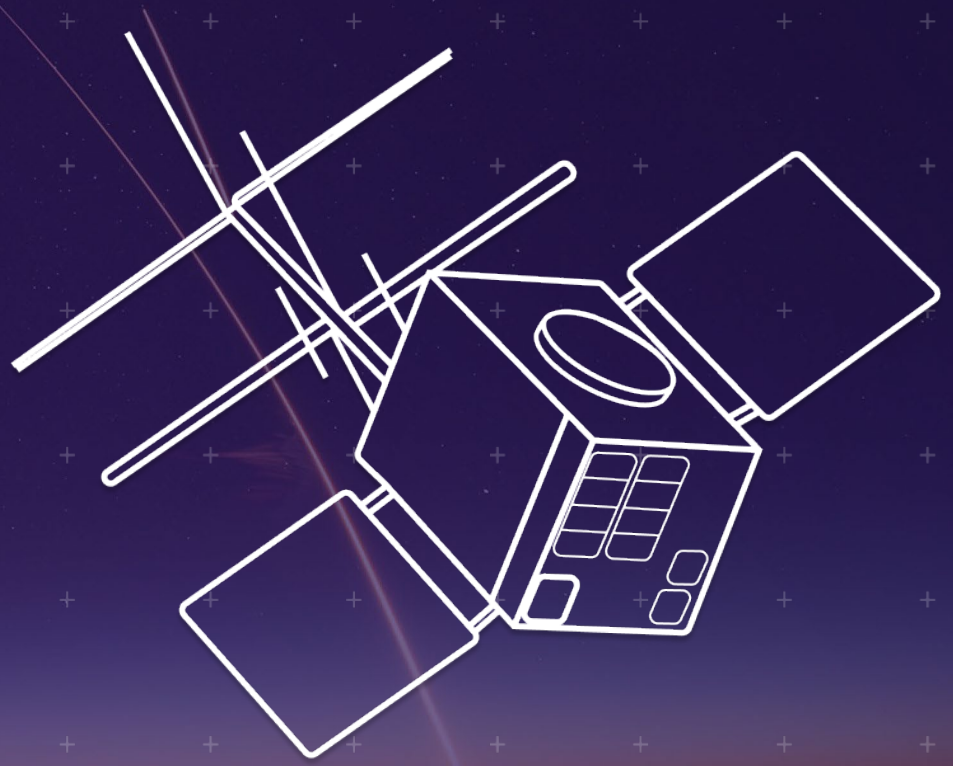
SPACE NORWAY

KONGSBERG

esa

Project ICING

Independent Critical Navigation

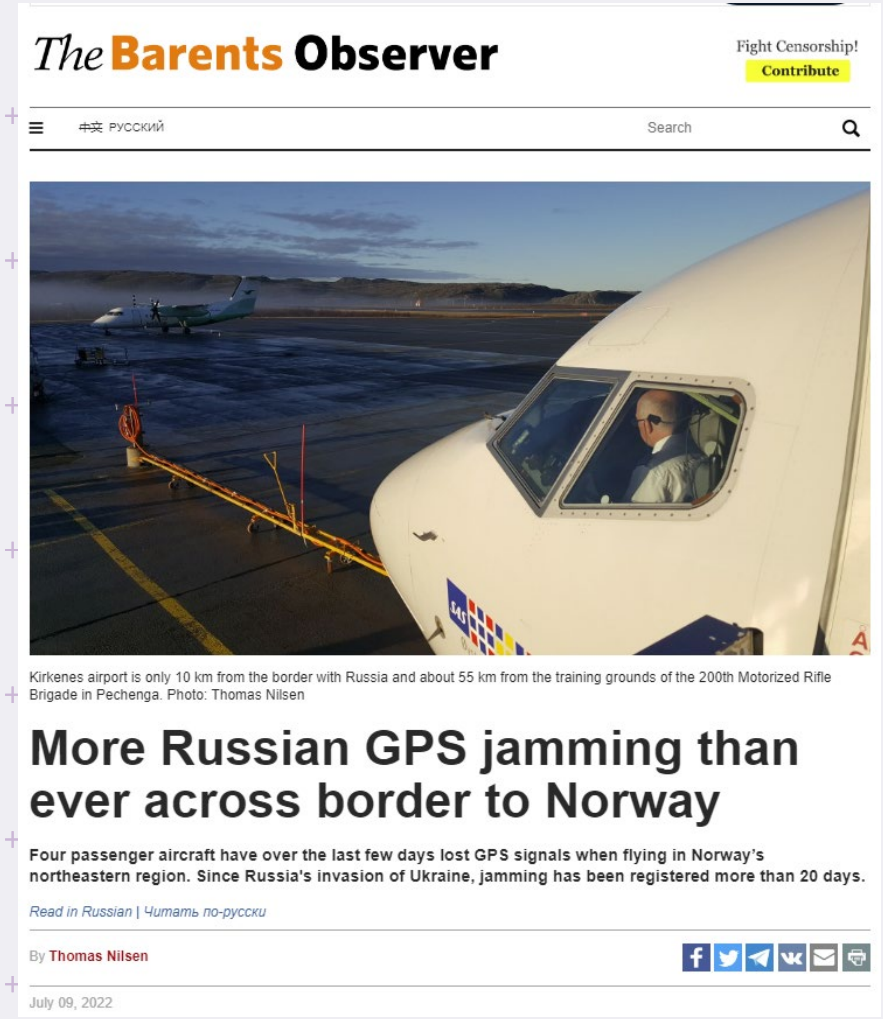


25.01.2024

Contents

Rationale and background

- PNT is essential for critical infrastructure
  - Poor coverage from traditional GNSS; weak satellite signals; vulnerable to disturbances and spoofing
  - Loss of GNSS compromise charting systems, AIS, and onboard GNSS receivers
  - Increased frequency of jamming in Northern Norway drive the need for contingency systems
- National context of ICING
  - Loss of GNSS jeopardize critical operations: navigation at sea, search & rescue, air traffic control
  - Norway is experiencing an increasing amount of disturbances, and expect more
  - Alternative means of navigation is highlighted as “Norway’s protection against GPS jamming”, says former Minister of Defense
- VDES (VHF Data Exchange System) provides a possible alternative
  - Digitized communication signals, providing possibility for data exchange
  - Newly launched NorSat-TD satellite with VDES capabilities provide an opportunity to investigate



The Barents Observer

Fight Censorship! Contribute

РУССКИЙ Search

Kirkenes airport is only 10 km from the border with Russia and about 55 km from the training grounds of the 200th Motorized Rifle Brigade in Pechenga. Photo: Thomas Nilsen

More Russian GPS jamming than ever across border to Norway

Four passenger aircraft have over the last few days lost GPS signals when flying in Norway’s northeastern region. Since Russia's invasion of Ukraine, jamming has been registered more than 20 days.

Read in Russian | Читать по-русски

By Thomas Nilsen

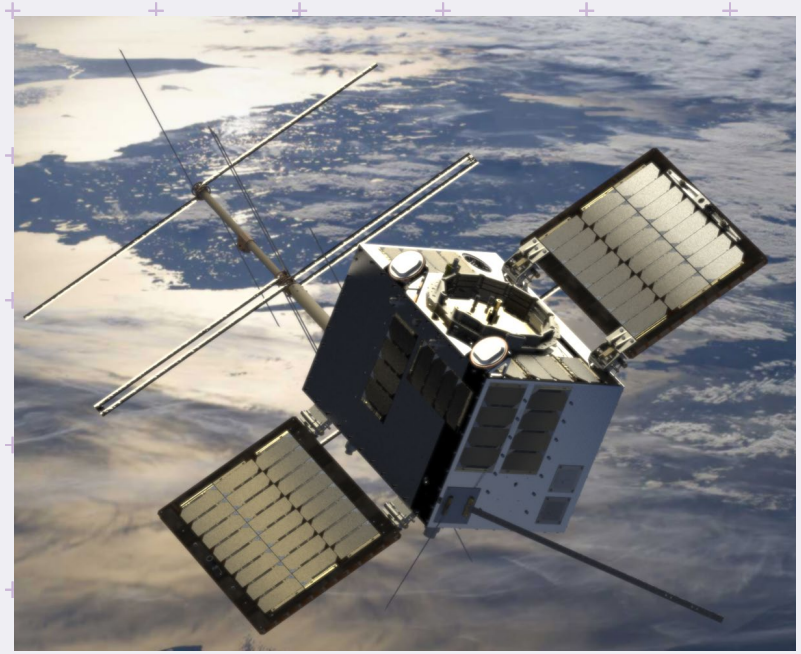
July 09, 2022

ESA ICING project – Independent Critical Navigation

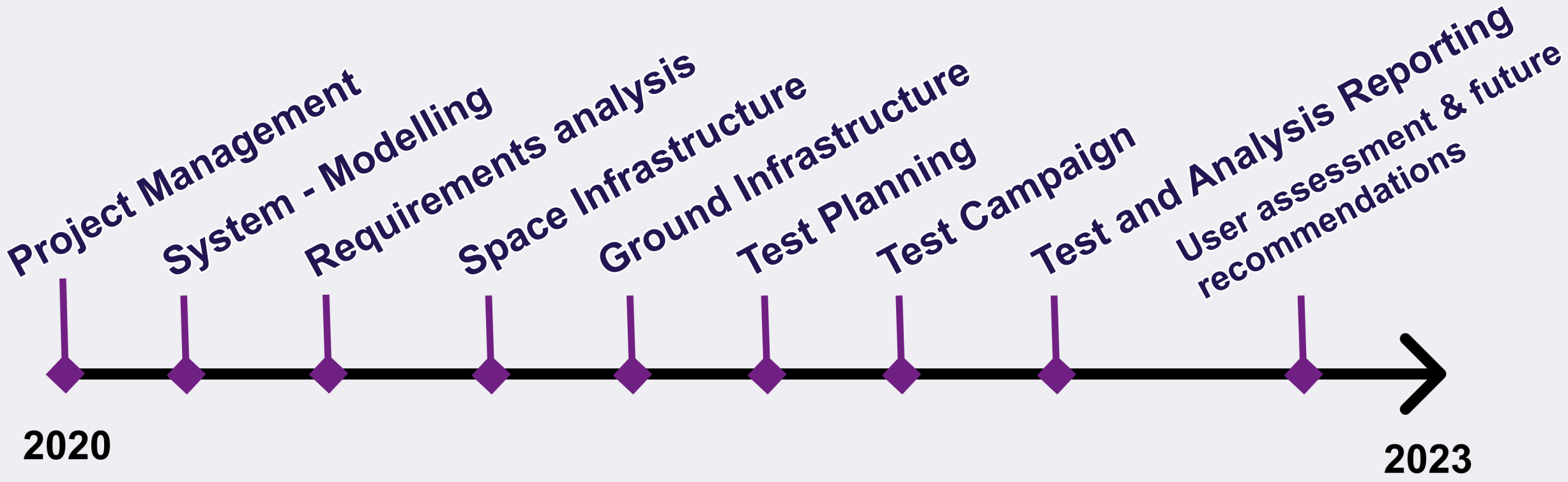
- The Consortium consist of Space Norway (SPN) and Kongsberg Discovery, Seatex (KSX)
  - SPN was Prime, Design Authority and owner of VDE-SAT payload on NorSat-TD
  - KSX delivered VDE-SAT payload with updated FW, VDES mobile station and VDES simulator software
- ESA funded project under the NAVISP E3 Program to test a concept utilizing VDE-SAT VHF satellites to provide pseudo-range signals as a source of PNT.
- Timing accuracy to be measured at one fixed locations in Norway.
- The aim is to achieve a first step towards a service with quality for potential maritime use.
- VDE-SAT ranging has a potential for complementing other platforms used for independent PNT such as Terrestrial R-mode.

NorSat-TD: Test platform for ICING

- NorSat-TD is a near identical satellite to NorSat-2. It is a test and demonstration platform.
- Owned by Norwegian Space Agency
- Test payloads financed by various companies
- Constructed by UTIAS, Defiant bus
- 508 km, 97 degrees inclined LEO
- Propulsion for orbit phasing
- Launched 15th of April 2023 and commissioning finished in June 2023.
- SPN payloads
  - Similar VDES to NorSat-2 in use since 2017
  - SDR VDE-SAT transceiver developed by KSX
  - 8 dBi deployable RHCP Yagi limb pointing antenna, including inspection camera
  - 1 Mbps S-Band feeder links for F/W uploads
- Energy budget supports >30% orbit duty-cycle

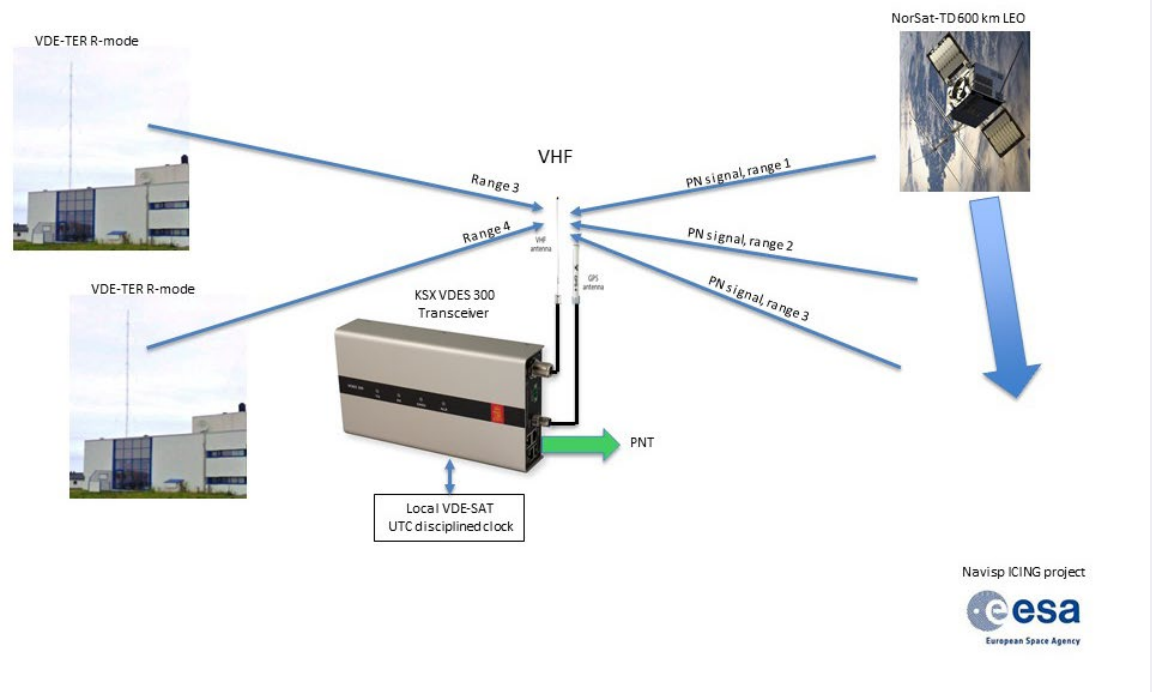


Project Work Packages



Technical concept: VDE-SAT Precision Time Broadcast

- Broadcast VDES pseudorange packet
  - Static content as ranging sequence with good autocorrelation properties
  - Target pseudorange accuracy < 300 m
- Measure multiple pseudoranges during a pass
- Discipline local UTC clock and keep drift at a minimum using external clocks
- Low cost VDES transceiver and antennas with TCXO and software upgrades on ships
- Low cost VDES reference stations foreseen for propagation corrections
- Additional VDE-SAT application on existing infrastructure



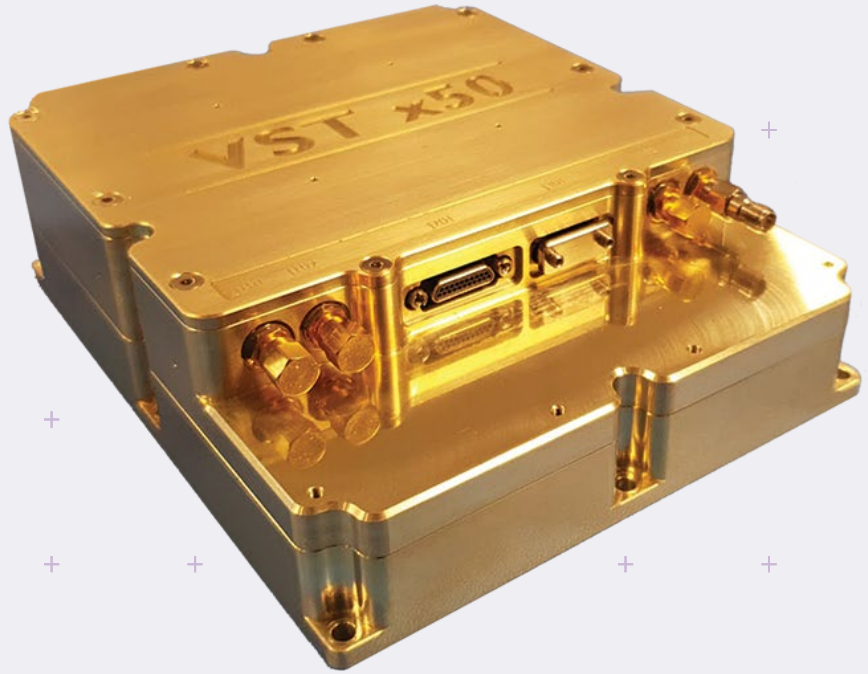
Use VDES allocated VHF frequencies

- 157 and 162 MHz allocated at WRC-19 for communications, not navigation
- Available from 2021, but requires national clearing, started in Norway, experimental use already allowed
- Standard defined in ITU-R M.2092-(1)
- ITU approval entered into force 23.2.2022 (process started before 2015)
- Approval of new specialized waveform for navigation would be long process
  - ICING project uses existing 141 kHz wide waveform Link ID 29
- Nominally broadcasted in each sub-frame (every 20sec)
  - Transmission rate doubled for ICING to increase data for analysis
- 690 byte payload
  - 590 bytes static content – optimized for autocorrelation properties
  - 100 byte Navdata

VDES Payload

- VST x50 is 2nd generation VDES transceiver from Kongsberg
  - Tightly synchronized to GNSS PPS
  - Linear 2 W transmitter supporting 157/162 MHz and multi-carrier operation
  - Engineering model installed in flat-sat at UTIAS/SFL for verification and testing

- Firmware modifications done to support ICING
  - Support for transmitting navigation message
  - Interface for satellite position, velocity etc.
  - Correct for internal clock drift
  - Satellite bulletin board with R-mode support



VDES Mobile Station

- VDES 300 Ship terminal from Kongsberg
  - AIS/VDE-SAT/VDE-TER/ASM support in one unit
- Same form factor as existing Kongsberg AIS products
  - Easy replacement – can keep existing antennas and cables
- Experimental R-mode capabilities
- Multi-channel IQ sample data capture support
  - Output on Ethernet interface to external equipment

Test setup

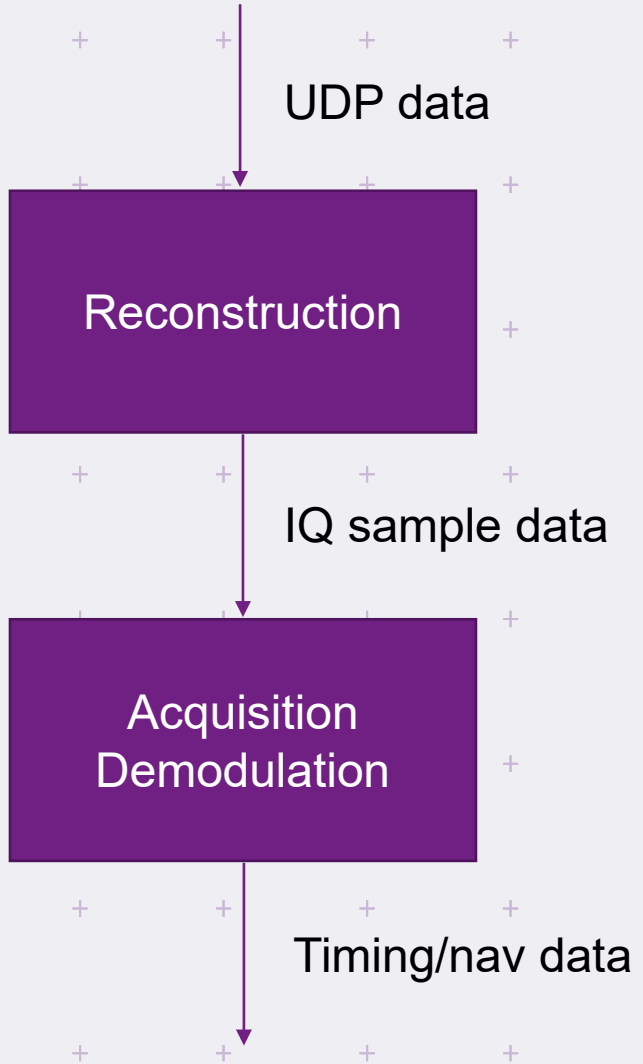
- Antenna mounted on roof of Kongsberg offices in Trondheim
  - Comrod AV7M – regular maritime AIS antenna
  - 3.4 dB cable loss @ 162 MHz
- GNSS signal provided by common high-end antenna
  - For synchronization between satellite and receiver
- External Spectracom 10 MHz rubidium clock
  - Used as stable reference when GNSS signal is lost
- Test computer
  - Storing IQ sample data
  - Processing of data

Test campaign

- The test campaign timeline:
  - Flat sat testing: 29th August to 2nd September 2022 – continued remotely
  - Launch: Saturday the 15th of April 2023 08:48 CET – planned launch date September 2021
  - ICING FW uploaded to NorSat-TD: 21st of June 2023
  - Start of initial ICING operation: 27th of June 2023
  - First successfully received pass: 27th of June 11:57 CET
  - Start of full ICING operation: 10th of July – after FW upgrade
  - Last successfully received pass: 22nd of October 10:46:00 CET
  - End of ICING operation: 31st of October 2023
- 190 passes in total
  - 50 with successful range measurements (since 10th of July).
- 8448 transmitted ranging signals
  - 1129 received without packet loss. 8 of these were identified as outliers.

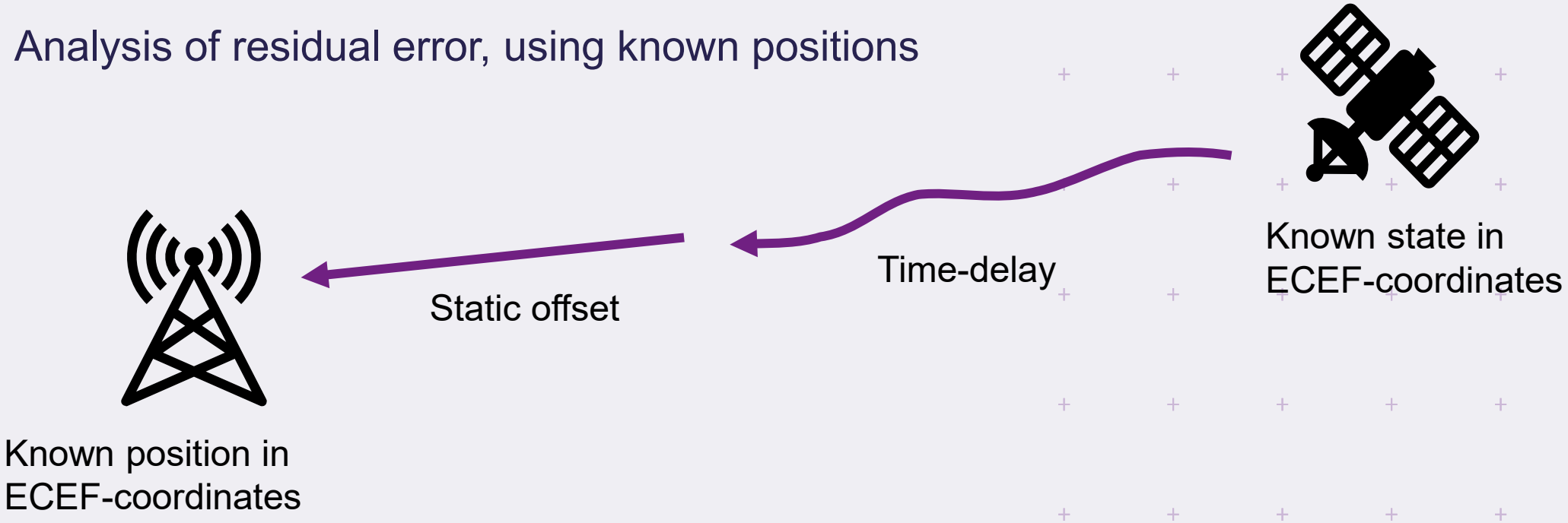
Timing Estimation

- Reconstruction of sample data
  - In case of lost packets on UDP link
- Kongsberg VDES Physical Layer simulator software
  - Estimation of timing delay
  - Demodulation of navigation message
- Timing estimates and nav data used in PVT solution



Analysis and positioning tool

- Analysis of residual error, using known positions



- Characterise current performance level: mean, standard deviation, model fit
- Parametric analysis to find correlations

Analysis and positioning tool

- Analysis tool is based on importing processed range measurements
- Observations, navigation messages, and telemetry data

- Telemetry data as an alternative to faulty position in navigational message
  - Same source as navigation message
- Small slot number fix
  - No impact on performance

- Telemetry is interpolated to navigation message timestamp
  - Cubic spline, a well-known method
  - Introduces no significant error: cm-level with half the points

Analysis and positioning tool

- Options for visual and numerical analysis
  - Residuals over time
  - Histogram distributions
  - Statistical description
  - Model fit
  - Parametric analysis
  - Applying corrections
  - etc…
- All source code (Python) delivered in full in EIDP, with examples

Analysis and positioning tool

- Positioning tool
  - The current positioning performance under a single satellite
- A general positioning tool was developed
  - Independent of analysis tools
  - Applicable here, and in case of combined sources
  - A prototype software for a future real-time service
  - Readily extendable
    - Corrections
    - More complex positioning
  - Verified and validated using GPS data
- Full source code (Python) available in EIDP, with V&V routines

Positioning tool

- Iterated least-squares estimate
  - Four or more observations required
  - Levenberg-Marquardt algorithm, robust in collinear problems (Moré, 1978)
  - Light-time, and Sagnac delay correction (Hu and Farrell, 2019)
  - Estimated position projected to Earth
    - Great-circle distance, accurate at short distances
  - Possible additional ground constraint
    - Rudimentary implemented as an additional pseudorange

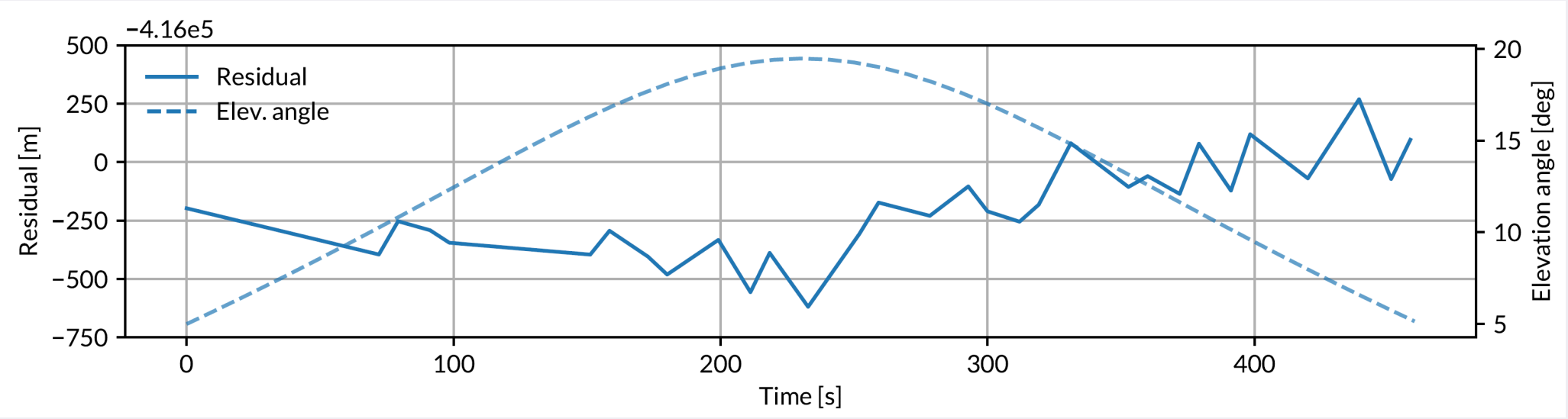
- Applied in a variety of systems

Results

- Residual behaviour and characteristics
- Residual distribution and model fit
- Parametric analysis

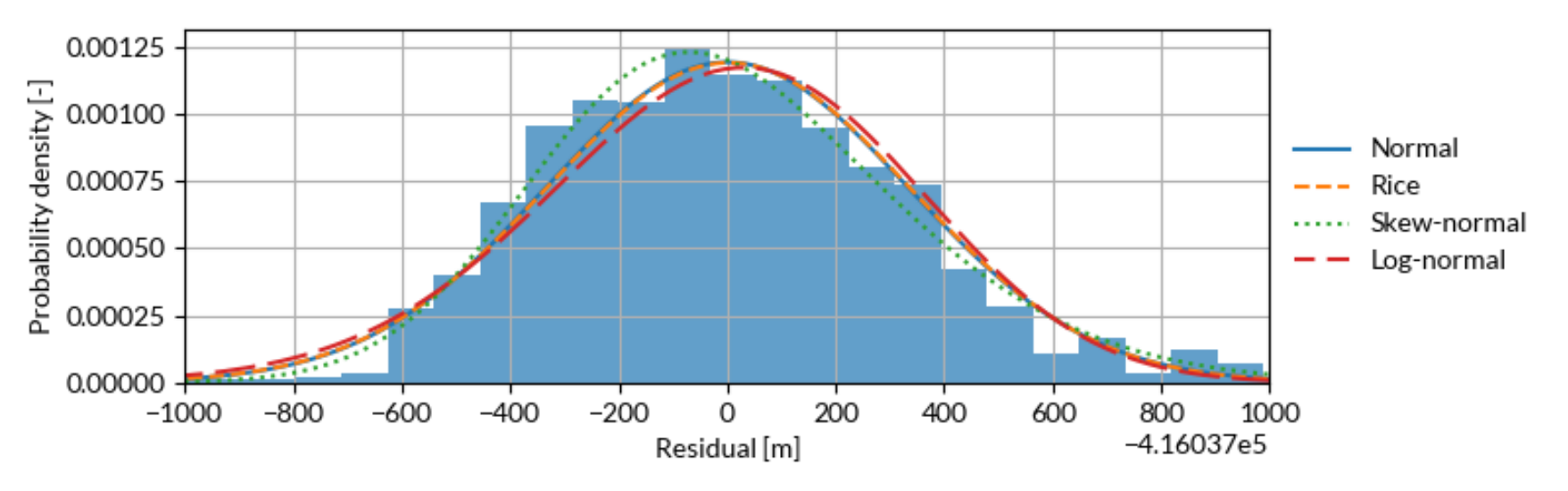
- Corrections: NeQuick-G of Galileo (European Commission, 2016)
  - Before repeating all of the above

Residual through a pass



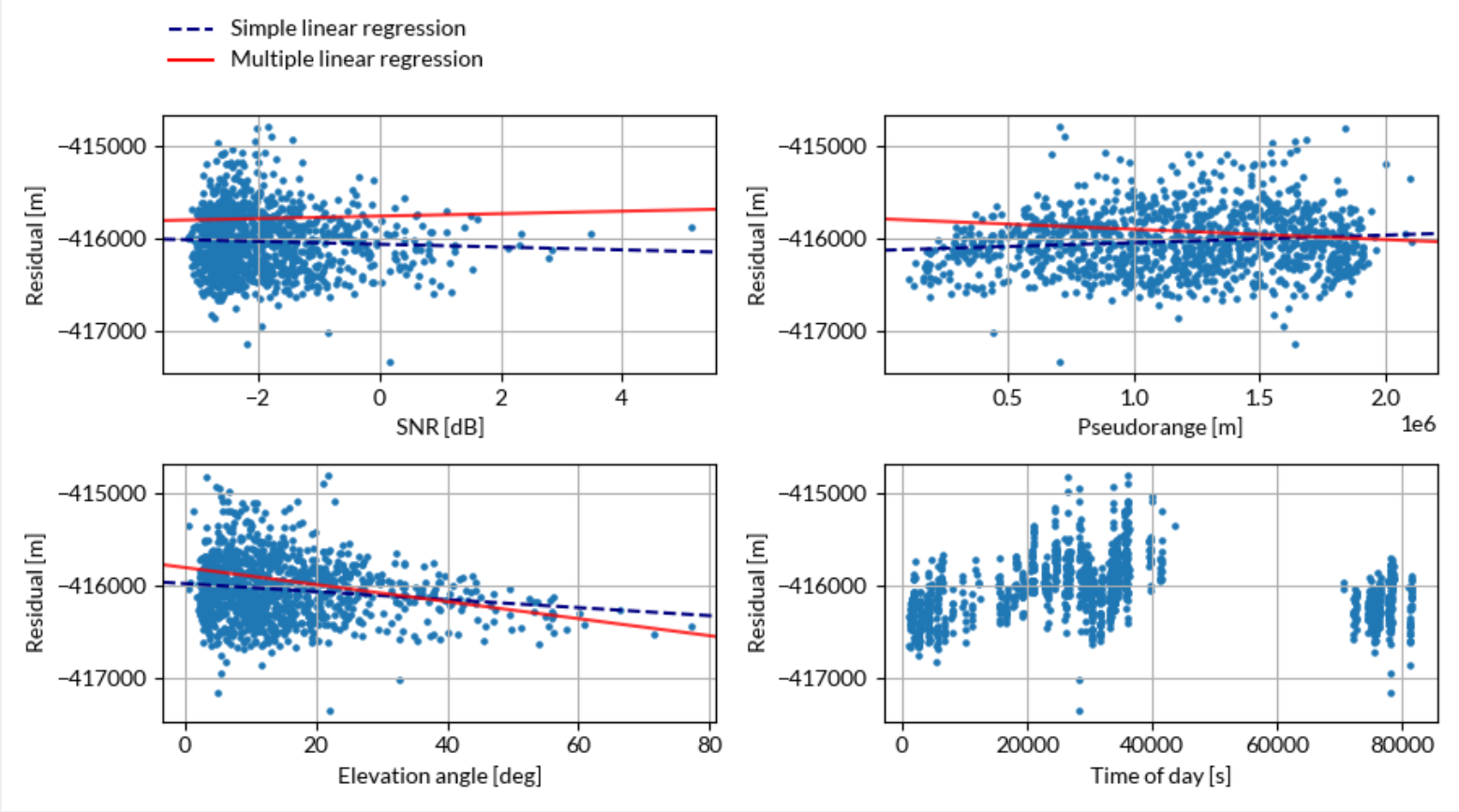
Distribution of pseudorange residuals

- Independent continuous random variable
- Spread, σ = 335.2 m
- Bias, -416037.0 m



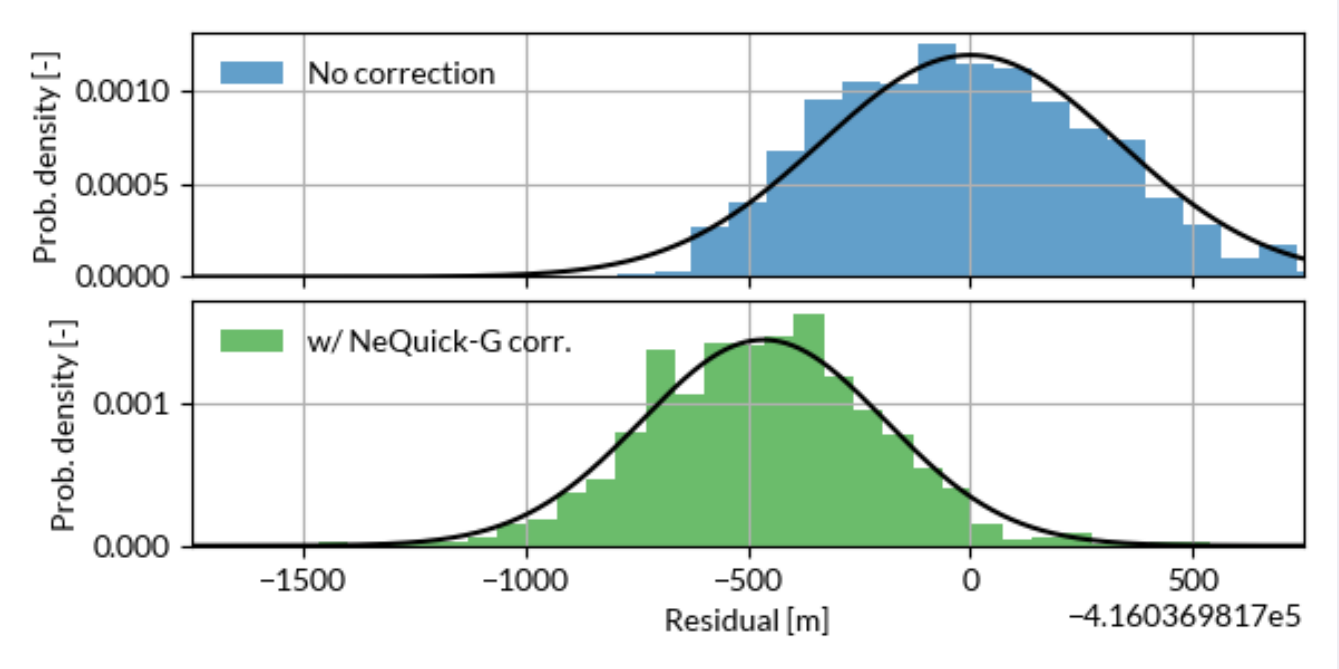
Parametric analysis

- SNR, Pseudorange, Elevation angle, Time-of-day



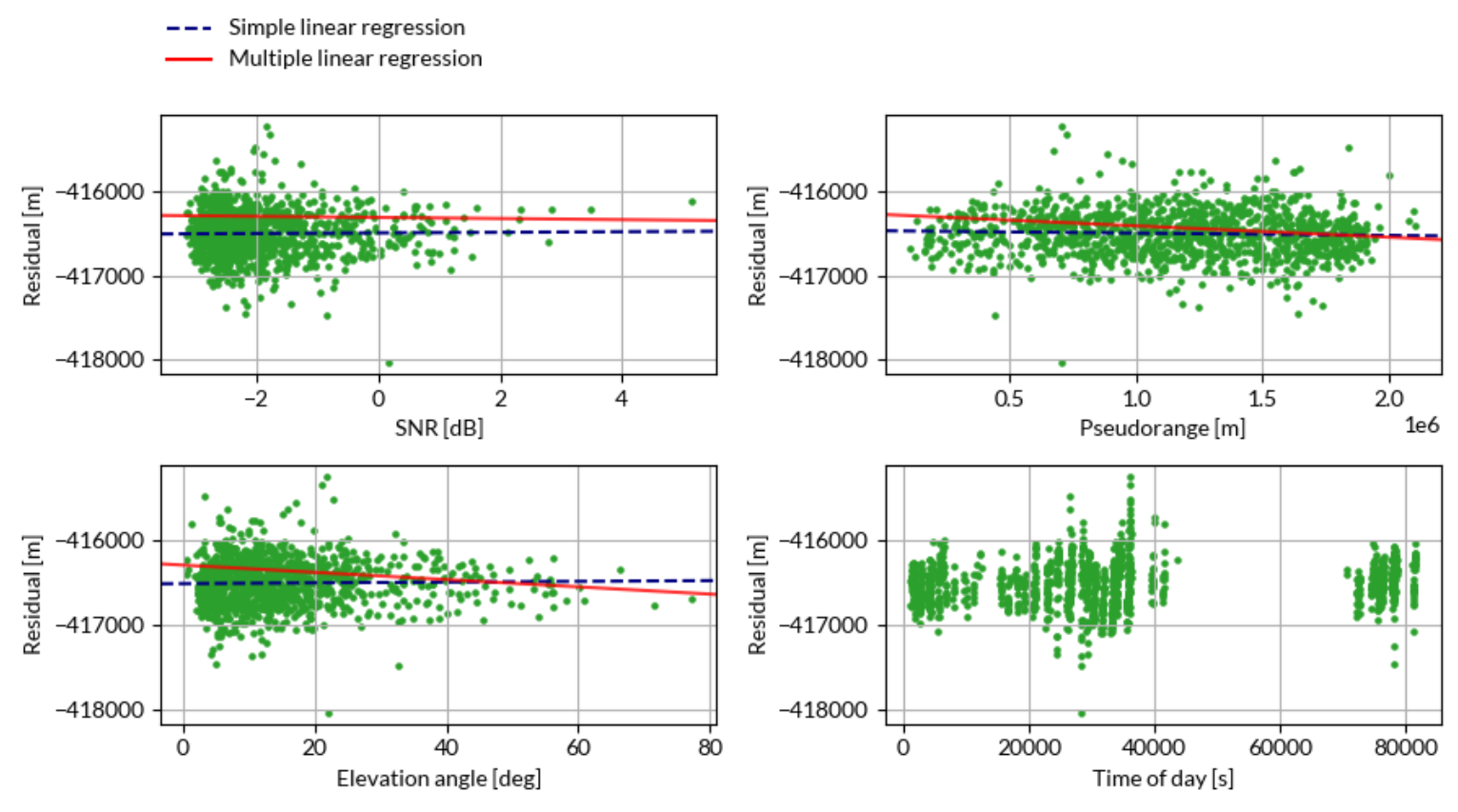
Distribution of pseudorange residuals

- Independent continuous random variable
- Spread, ~~σ = 335.2 m~~ σ = 274.8 m
- Bias, about 500 m shorter
- Normal distribution



Parametric analysis

- Correlations with ionospheric time-delay are removed

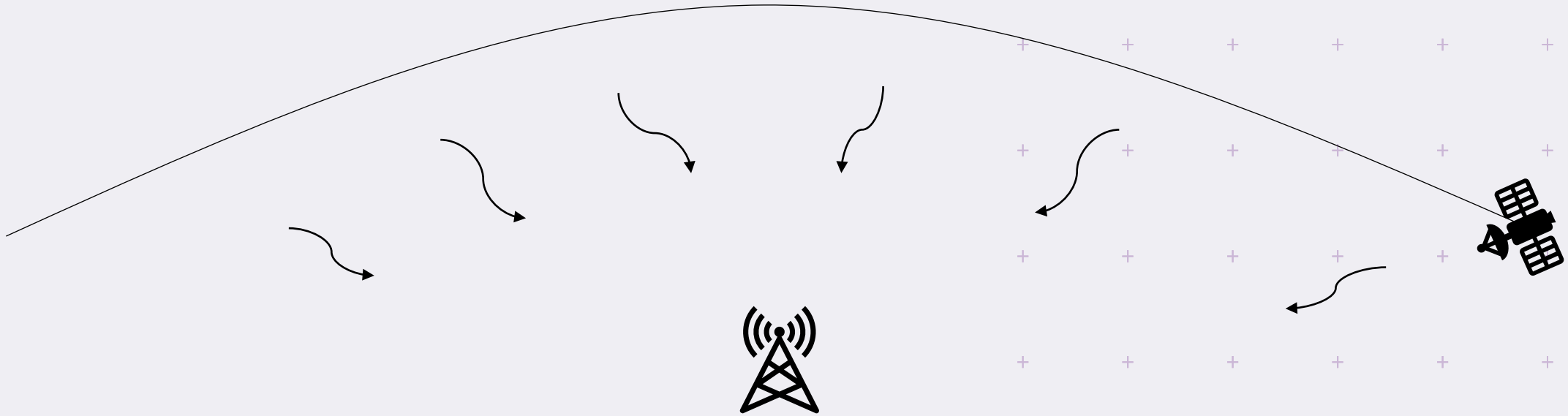


Takeaway from results

- Multiple pointers to the ionospheric time-delay
  - Correlation in parametric analysis
  - Successful correction using NeQuick-G
- No correlation with SNR: multipath specular reflection
  - In contrast to the original hypothesis
  - Will require a further study
- We applied the NeQuick-G ionospheric correction model
  - Improved signal quality
  - A need for a VDES-specific correction model

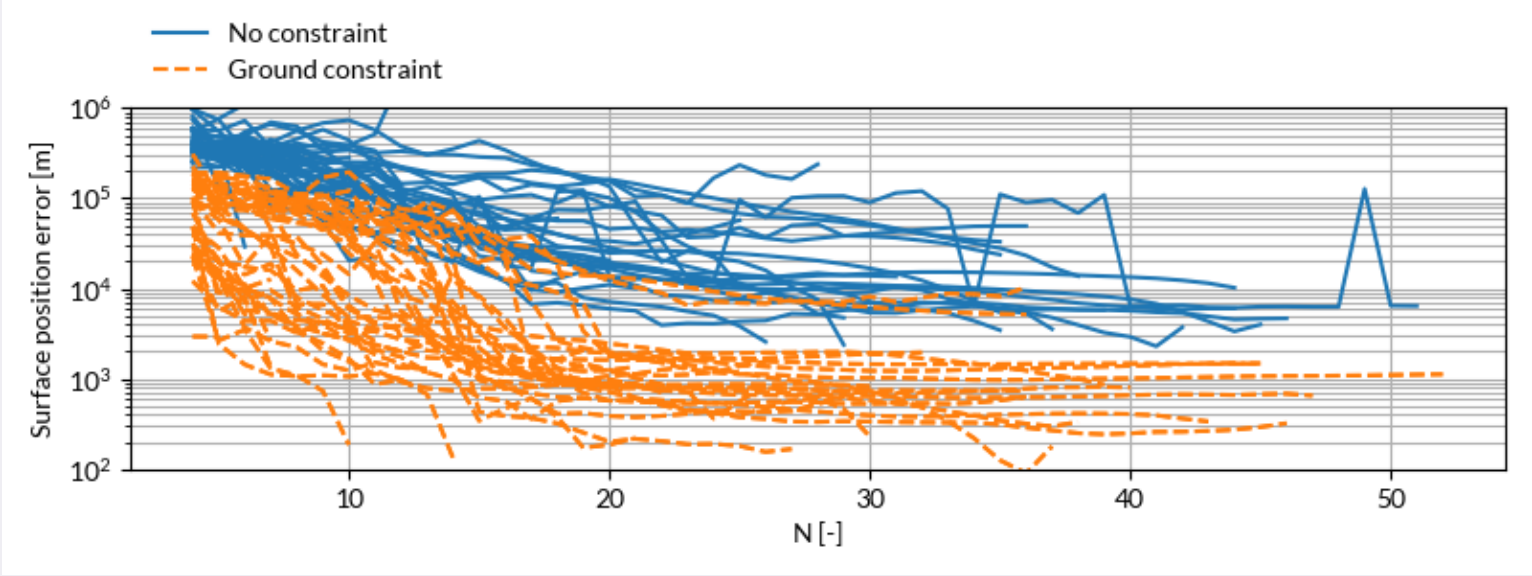
Results

- Single-satellite positioning
- Four or more (N) consecutive measurements through a pass
- For all N, with and without ground constraint



Results

- Decreasing trend
- Ground constraint improves accuracy by 10-100 times
- Little improvement for N > 20
- Steep declines, believed to be a geometric relation



Conclusions

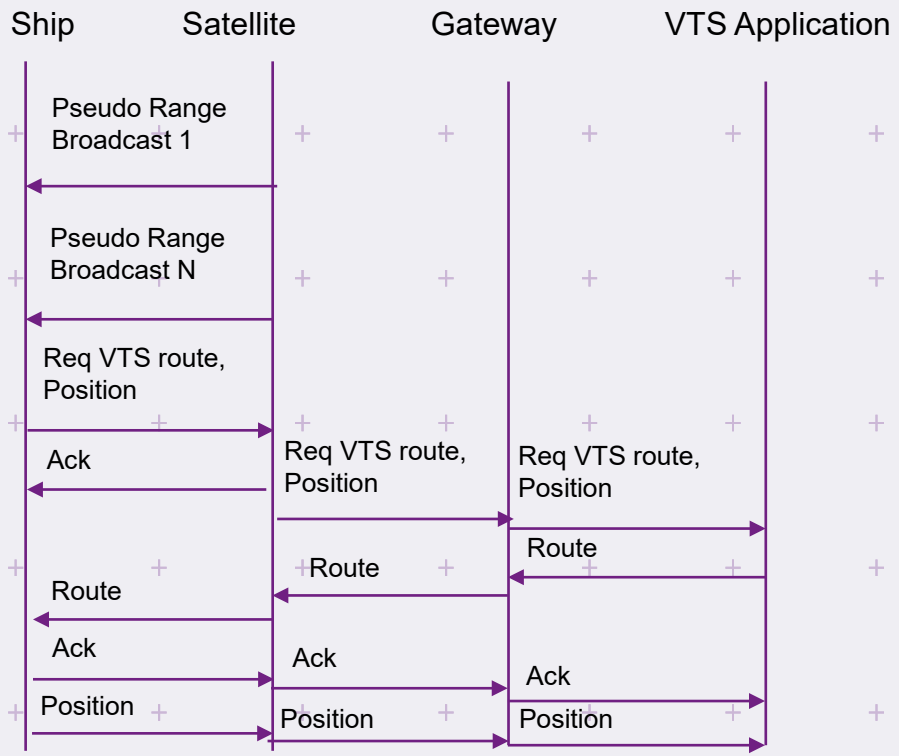
- 1121 pseudoranges show the current range distribution has:
  - A large, constant bias, believed to be due to pre-compensation and other static delay
  - A spread of $\sigma = 335.2\ m$
  - Good evidence that ionospheric time-delay is a large (correctable) factor
  - Positioning close to 1 km accuracy: A target metric
  - Results from Wirsing et al (2021) show VDES R-mode positioning within 22 m (95-th percentile)
- Still unanswered questions on the remaining sources of error
  - Noise from multipath, autocorrelation technique, tropospheric error
  - More data and more complex measurements can answer this
- Further development is necessary for a real-time operational demonstration of ranging
  - Ranging capabilities at the user
  - Dynamic user
  - Updated navigational message with correction terms
- ESA support critical in the success of the project

Recommendations

- Two possible new VDES services
  - Precision Time Broadcasting Service (integrity check, back-up position determination
  - Coastal Administration Vessel Position Polling/Reporting (VTS)

- Improvements
  - Reduce PER and improve accuracy by correlation over fraction of 2.4s burst
  - Calculate ship position in terminal
  - Correct 1 s time error in Navdata message
  - Upgrade satellite software to remove clock translation error
  - Ionospheric parameters in Navdata message

- Tests
  - Test drift of satellite synched ship terminal time
  - Compare linear and CP antenna performance
  - Test position determination with VDE-SAT/TER VDE-SAT only
  - Ocean Space Lab vessel
  - Possibly new VTS service for Norwegian Coastal Administration



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