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L'impegno italiano nel settore dei CubeSat: tecnologie e missioni future

2° edizione

Applicazioni di Signal Intelligence & VDES per satelliti LEO

3 Luglio 2024, DAY 2, 12:45 -13:00

2-4 July 2024 | Roma @ ASI | Italy

Marco Andrenacci, MBI

Summary

This presentation addresses recent research and development activities on VHF Data Exchange System (VDES) and SIGINT payloads for Cubesat satellites led by MBI S.r.L..

- ***SIGNAL INTELLIGENCE – AIS spoofing detection:*** *AIS spoofing algorithm for Cubesat payloads. Tested on-ground using real on-board recordings from the VDES live test campaign*
  - ***New test campaign carried out in Q2-2024 in collaboration with Space Norway using Nor-Sat-2***
  - ***AIS Validation algorithm refined using innovative frequency, time and range metrics***

- ***SIGNAL INTELLIGENCE – Geo-Localization****: Geo-Localization Algorithm for Cubesat payloads able to geo-localize ground VHF emitters with a precision better than 1 km using a single satellite pass.*
  - ***Geo-localization algorithm optimized with new initialization module***
  - ***Precision much better than 1 km***

- ***VDES (VHF Data Exchange System) – VOCS project****: RF breadboarding and DSP development of VDE-SAT payload for LEO satellites in the framework of the ARTES AT project VOCS coordinated by MBI and with DWave and TAS-I as project partners*
  - ***TRR completed, laboratory tests on-going, FR by end of July 2024***
  - ***TRL4 RF breadboard successfully tested***
  - ***VDE-SAT DSP running on low-power board Zynq-7035 SoC successfully tested***

MBI at a glance

M.B.I. S.r.l. is part of the privately-owned MBI Group employing about 40 highly qualified staff with headquarters in Pisa, Italy.

The group's core business:

- Satellite communication and applications (SATCOM)
- Business Analytics and Optimization (BAO)
- Worldwide VSAT reselling with www.broadsat.com

MBI has been developing and integrating ICT solutions and services since 2001. Its main focus is to build products and services innovating through Research & Development activities, made with several companies and research centres:

- >50% revenues reinvested in R&D
- Holistic approach

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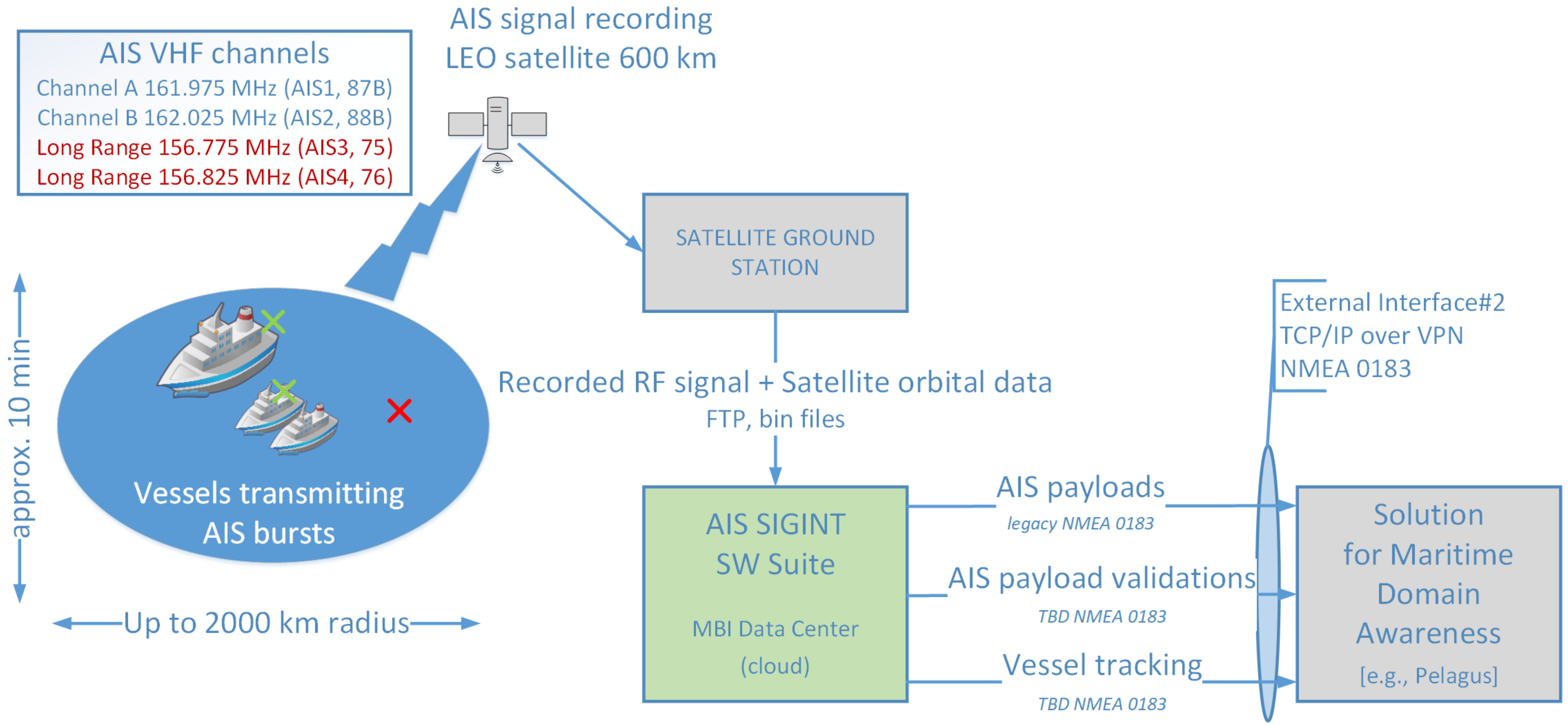
AIS spoofing detection (aka AIS validation), 1/6

- The automatic identification system (AIS) is an automatic tracking system that uses VHF transceivers (dipole antenna) on ships and is used by vessel traffic services (VTS).
    - *Ships with 300 or more gross tonnage (GT) and all passenger ships regardless of size shall use AIS*
    - *Ship positions and other data are periodically transmitted using AIS messages over VHF frequency*
    - *AIS signals can be received on-board of LEO satellites thus allowing signal intelligence analysis*
- AIS spoofing (AIS bursts with deliberately wrong position info) is becoming a big problem: 82% increase in AIS spoofing during 2021-2023! [1]
- AIS spoofing is detected on-board comparing AIS expected metrics vs RF estimated ones:
    - *AIS expected metrics are calculated using ship position and other data reported within AIS payload*
    - *AIS estimated metrics are measured on-board using RF signal associated to a given AIS burst*
    - *Several validation metrics are used: Doppler shift (not only!), ship-satellite range & timestamps*
    - *Statistical analysis of the differences between Expected and Estimated metrics using thousands of AIS bursts decoded during the test campaign is used to define probability density functions of the validation metrics. Finally, global Reliability Index (RI) is computed using a thresholds approach*

[1]: https://www.cnbc.com/2023/09/26/russian-dark-ships-vessels-fake-their-locations-to-move-oil-around-the-world.html

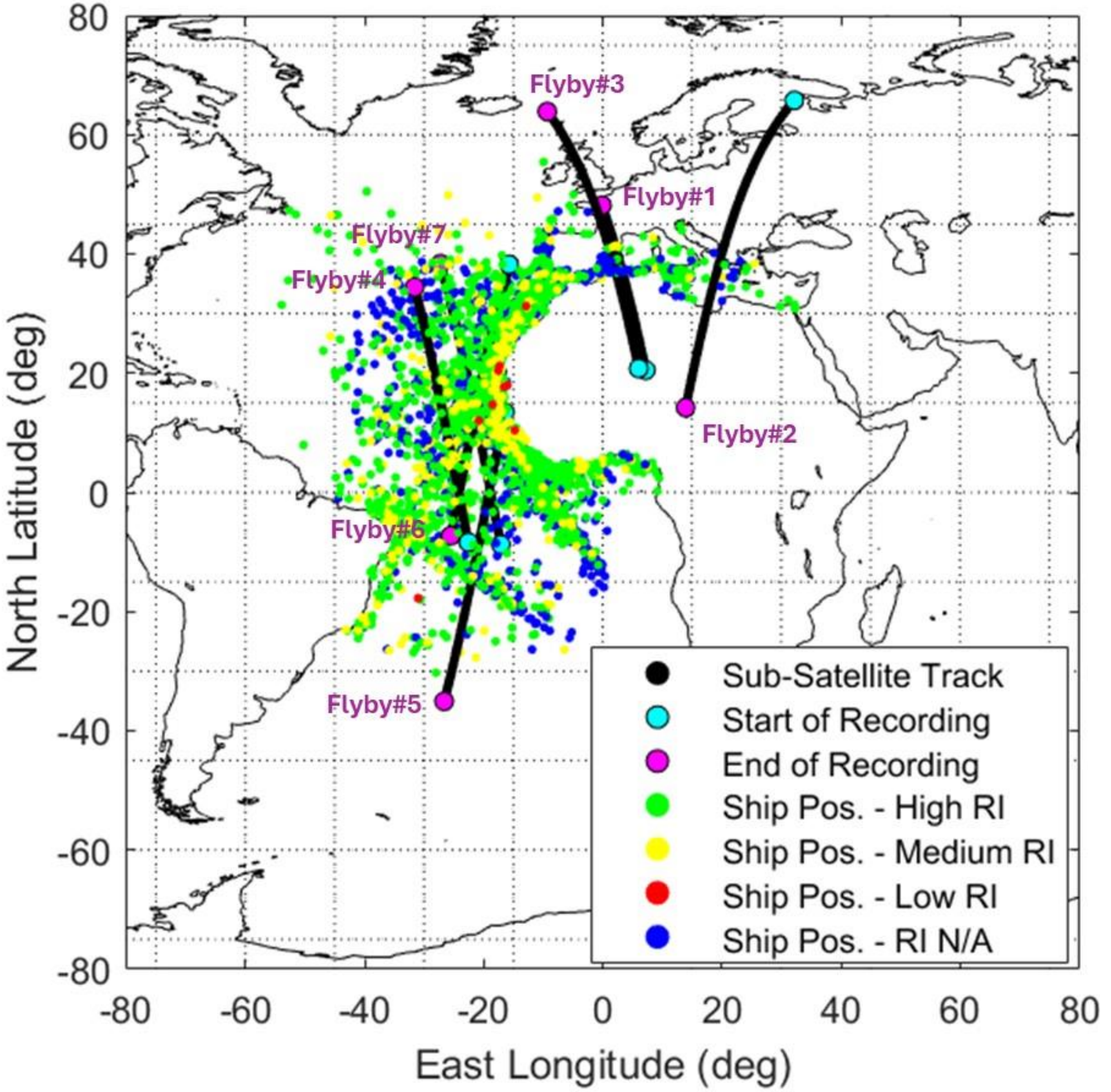
AIS spoofing detection (aka AIS validation), 2/6

- End-to-end solution based on the MBI AIS signal intelligence SW Suite



AIS spoofing detection (aka AIS validation), 3/6

- New test campaign in collaboration with Space Norway using NorSat-2 satellite:
  - 10 recordings over Atlantic Ocean and Mediterranean Sea carried out in Q2-2024. Last 3 recordings not yet done.
- NorSat-2:
  - orbit inclination: 97° (sun-synchronous orbit) | orbit period: 98 min | altitude: 600 km
  - RHCP 8 dBi Yagi antenna pointed at the horizon
  - F0=162000MHz | Sampling rate is 134.4 ksample/s | AGC off
- Typical recording duration of 12 minutes
  - Considering a max vessel speed of 35 knot the max displacement of vessels during the flyby is approx. 11 km
- AIS Receiver with SIC and SIGINT developed by MBI



AIS spoofing detection (aka AIS validation), 4/6

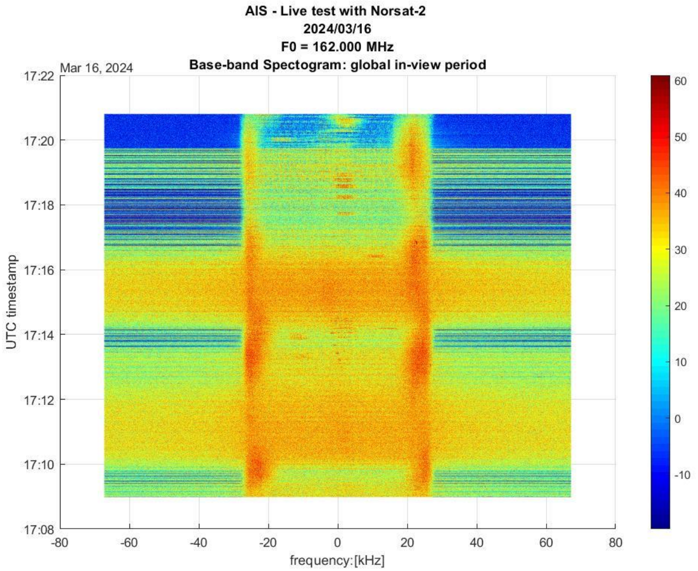
SPECTRUM ANALYSIS

- AIS VHF channels strongly interfered (probably by terrestrial licensed VHF emitters) when satellite is flying above Europe
- Number of correctly demodulated AIS burst dramatically falls when interference is present as AIS protocol is not able to cope with it

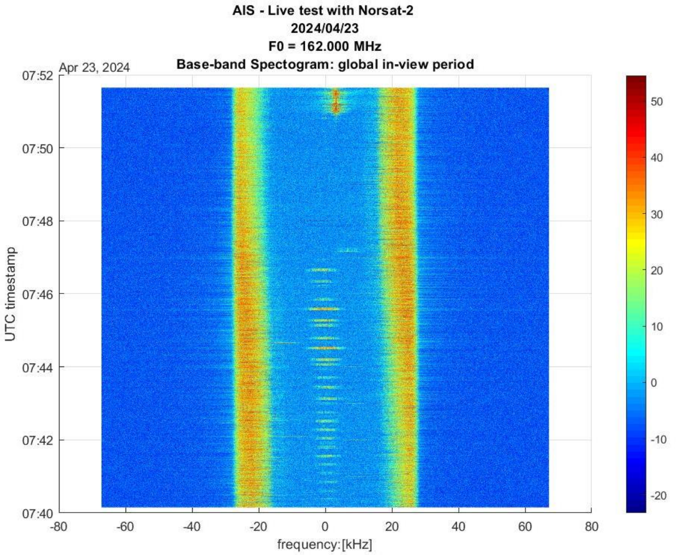
Flyby	Area	CRC ON AIS bursts			max % saturated samples/AIS slot (*)
		Total	SIC#0	SIC#1	
1	Mediterranean Sea, west side	216	216	0	7,5
2	Mediterranean Sea, est side	27	27	0	7,7
3	Mediterranean Sea, west side	50	50	0	8,8
4	Africa, west coast	7.012	6.961	51	0
5	Africa, west coast	6.457	6.414	43	0
6	Africa, west coast	7.608	7.549	59	0
7	Africa, west coast	6.226	6.196	30	0
		27.596	27.413	183	-

(*): max % of samples above 80% of EndOfScale value per slot 0,66%

Flyby#2

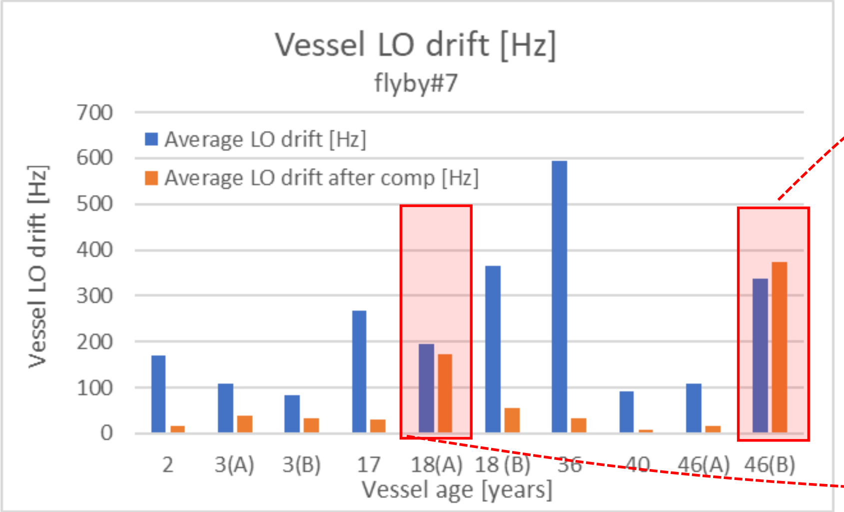


Flyby#7

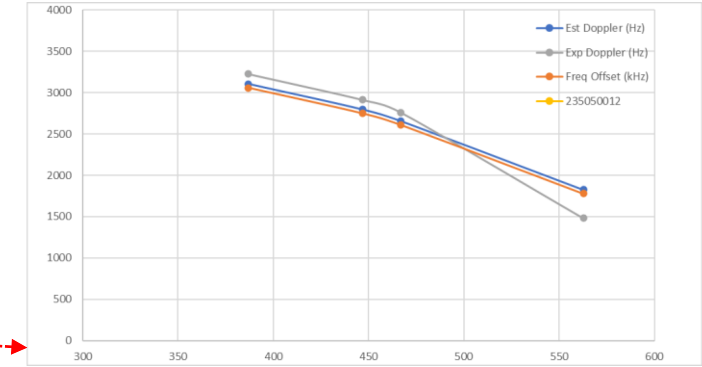


AIS spoofing detection (aka AIS validation), 5/6

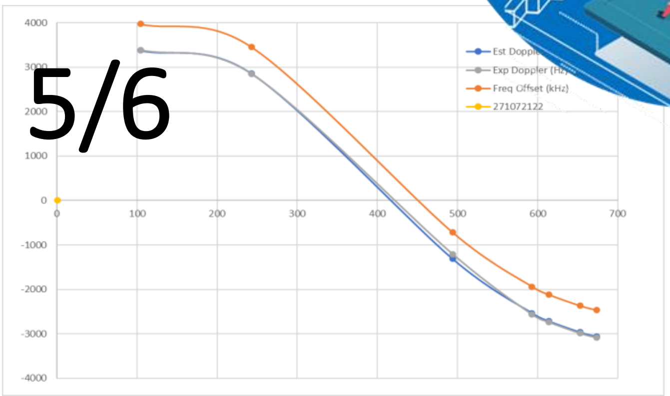
- LOs on-board of old vessel are usually affected by larger frequency drift
- Vessel LO drifts are removed by averaging estimated and expected metrics:
    - *blue (expected) and grey curves (estimated and comp) are overlapped each other -> Doppler Reliability Index high*
    - *Doppler Reliability Index is low in two cases where estimated values does not converge to expected*



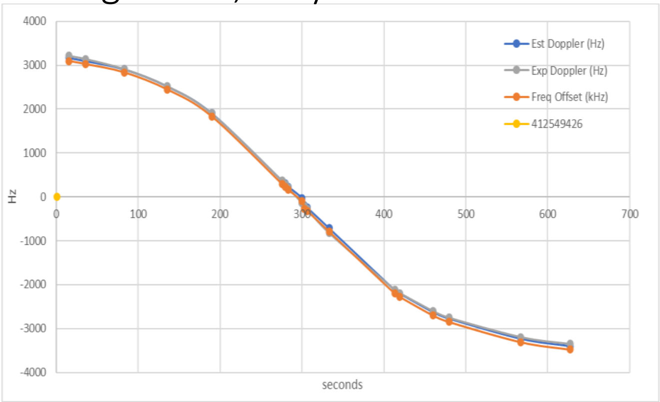
Fishing vessel, 18A years



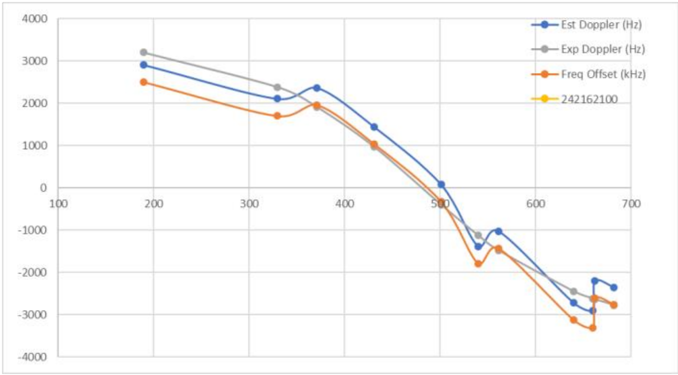
Fishing vessel, 36 years



Fishing vessel, 3A years



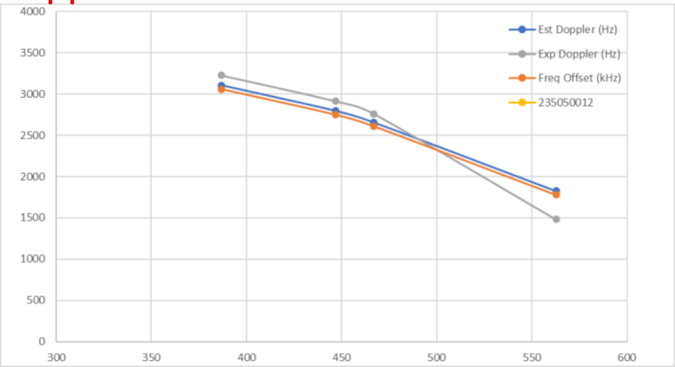
Fishing vessel, 46B years



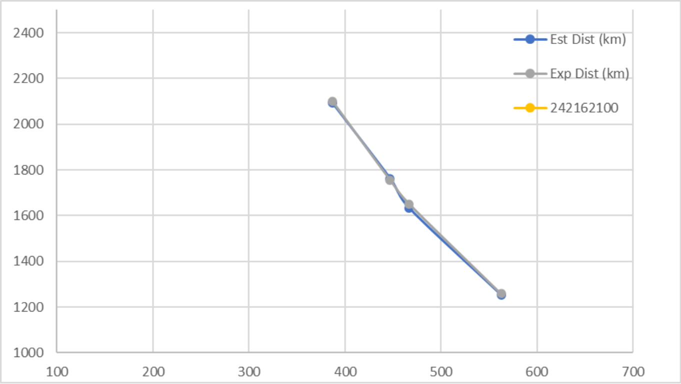
AIS spoofing detection (aka AIS validation), 6/6

Fishing vessel, 18A years

Doppler-based VM

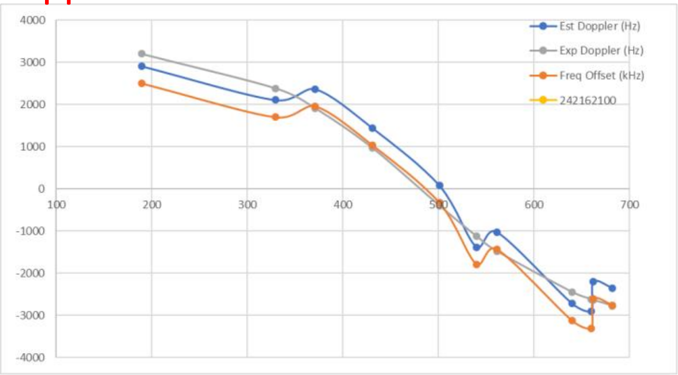


Range-based VM & Timestamp-based VM

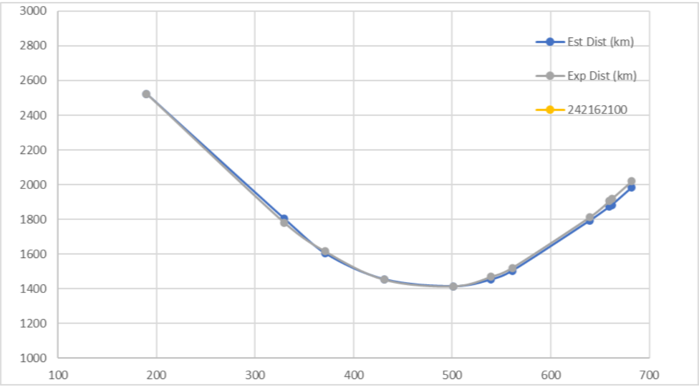


Fishing vessel, 46B years

Doppler-based VM

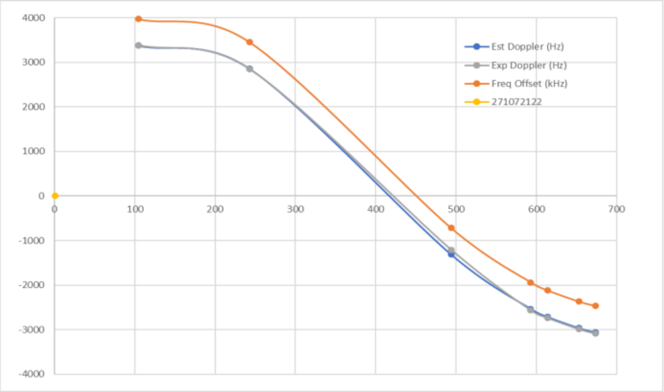


Range-based VM & Timestamp-based VM

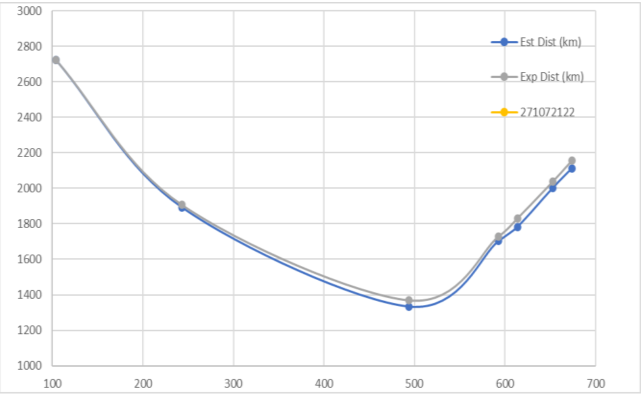


Fishing vessel, 36 years

Doppler-based VM

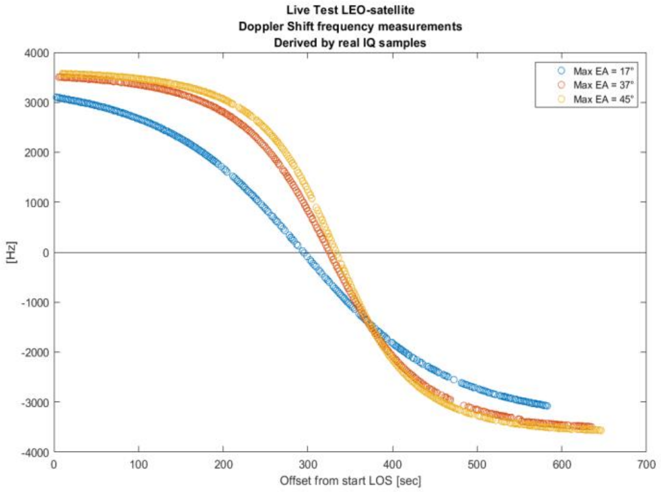


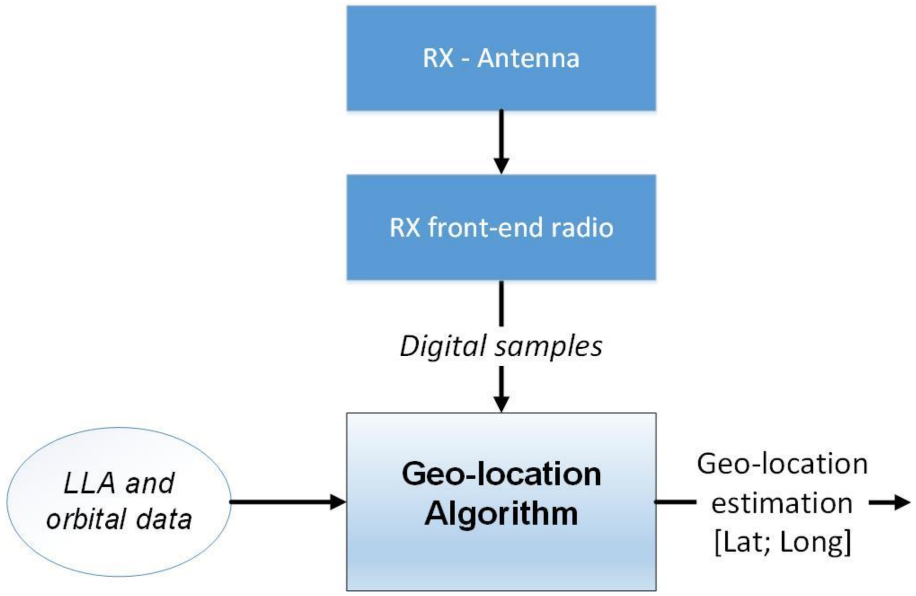
Range-based VM & Timestamp-based VM



SIGNAL INTELLIGENCE – Geo-Localization – 1/4

- The Geo-Localization Algorithm (GLA) can be hosted on-board of LEO satellites or on-ground
- It is fed in real or off time with ONLY the following timestamped data (see bottom-right diagram):
  - *satellite orbital data: orbital velocity, acceleration and LLA (Lat, Long and Altitude)*
  - *digital samples of the monitored RF spectrum*
- The algorithm performs spectrum analysis of the incoming digital samples extrapolating Doppler curves [Hz and Hz/sec] (see top-right diagram) and carrier frequency of the RF emitter. Finally, geo-location of ground emitter is computed (Lat, Long)
  - *For more info see “Radio Frequency Signals Detection and Geolocation using single LEO satellite in the VHF band” (*)*

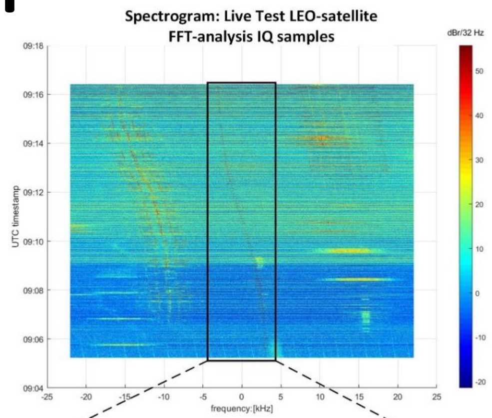


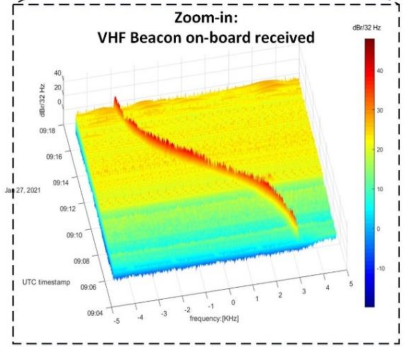


(*): https://www.researchgate.net/publication/367340897_Radio_Frequency_Signals_Detection_and_Geolocation_using_single_LEO_satellite_in_the_VHF_band

SIGNAL INTELLIGENCE – Geo-Localization – 2/4

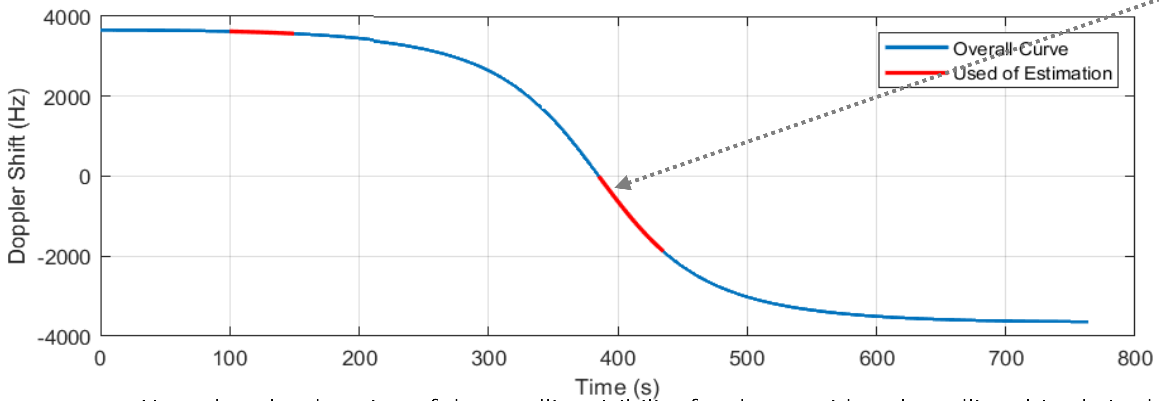
Spectrogram (limited ± 22 kHz) of Pass#1 derived by FFT-analysis of digital samples with a frequency resolution of 32 Hz

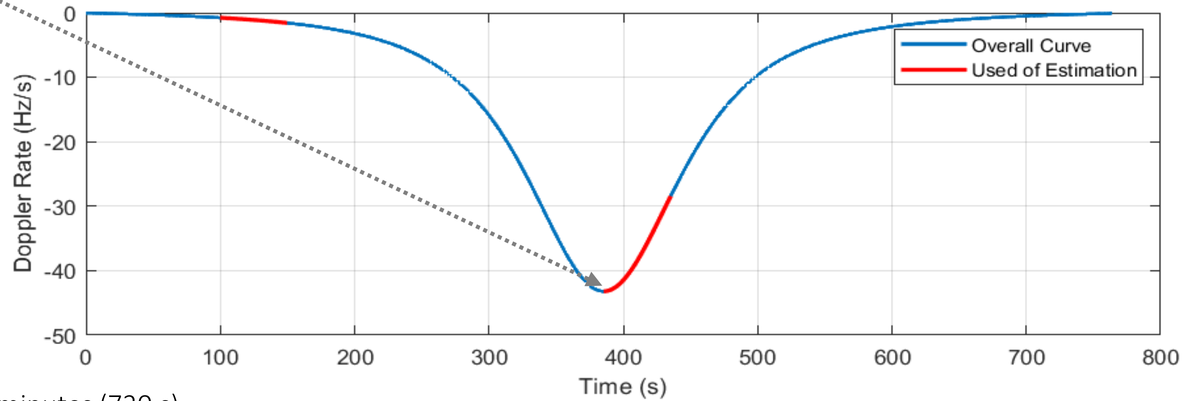




- The Geo-Localization algorithm converges very rapidly
  - ***Introduced new Iterative grid search algorithm based on Doppler rate as cost function to initialize GLA (increased robustness against LOs drifts)***
  - ***Carried out tests in presence of RF sources with LO instability***
  - *On average only 60 seconds of recording of the RF emitter signal are enough when satellite is passing at maximum elevation ("zero Doppler point"). Longer duration needed when the signal of the RF emitter is not recorded in a temporal around of the "zero Doppler point"*
  - *Figures show that the algorithm converges using a small percentage (about 10%, refer to Table in next slide) of the Doppler measurements*

«zero Doppler point», coincides with maximum elevation





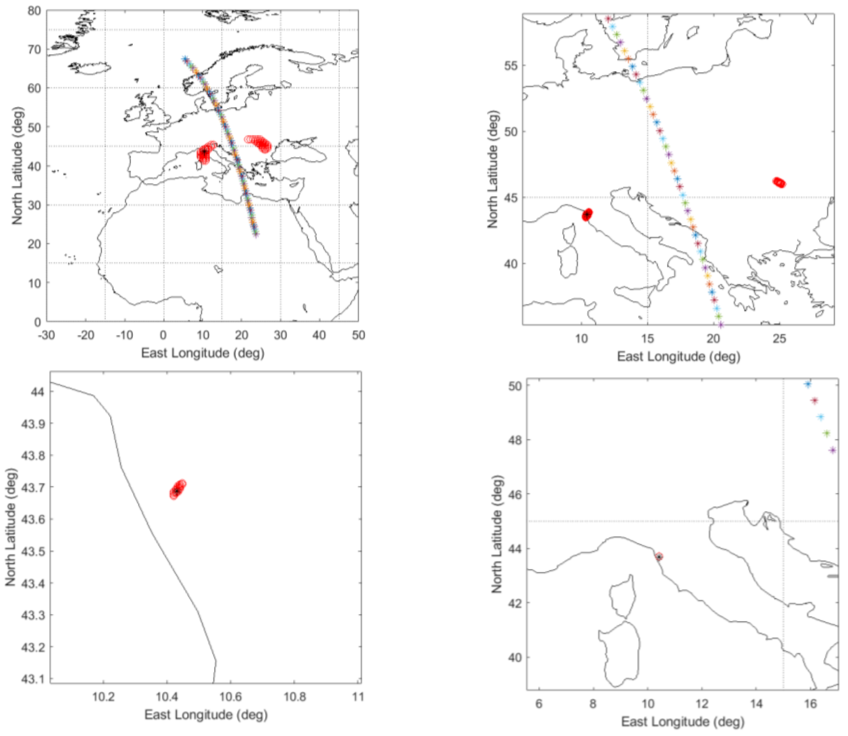
Note that the duration of the satellite visibility for the considered satellite altitude is about 12 minutes (720 s)

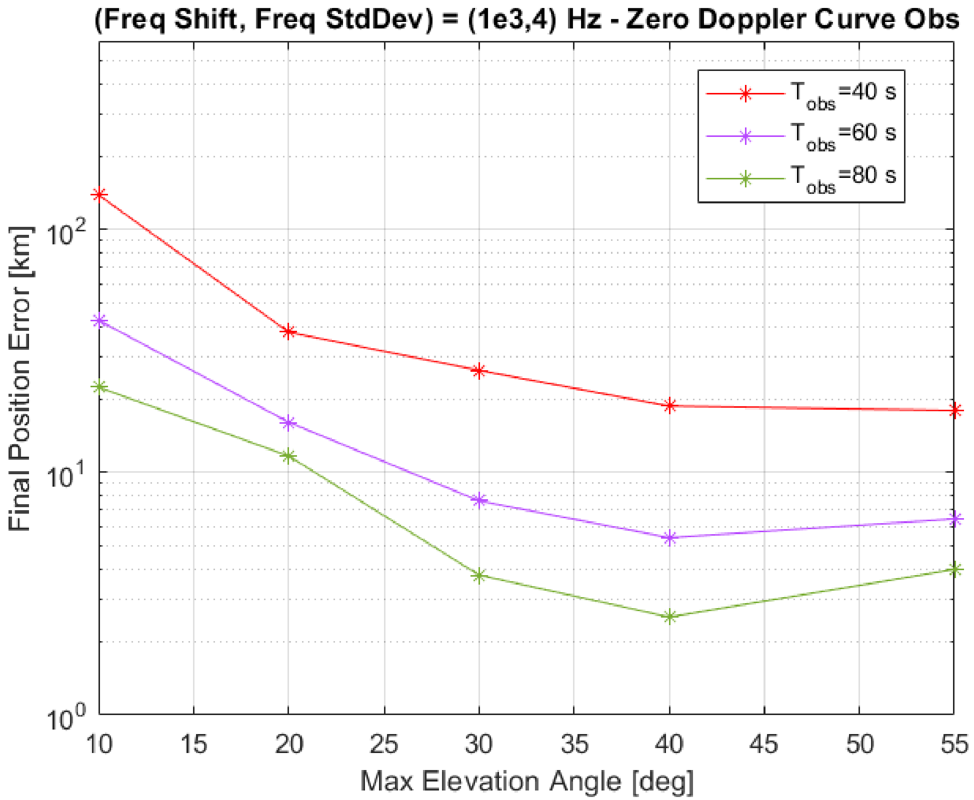
SIGNAL INTELLIGENCE – Geo-Localization – 3/4

- Geo-Localization accuracy obtained running GLA (single satellite – single pass) fed with real data collected by the LEO satellite ranges from 0.9 km to 3.1 Km by a **known RF source** emitting a “well stable” CW
- On the contrary, geo-localization accuracy decreases in presence of an RF source with unknown carrier frequency. Assuming a frequency shift of 1 KHz and 5 Hz of standard deviation:
  - If zero Doppler point is not included within the recording geo-localization accuracy may be even larger than some tens of km
  - If zero Doppler point is included then accuracy is better than 3 km in presence of maximum elevation above 30° with recording of only 80 seconds

SIGNAL INTELLIGENCE – Geo-Localization – 4/4

- Left diagrams shows how Iterative grid search algorithm quickly converges when using Doppler rate as cost function to initialize GLA
- Right diagram shows geo-localization accuracy in presence of an RF source with LO inaccuracy





VDES (VHF Data Exchange System) – VOCS project, 1/2

- MBI has been selected by ESA to execute the ITT named "Breadboarding of critical technologies enabling VHF data exchange payloads" (ARTES AT activity 5C.441), the VOCS project. Key facts:
  - *MBI (prime), DWave and TAS-I*
  - *KOM was held on 23rd June 2022, TRR successfully completed & lab test phase on-going*
  - *FR by 2024 summer break*
- The VOCS project focuses on VDE-SAT payload for small LEO satellites both Cubesats and Microsatellites:
  - *laboratory testing of the verification platforms (SAT-VDE) developed for Cubesat and Microsatellites*
- Main outcomes are:
  - ***SW/FW****: VDE-SAT on-board firmware (C++ and HDL) addressing the full stack of VDE-SAT and AIS-ASM (TBC) running (lab testing) on low power processing board such as Xilinx Zinq-7000 (target device is Xilinx Z-7035 coupled with Analog Devices AD9361).*
  - ***RF breadboarding****: reference RF breadboarding for SAT-VDE LEO satellite payload*
    - *TX and RX*
    - *Half-duplex (Cubesat, VDE-SAT 1U) & Full duplex (Microsats)*

VDES (VHF Data Exchange System) – VOCS project, 2/2

- VOCS RF front-end (TRL4, see data-sheet and pictures) can be interfaced with COTS on-board processors such as those of Gomspace and Alen Space both Z7000-based

VDES (VHF) Board for CubeSat applications

Compliant with standard 1U CubeSat

RF Capabilities
1 TX VHF board
1 RX VHF board
VDES Frequency: 156 – 162 MHz
Peak Power: 5 W

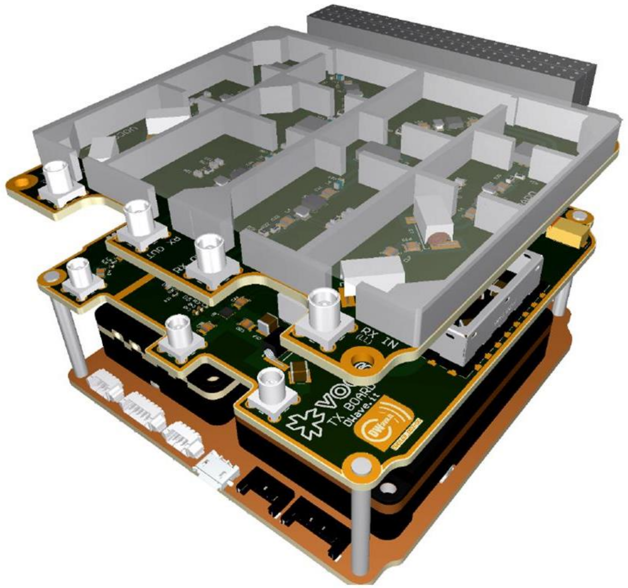
Processing Platforms
GOMSpace NanoDock SDR
GOMSpace NanoCom TR-600
Z7000 module

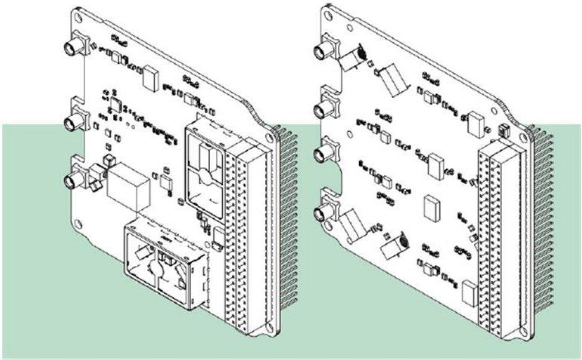
Interface
MCX RF Connectors

Synchronization
Require time reference (UTC clock, pps time) from GNSS Receiver

Software
C/C++
HDL
Linux

Dimension
Total Dimensions: 90x96x65mm
Total Weight: 0.750Kg





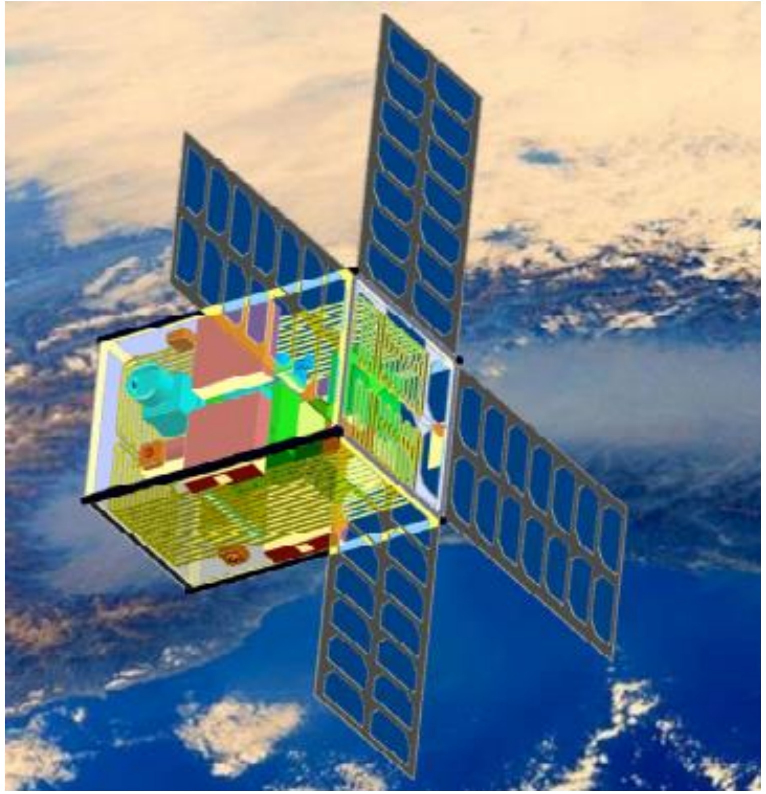
Day 2 - 3 Luglio 2024: 14.30-14.45 M. Bonaventura - Dwave Front-End VHF per payload satellitare: un sistema compatto ad alta efficienza per la ricetrasmissione con standard VDE-SAT

EXCITE Cubesat, *in-orbit-demonstration*

- *EXCITE is the mission proposed by University of Pisa, MBI and others in response to the ASI's call for Future Cubesat Missions (*)*
- *Phase A will start in Q2-2024*
- *MBI will provide on-board communication experimental payloads of the 12U EXCITE Cubesat*
  - *S-band IoT*

Day 2 - 3 Luglio 2024: 16.45-17.00 S. Marcuccio - UniPi Sviluppo della missione di dimostrazione tecnologica EXCITE

(*): https://www.asi.it/bandi_e_concorsi/bando-per-future-missioni-cubesat/



Excite Cubesat

Next Steps

- **SIGNAL INTELLIGENCE – AIS spoofing detection:**
    - #1: Development of a product based on the on-board recording and ground processing
    - #2: SIGINT processing moved on-board
- **SIGNAL INTELLIGENCE – Geo-Localization**:
    - Use of AI/ML to identify S-curves
- **VDES (VHF Data Exchange System) – VOCS project**:
    - IOD

Contacts

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