spire

GNSS Interference Monitoring from LEO

NAVISP EL2-117 Final Presentation

13-01-2022

<u>Advanced Signal Processing Group</u>

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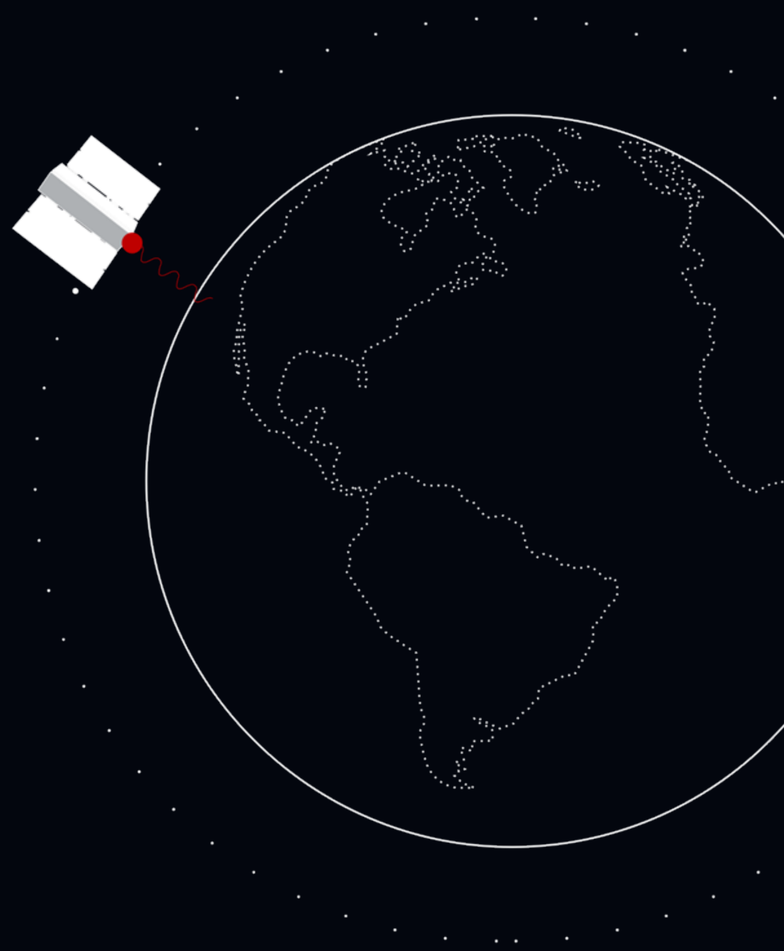
Agenda

1. Context and Rationale
    a. Spire Overview
    b. PNT Situation Awareness
2. Project Overview and Highlights
3. Ongoing Projects and Customer Needs
4. Competitiveness and Opportunities
5. Benefits of working with ESA

Context and Rationale



Spire Global

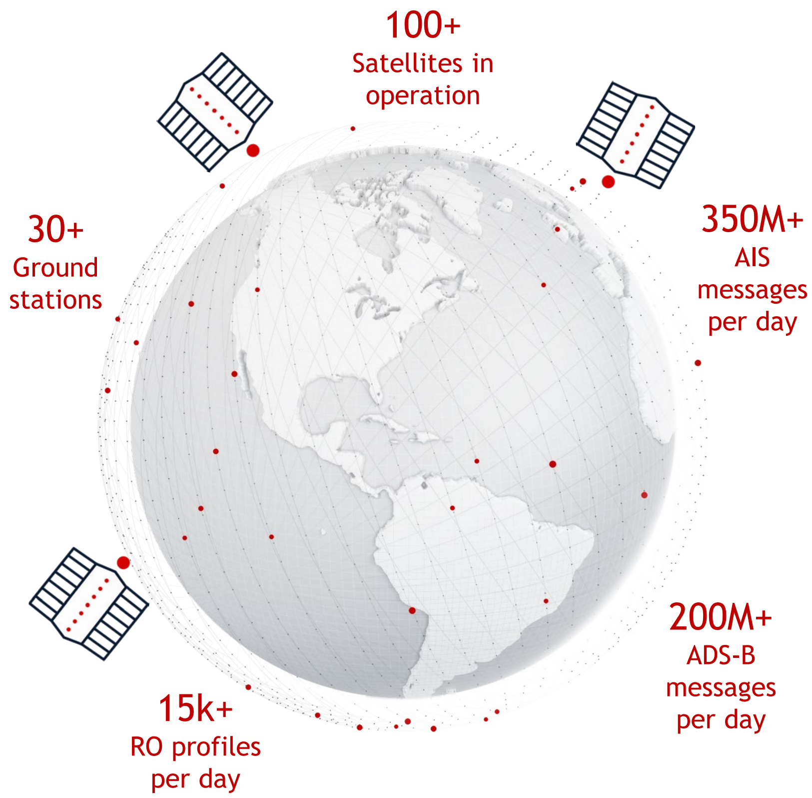
In a nutshell

Spire Global Inc. is a leading provider of
space-based data, analytics, and space services and
is an industry leader in small-satellite and RF payloads manufacturing

Spire operates its own constellation of 100+ satellites to track maritime (i.e., AIS) and aviation (i.e., ADS-B) activity and for **EO (i.e., GNSS-R and GNSS-RO)**, and to provide space services to customers

Spire's fleet is:

- Made of Spire's multi-purpose satellites, LEMUR (Low Earth Multi-Use Receiver), deployed across a variety of planes in LEO to provide global coverage and high revisit rates
- Paired with Spire's global network of 30+ ground stations for low-latency data downlink and with a cloud-based infrastructure for data processing and dissemination



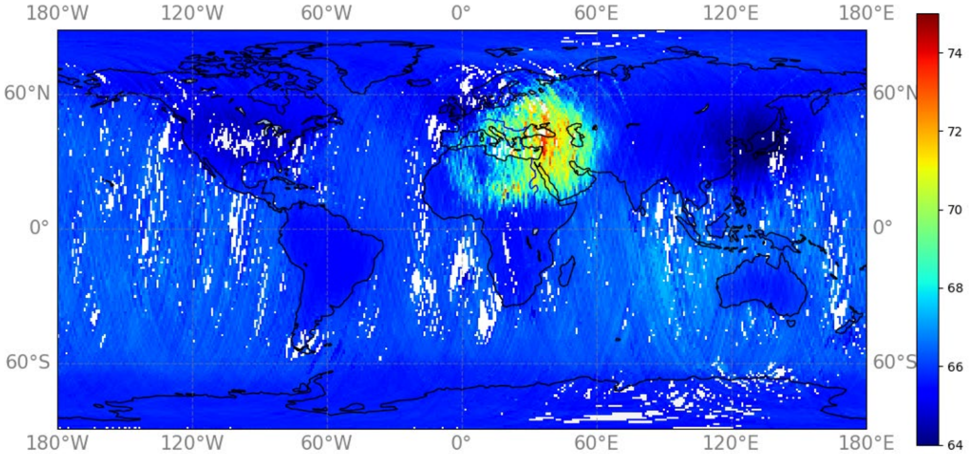
GNSS Interference Monitoring

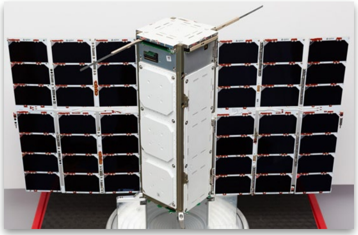
Spire EO assets

Spire currently has 40+ active satellites for GNSS-R and GNSS-RO equipped with Spire's **science-grade GNSS receiver, STRATOS** processes GNSS signals for satellite Precise Orbit Determination (POD) and remote sensing

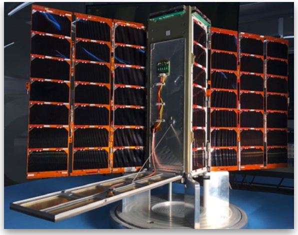
Payloads with STRATOS can be tasked with raw **IQ/IF data collection** to perform **RF spectrum monitoring in L-band**:
this capability has been exploited to demonstrate proof-of-concept GNSS interference monitoring from LEO

Noise power estimate [dBm] around 1575 MHz over a 10-day period





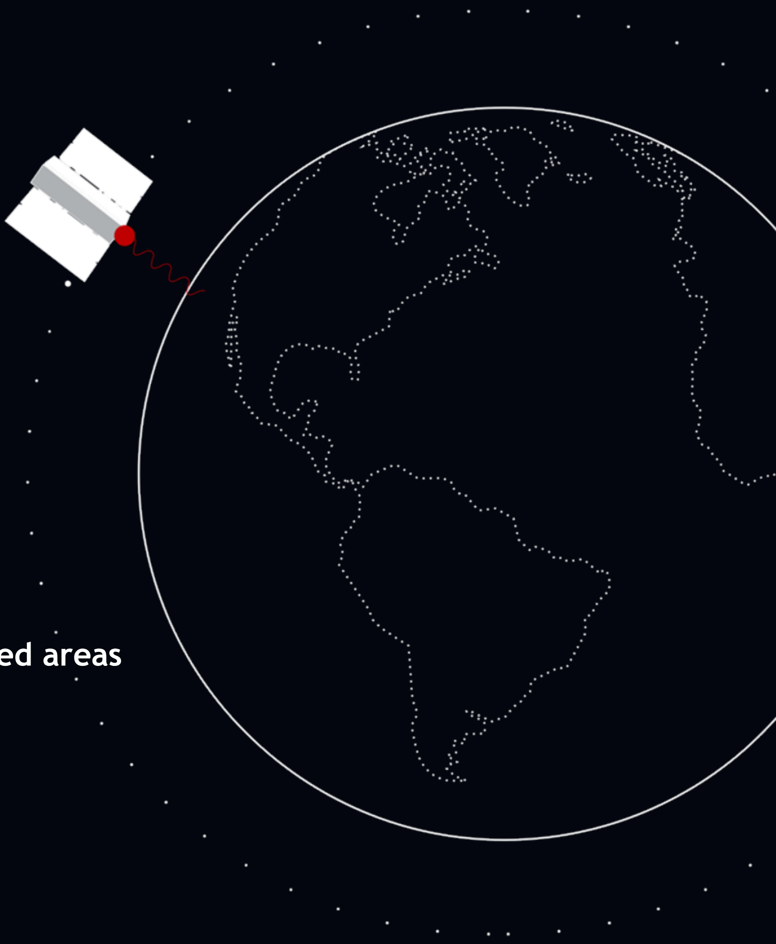
Spire GNSS-RO satellites



Spire GNSS-R Batch 1 (Dec 2019)

Spire GNSS-R Batch 2 (Jan 2021)

Project Overview and Highlights



Goals:

- Demonstrating the capability of Spire’s EO assets
  to enable the monitoring of sources of GNSS interference in localized areas
- Laying the foundations for the productization of a service
  for low-latency PNT situational awareness at a global scale

Localized Spectrum Awareness

1. Collection of IF/IQ data

- Area, band, time slot are stipulated
- Suitable GNSS-R/RO satellite in view is scheduled
- On-board STRATOS is tasked for raw data collection
- Attitude maneuvers might be executed to maximize SNR
- Ground station downlinks are scheduled

2. Interference detection

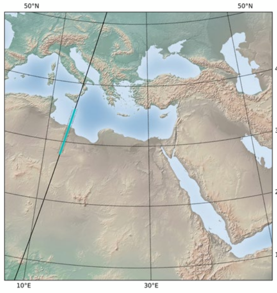
Collected data is post-processed on ground to detect:
- Power or cross-correlation above noise
- PRN code modulations

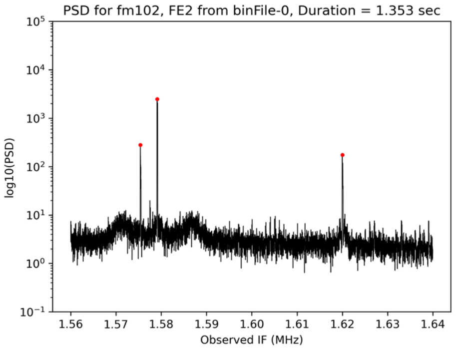
Observables of detected interference are measured in the delay-Doppler domain:
- TOA and FOA
- TDOA and FDOA
- RSS

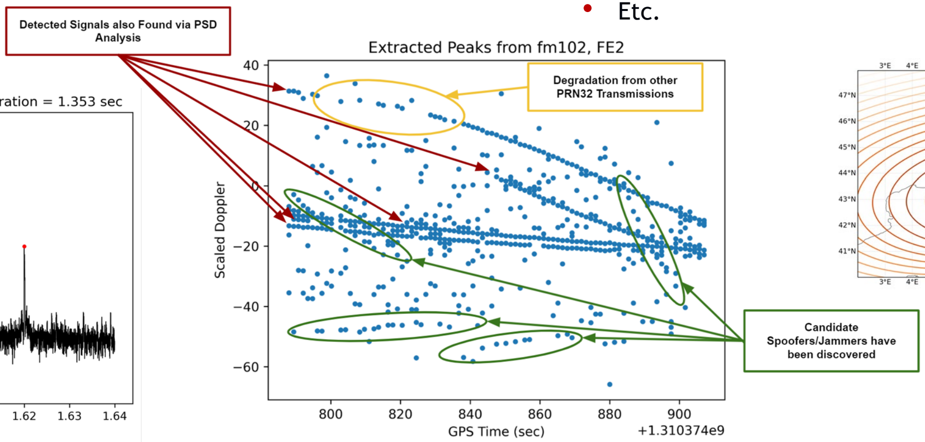
3. Source geolocation

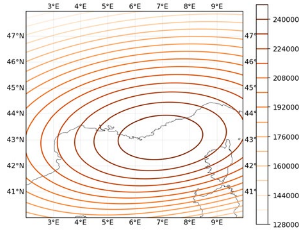
Algorithms [1] for
- Single Satellite Geolocation (SSG)
- Multiple Satellite Geolocation (MSG)

combine:
- Observables
- Satellite orbits
- Receiver clock bias
- Receiver clock drift
- Transmit frequency (SSG only)
- Etc.









(Example of GNSS jamming/spoofing in Northern Sahara)

[1] Known state-of-the-art algorithms were used for NAVISP

Project Key Milestones

Proof of concept GNSS interference monitoring

1. Scheduling process of IF/IQ data collections with Spire GNSS-R/RO satellites
2. Evaluation of the errors affecting satellite orbits and clocks (on-board solution vs. POD)
3. Design of algorithms for detection of different types of GNSS interference
4. Design of algorithms for SSG and MSG of interference sources
5. <u>Evaluation of theoretical MSG precision based on Cramer-Rao Lower Bound (CRLB)</u>
6. <u>Experiments for SSG and MSG with data collected over known interference sources</u>

FEDERAL AVIATION ADMINISTRATION

FLIGHT ADVISORY
GPS INTERFERENCE TESTING

NEVADA TEST AND TRAINING RANGE
(NTTR) 22-01

25 January – 10 February
Nevada Test and Training Range, NV

GPS testing is scheduled as follows and may result in unreliable or unavailable GPS signal.

A. Location: Centered at 374117N1161549W or the BTY VOR 007 degree radial at 58 NM.

B. Dates and times **(Dates and times are based on GMT (Z).):**

25 – 27 JAN 22	DLY	2230Z – 2359Z
01 – 04 FEB 22	DLY	2230Z – 2359Z
08 – 10 FEB 22	DLY	2230Z – 2359Z

C. Duration: Each event may last the entire requested period.

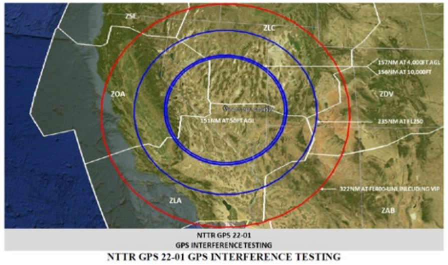
D. NOTAM INFO: NAV GPS (NTTR GPS 22-01) (INCLUDING WAAS, GBAS, AND ADS-B) MAY NOT BE AVBL WI A 322NM RADIUS CENTERED AT 374117N1161549W (BTY007058) FL400-UNL,
235NM RADIUS AT FL250,
156NM RADIUS AT 10000FT,
157NM RADIUS AT 4000FT AGL,
151NM RADIUS AT 50FT AGL.

E. Pilots are encouraged to report anomalies in accordance with the Aeronautical Information Manual (AIM) paragraphs 1-1-13 and 5-3-3.

The NOTAMs discussed in this advisory may change with little or no notice. Pilots are advised to check NOTAMs frequently for possible changes prior to operations in the area. NOTAMs will be published at least 24 hours in advance of any GPS tests.

Released
24 January 2022

GNSS interference exercise
Nevada Test and Training Range
Western United States

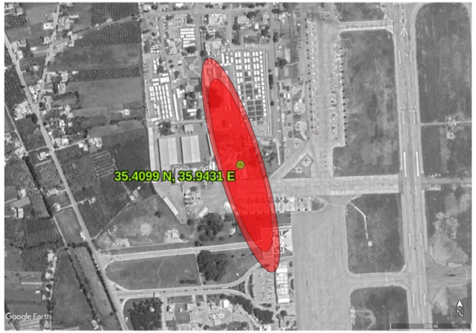


NTTR GPS 22-01 GPS INTERFERENCE TESTING

GNSS jammer allegedly located at a Russian air base in Syria [1]

First results from three years of GNSS Interference Monitoring from Low Earth Orbit

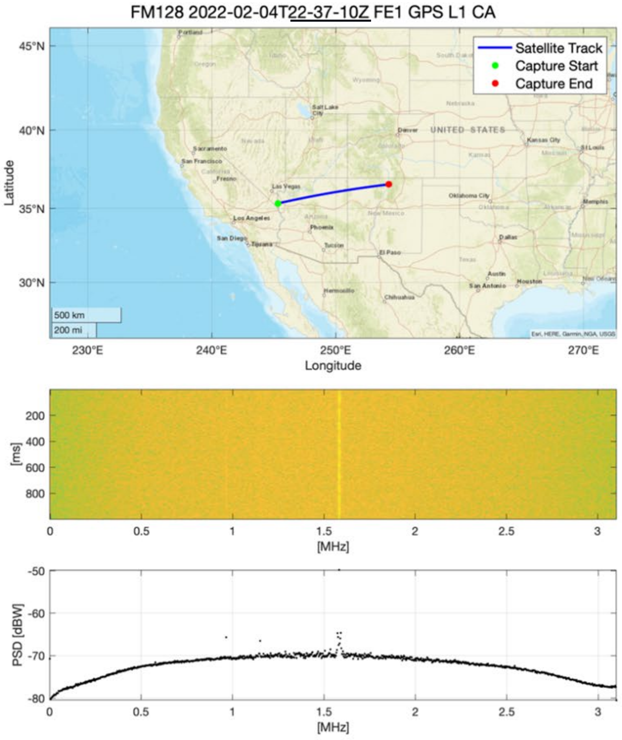
Matthew J. Murrian*, Lakshay Narula†, Peter A. Iannucci*, Scott Budzien‡, Brady W. O'Hanlon§, Mark L. Psiaki¶, Todd E. Humphreys*
*Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin
†Department of Electrical and Computer Engineering, The University of Texas at Austin
‡Naval Research Laboratory
§Cornell University
¶Department of Aerospace and Ocean Engineering, Virginia Tech

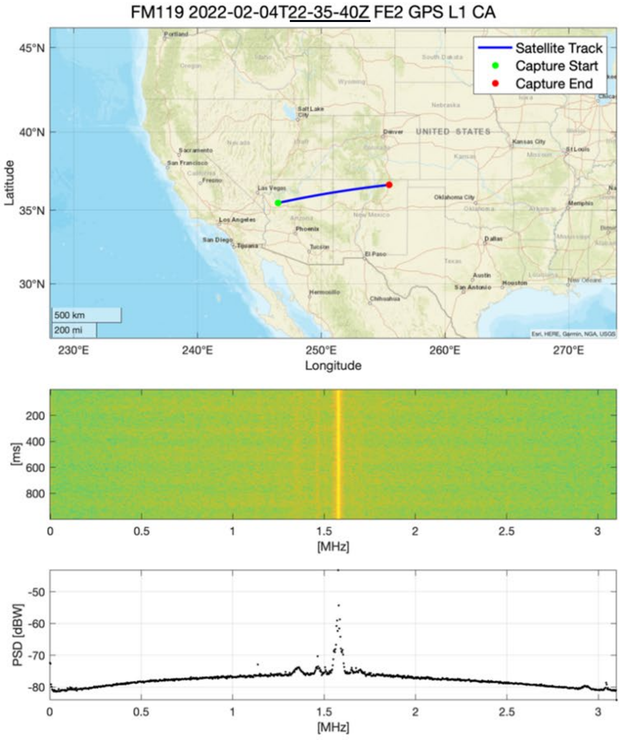


[1] M. J. Murrian, L. Narula, P. A. Iannucci, S. Budzien, B. W. O'Hanlon, M. L. Psiaki and T. E. Humphreys, *First results from three years of GNSS interference monitoring from low Earth orbit*, Journal of the Institute of Navigation, Dec 2021

Nevada GNSS Interference Exercise

Power detection

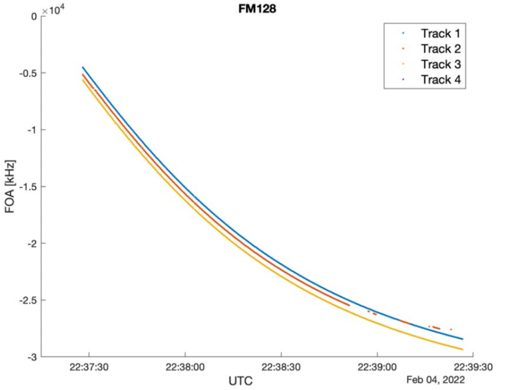




This is not a conjunction event because the two satellites fly over the emitter about 2 minutes apart

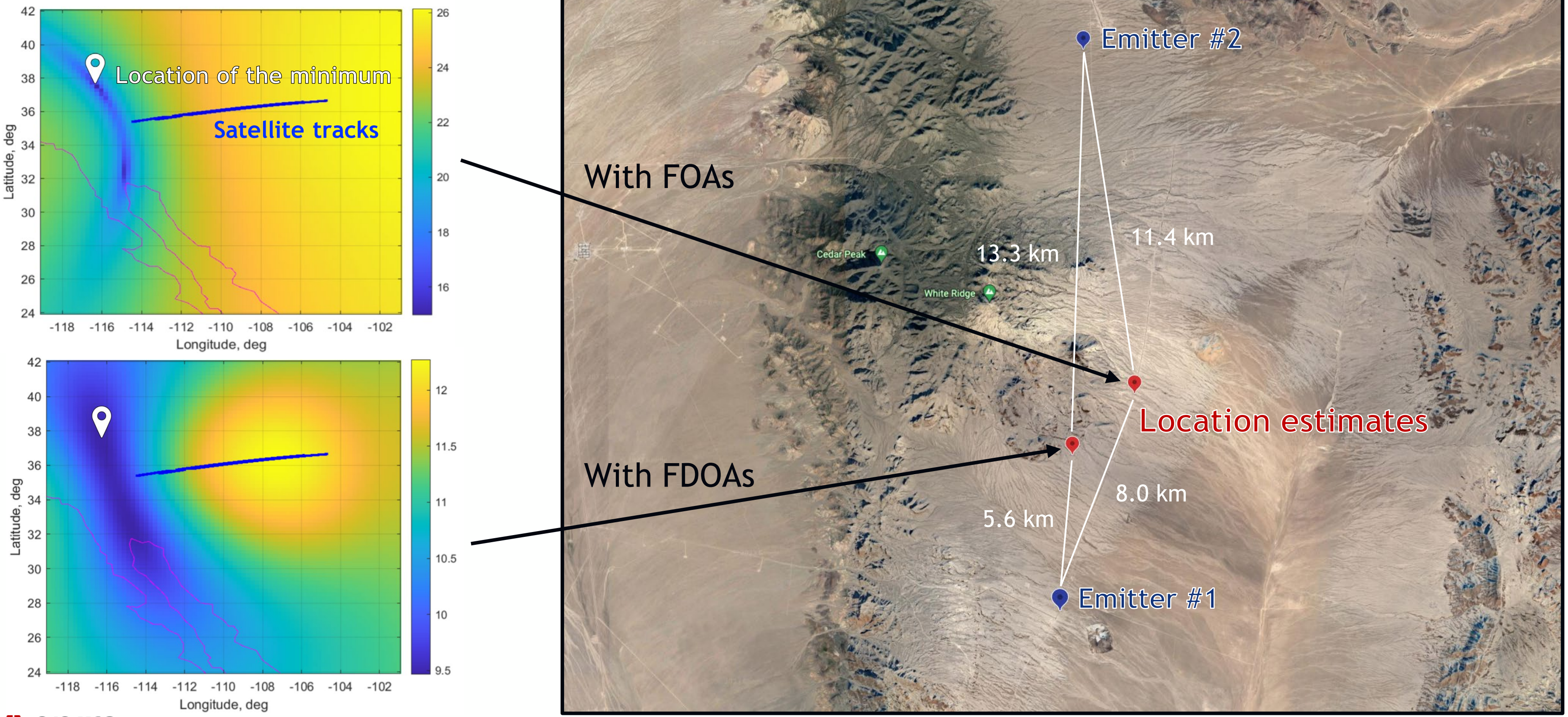
Only SSG is feasible whereas MSG is not

Power peaks tracked above the noise floor



Nevada GNSS Interference Exercise

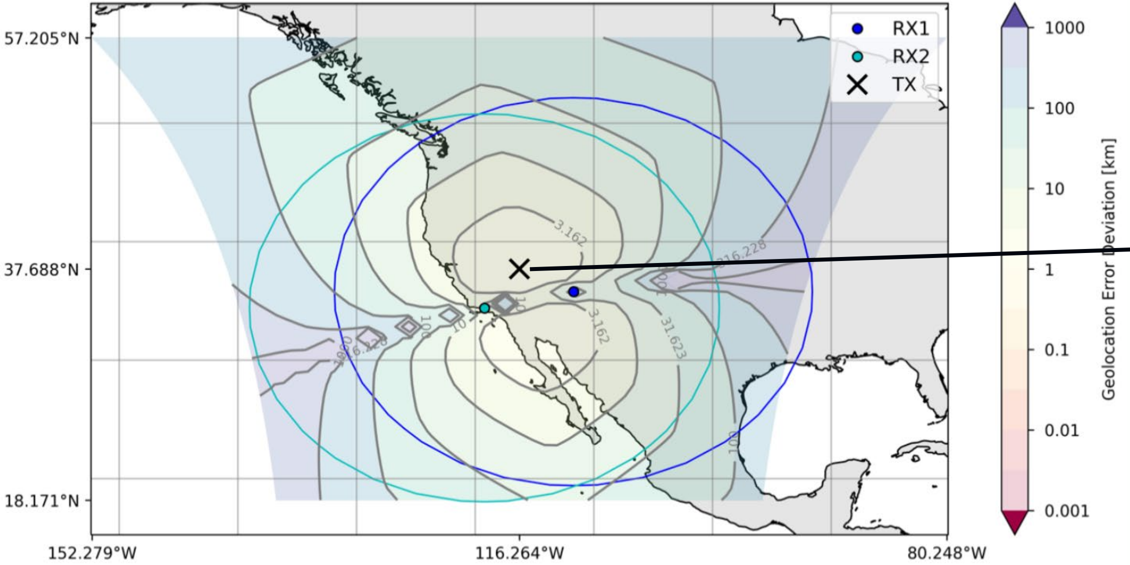
Cost functions of SSG



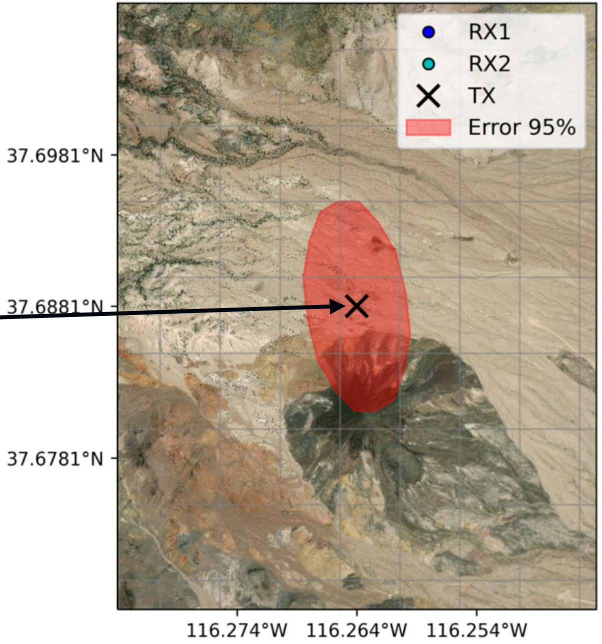
Nevada GNSS Interference Exercise

Theoretical precision of MSG

One hypothetical source of interference over 10 kHz around L1 with 30 dBm of EIRP
that is hypothetically placed on ground at the midpoint between the two emitters
is expected to be geolocated with a horizontal precision of up to 3 km during the satellite pass

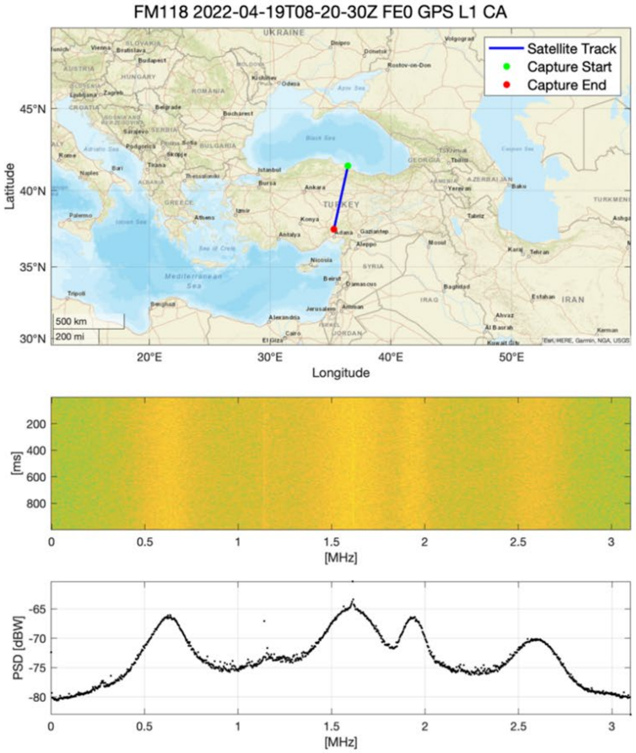


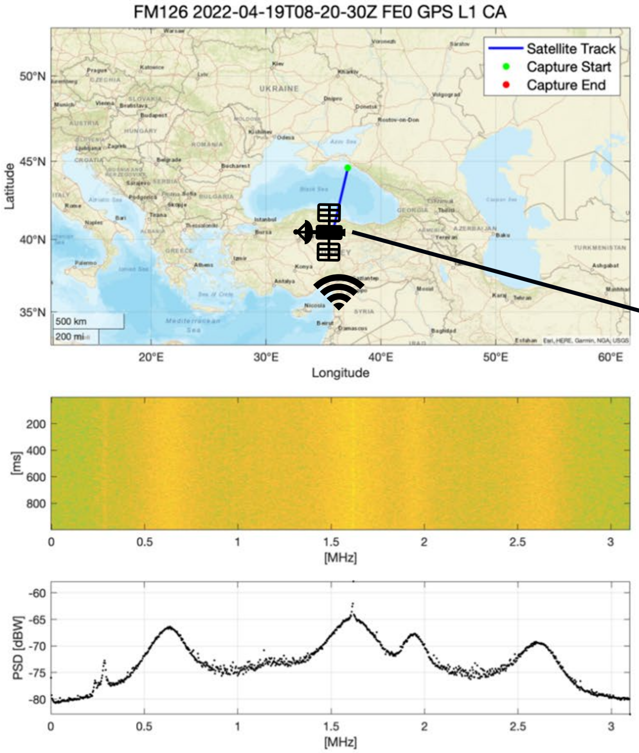
Circular Error Probable (CEP) contour map with 95% confidence



Error ellipse

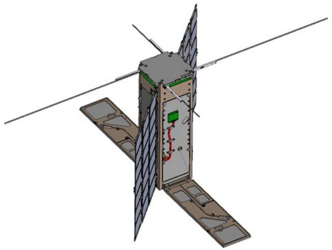
Syrian GNSS Jammer
Power detection





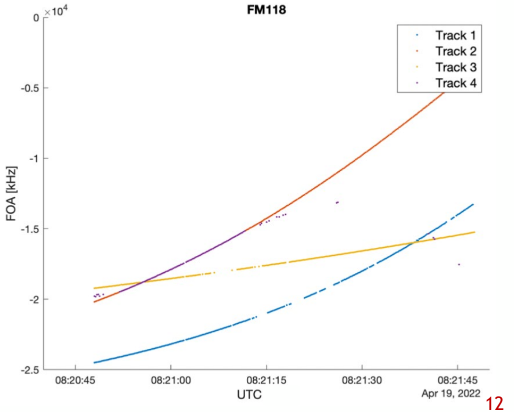
MSG is feasible

This is regarded as a conjunction event because the two satellites fly in parallel



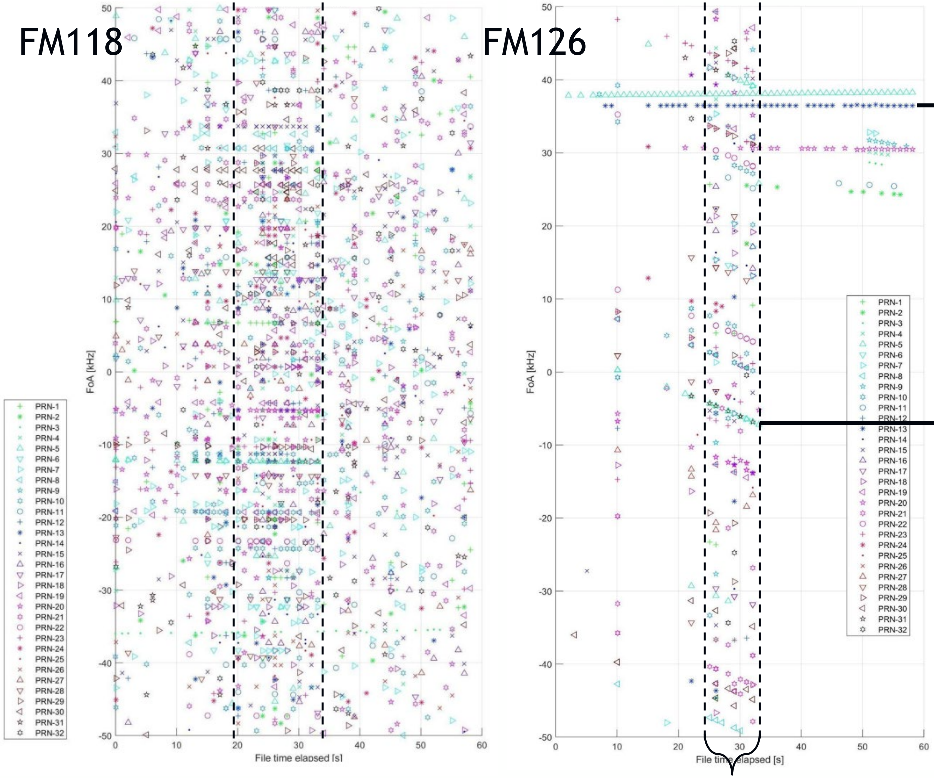
Using front-side RO antenna

Power peaks tracked above the noise floor



Syrian GNSS Jammer

Acquisition of GPS L1 C/A



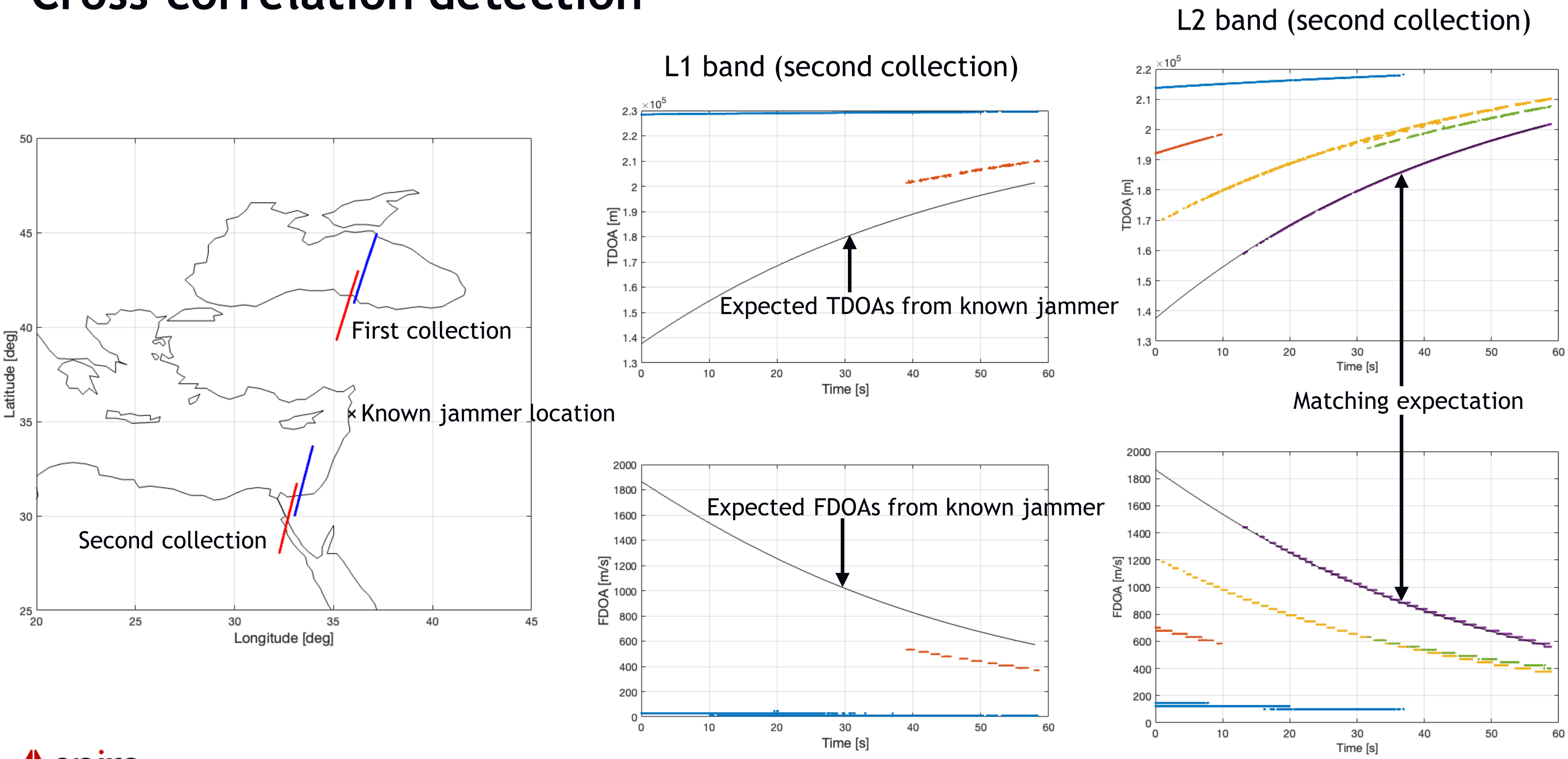
Authentic GPS satellites

Matched-spectrum jammers or spoofers

Time window in which the jammer is expected in view

Syrian GNSS Jammer

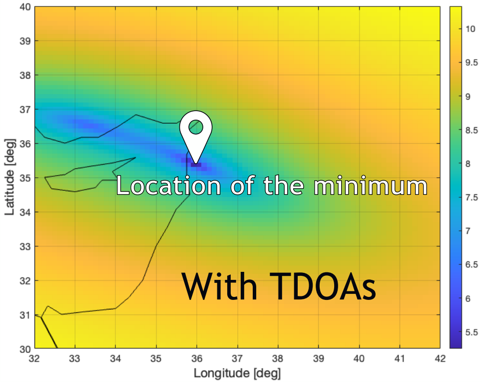
Cross-correlation detection

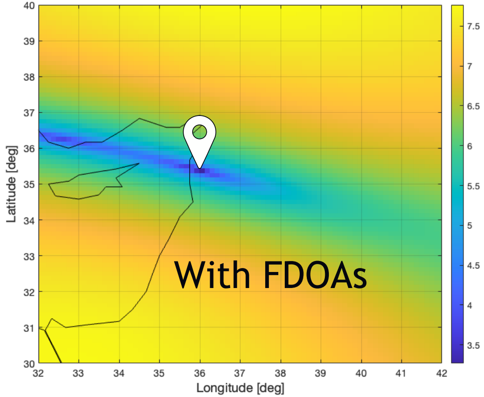


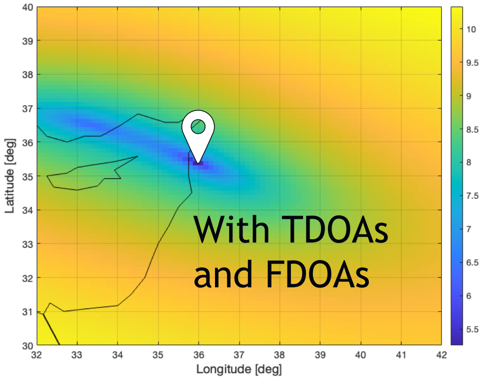
Syrian GNSS Jammer

Accuracy of MSG in L2 band

Cost functions





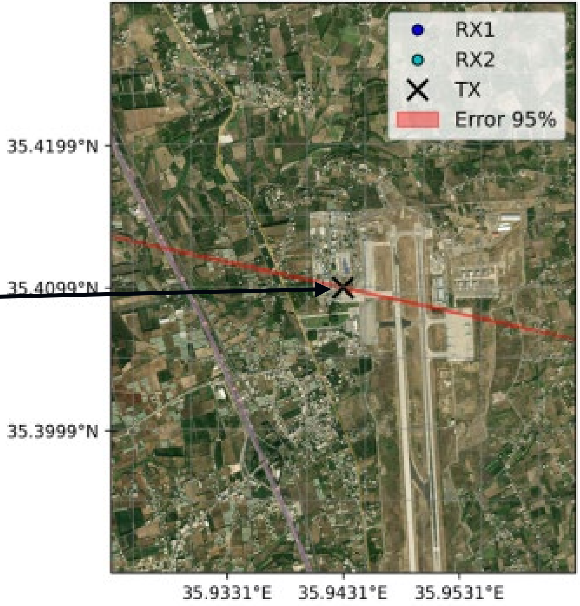


Error ellipse:
74 m x 19 m @ 148 deg wrt East

Syrian GNSS Jammer
Theoretical precision of MSG

One hypothetical source of interference over 4 MHz around L1 with 49 dBm of EIRP that is placed at the alleged jammer location is expected to be geolocated with a horizontal precision of up to 2 km during the satellite pass
This precision actually corresponds to an error ellipse with the major semi-axis extremely elongated

Circular Error Probable (CEP) contour map with 95% confidence



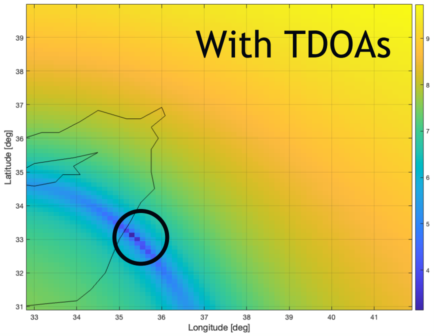
Error ellipse

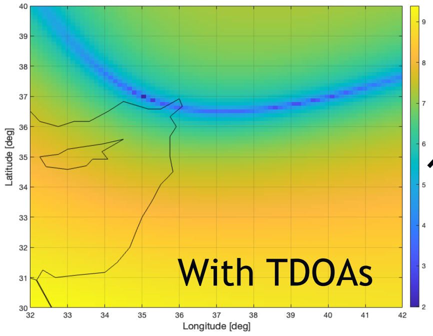
Syrian GNSS Jammer

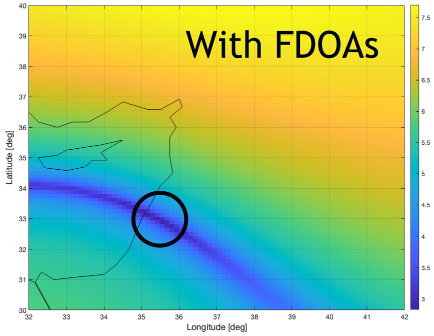
Accuracy of MSG in L1 band

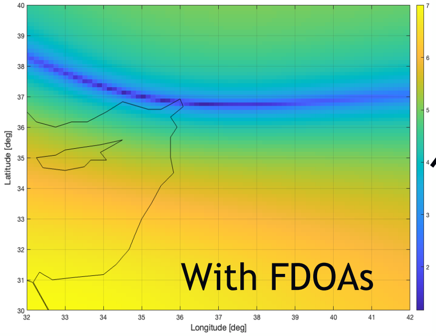
North of Israel?

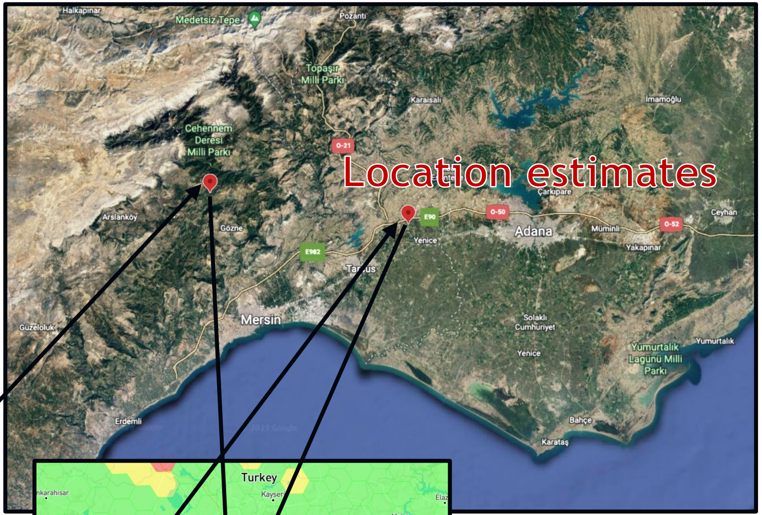
South of Turkey?

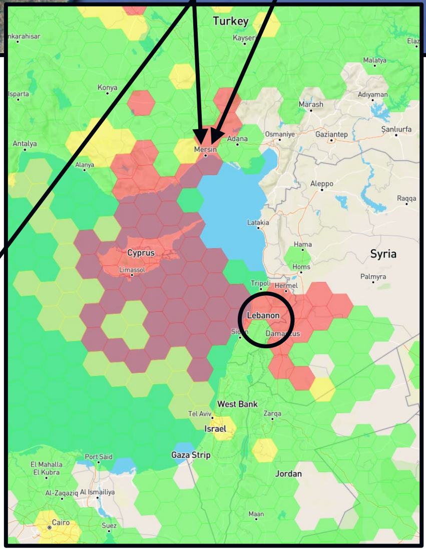












Error ellipses:
77 m x 15 m @ 2 deg wrt East
456 m x 47 m @ 151 deg wrt East

gpsjam.org
(same day)

Ongoing Projects and Customer Needs

Prior and Ongoing Projects

ESA NAVISP Program

- Prototyping GNSS jamming detection and geolocation with existing assets
- 1 year

GPS WORLD — GNSS POSITIONING NAVIGATION TIMING

Spire to develop flexible geolocation signal-processing tools for ESA

December 8, 2021 - By Tracy Cozzens

Spire Global has been awarded a contract under the European Space Agency's (ESA) Navigation Innovation and Support Programme (NAVISP), specifically "Element 2 – Competitiveness in PNT." The contract is funded by the United Kingdom Space Agency.

ONI NICSAT2 Program

- Designing, manufacturing, testing, integrating, launching, and operating two 6U
- 2-3 years
- Equipped with optical sensor

The Australian Office of National Intelligence (ONI) partnered with Spire to develop and deploy a CubeSat with advanced machine learning capabilities

Australian Government — Office of National Intelligence — ONI

ONI was formally established on December 20, 2018 after the passage of the Office of National Intelligence Act in November 2018. The office's role is to "ensure Australia has an agile, integrated intelligence enterprise" to meet the country's evolving security challenges. ONI ensures the National Intelligence Community's talent is equipped with the best technologies.

Spire supported ONI's commitment to innovation by supplying best-in-class emerging technologies for the office's first experimental satellite with machine learning capabilities.

NATIONAL INTELLIGENCE COMMUNITY SATELLITE (NICSAT) PROGRAM

NRO CDRC

- Competing with 5 other awardees in demonstrating commercial RF geolocation
- 2 years
- Exploiting the whole Spire ground infrastructure and constellation
- Equipped with optical sensor

Spire Global Awarded NRO Contract for Radio Frequency Data

Spire's data will be used by the agency to evaluate the integration of commercial radio frequency (RF) into its overhead architecture

DEEP Program

- Demonstrating GNSS jamming detection and geolocation with existing assets
- 8 months
- Extended to DEEP2

SPACENEWS

Space Force using Spire data to detect satellite jamming

Spire satellites track maritime, weather, and aviation data from space. Credit: Spire Global

Spire is providing GPS telemetry data to help detect jamming as part of a project run by the U.S. Space Systems Command

SNC L-Band Program

- Designing, manufacturing, testing, integrating, launching, and operating a cluster of four 6U satellites
- 3 years
- Detecting also SATCOM in L-band

businesswire

Spire Global and SNC Announce Strategic Partnership on Space Services Program

Spire will build four 6U LEMUR satellites for SNC to conduct RF collection and analysis

March 07, 2022 08:45 AM Eastern Standard Time

VIENNA, Va.--(BUSINESS WIRE)--Spire Global, Inc. (NYSE: SPIR), a leading provider of space-based data, analytics, and space services, today announced a partnership with Sierra Nevada Corporation (SNC) on a space services program to address a growing market need for radio frequency (RF) collection and analysis. Spire's cluster of four 6U satellites will enhance SNC technology that detects and geolocates certain objects based on targeted RF emissions. The program will provide valuable insight into how military and government organizations can better manage RF emissions and safeguard against RF and GPS interference.

UK DASA Program

- Designing, manufacturing, testing, integrating, launching, and operating two 6U satellites
- 2 years
- Detecting only SATCOM in L-band

Bloomberg

Spire Global Receives DASA Next-Gen Space Tech Funding for RF Signals Detection and Geolocation Project

Services for Customer Needs

RF Data Collections

Customer:

- Requests collection of RF data for a SOI [1] over an AOI [2] through contract negotiations.
- Tasks Spire satellites through API.

Service:

- Spire provides the raw IF/IQ data collected.

[1] Signal Of Interest
[2] Area Of Interest

RF Geolocation Services

Customer:

- Requests collection of RF data and analysis for a SOI over an AOI through contract negotiations.
- Customizes frequency of collects, number of reports, and desired latency.

Service:

Spire provides report with <u>RF signal analysis</u>.
The collection of raw IF/IQ data can be provided upon request.

Space Services RF Constellations

Customer:

- Works with Spire to define satellite mission needs through contract negotiations and program execution.
- Tasks their dedicated satellites through API.
- Receives their data and products from API.

Service:

- Spire builds and operates satellites to customer's specifications and delivers data and products (e.g., geolocation) to customer.

Persistent RF Surveillance

Customer:

- Receives subscription service scaled through negotiations based on payload type, frequency bands, and SOIs.

Service:

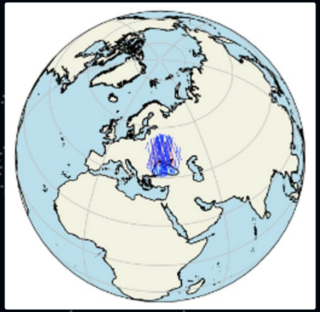
- Spire provides through an API or delivery service the <u>RF signal analyses</u> (e.g., for PNT situational awareness).

RF signal analysis provides source geolocation fixes with uncertainty ellipses

Competitiveness and Opportunities

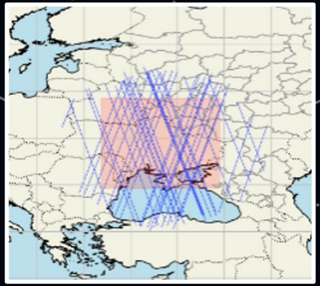
Spire currently has:

- The capabilities to control all stages of a constellation, from conception to operation, except for launch
- The facilities and expertise to develop and build all satellite components in house
- A record of programs related to RF geolocation with ESA, US Govt, UK Govt, NRO, Space Force, Australian ONI, etc.
- A worldwide footprint of operations (US, Europe, UK, Asia, and more)
- An operational constellation of GNSS-R/RO satellites for geolocation in L-band
- The low-latency provision of GNSS interference monitoring on track for the end of the year



Going forward, Spire aims at:

- Building RF geolocation services and infrastructure with a dedicated path of development
- Harnessing the global coverage enabled by GNSS-R/RO satellites
- Pursuing RF intelligence in bands like VHF, UHF, S-band, X-band, in addition to L-band



Benefits of Working with ESA

The NAVISP program has offered guidance and financial coverage to prototype and demonstrate Spire’s GNSS interreference monitoring proof of concept

ESA review process has provided a first insight into the expectations and requirements of a customer educated in the field of RF geolocation

- For example, this interaction has motivated the development of a simulation software to predict the geolocation accuracy of different interference sources with different satellite geometries

ESA feedbacks have raised awareness on missing or potential product features

- For example, the estimation of ranges of GNSS signal outage and degradation has been identified as an interesting intelligence by-product of interference geolocation for GNSS users

Contacts

For questions about Spire services, latencies, costs, and plans:

Jeroen Cappaert, CTO and Co-Founder jeroen.cappaert@spire.com

For technical questions related to the project:

Giacomo Pojani, Ph.D., Senior DSP Engineer giacomo.pojani@spire.com

Additional Facts

- Spire satellites are primarily in SSO with an approximate average **revisit rate of twice per day** for a given area of interest
- **Conjunction events** of two or more satellites flying simultaneously over a given area of interest occur **twice per week** on average
- New satellites are routinely launched in small batches to enhance coverage and promote spatial and temporal diversity