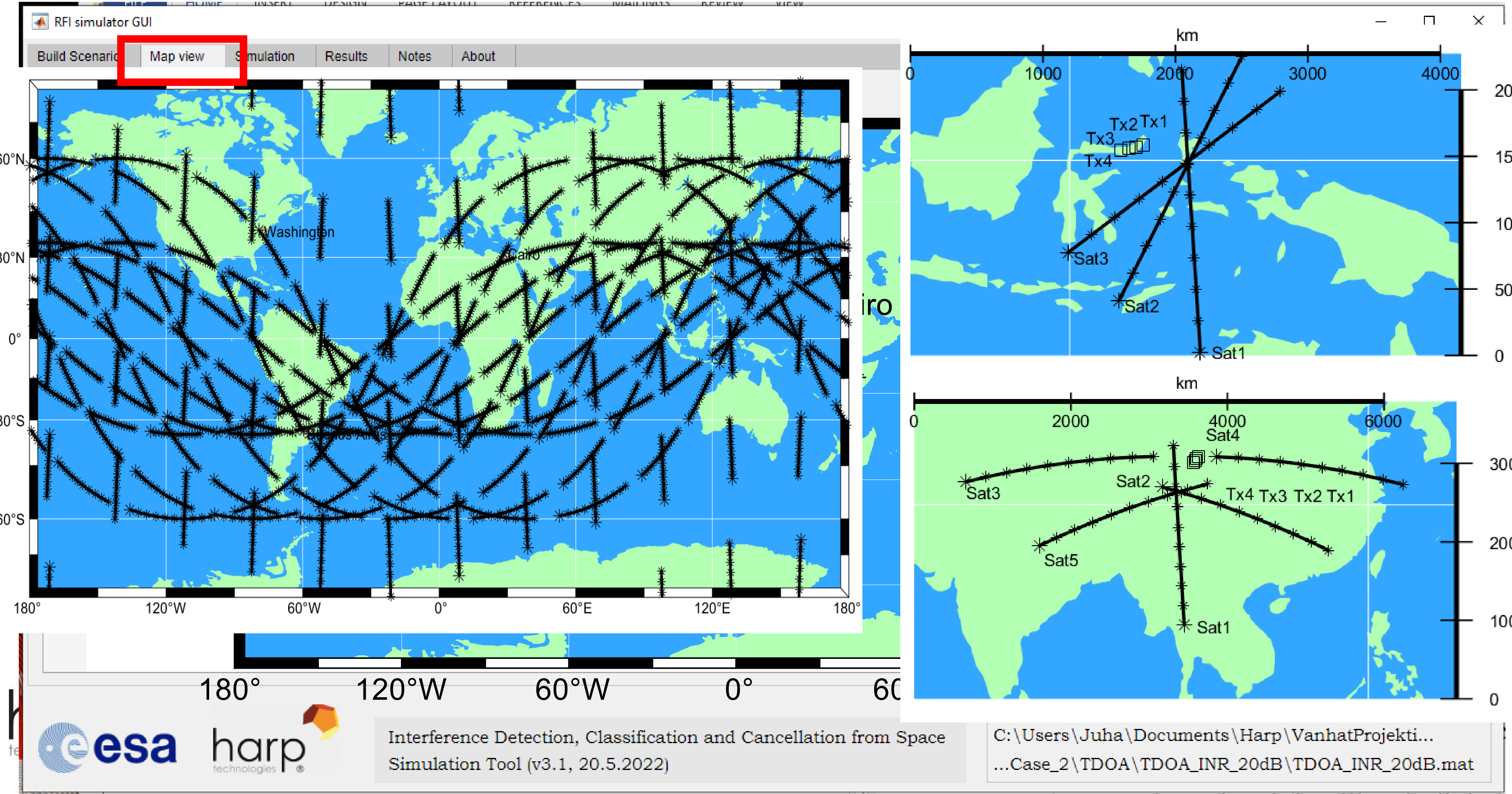

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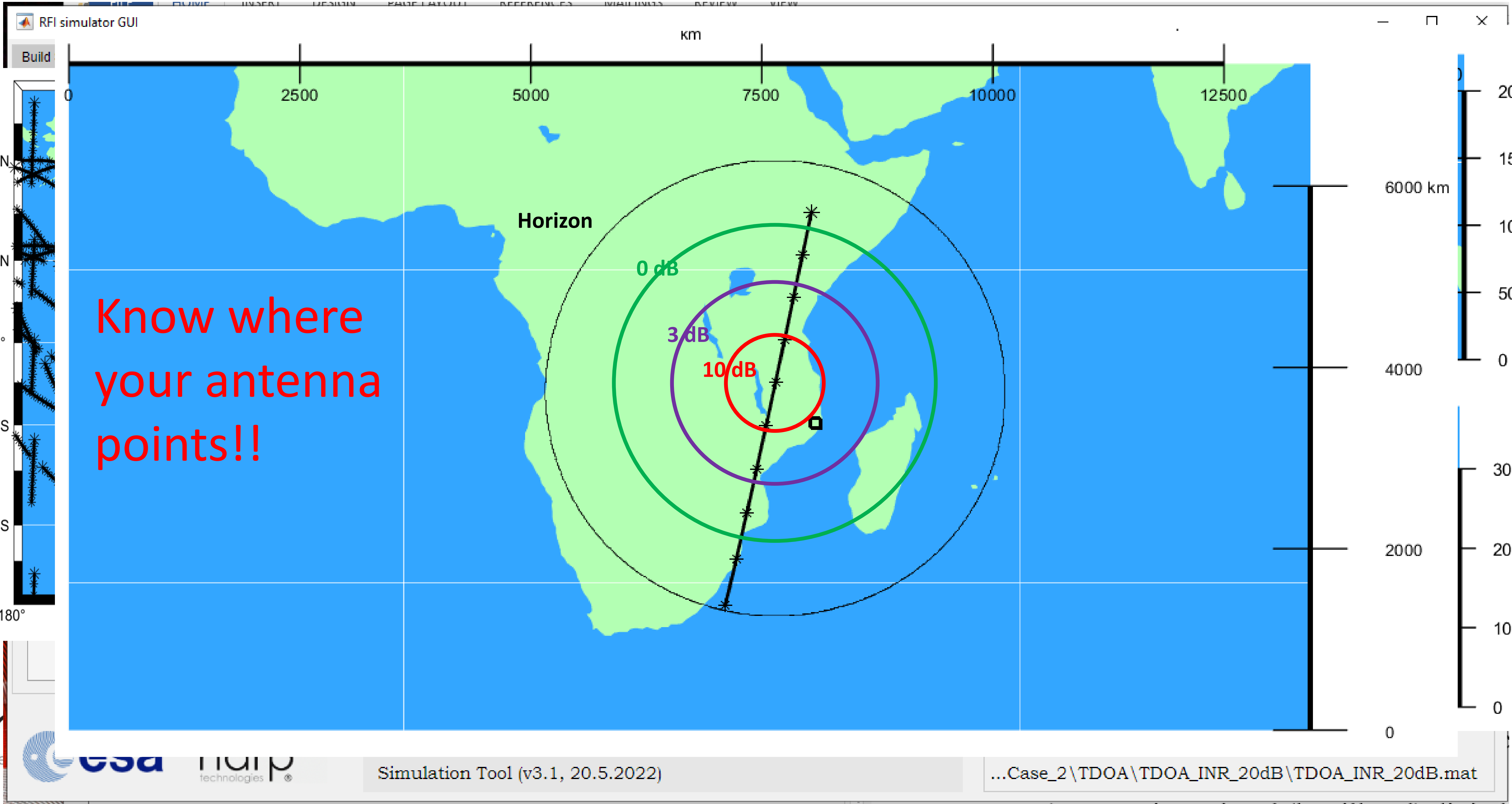

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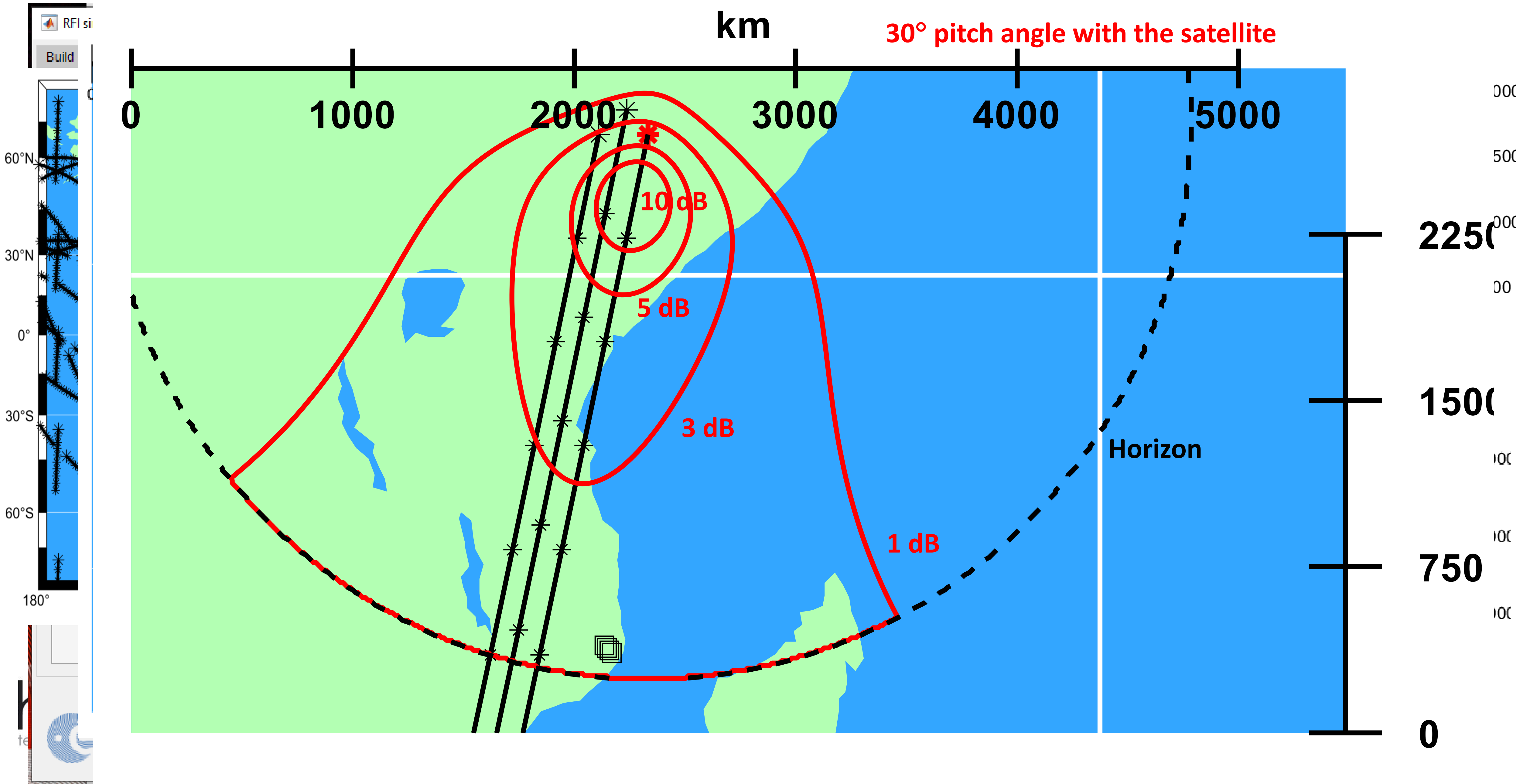

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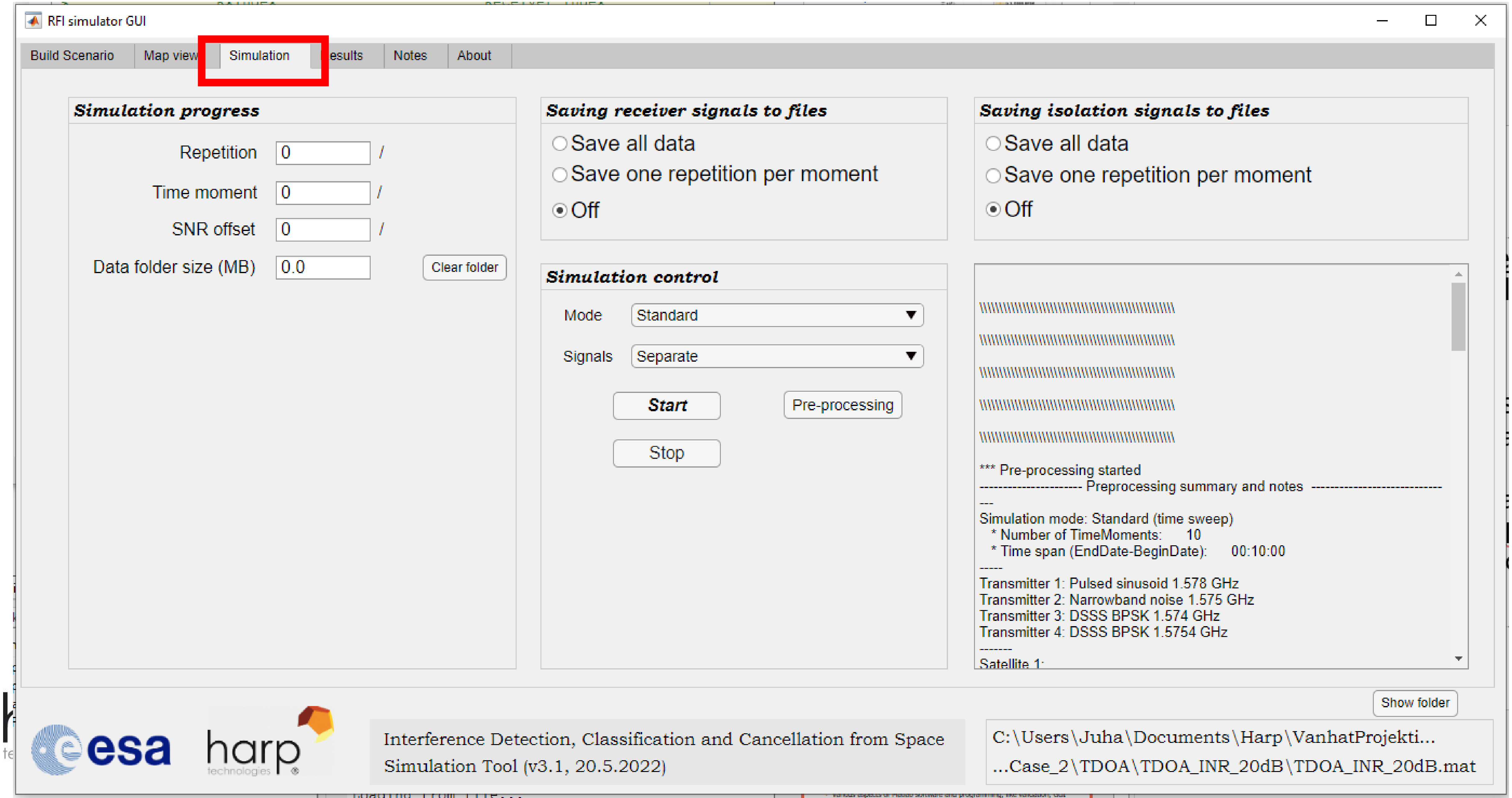

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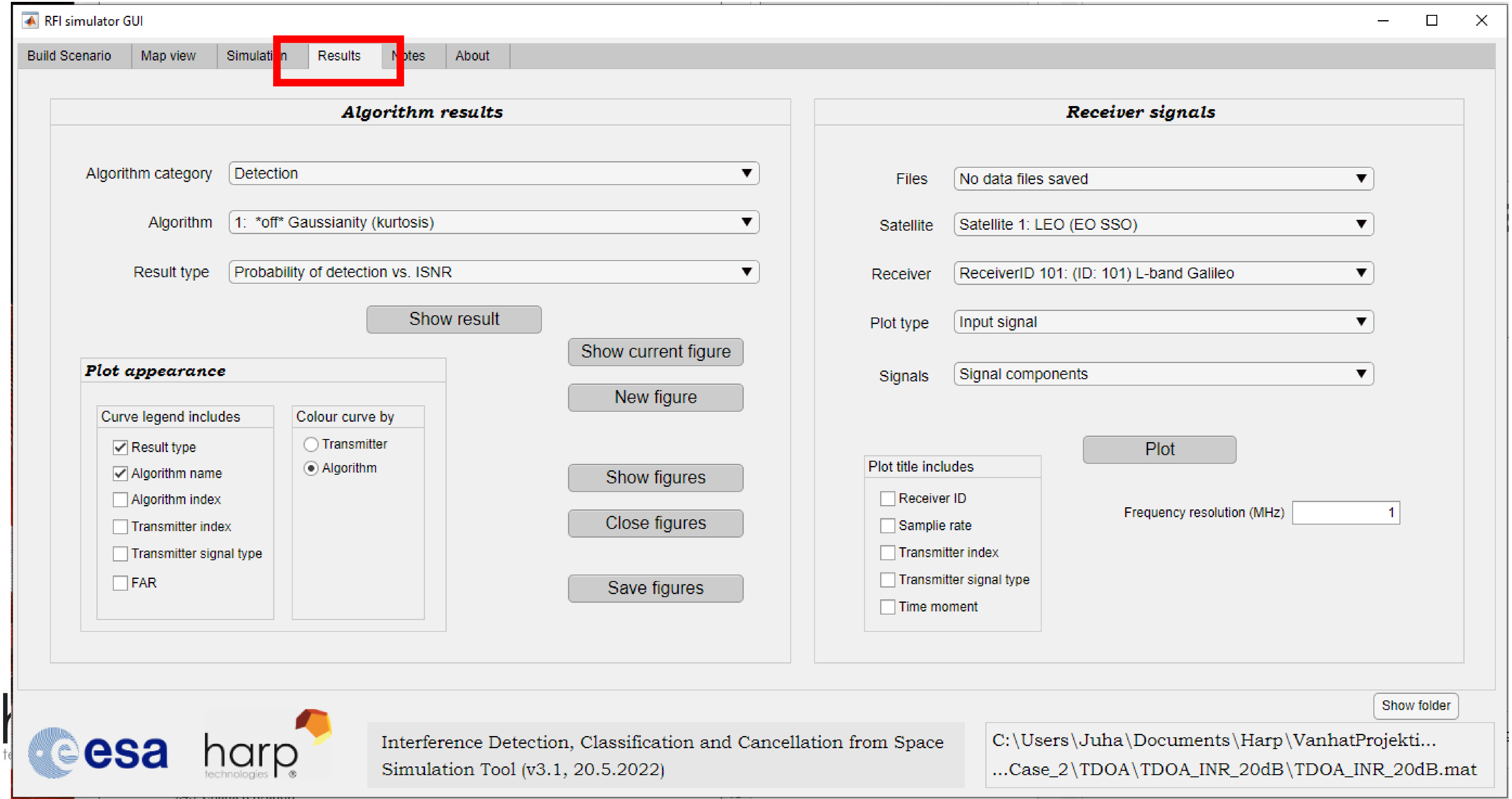

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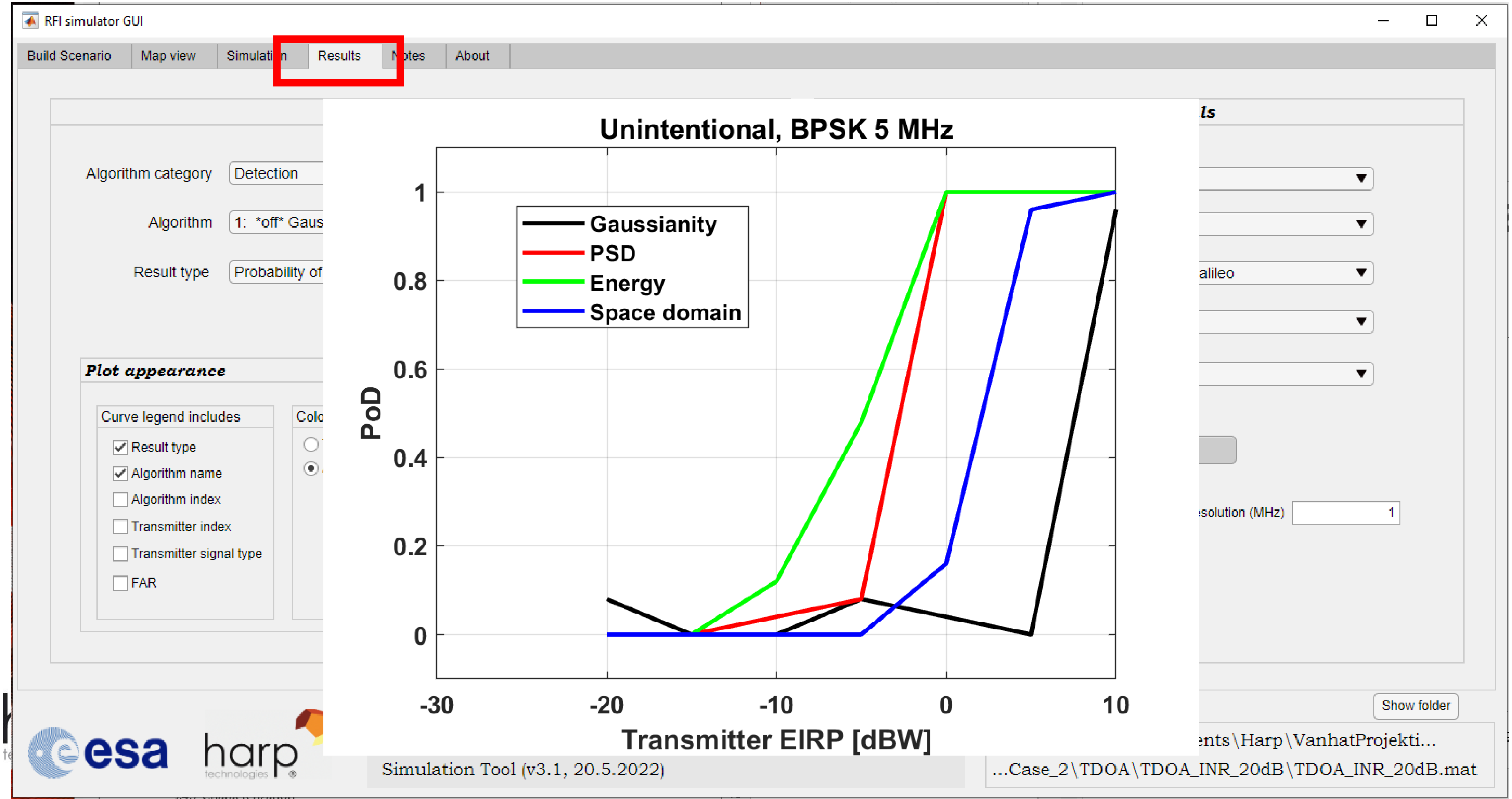

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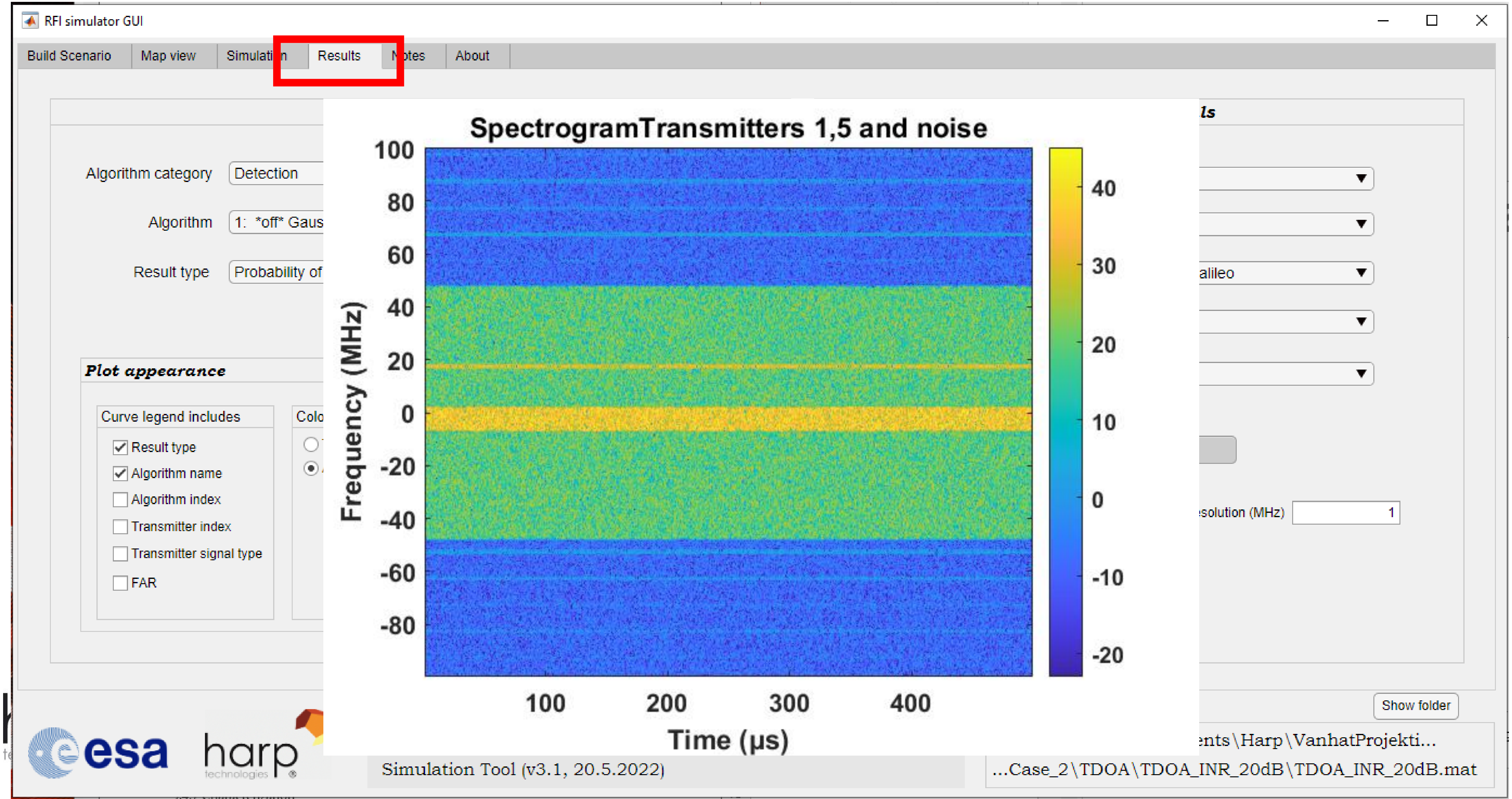

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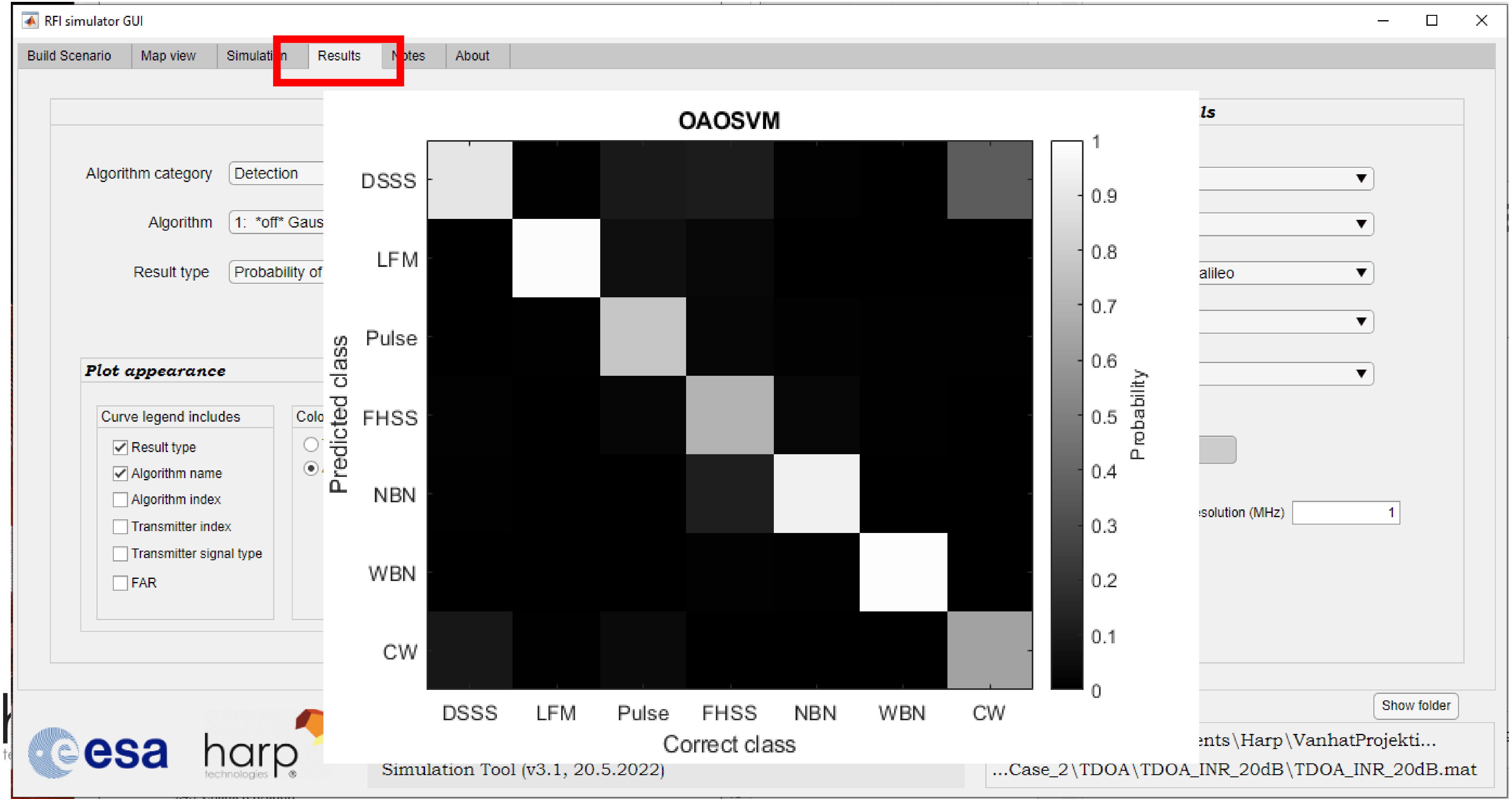

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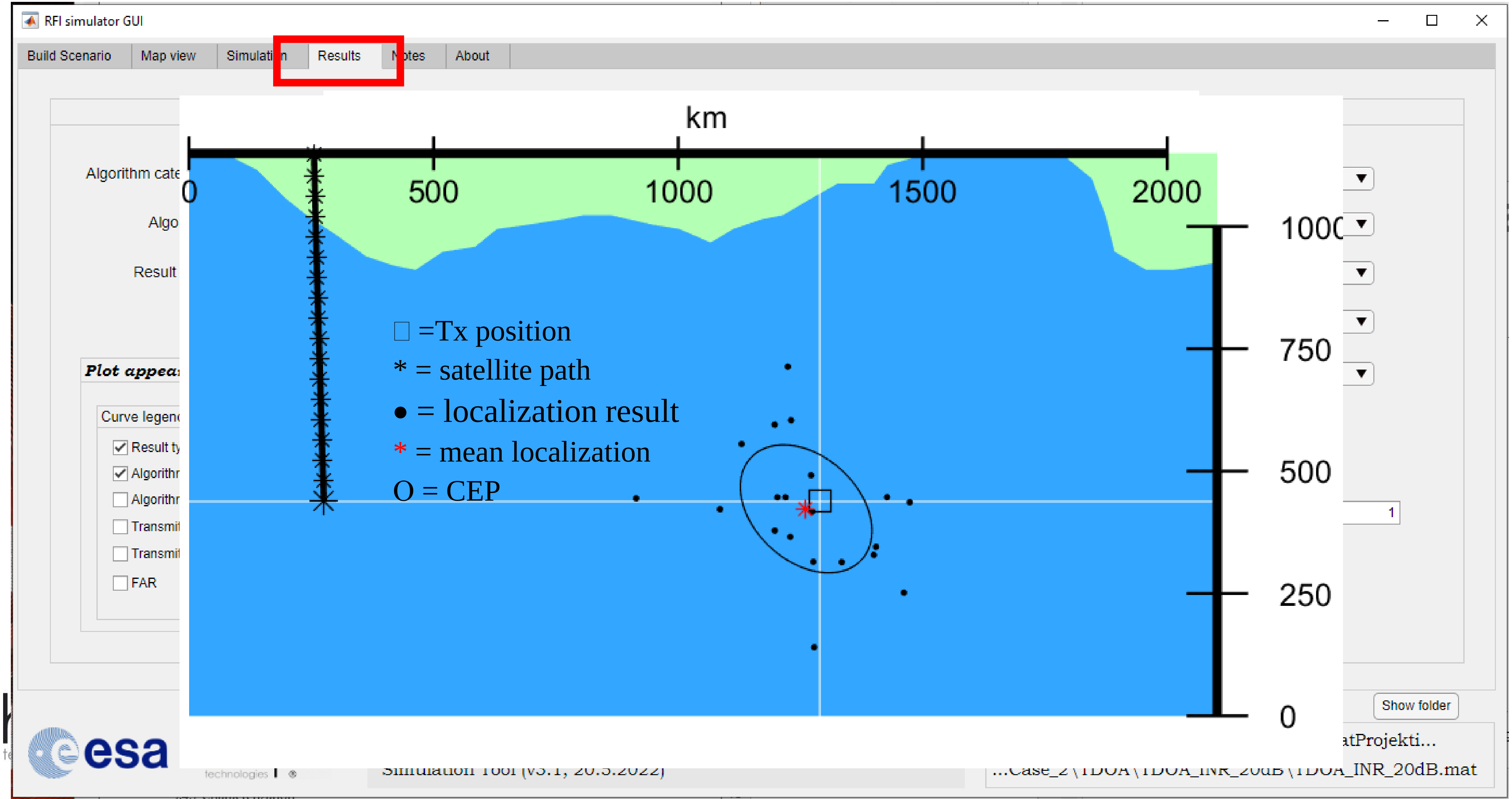

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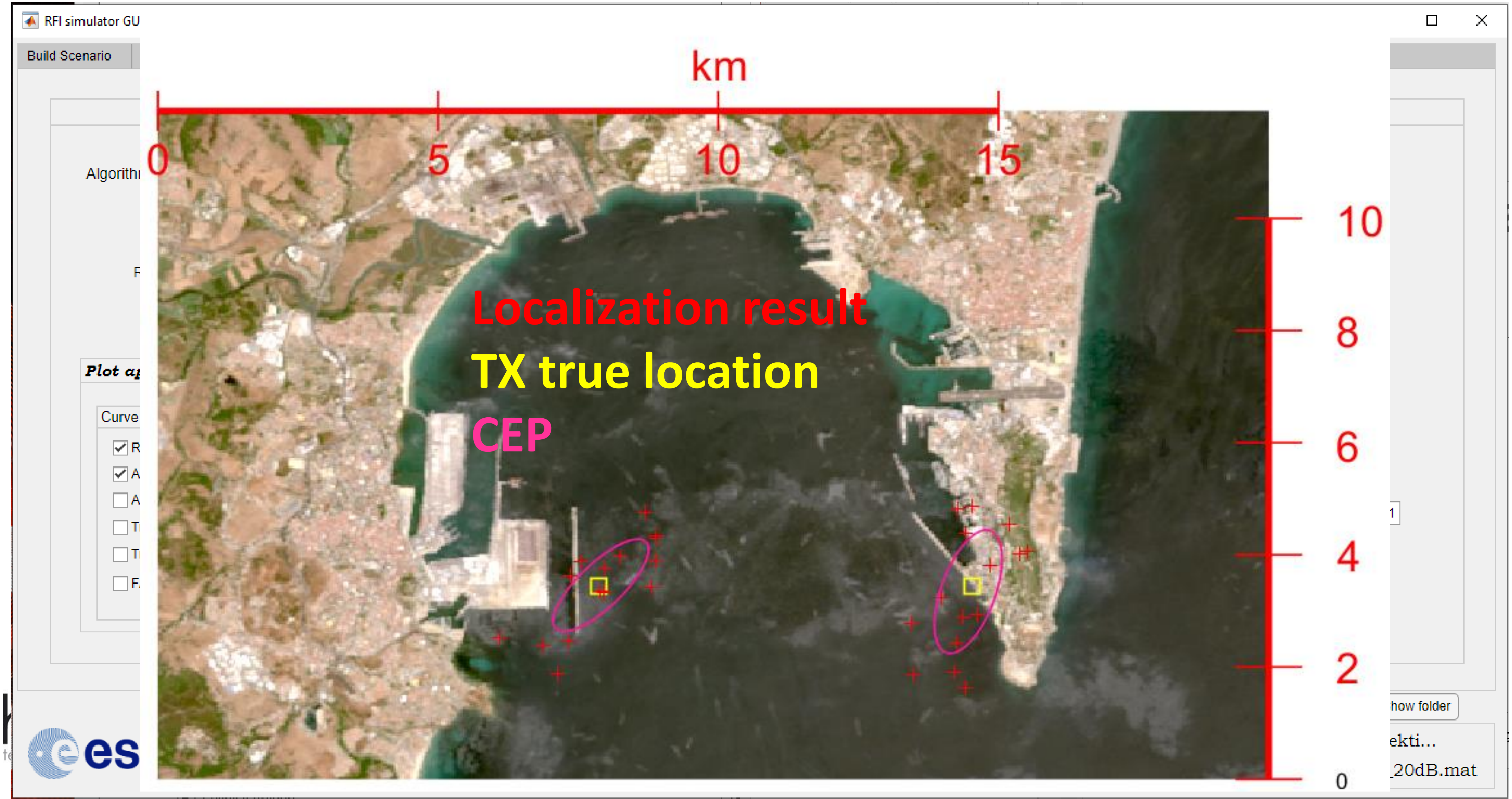


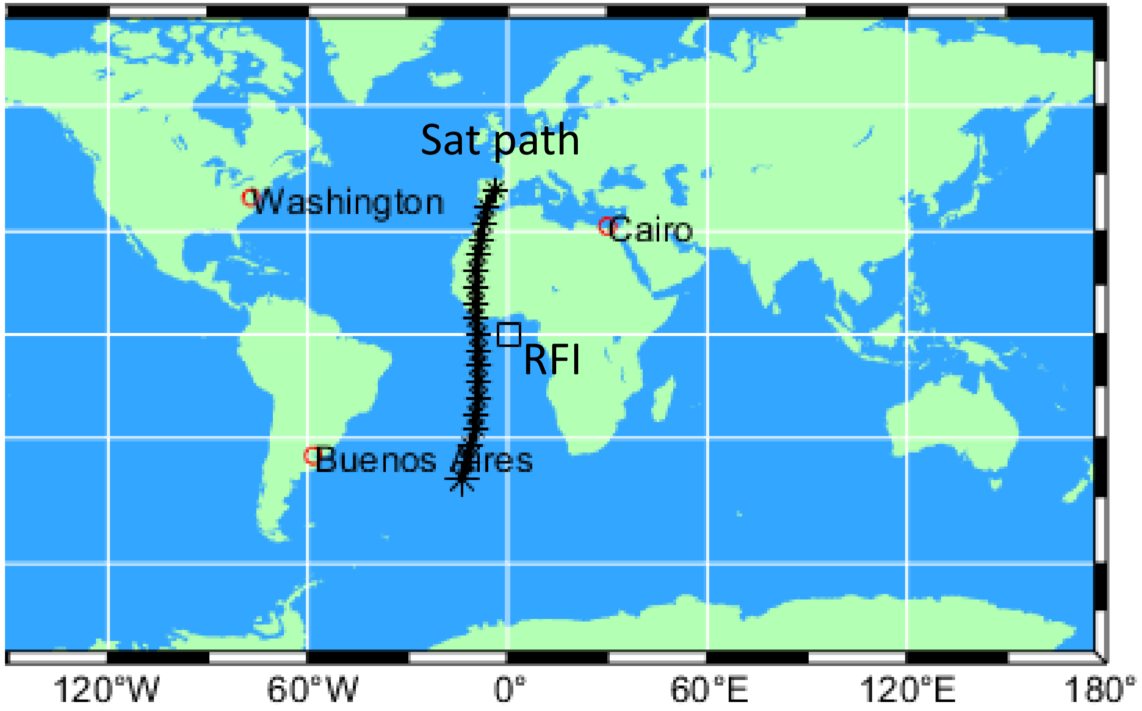
Contents

Algorithm Study Approach

- For each algorithm under study
  1. Algorithm description and study
  2. Implementation
  3. Verification
  4. Performance testing and analysis
- In addition, specific interesting scenarios studied

Typical Test Signals and Environment

- 7 reference RFI signals
  - DSSS BPSK, LFM, pulse, CW, NBN, WBN, FHSS
- Galileo S-band scenario
  - Orbital parameters of a Galileo satellite (MEO)
  - S-band receiver and antenna model those of Galileo system
- Other scenarios: LEO satellite constellation, LEO tandem/triplet formations



Reference S-band RFI Signals

RFI Signal	Typical parameters (f0 = 2.07 GHz for all)
DSSS BPSK	Chip rate: 500 kHz; Symbol rate: 50 kHz;
LFM	Pulse time: 2 ms; Linear sweep; B_sweep = 2 MHz;
Pulse	PRF = 1 kHz; Duty cycle = 1 %
CW	
Narrow-band noise	B = 2 MHz;
Wide-band noise	B = 40 MHz;
FHSS	N= 85; hop rate = 4 kHz; symbol rate = 1 MHz; f_delta = 8.5 MHz; M_FSK = 2;

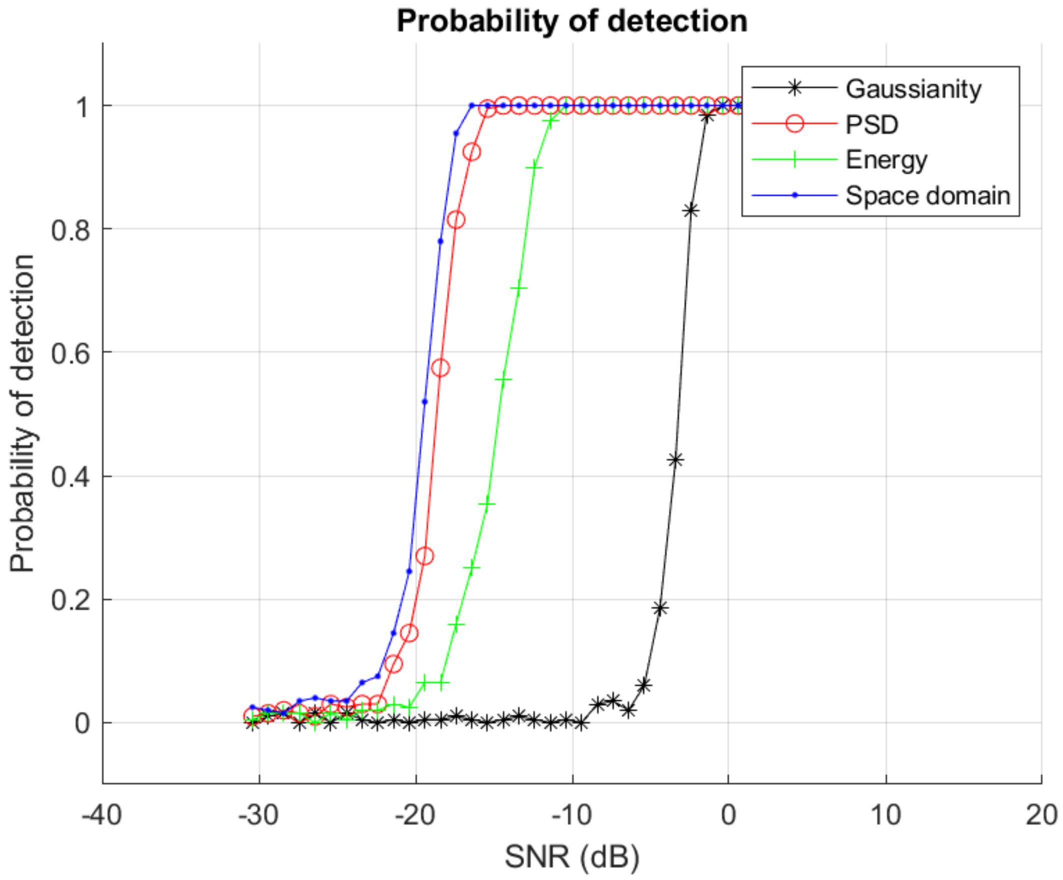
Detection

- Energy Detector (time domain power detector)
- Power Spectral Density (frequency domain power detector)
- Gaussianity Tests (time domain gaussianity test)
- Space-domain detector (multi-signal cross-correlation)
  - Here, we used SAR antenna array scaled to S-band

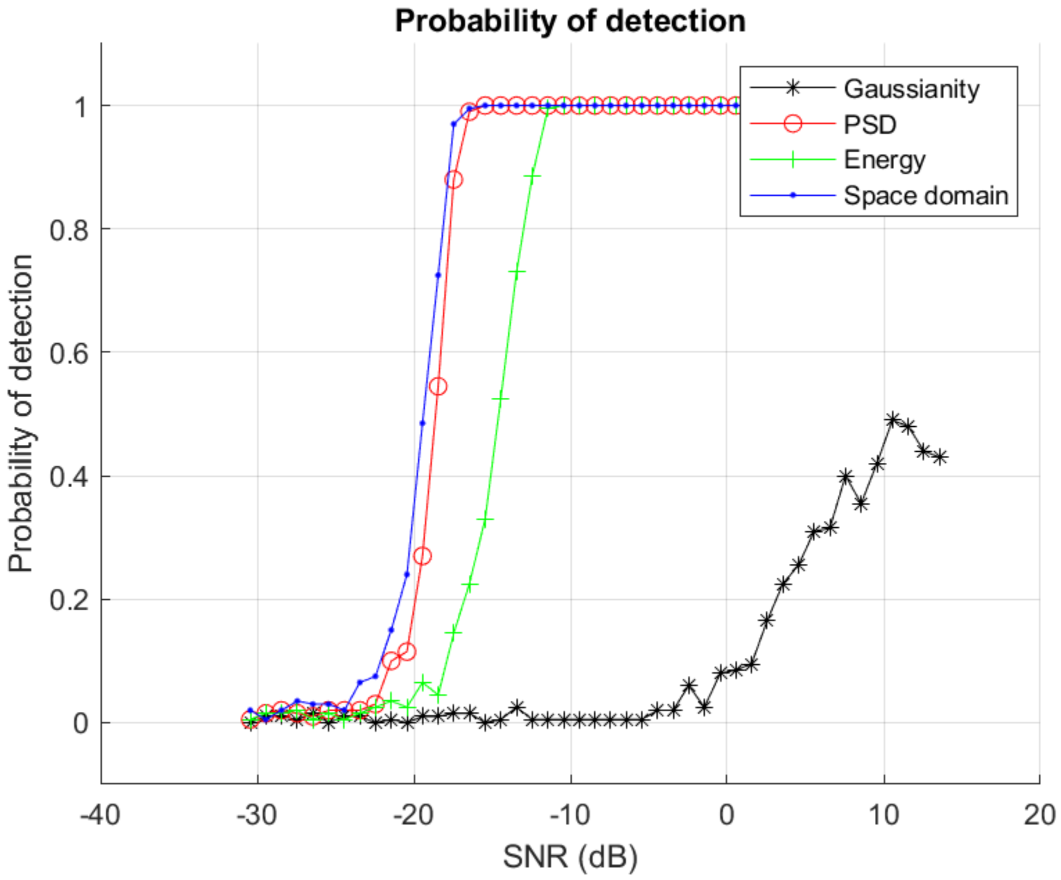
Detection, Example 1

- Probability of detection against as a function of Interference-to-Noise Ratio (INR) two RFI signal types

RFI: DSSS BPSK



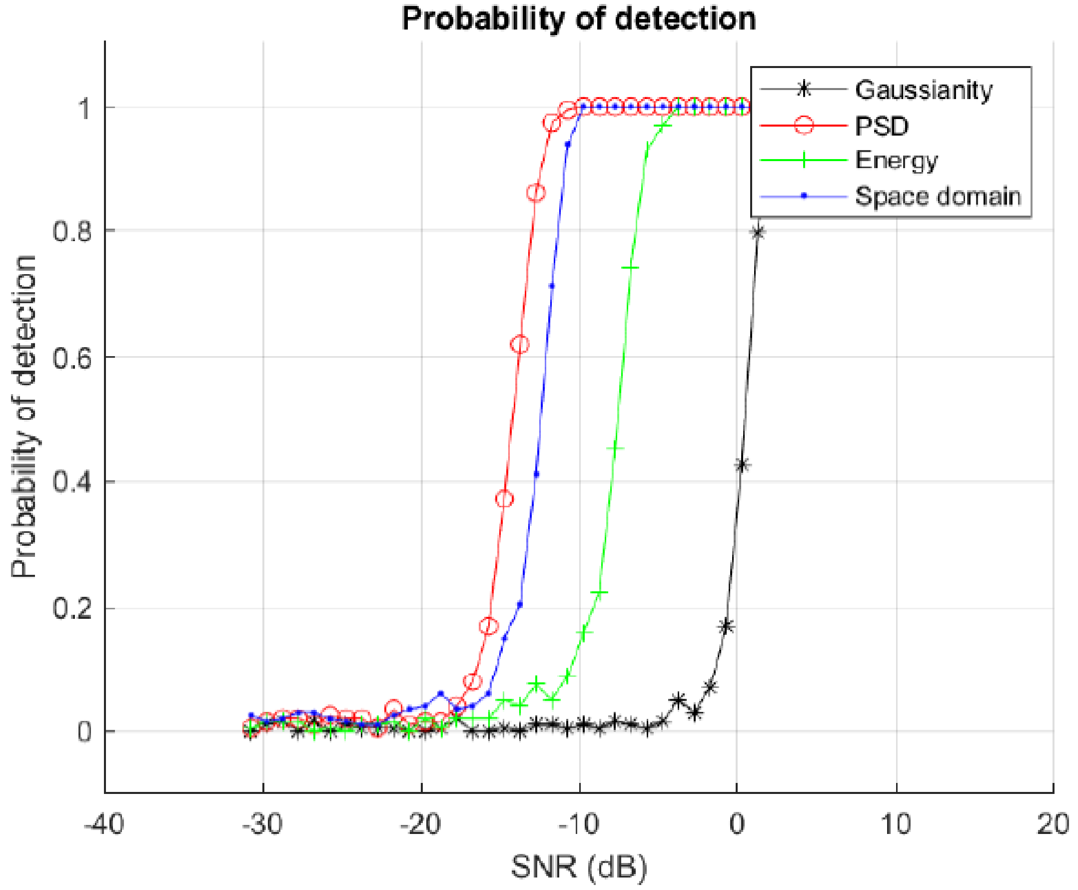
RFI: Narrow-band Noise



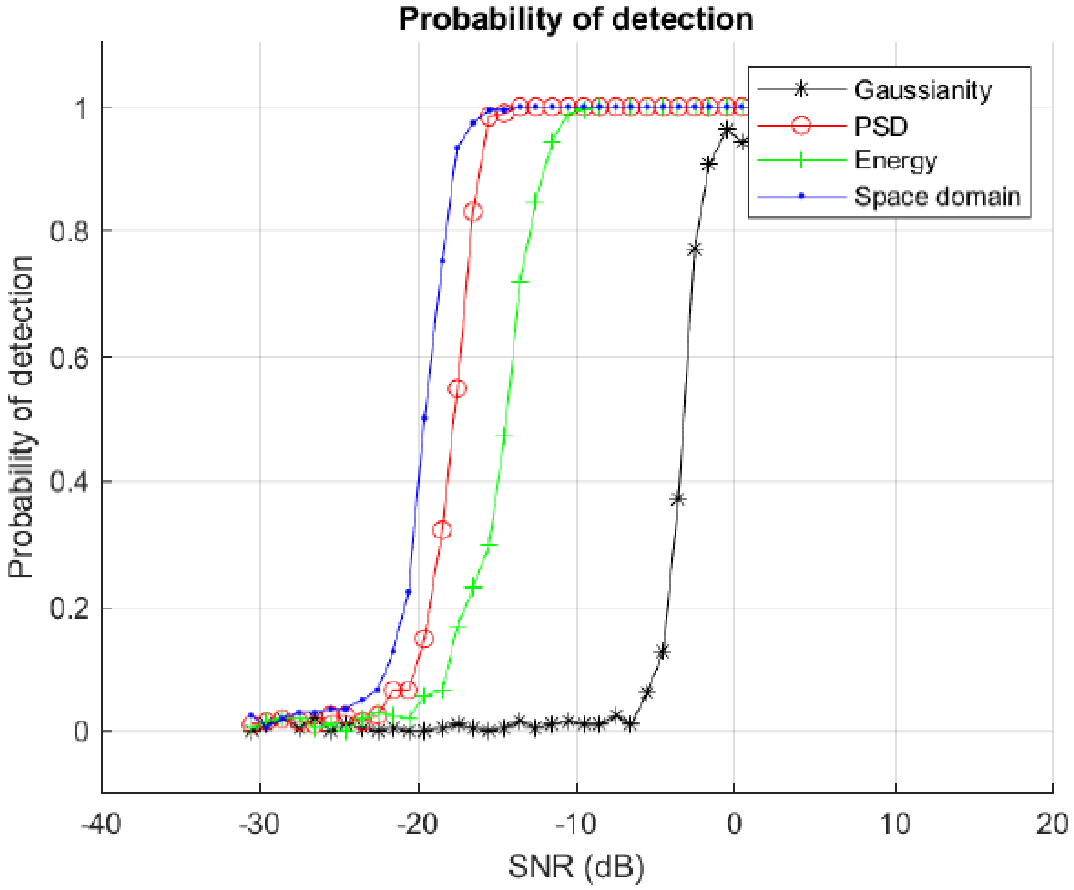
Detection, Example 1

- Probability of detection against as a function of Interference-to-Noise Ratio (INR) two RFI signal types

RFI: pulse

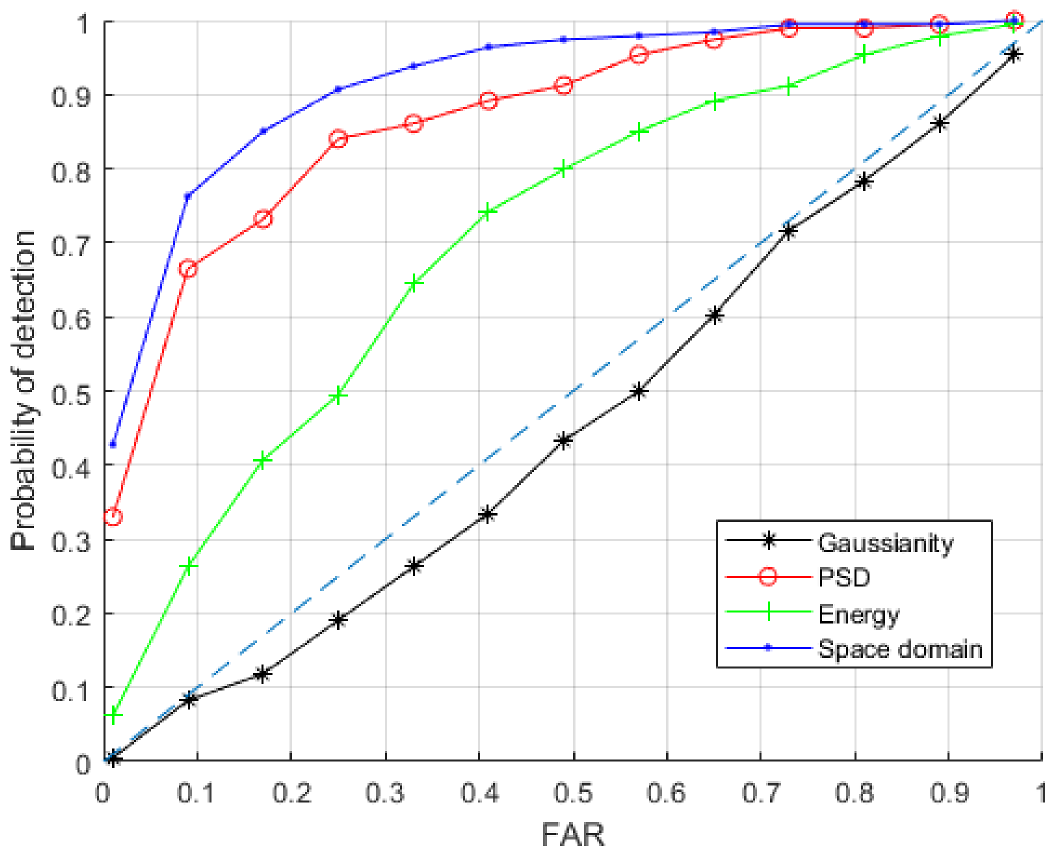


RFI: FHSS



Detection, Example 2

- ROC analysis studies the PoD as a function of FAR in certain fixed SNR conditions.
- Left: ROC curvues for detection algorithms for DSSS BPSK signal at SNR = -20 dB



Conclusions on Detection

- Generally, detection threshold of different detectors/RFIs varies in -20 dB → 0 dB in terms of INR
- Frequency-domain detectors with high spectral resultion are (obviously) more efficient than time domain detectors
- Time-domain detectors can serve as computationally light, medium performance detectors
- FFT-, cross-frequency-, and correlation-based detection algorithms is foreseen to develop in the future

Classification Algorithms

- Two families of Machine Learning algorithms were considered:
  - Support Vector Machines are based on mapping of the data to higher-dimensional space and finding of boundary conditions between classes
  - Neural Networks are based on layered networks of elementary units, each performing a simple weighing of a feature. Network is teached to respond to labeled dataset with certain output.
- Require teaching of the classifier with a labelled dataset
- Various methods for classifier teaching, classifier architecture, signal featuring, cost function definition can be used
- Some classifiers included in the simulator delivery, but user can import classifier of his/her own as well

Classification Algorithms

- 7 signal classes: DSSS BPSK, LFM, pulse, CW, NBN, WBN, FHSS
- 200/2000 signals in each class (with random parameters) considered for teaching
- Signal sampling and receiving sceanrio: S-band Galileo uplink receiver
- Probability of correct classification analyzed with a signal set of 200 signals per each class with randomized parameters

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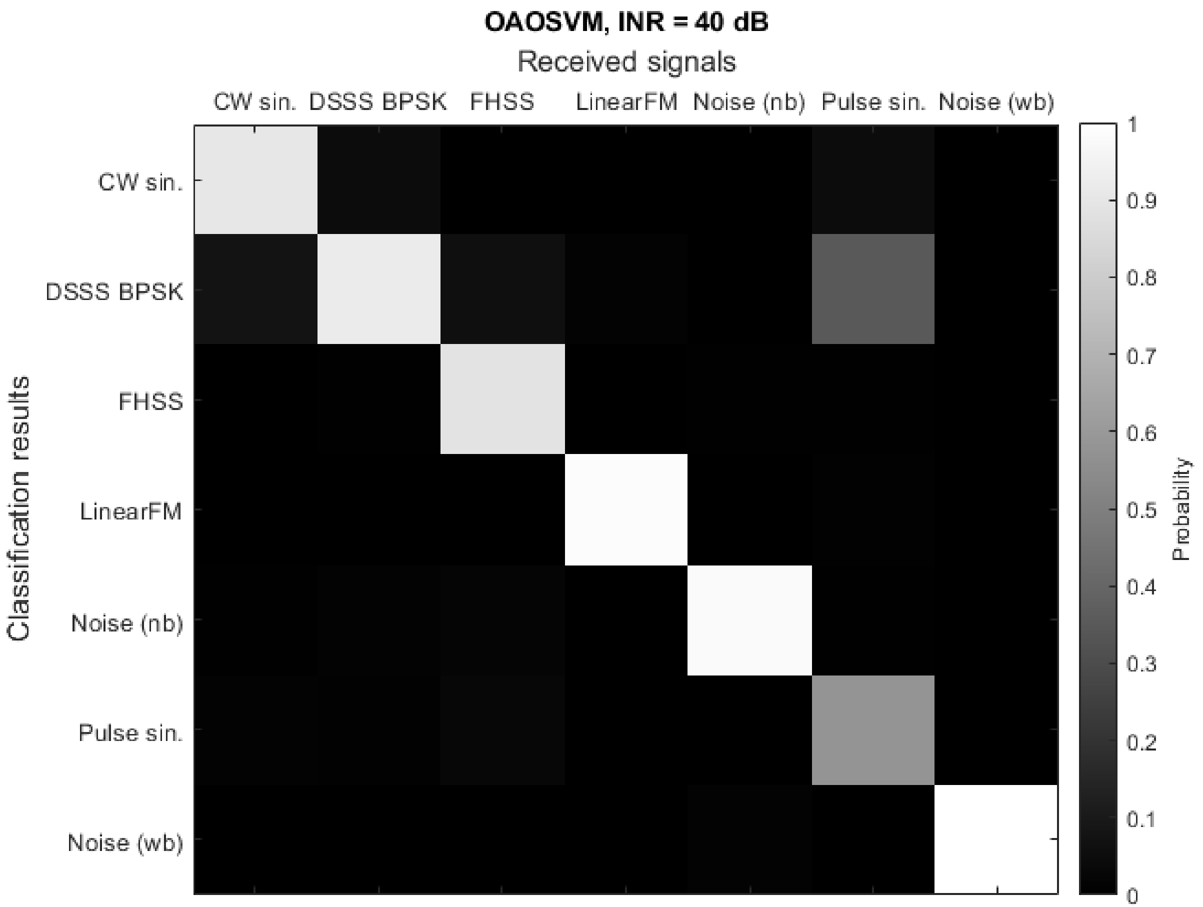
Classification 1, Support Vector Machines

- Support Vector Machines were studied for
  - SVM architectures: One-Against-One, One-Against-All, Multi-Class
  - Features: Time domain features, Spectral Correlation Function, Power Spectral Density
  - Kernel (mapping) functions
  - Teaching set size
  - Intensity of the RFI

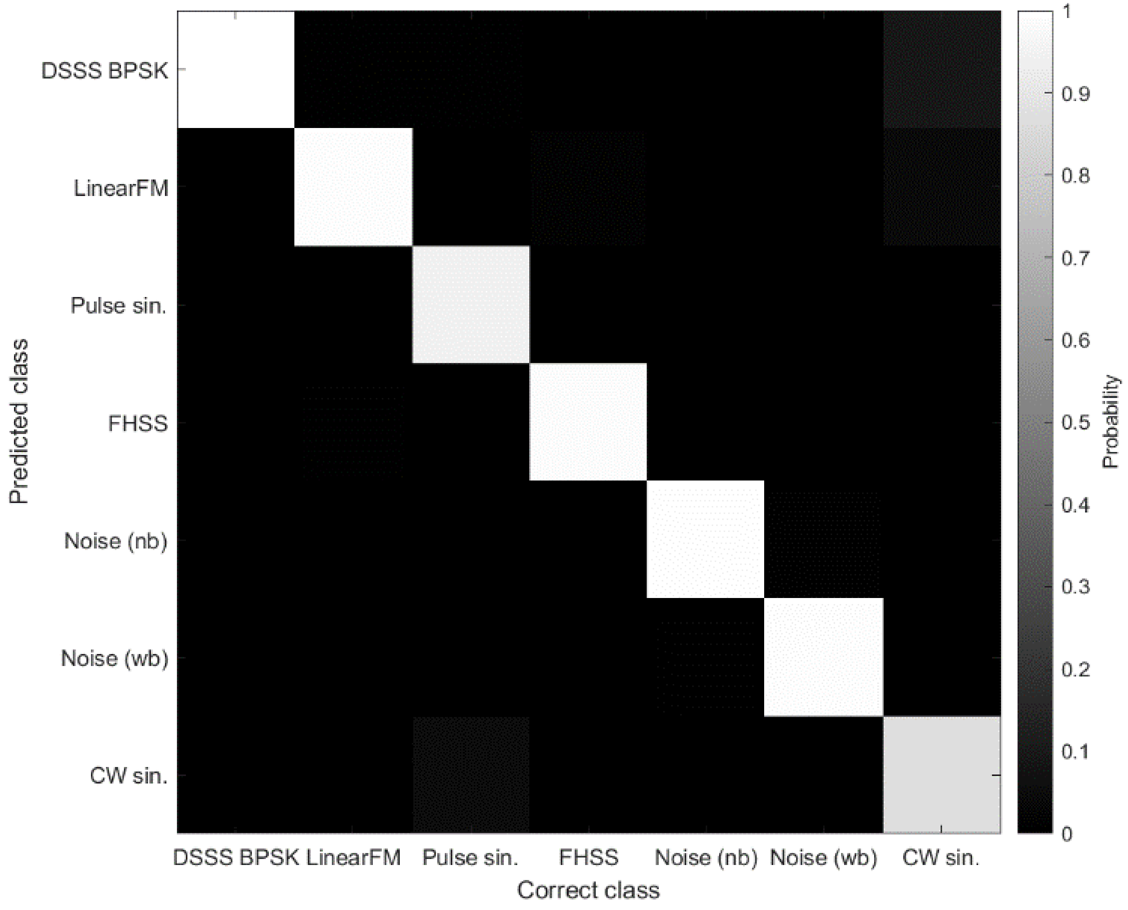
Classification 1, Support Vector Machines

- Best performance was achieved with SVM with
  - One-Agains-One architecture
  - Spectral correlation function
  - Exponential mapping
  - Frequency normalisation pre-processing
- Right: 90% correct classification with high INR

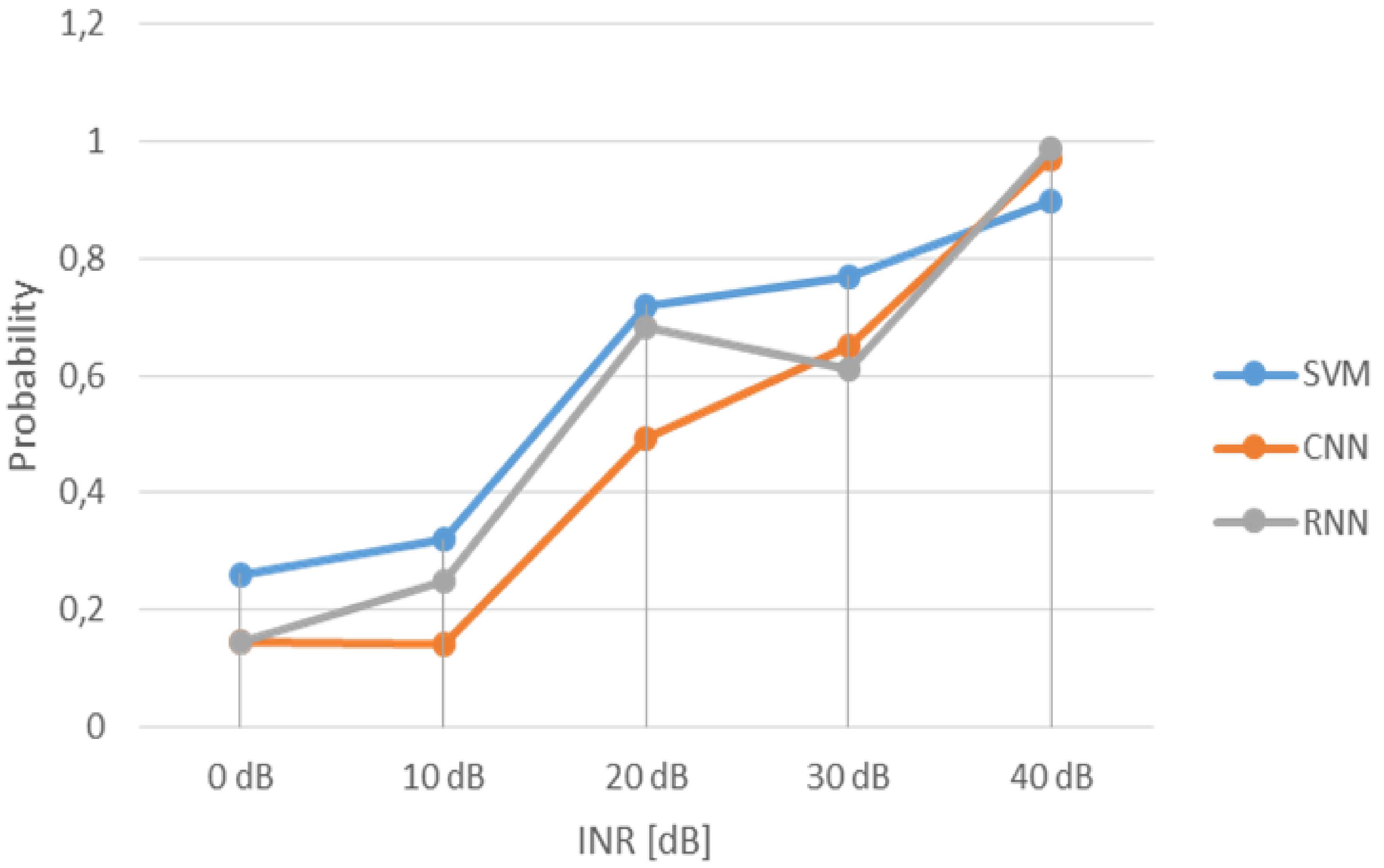


Classification 2, Neural Networks

- Examples of Recurrent and Convolutional NN (RNN and CNN) were tested
- Various networks can be established with Matlab's Deep Learning Toolbox and imported to IDS Simulator
- We studied teaching algorithms, teaching set and batch size, and some network architectures.
- Right: 98% correct classification with high INR



Comparison of Classification Methods



Conclusions on Classification

- Optimal training of a classifier is extremely complex and application dependent act. Some remarks are made based on the study:
  - SVM seem to work somewhat better at lower INR levels (< 20 dB) than neural networks. (With the ideal signal the performance is only PoCC = 90 %.); This is important result since low INR scenarios are typically of interest
  - CW and pulsed signals seem are the most difficult to classify by all classifiers
  - The RNN seem to perform clearly better than CNN when INR is lower
  - The RNN performs slightly better when limited number of teaching signals are used to train the network.

Conclusions on Classification

- Neural Networks are widely studied and applied in variety of applications → Strong market pull for technology supporting the technology, like chipsets and DSP IP cores
- Reprogrammability is flexible
- Requires representative teaching sets

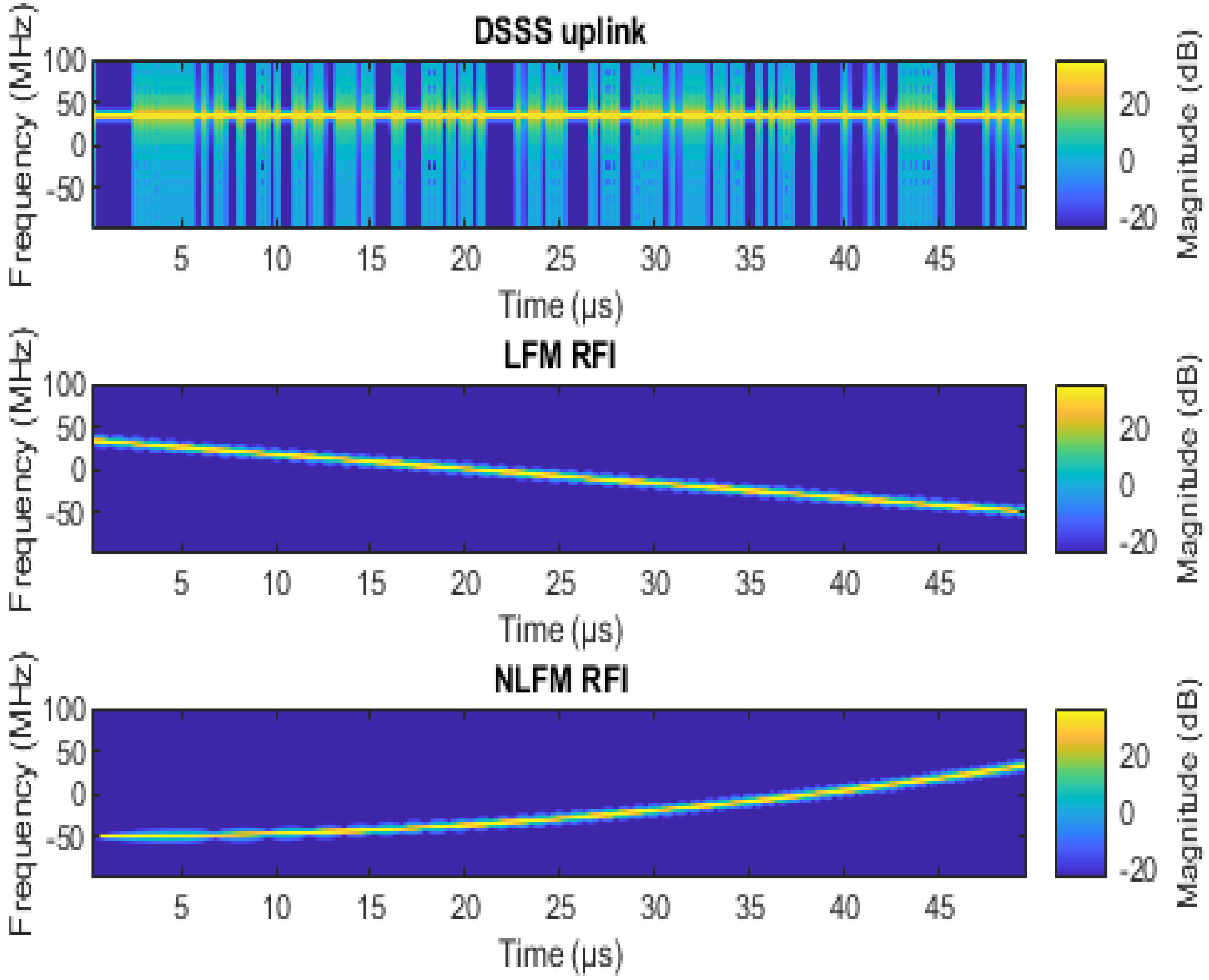
Isolation/Separation Algorithms

Isolation	Short-Time Fourier Transform (STFT)
	Fourier Synchro-Squeezed Transform (FSST)
	Single-channel Quadratic Time-Frequency Domain (SQTFD)
	Multi-channel Quadratic Time-Frequency Domain (MQTFD)
	Independent Component Analysis (ICA)
	Convolutive ICA (CICA)

- Time-frequency-domain methods using ridge detection
- Independent Component Analysis is based on multi-signal (several antennas + receivers) covariance analysis

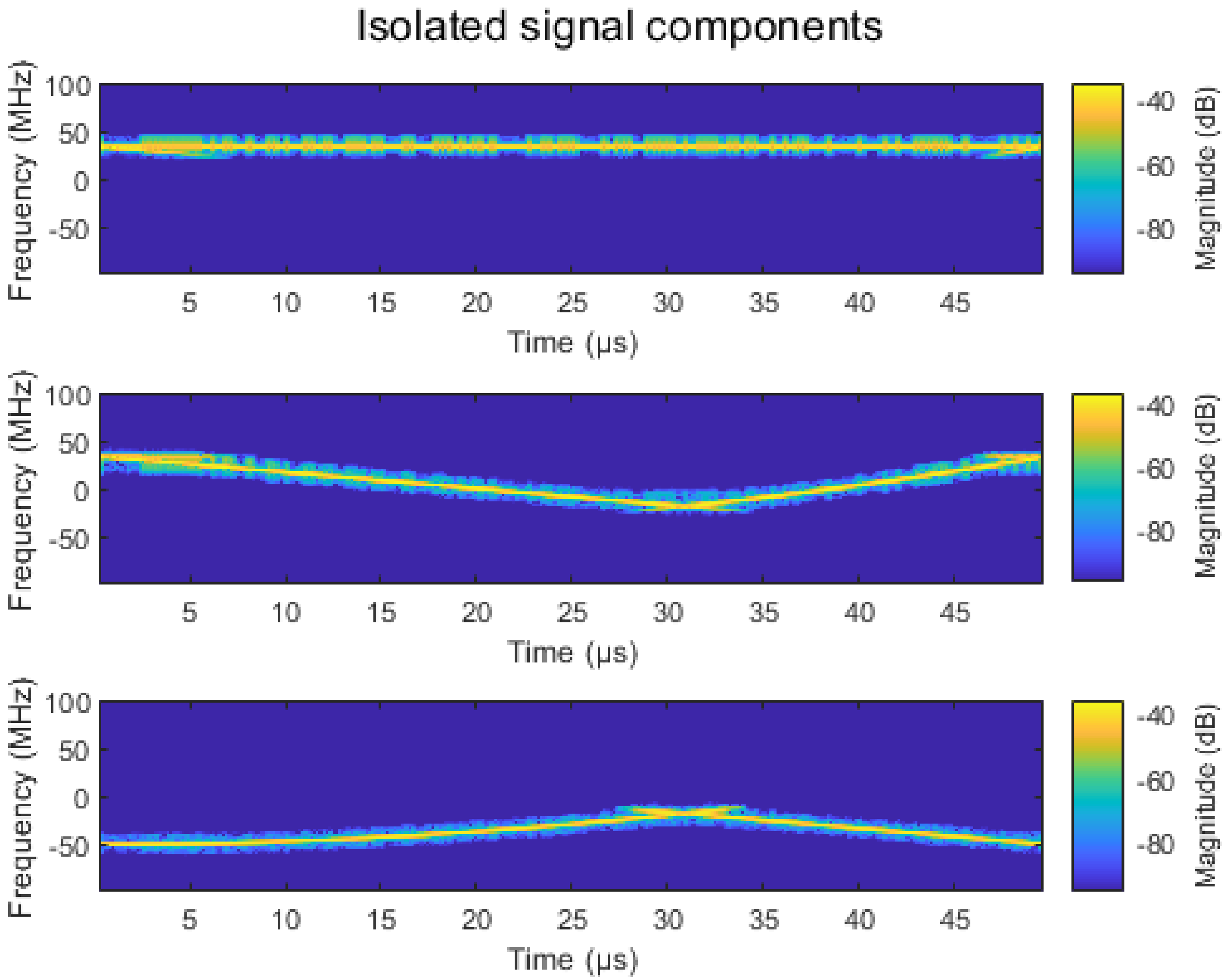
Isolation Example, 1

- We show the performance of all isolation algorithms
- Three RFI signals are present and isolation applied
- FOM for normalized error between signal input component and isolated component (0 – 1).
- Here: input signals



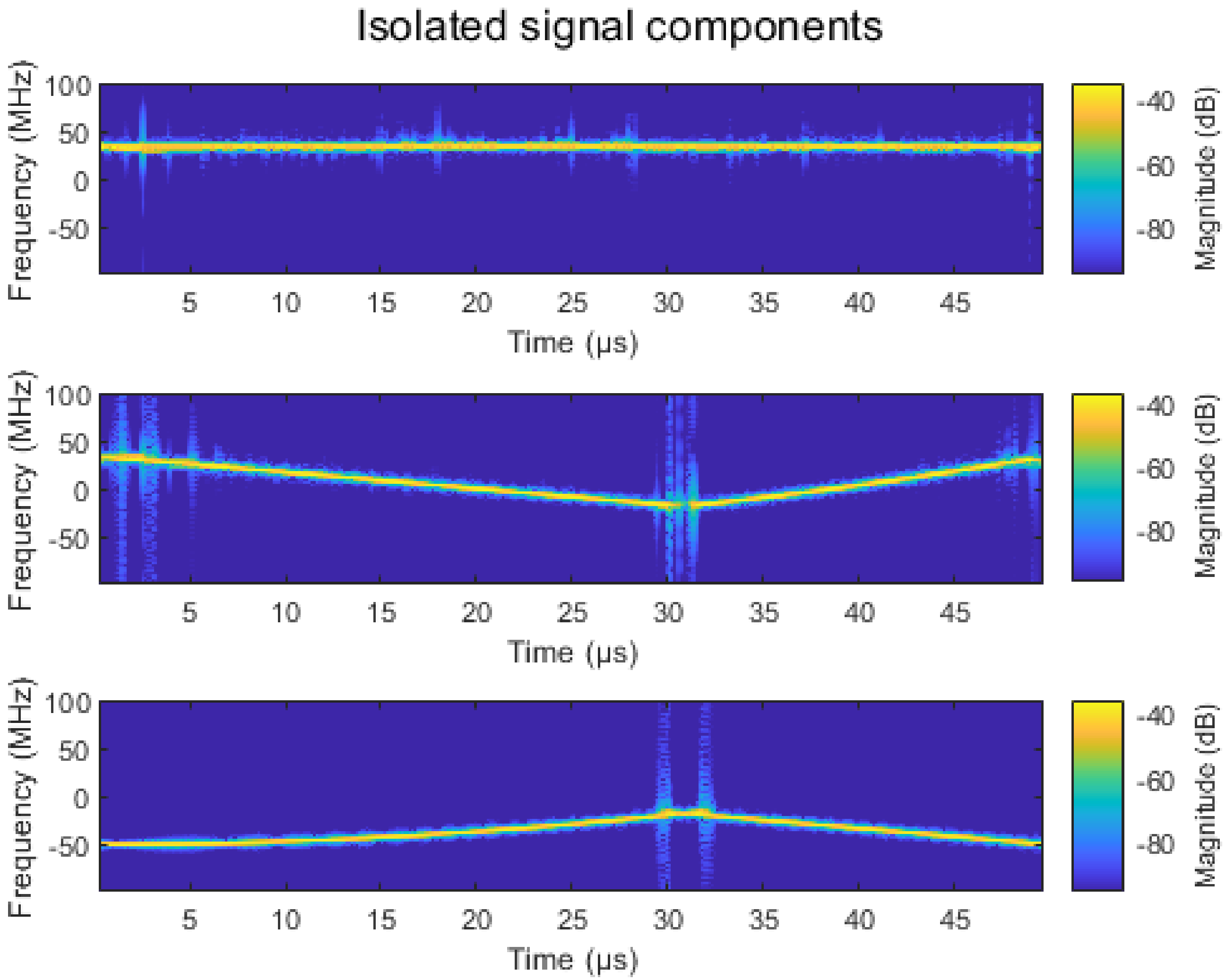
Isolation Example, 1

- Algorithm: STFT
- Signals are mixed and isolation applied
- Right: Isolated signal components
- FOM calculated:
  - DSSS: 0.08
  - LFM: 0.41
  - NLFM: 0.37



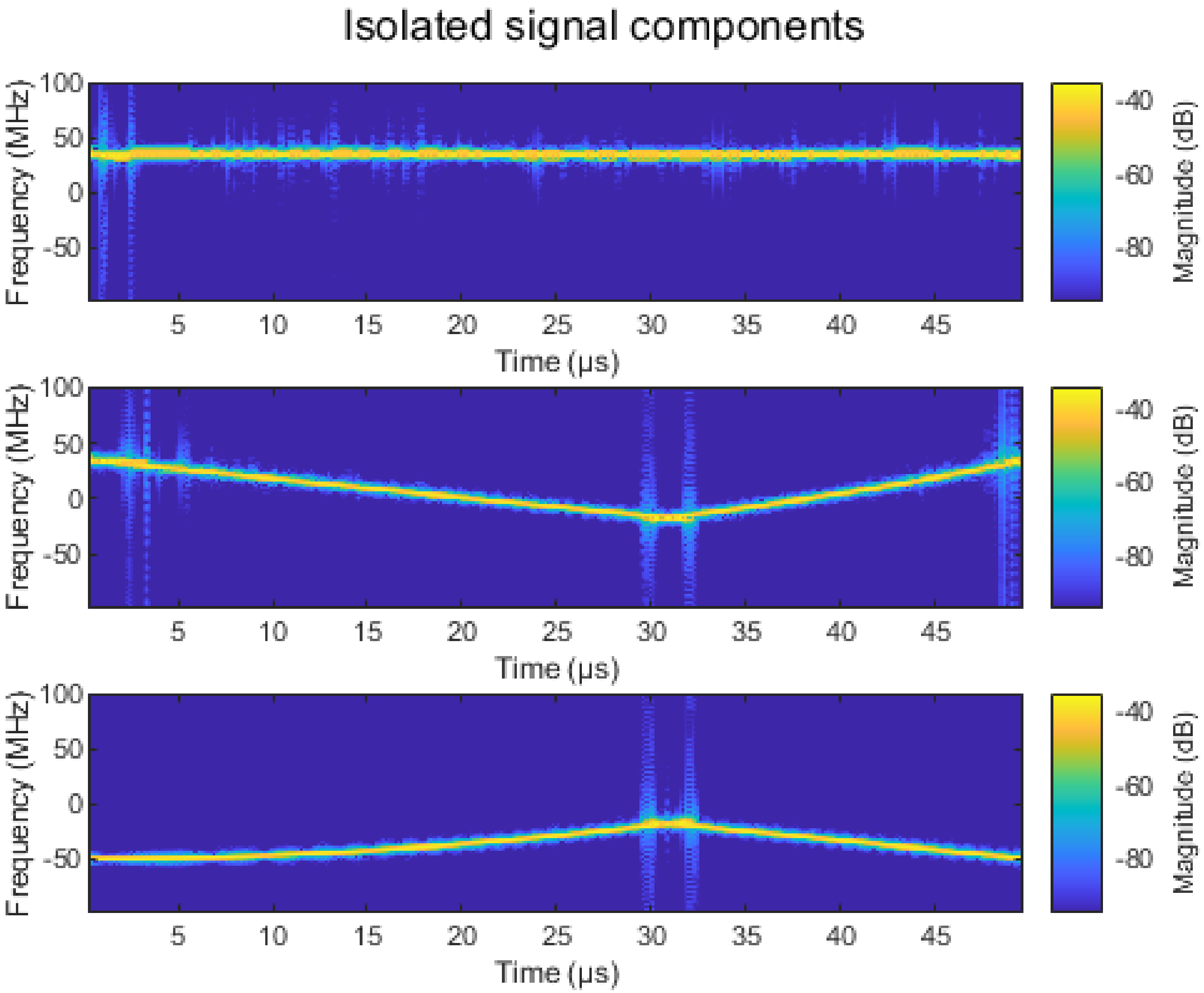
Isolation Example, 1

- Algorithm: FSST
- Signals are mixed and isolation applied
- Right: Isolated signal components
- FOM calculated:
  - DSSS: 0.08
  - LFM: 0.39
  - NLFM: 0.37



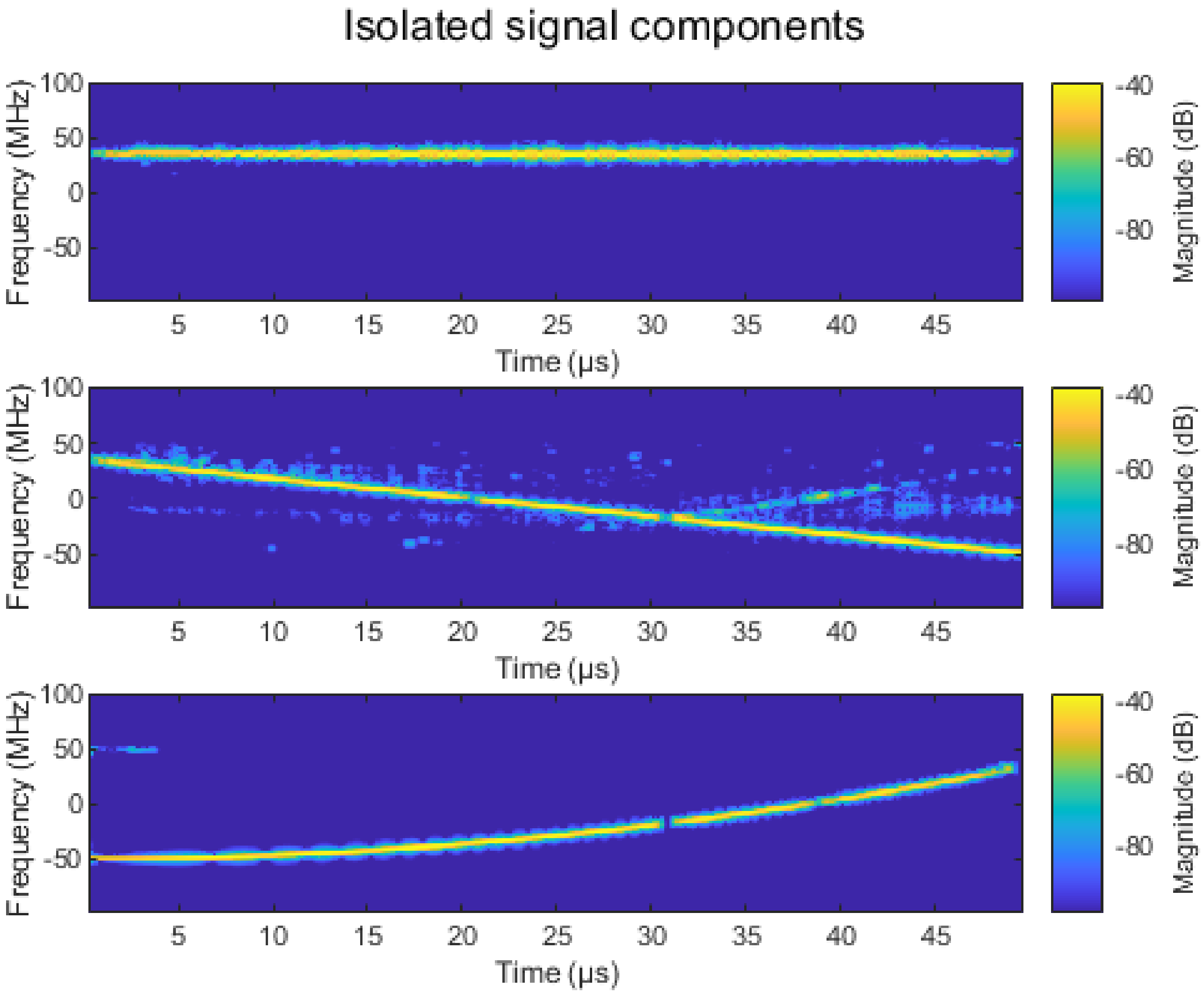
Isolation Example, 1

- Algorithm: SQTFD
- Signals are mixed and isolation applied
- Right: Isolated signal components
- FOM calculated:
  - DSSS: 0.07
  - LFM: 0.40
  - NLFM: 0.37



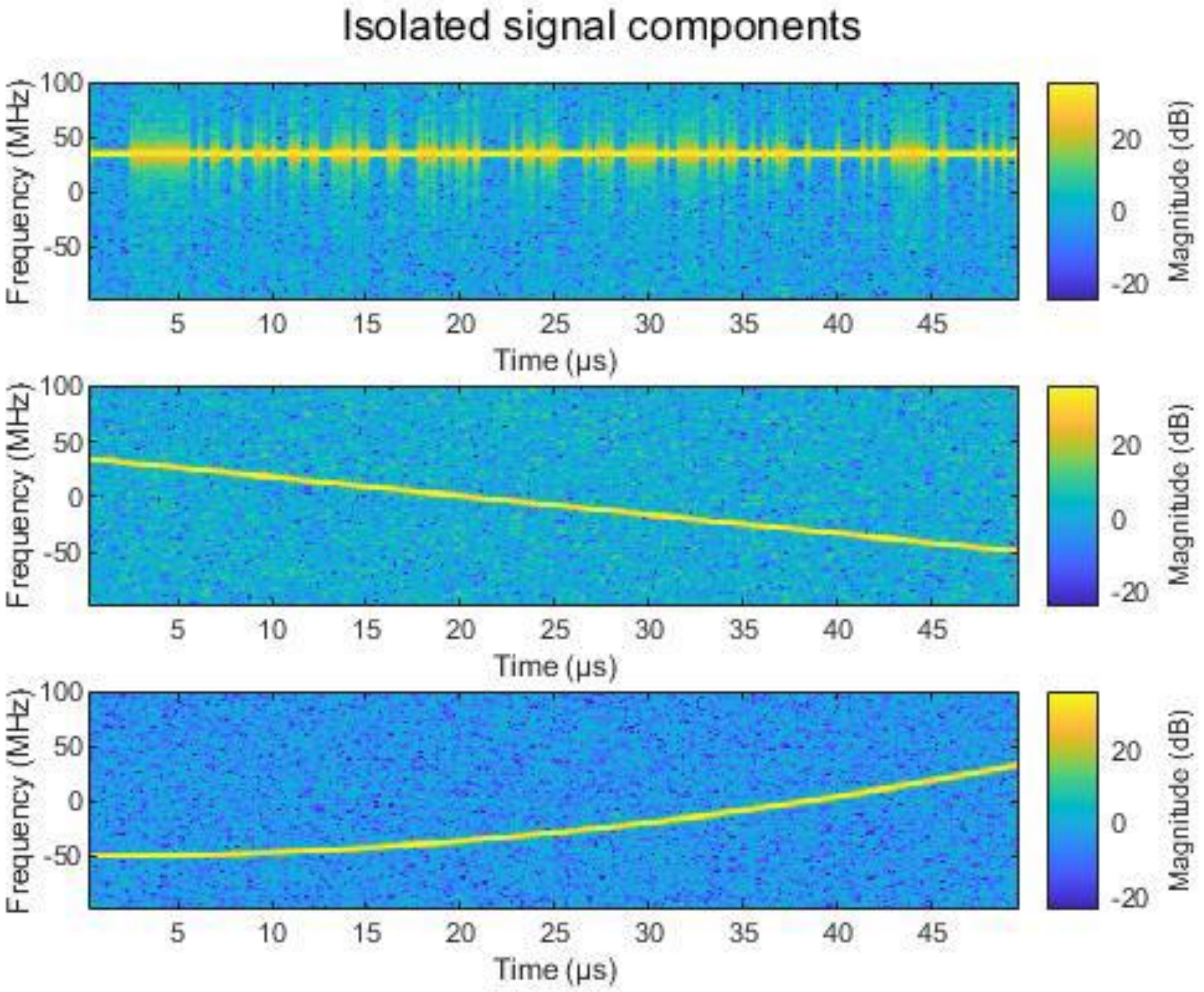
Isolation Example, 1

- Algorithm: MQTFD
- Signals are mixed and isolation applied
- Right: Isolated signal components
- FOM calculated:
  - DSSS: 0.10
  - LFM: 0.06
  - NLFM: 0.19



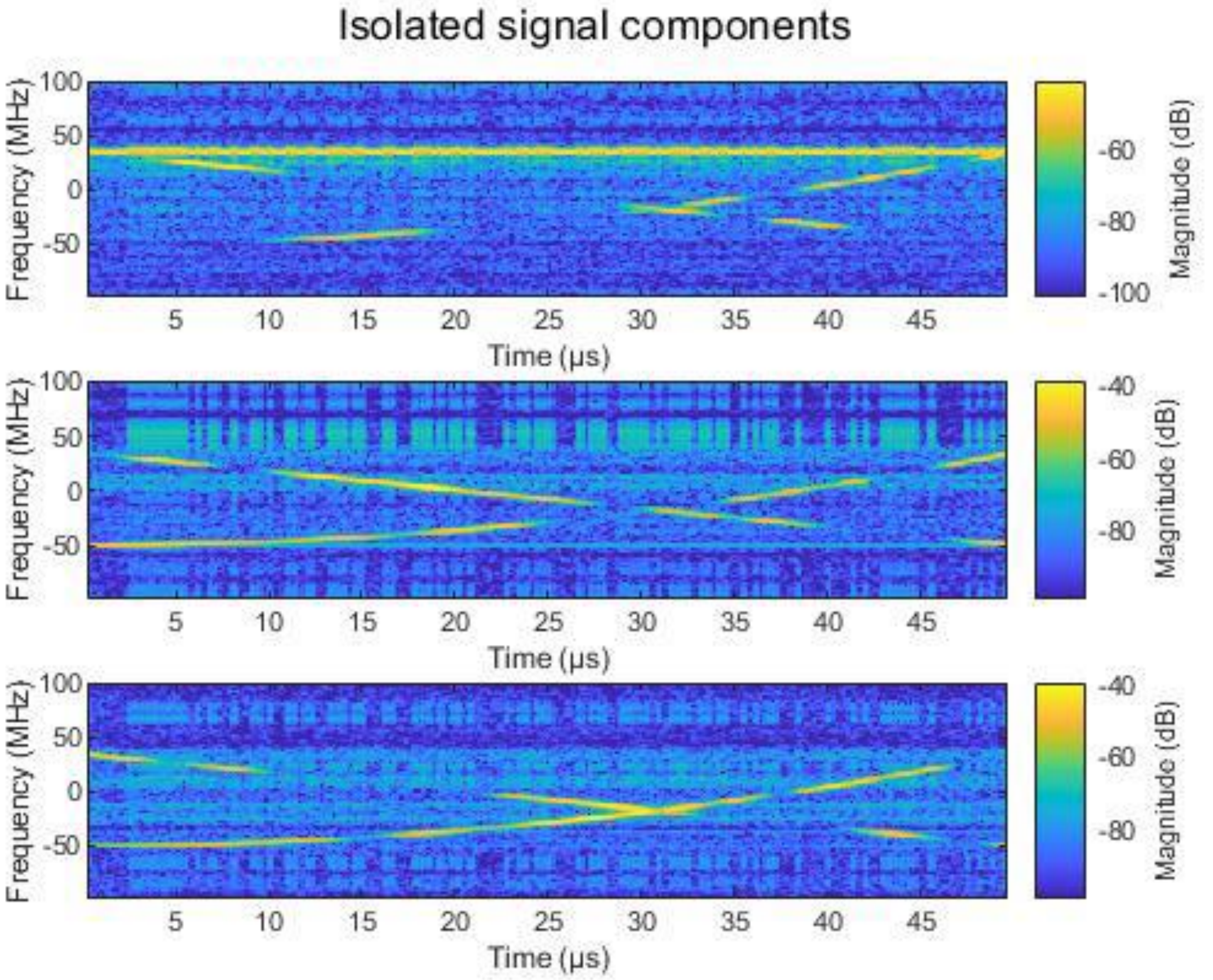
Isolation Example, 1

- Algorithm: ICA
- Signals are mixed and isolation applied
- Right: Isolated signal components
- FOM calculated:
  - DSSS: 0.01
  - LFM: 0.02
  - NLFM: 0.01



Isolation Example, 1

- Algorithm: CICA
- Signals are mixed and isolation applied
- Right: Isolated signal components
- FOM calculated:
  - DSSS: 0.57
  - LFM: 0.82
  - NLFM: 0.75



Conclusions on Isolation

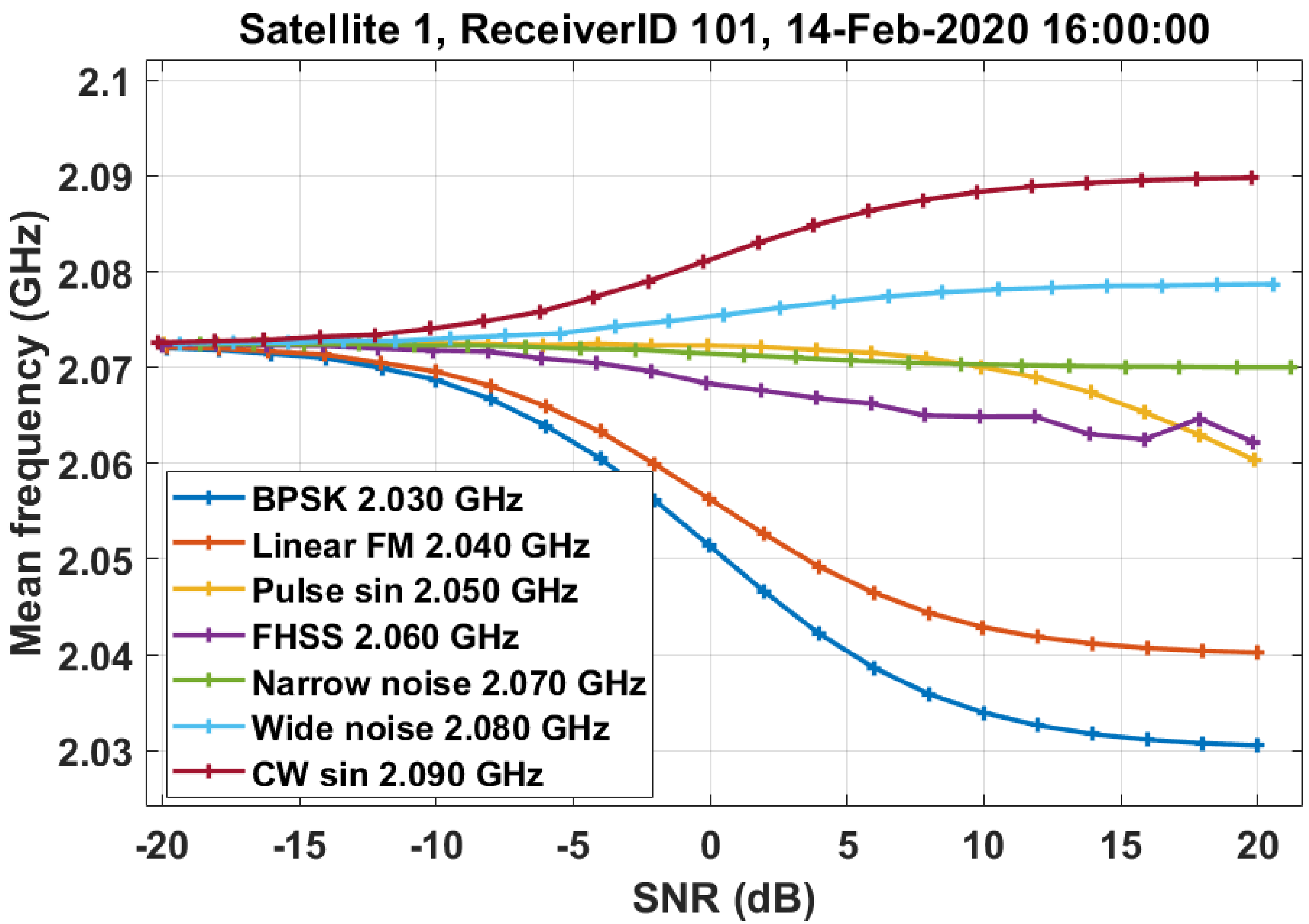
- Ridge detection -based algorithms work well with spectrally isolable continuous signals. Not so well for spectrally mixed signals. They also require estimates of signal bandwidth
- Noise, pulsed and spectrally hopping signals are difficult waveforms
- Multi-channel methods (MQTFD, ICA) can separate spectrally crossing signals, but require noise cancellation algorithms (not part of the study)
- All algorithms <u>require number of signals to isolate </u>or heuristic thresholds. Such algorithms were not studied.
- ICA shows great potential, but requires receiver array

Characterization

- A set of characterization algorithms available in the Matlab Signal processing toolbox integrated.
- Spectral analysis based
  - Mean Frequency
  - Occupied bandwidth
  - Spectral kurtosis
- Time domain analysis for pulsed signals
  - Pulse width
  - Duty cycle

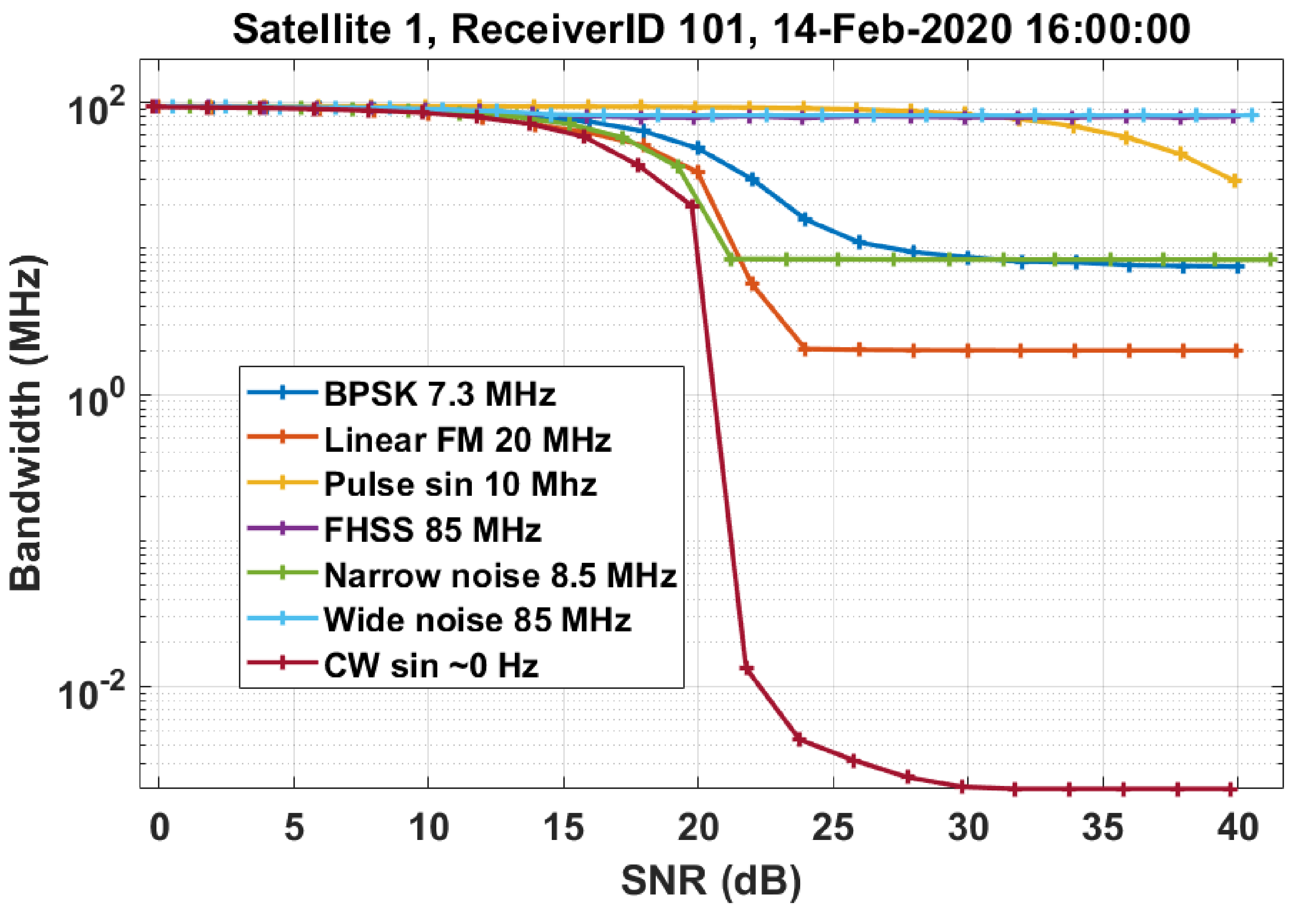
Characterization, Example 1

- Accuracy of the **signal mean frequency** estimation for Galileo S-band receiver
- 5-10 dB INR is needed for <10% error in mean frequency
- At low SNR the algorithm converges to the receiver band centre frequency



Characterization, Example 2

- Accuracy of the **signal bandwidth** estimation for Galileo S-band receiver
- At low SNR the algorithm converges to the receiver banwidth
- High SNR is needed (>15 dB) for medium accuracy. Pulse bandwidth is practically impossible to estimate



Conclusions on Characterization

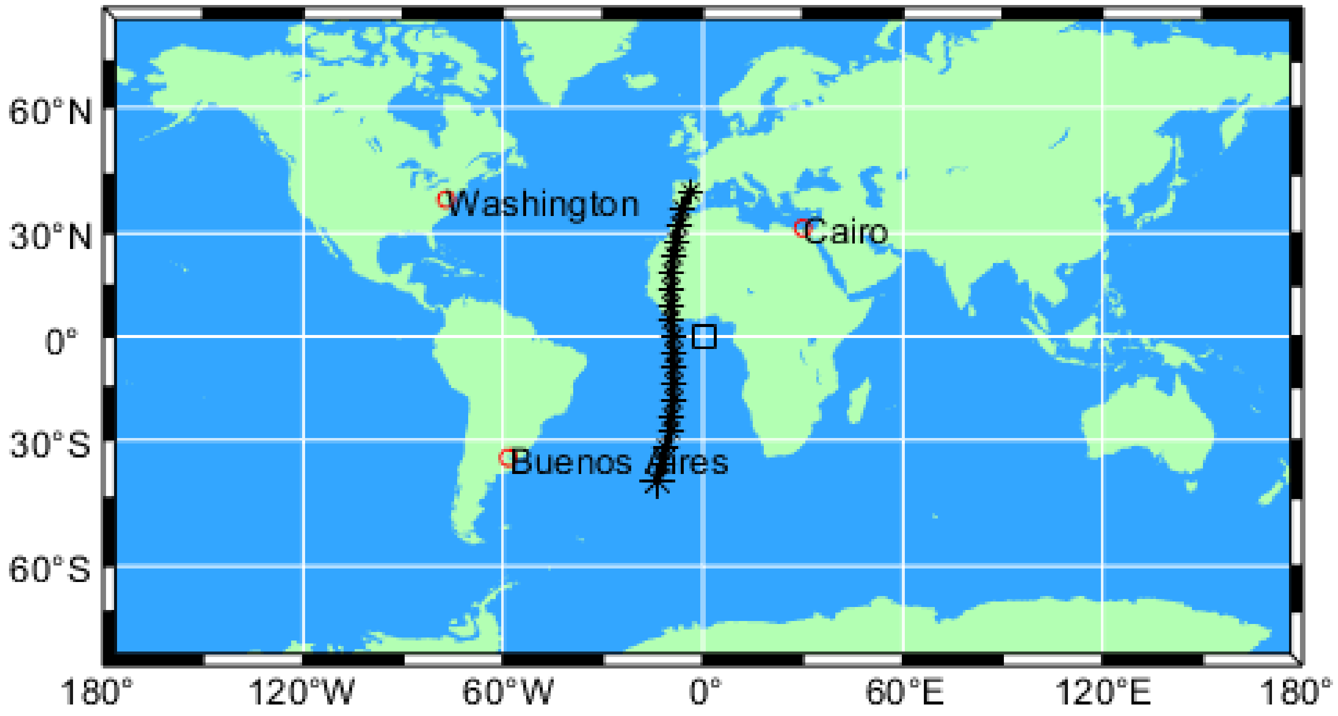
- Characterization algorithms require spectral analysis capabilities (similarly as efficient detection)
- Characterizaiton of SNR would be useful addition
- Characterization algorithms are required to enable+improve performance of other algorithms (classificaiton, isolation, localization)

Localization

- MUSIC (Multiple Signal Classification) ← Single satellite
  - AoA method based on signal covariance analysis from several spatially distributed antennas.
  - Tested with SAR antenna configuration (scaled to S-band)
- TDOA&FDOA using CAF ← Two satellites
  - Signal time and frequency difference determination from CAF
  - Pixel aggregation with Least-Mean-Square method
- TDOA using CAF (Cross Ambiguity Function) ← Three satellites
  - Signal time difference determination from CAF
  - Pixel aggregation with Least-Mean-Square method

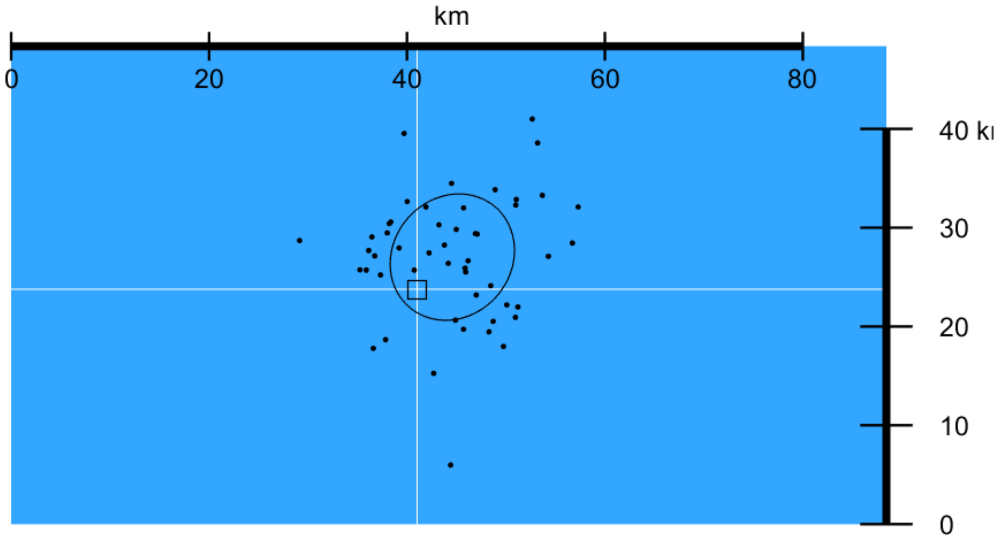
MUSIC, Example 1

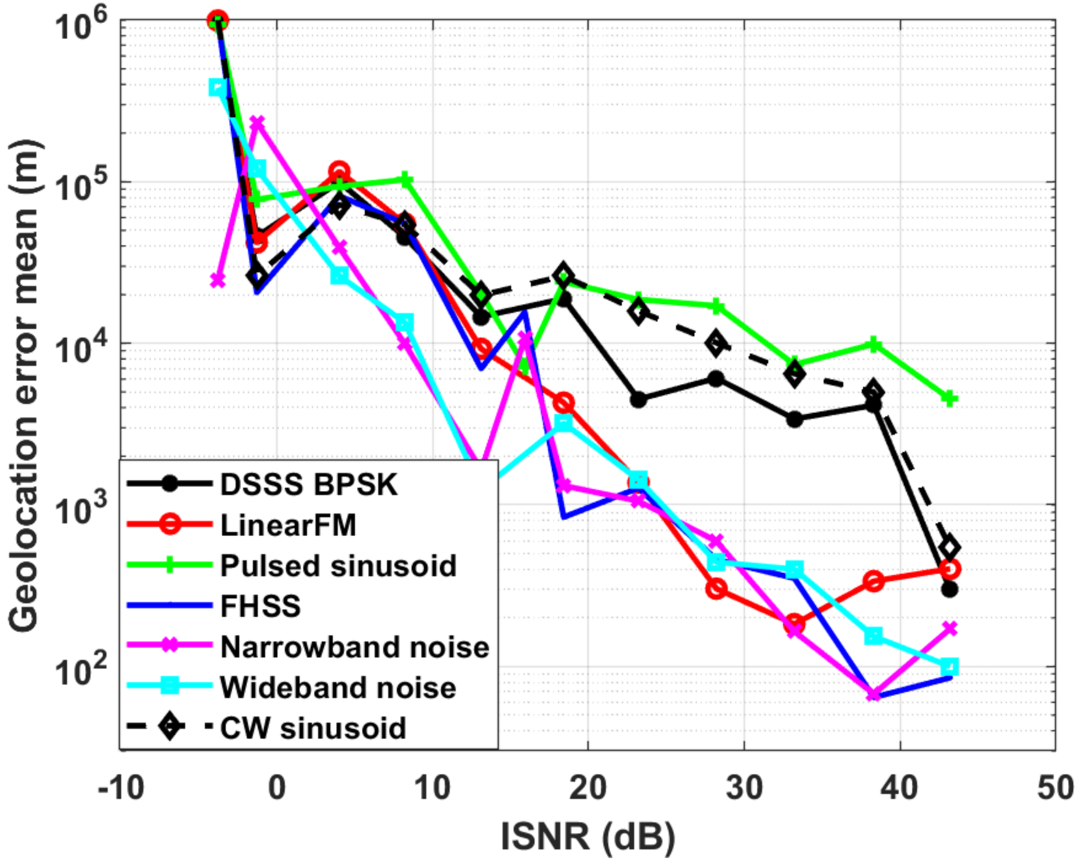
- Galileo S-band receiver characteristics
- Hexagonal antenna array with 6 receivers
- 22 km orbit height
- 7 reference RFI types
- 19 time moments (50 samples at each moment)



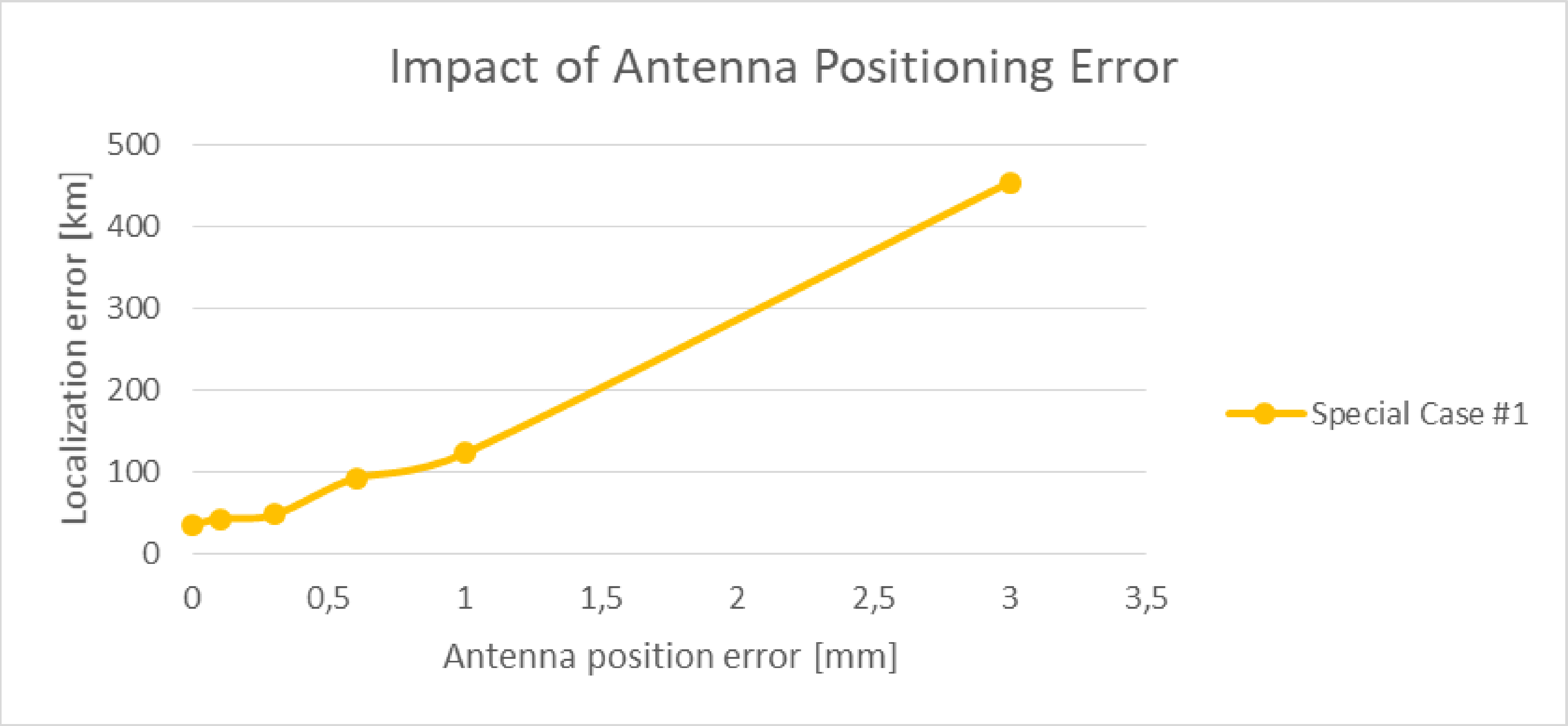
MUSIC, Example 1

- Right: Localization mean error vs. INR
- Below: 50 localizations at time moment 15:00 for BPSK

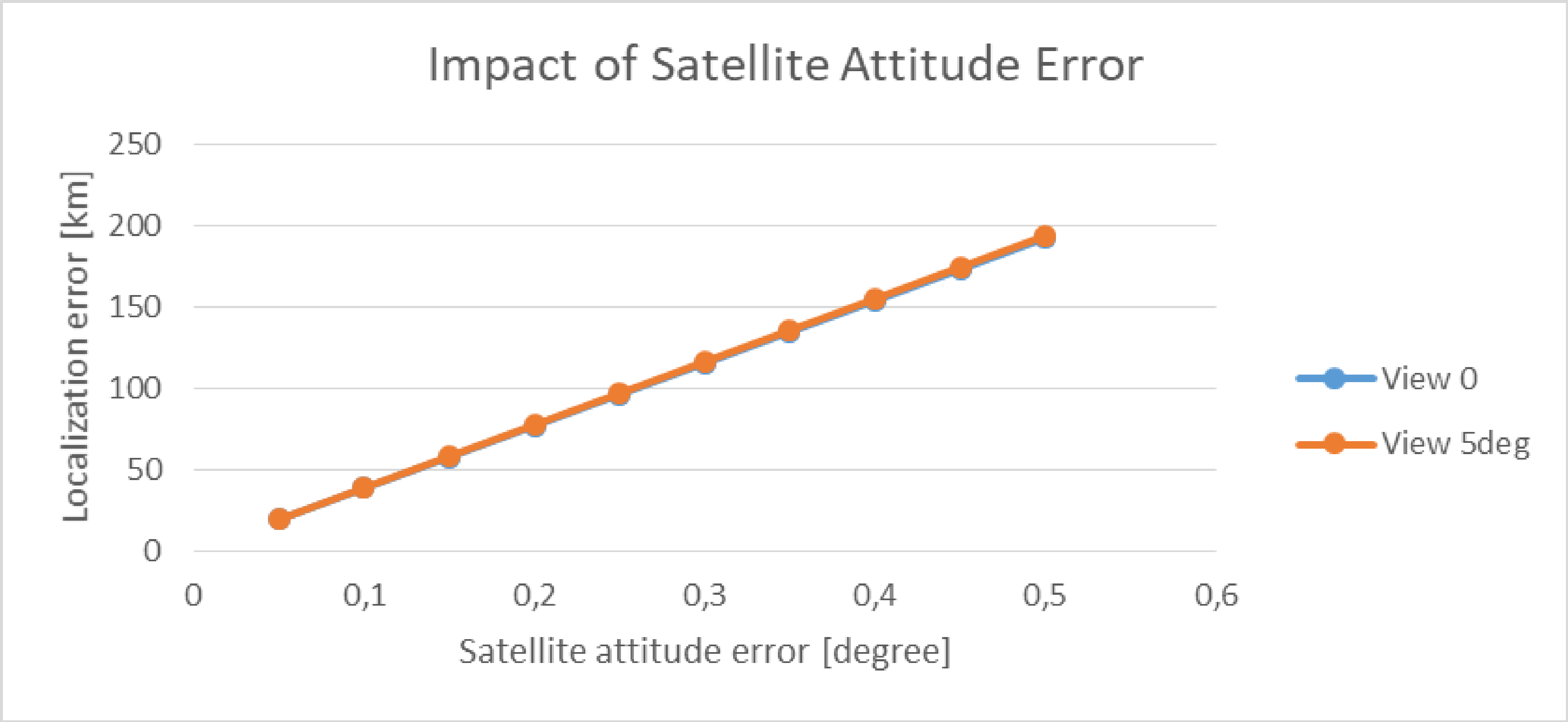




MUSIC, Example 1

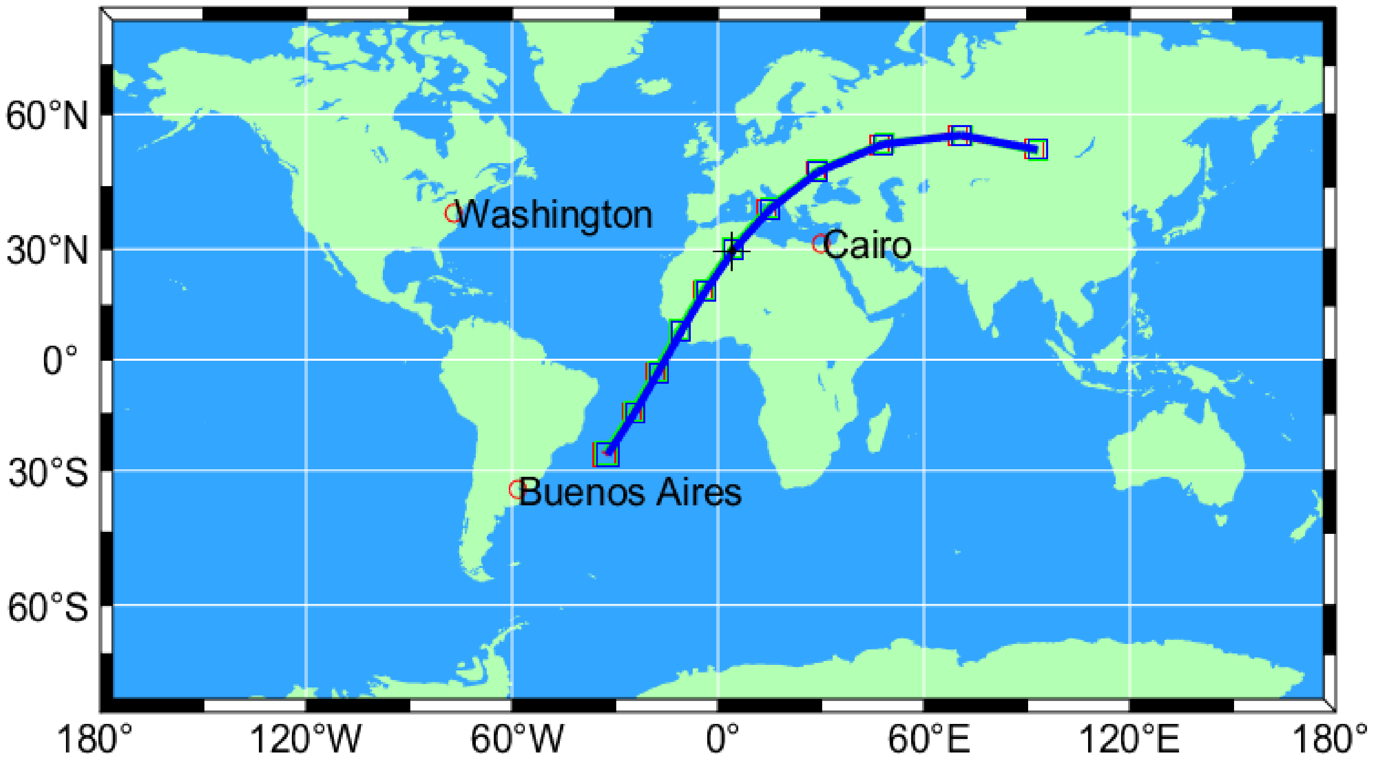


MUSIC, Example 1



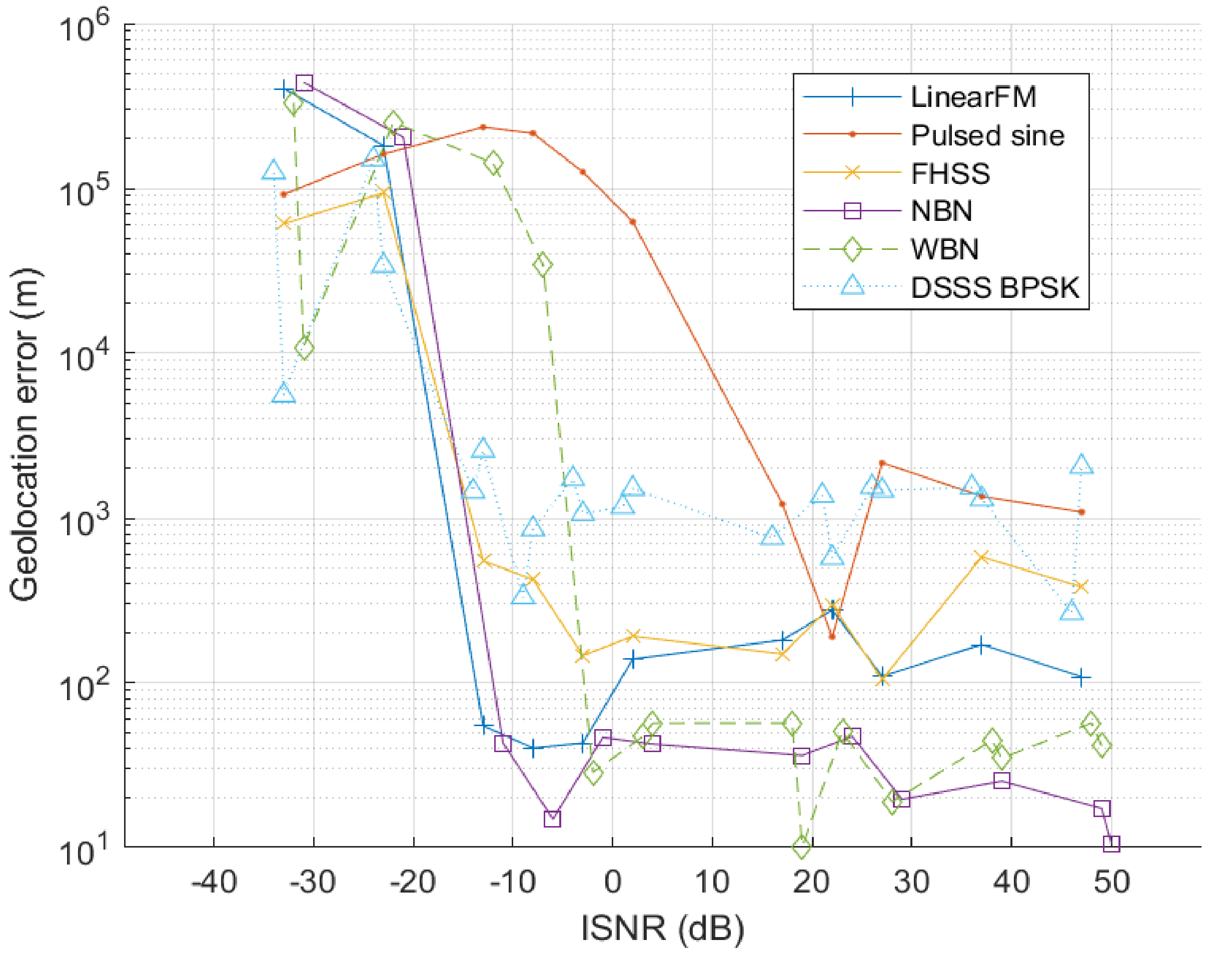
TDOA, Example 1

- Triplet of LEO satellites (~100 km triangle)
- S-band receivers on satellites
- 7 reference RFI transmitters



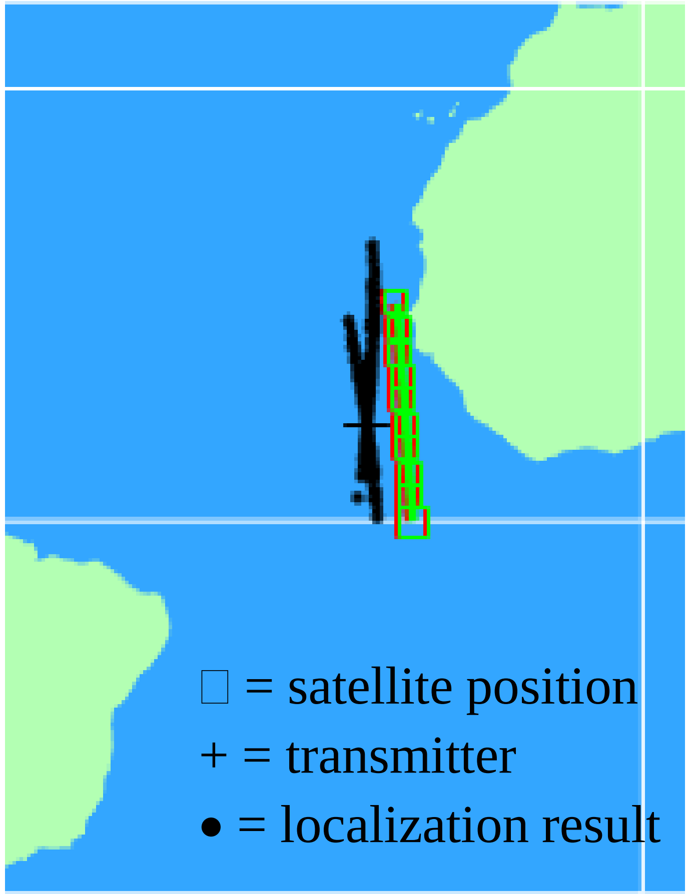
TDOA, Example 1

- Localization performance in the presence of single RFI
- INR sweep of RFI power
- Right: STD of single sample localization
- Km-scale accuracy achieved with most RFI types <0 dB INR (vs MUSIC)



TDOA&FDOA, Example 1

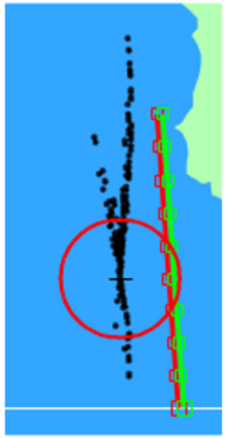
- Tandem LEO system
- S-band receivers on satellites
- 7 reference RFI transmitters



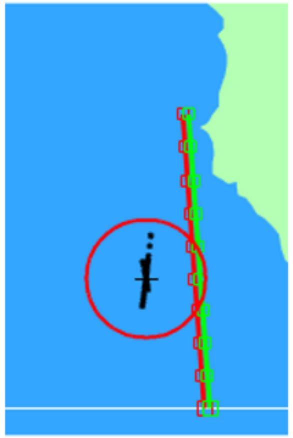
TDOA&FDOA, Example 1

- Localization performance in the presence of single RFI
- Single sample localization (20 samples in each of the 10 time moments)
- Poor results in accuracy

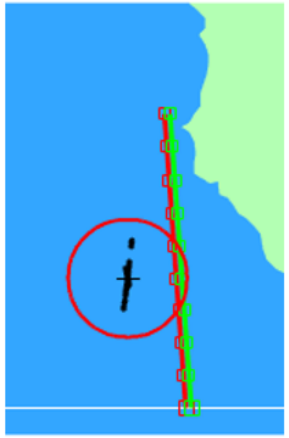
  → Pixel aggregation with LMS



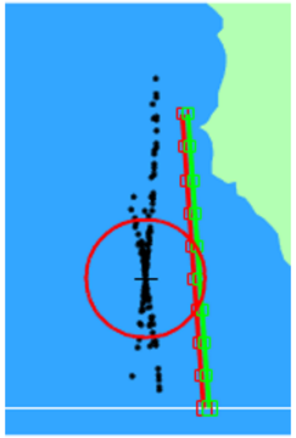
LFM (178)



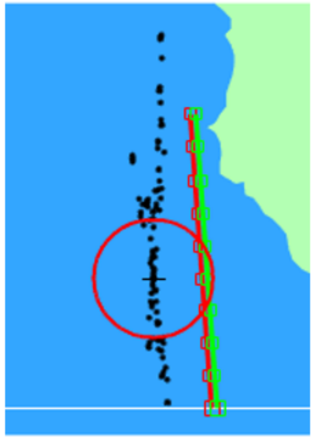
NBN (188)



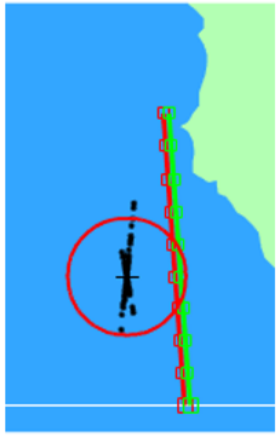
DSSS BPSK (194)



Pulsed sine (158)



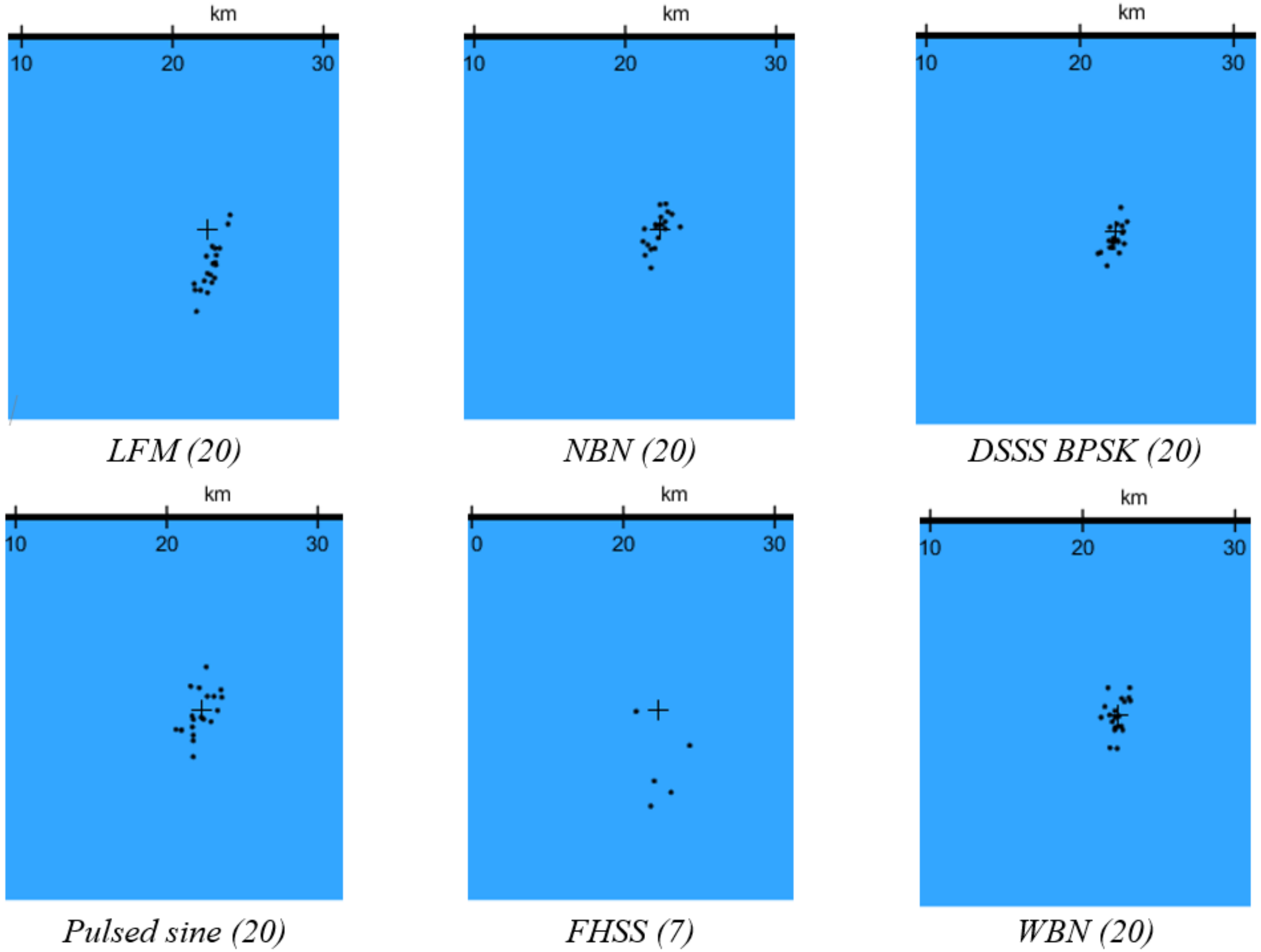
FHSS (140)



WBN (177)

TDOA&FDOA, Example 1

- Aggergation of three time moments (only) with the LMS method
- Here, repeated 20 times to get statistics
- Resulting localization accuracy 2-3 km for all signal types



TDOA&FDOA, Example 1

- Finally, studied as a function of INR caused by the RFI
- Surprisingly, localization result don’t gradually become worse, but in one point localiation just fails.
- Most signals localized with 2-3 km accuracy when SNR < 0 dB.

Accuracy [km] for various INR levels

SNR (dB)	LFM	Pulsed	FHSS	NBN	WBN	DSSS BPSK
26	1.2	3.0	8.0	1.5	1.9	1.3
16	1.2	1.6	2.4	1.8	1.8	2.4
6	1.7	-	0.0	1.5	1.6	1.6
-4	2.0	-	11.8	1.2	1.1	1.9
-13	1.6	-	12.2	1.3	-	3.7
-24	-	-	-	-	-	-

Conclusions on Localization

- We studied (and implemented) three localization methods that are applicable from
  - One satellite (MUSIC)
  - Two (or more) sats (TDOA&FDOA)
  - Three (or more) sats (TDOA)
- Pixel aggregation / averaging can be applied with all. Already having a few temporally (and geometrically) different samples improve the accuracy significantly
- To perform well TDOA&FDOA requires pixel aggregation, the frequency resolution is typically worse than time resolution

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Conclusions on Localization

- MUSIC can estimate the number of RFIs, however, threshold value for eigenvalues needed; CAF-based algorithms could detect multiple CAF peaks, but such algorithms were not studied.
- With MUSIC, error in the platform attitude transforms directly to the AoA error. This effects a lot especially in small platforms. Antenna phase centre accuracy becomes imporant at long distances.
- MUSIC requires estimate of the transmitter frequency → Benefits of characterization
- MUSIC requires highest INR to work in km scale.
- Optimal pixel aggregation scheme could be further studied.

Contents

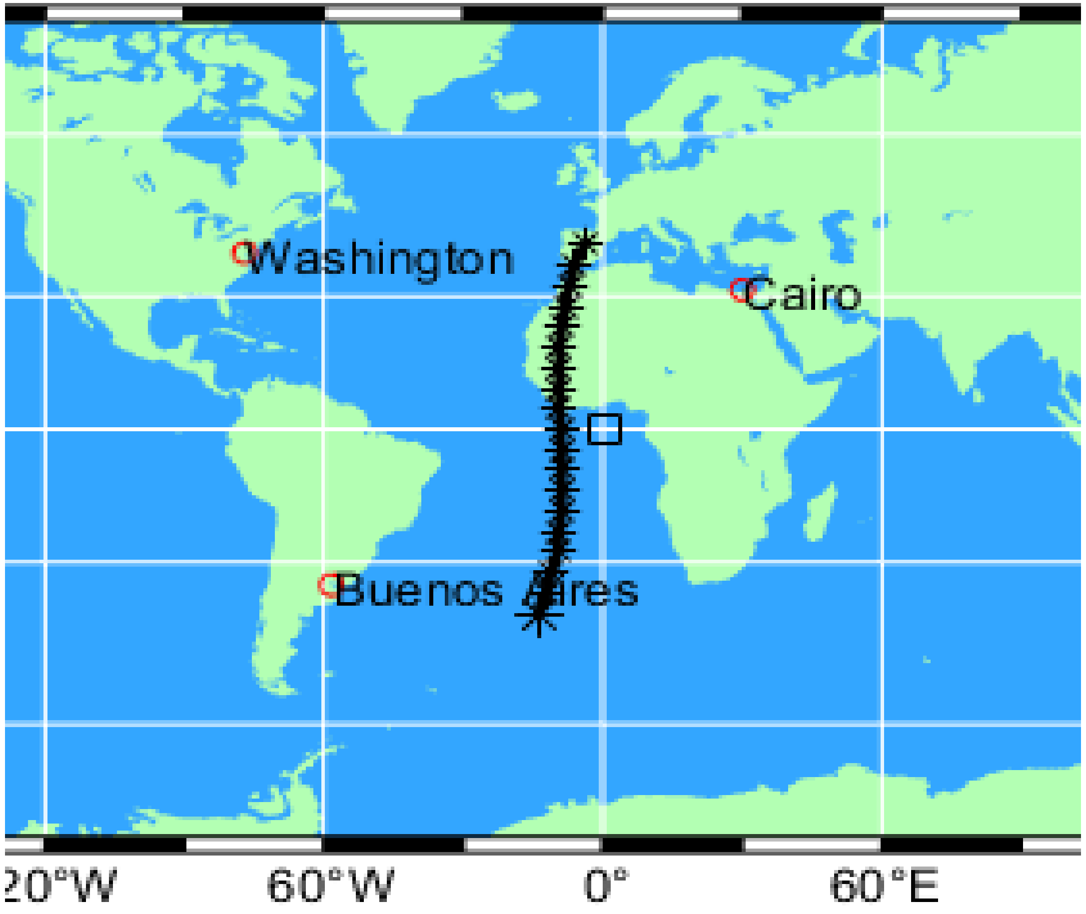
Specific Galile Threat Case Analysis

- Specific Case #1: S-band RFI threat to a Galileo satellite uplink. In this scenario an intentional "crook" points an RFI towards a Galileo satellite and makes a spoofing attack.

- Specific Case #2: RFI monitoring using a LEO formation flying. In this scenario a tandem/triplet satellite formation is used to apply TDOA(&FDOA) emitter localization. It locates emitters at uplink/service bands.

Case 1: Galileo S-band Threat

- Crook interfering with S-band uplink; spoofing attack;
- Crook's TX EIRP of 50 – 70 dBW
- We study how Crook's signal is
  - Detected
  - Isolated from Uplink signal
  - Localized



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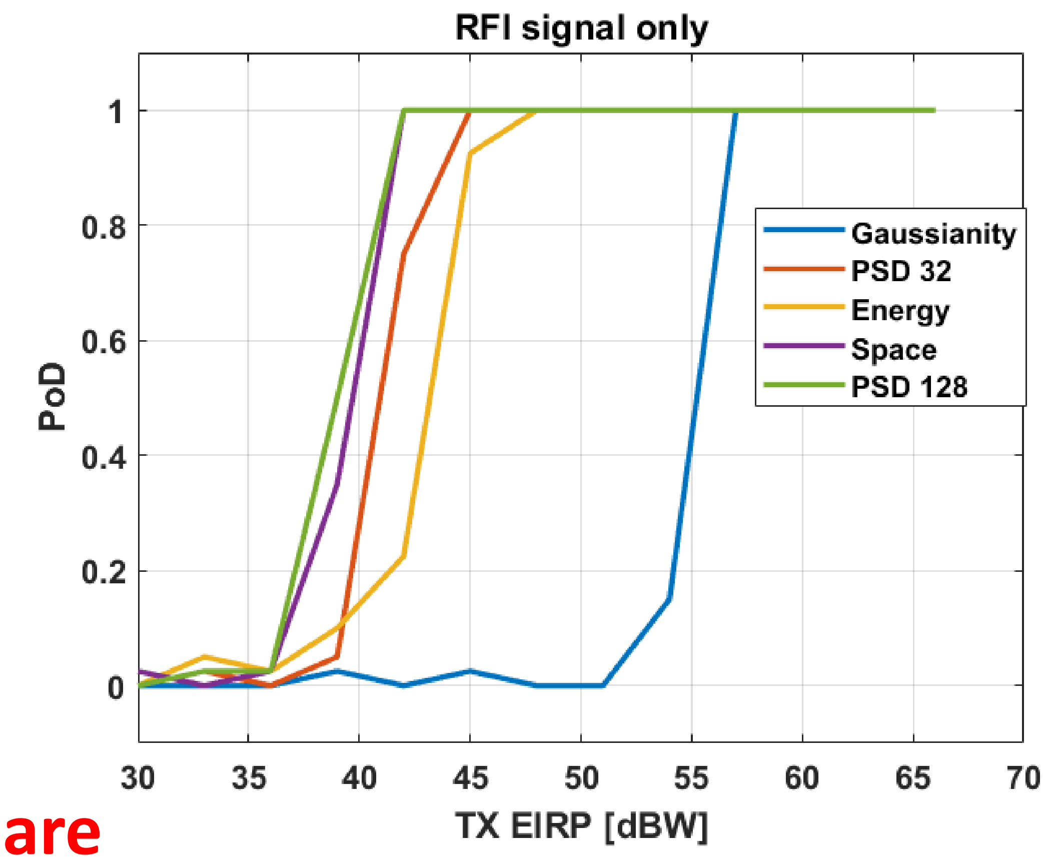

All considered algorithms are able to detect the Crook

Case 1: Galileo S-band Threat

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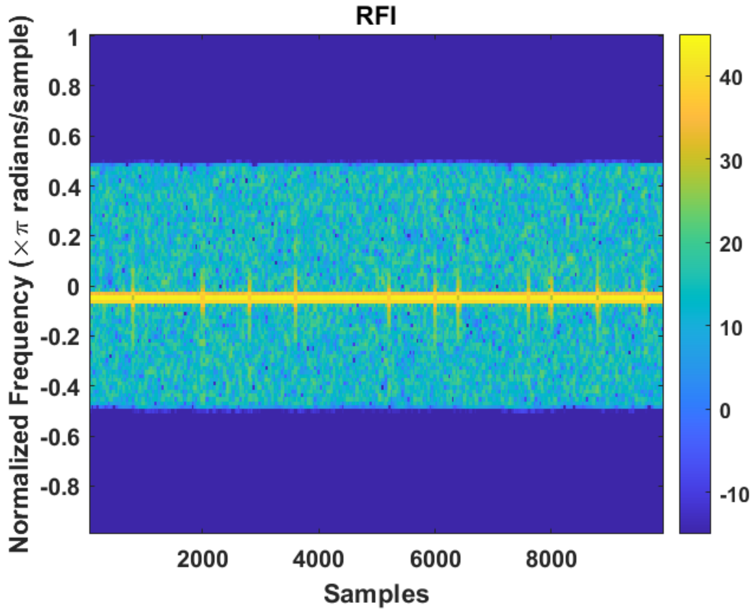

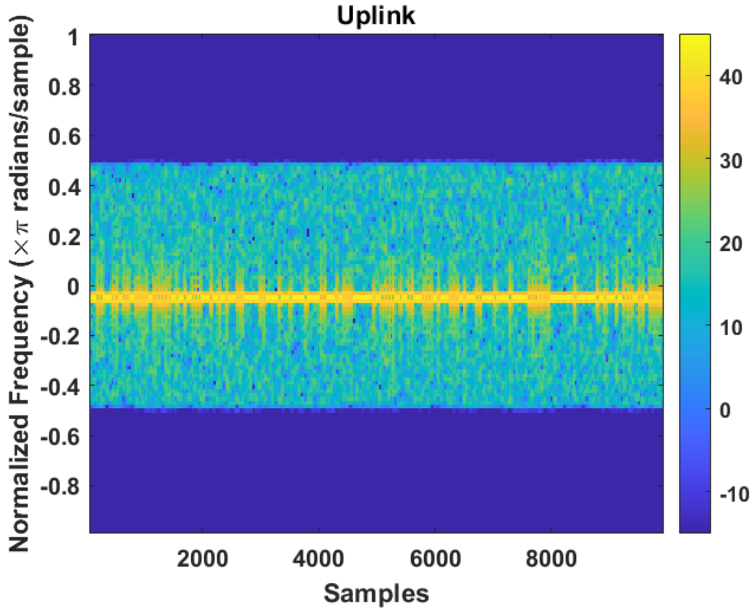

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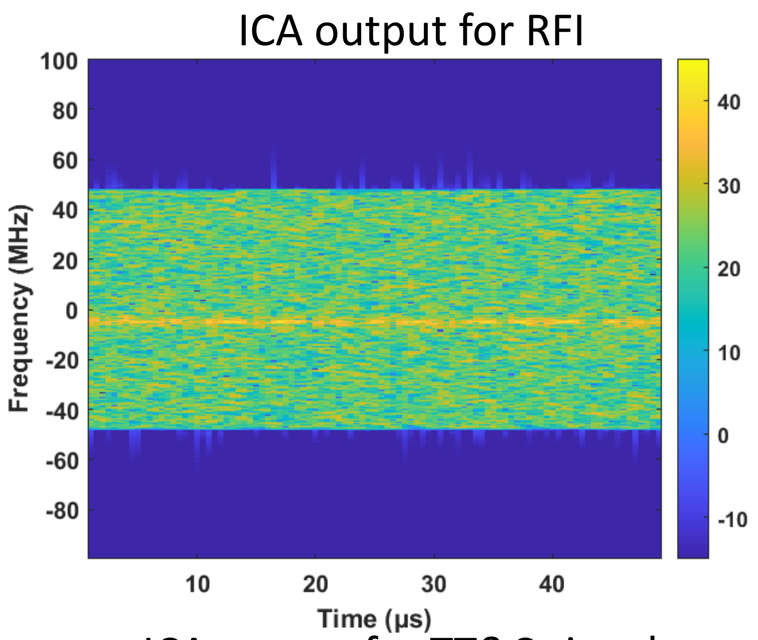

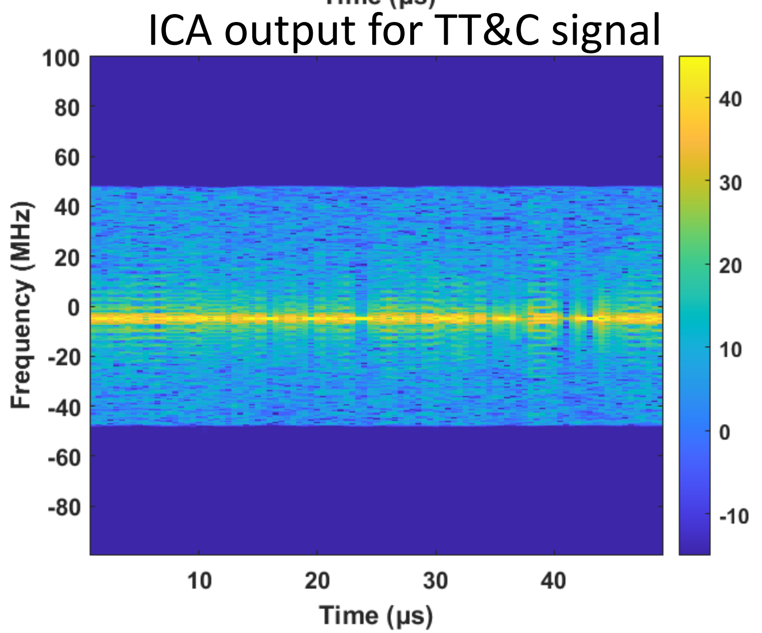

Only ICA was able to some extent isolate the signals

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Case 1: Galileo S-band Threat

- Crook interfering with S-band uplink; spoofing attack;
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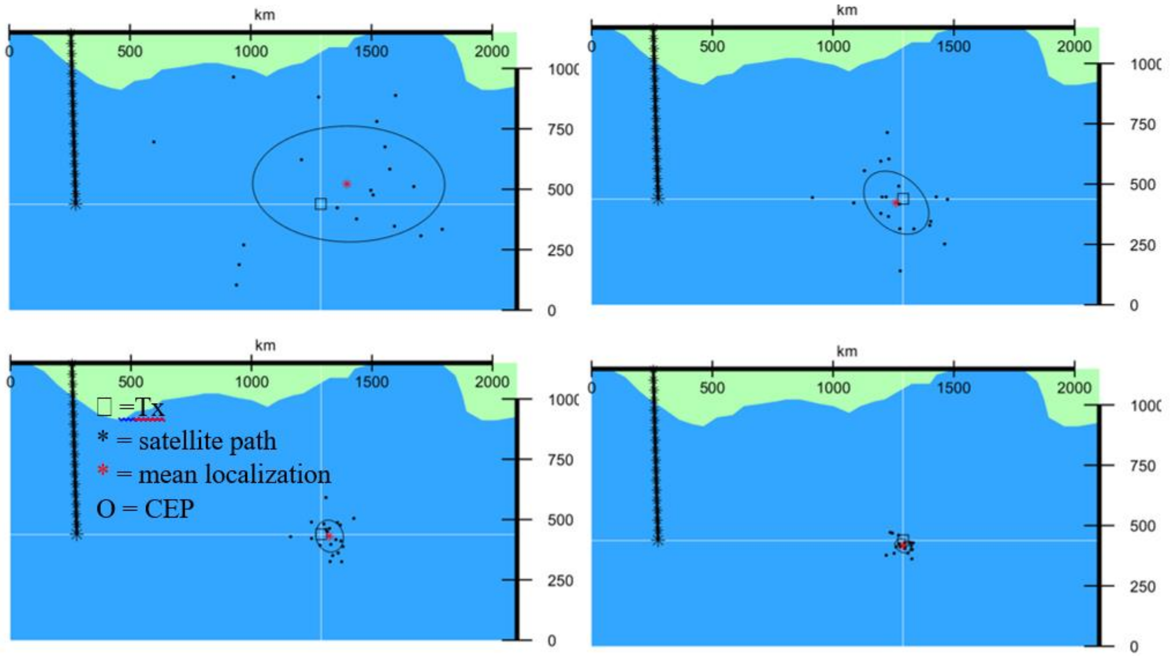
- We study how Crook's signal is
  - Detected
  - Isolated from Uplink signal
  - Localized with MUSIC



Loc results from 20 recorded signal samples for TX EIRP = 50, 55, 60, and 65 dBW

Resulting localization accuracies STD = 325, 102, 50, and 35 km, respectively

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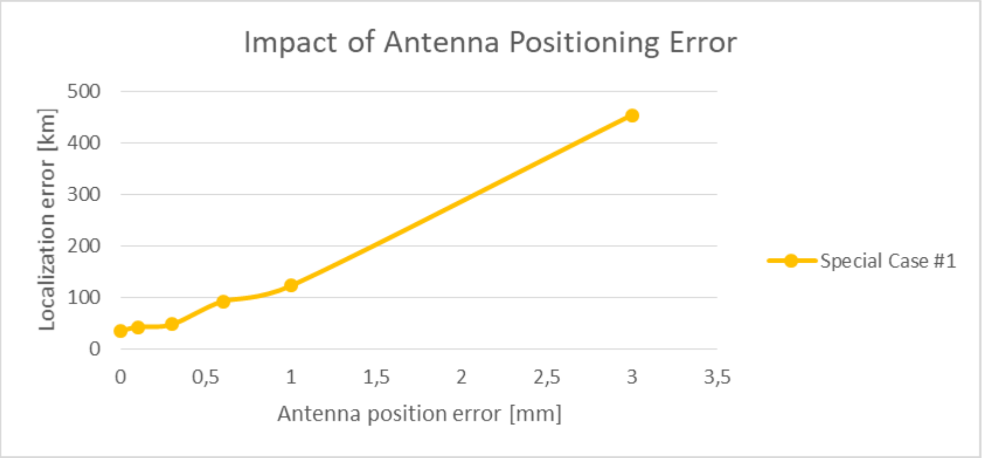
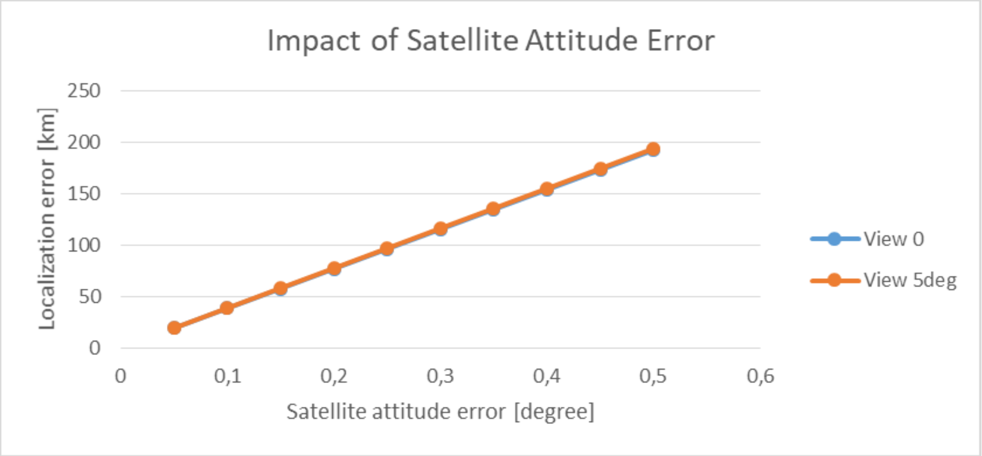
Case 1: Galileo S-band Threat

- Crook interfering with S-band uplink; spoofing attack;
- Crook's TX EIRP of 50 – 70 dBW
- We study how Crook's signal is
  - Detected
  - Isolated from Uplink signal
  - Localized with MUSIC





Antenna array phase errors and pointing errors play significant role!

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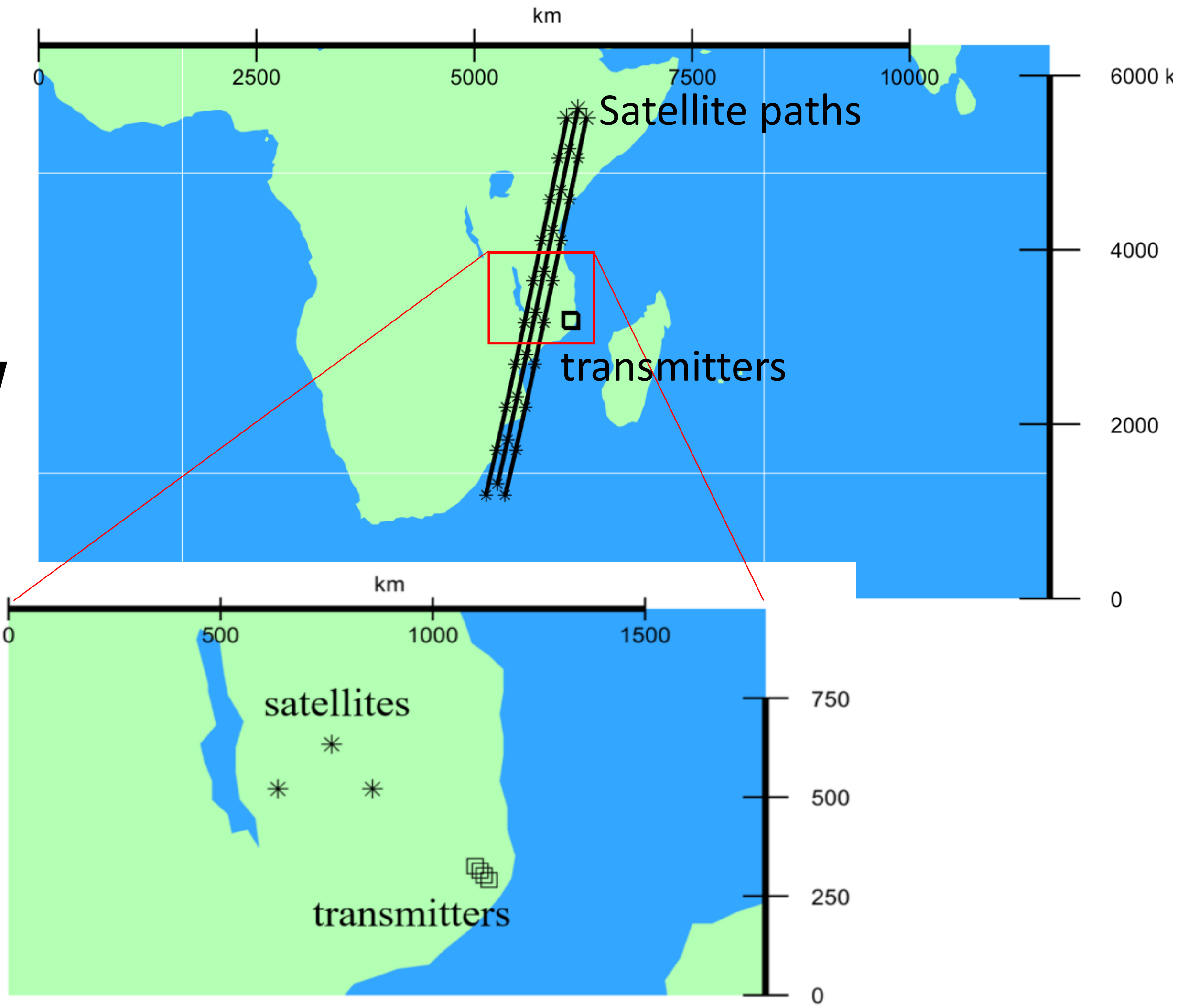
Case 2: LEO RFI Monitoring

- L-band scenario assumed; LEO satellite triplet
- Four potential RFIs
- Relevant RFI EIRP -20dBW→-5dBW
- We considered:
  - Detection
  - Localization



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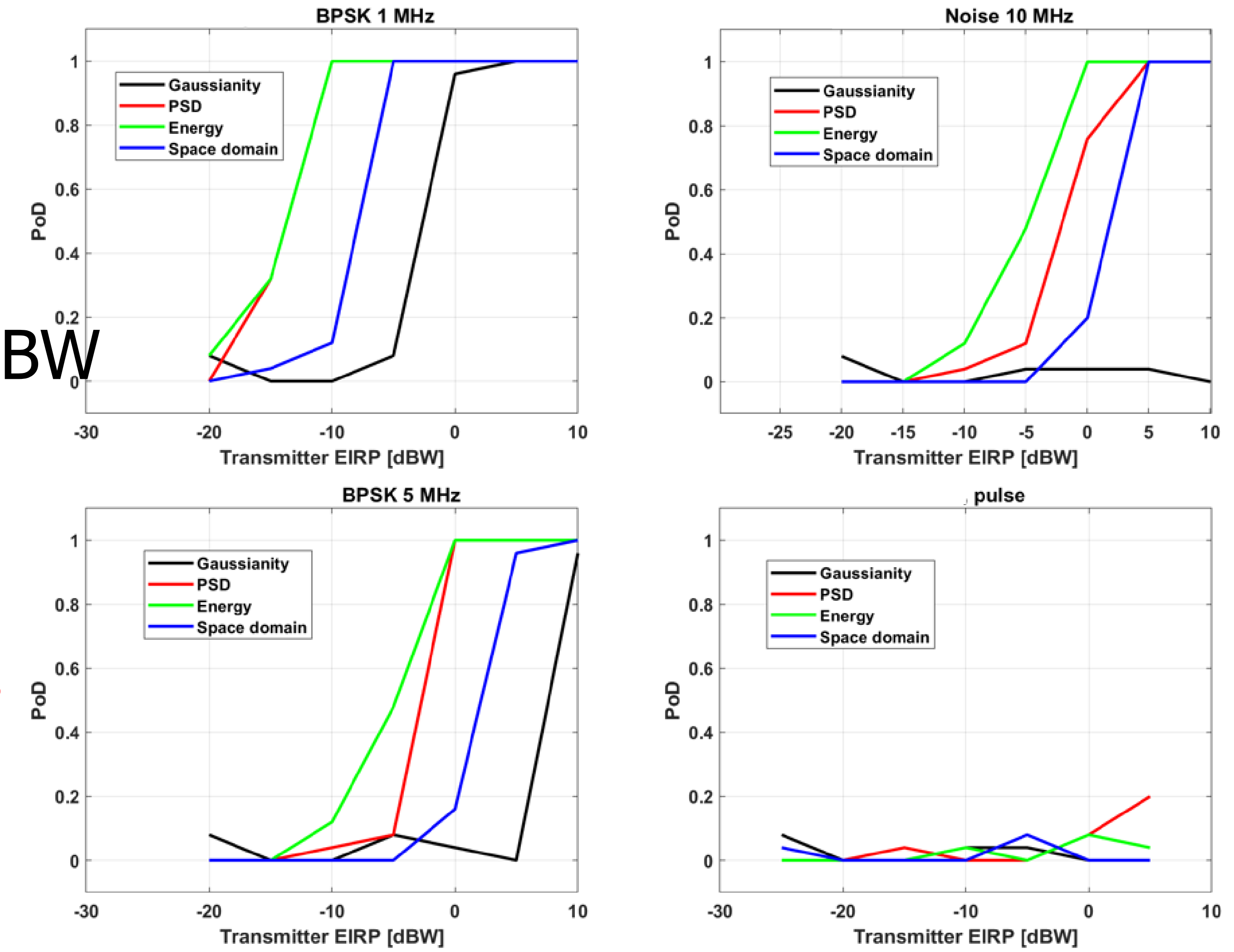
- L-band scenario assumed; LEO satellite triplet
- Four potential RFIs
- Relevant RFI EIRP -20dBW→-5dBW
- We considered:
  - Detection
  - Localization

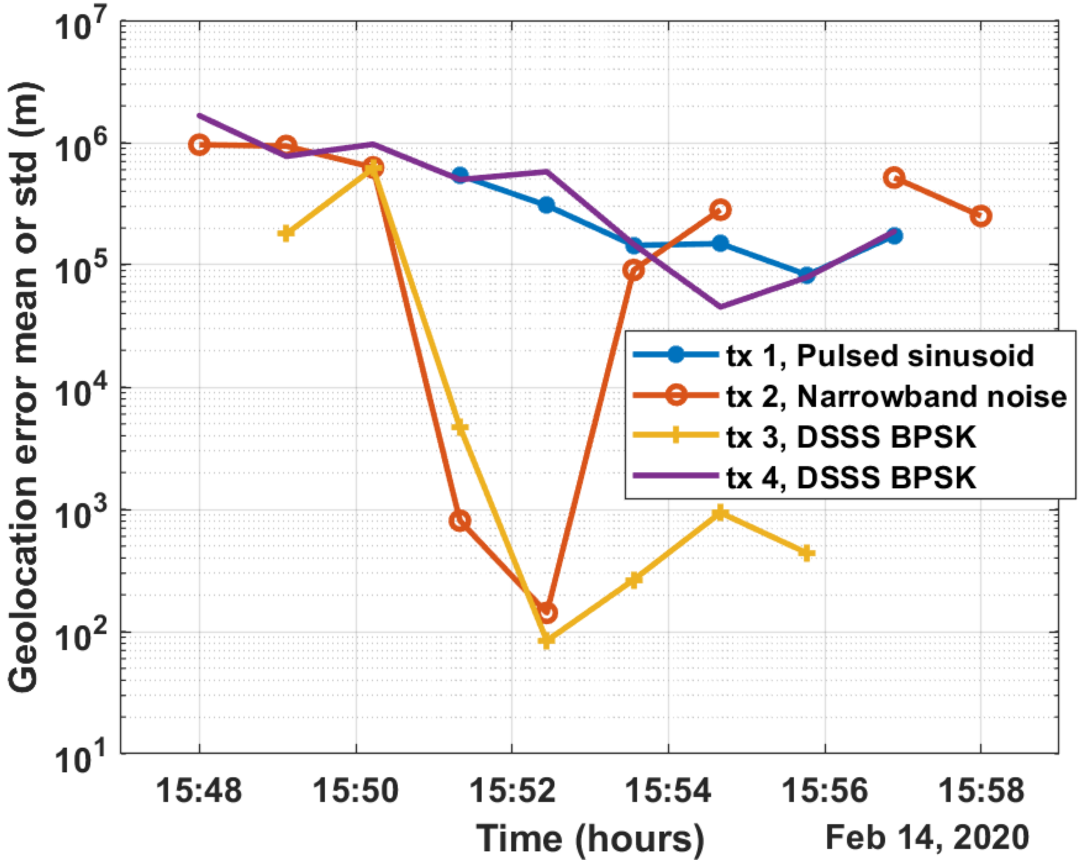
Detection starts to work at -10 – 0 dBW powers. Detection of weakest signals not successful



Case 2: LEO RFI Monitoring

- L-band scenario assumed; LEO satellite triplet
- Four potential RFIs
- Relevant RFI EIRP -20dBW→-5dBW
- We considered:
  - Detection
  - Localization: TDOA

TDOA from 3 satellites (EIRP = 5 dBW)

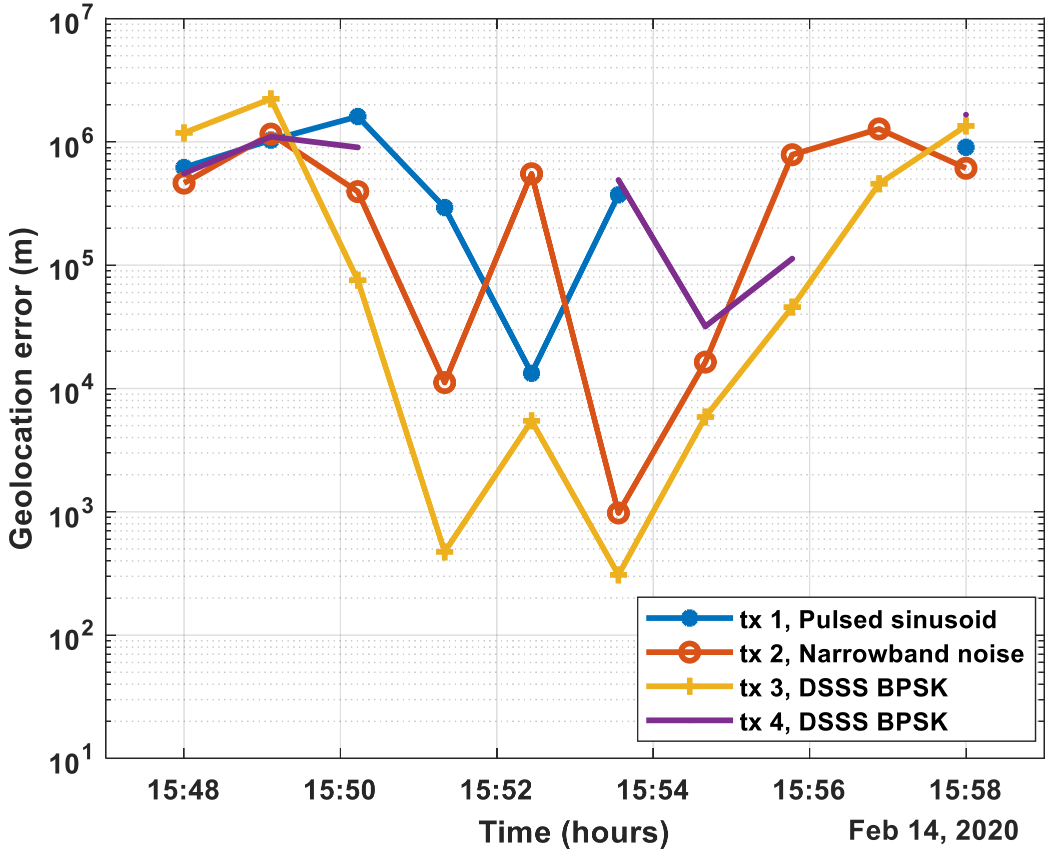


Localization not successful in desired -20→-5 dBW EIRP scale

Case 2: LEO RFI Monitoring

- L-band scenario assumed; LEO satellite triplet
- Four potential RFIs
- Relevant RFI EIRP -20dBW→-5dBW
- We considered:
  - Detection
  - Localization: TDOA&FDOA

TDOA&FDOA from 2 satellites (EIRP = 5 dBW)

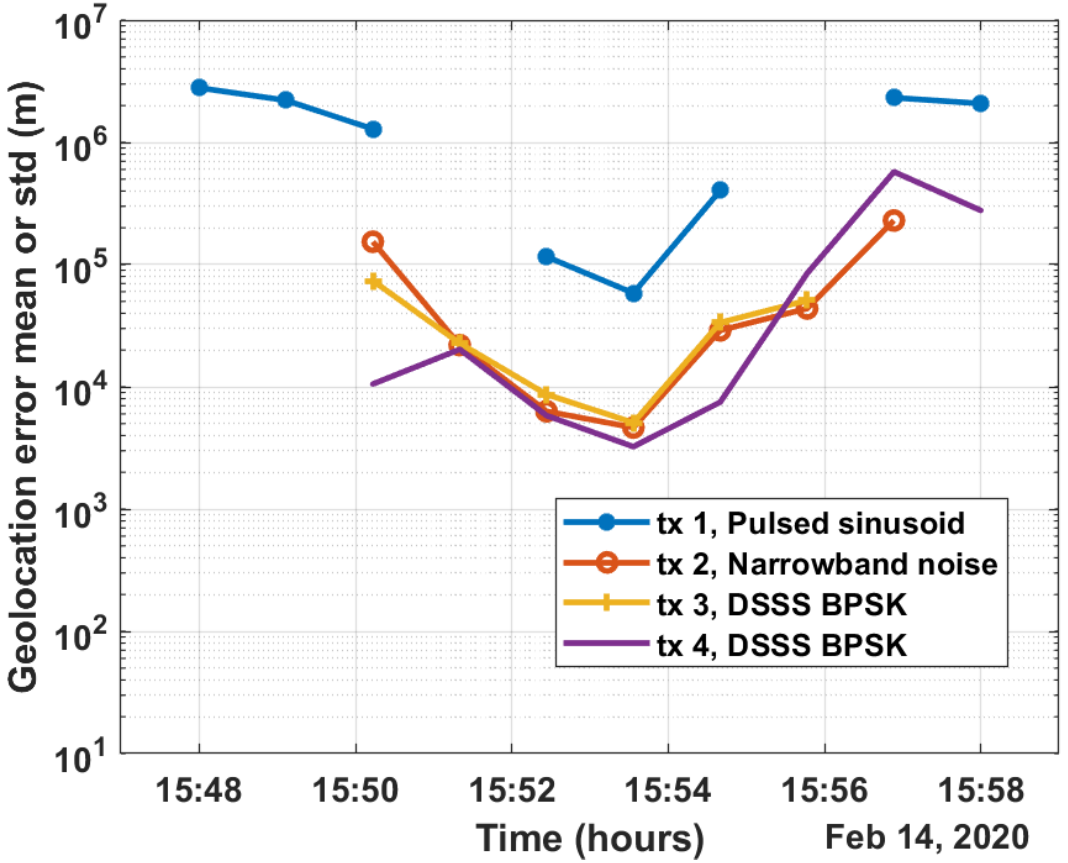


Localization not successful in desired -20→-5 dBW EIRP scale

Case 2: LEO RFI Monitoring

- L-band scenario assumed; LEO satellite triplet
- Four potential RFIs
- Relevant RFI EIRP -20dBW→-5dBW
- We considered:
  - Detection
  - Localization: MUSIC

MUSIC from 1 satellite (EIRP = 5 dBW)

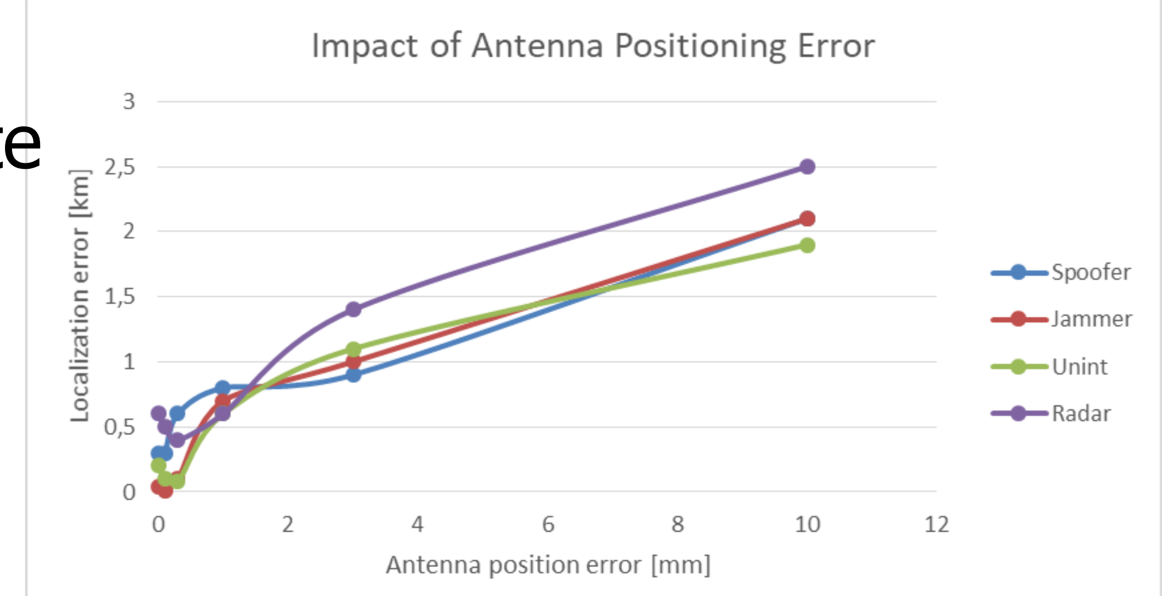


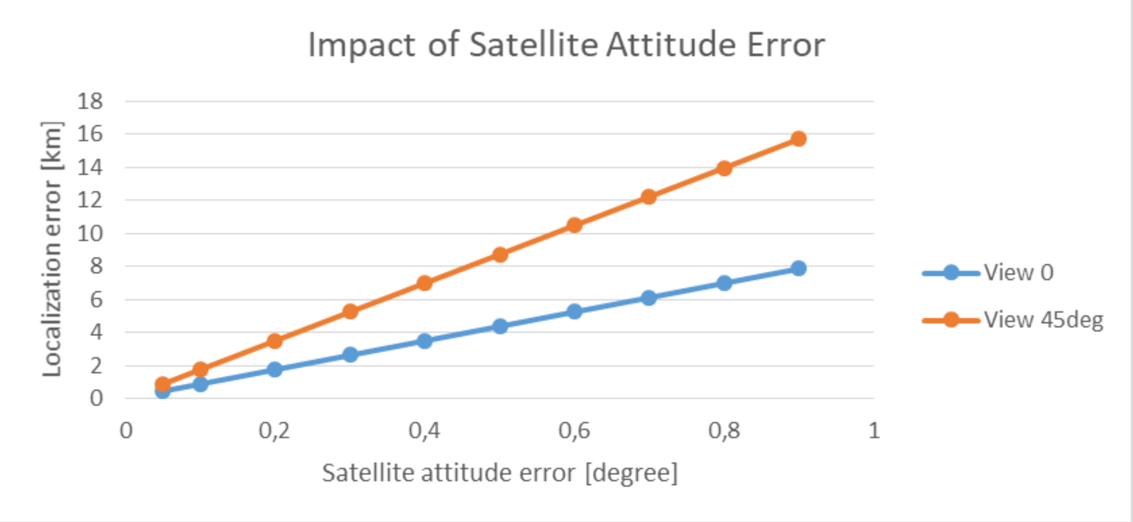
Localization not successful in desired -20→-5 dBW EIRP scale

Case 2: LEO RFI Monitoring

- L-band scenario assumed; LEO satellite triplet
- Four potential RFIs
- Relevant RFI EIRP -20dBW→-5dBW
- We considered:
  - Detection
  - Localization: MUSIC

From LEO the antenna phase is not critical, satellite attitude can be





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Contents

Conclusions, 1/4

- A simulator with wide space of tunable parameters for scenario, satellites, receivers, RFIs, etc., has been implemented
- Over 20 RFI counteraction algorithms studied and implemented
- RFI counteraction algorithms were tested mostly in various scenarios:
  - S-band MEO Galileo scenario
  - S-band LEO constellation / LEO satellite/tandem/triplet
  - L-band LEO constellation / LEO satellite/tandem/triplet

Conclusions, 2/4

- Spectral analysis based algorithms (in all DISCCL domains) are getting more common with the fast development of DSP chips and relevant IP-cores, thus spectral cross-frequency algorithms are recognized as most potential detection algorithms in the future.
- Neural Networks is also technology that develops fast due to its applicability to many domains and strong commercial pull, e.g. in image processing.
- Necessity of on-board isolation and classification remains open? Is there a need of medium-performance isolation/classification? Is on-ground analysis always a better setup?

Conclusions, 3/4

- Performance of localization methods from small satellite constellations (tandem/tiplet) was found to be (surprisingly?) good. There exists commercial companies doing that atm. Their potential is promising. More comprehensive study of them with thorough error modeling and analysis would be needed

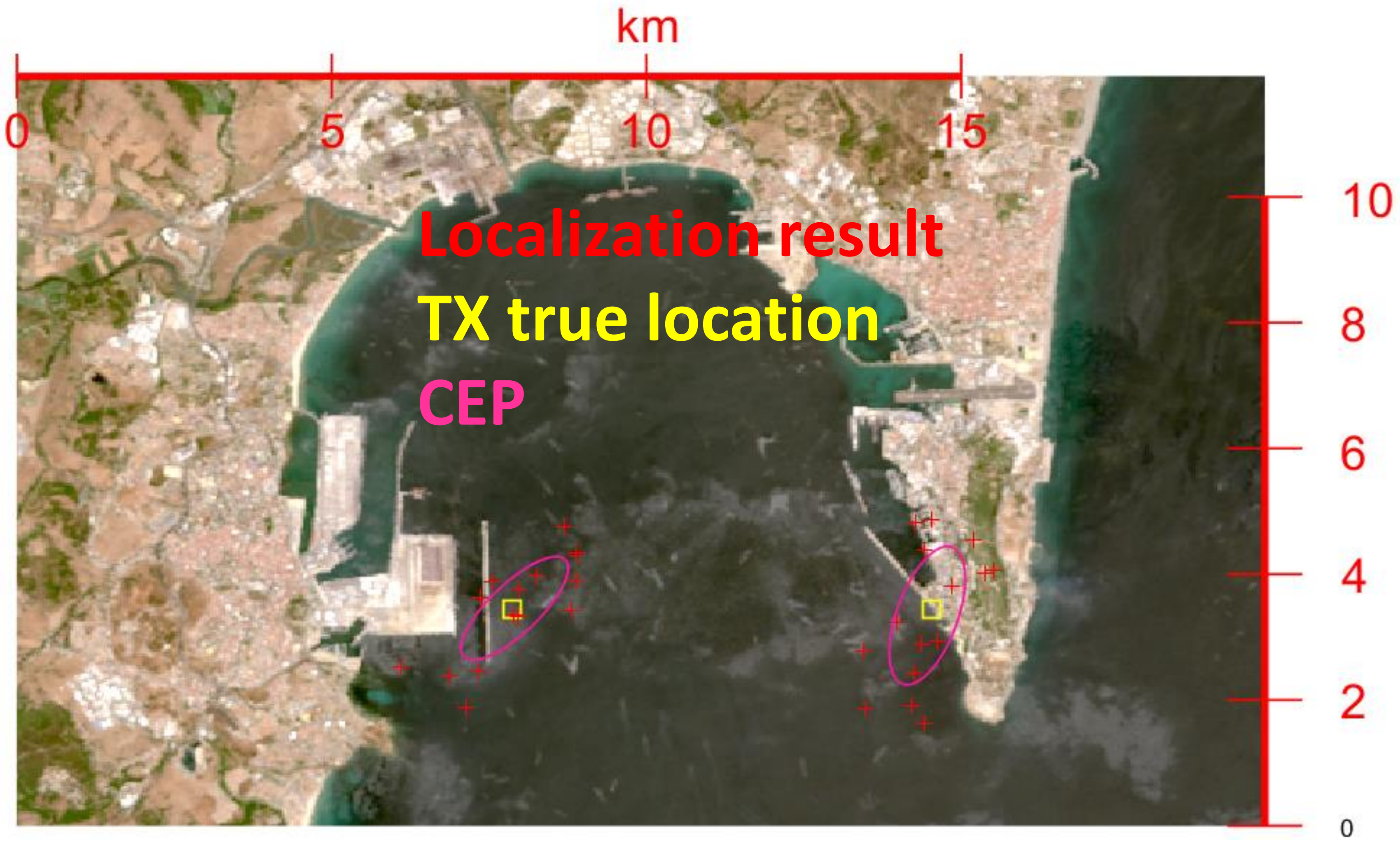
- >20 algorithms wer studied, ANY of the algorithms discussed in the activity would be (and are) worth a research program of its own. There exists number of variants, practical selections, and heuristic parameters related to many of them. Concluding much of their state-of-the art performance is not possible based on this activity.

Conclusions, 4/4

- Harp is utilizing the IDS Simulator in a number of activities started recently:
  - Feasibility Study for RFI Monitoring In-orbit-Demonstrator (ESA)
  - ELCANO – European LEO Constellation for Assured Navigation (ESA/EC)
  - Resource friendly classification (for Finnish MoD)
  - :
- Improved versions of the simulator may be available in the future….

Thank You!

Questions?



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