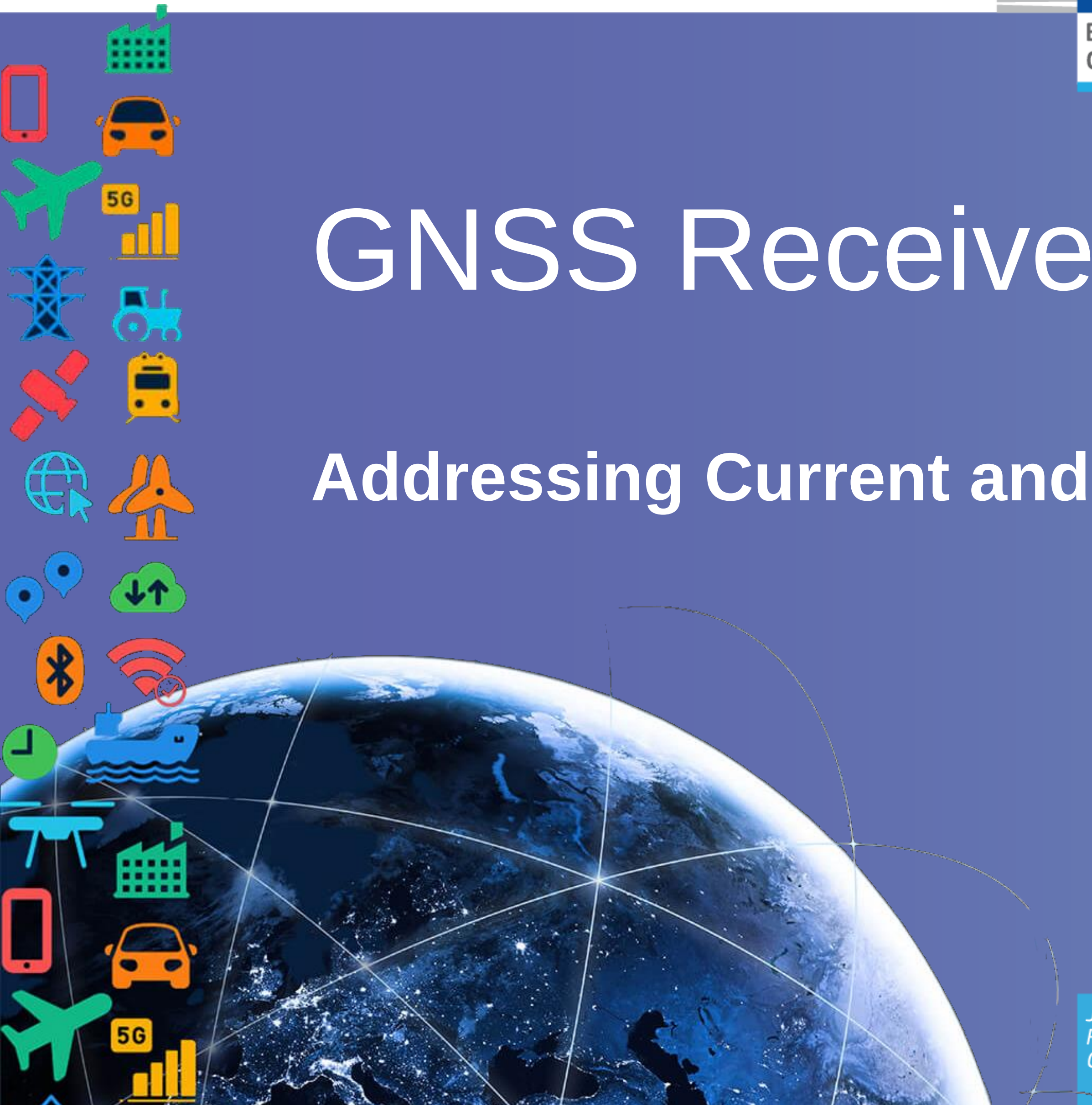

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GNSS Receiver Algorithm Trends

Addressing Current and Future Challenges

Joint Research Centre

Daniele Borio

ESA/ESTEC, 7/8 November 2023

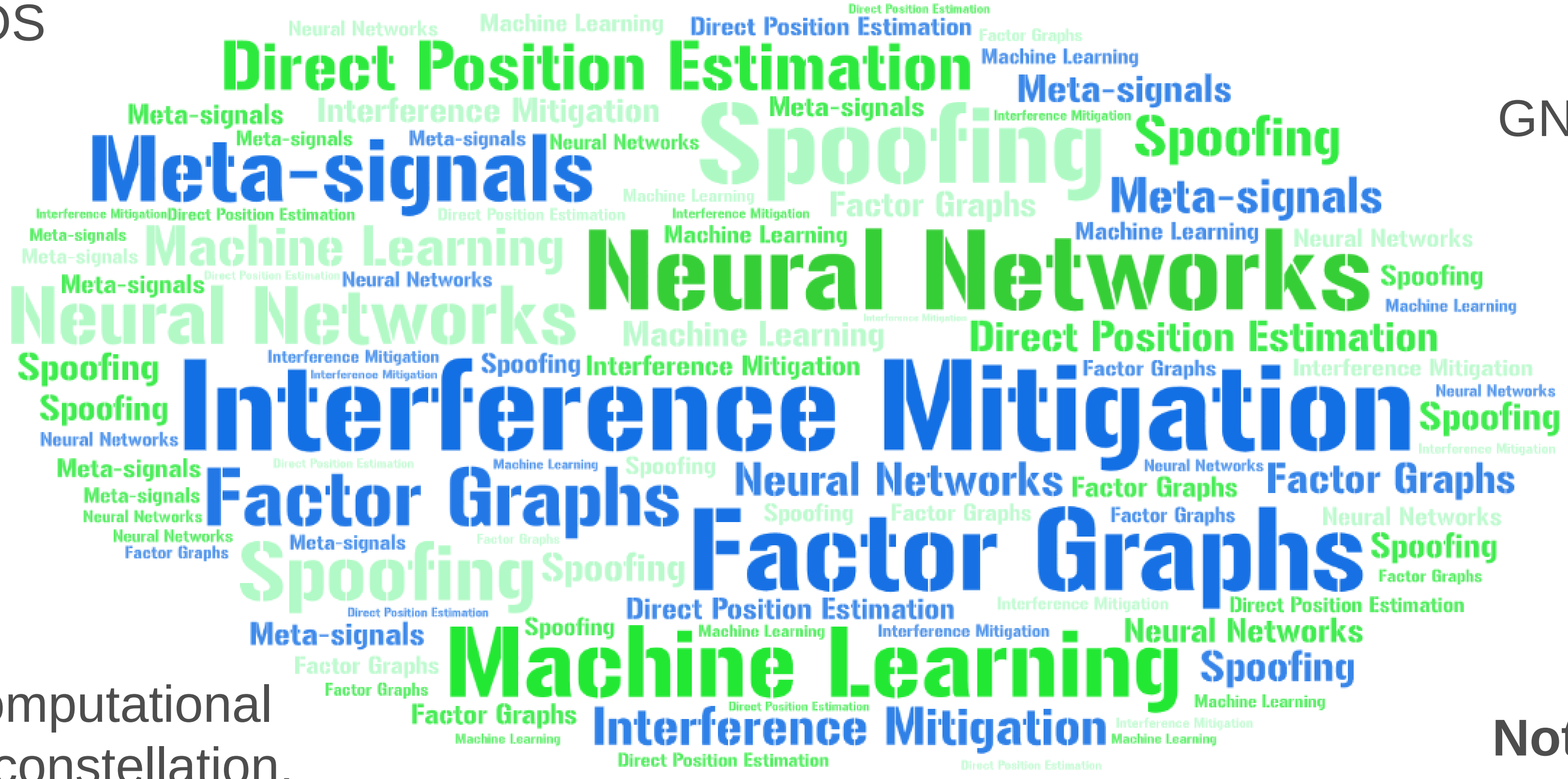
Introduction

Word cloud based on a search on the ION GNSS+ 2023 conference program

ION INSTITUTE OF NAVIGATION

Long lasting problems: multipath and NLOS mitigation, urban navigation, interference and spoofing, ...

GNSS receiver algorithms: evolving with **hardware capabilities** (e.g., increased computational capabilities, multi-constellation, multi-frequency measurements, external sensors ...)



GNSS receivers are also **evolving** to support **new services**:

Galileo OS-NMEA, HAS, Beidou B2b PPP, ...

Not covered in this presentation

quick overview of receiver algorithm trends

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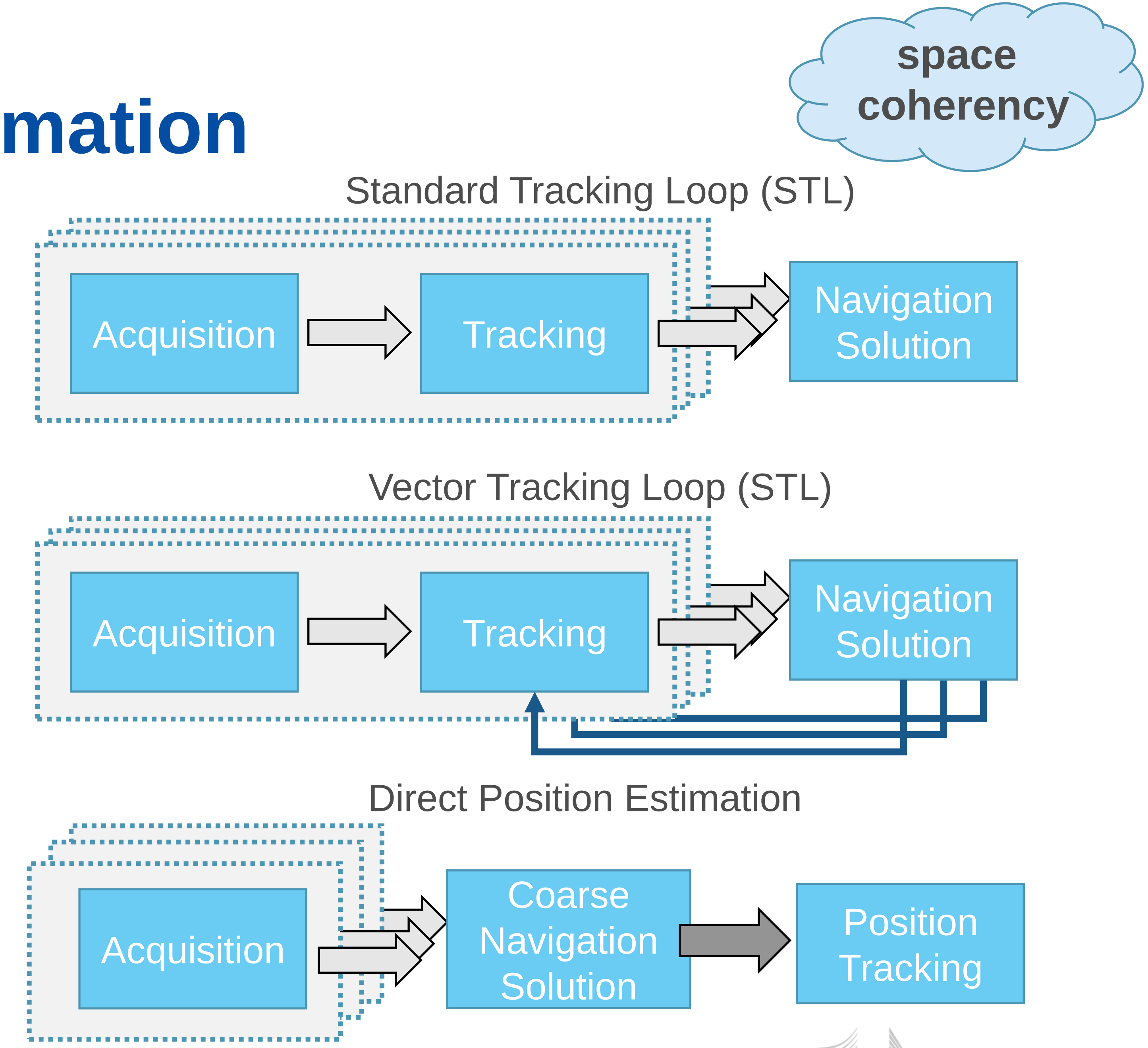
Direct Position Estimation



Principle:

- GNSS signals are received from the **same position** and with the **same user velocity**
- Individual GNSS signals are characterized by **code delays** and **Doppler frequencies** which are **function** of the user position and velocity
- Processing **directly** in the **position/velocity domain**

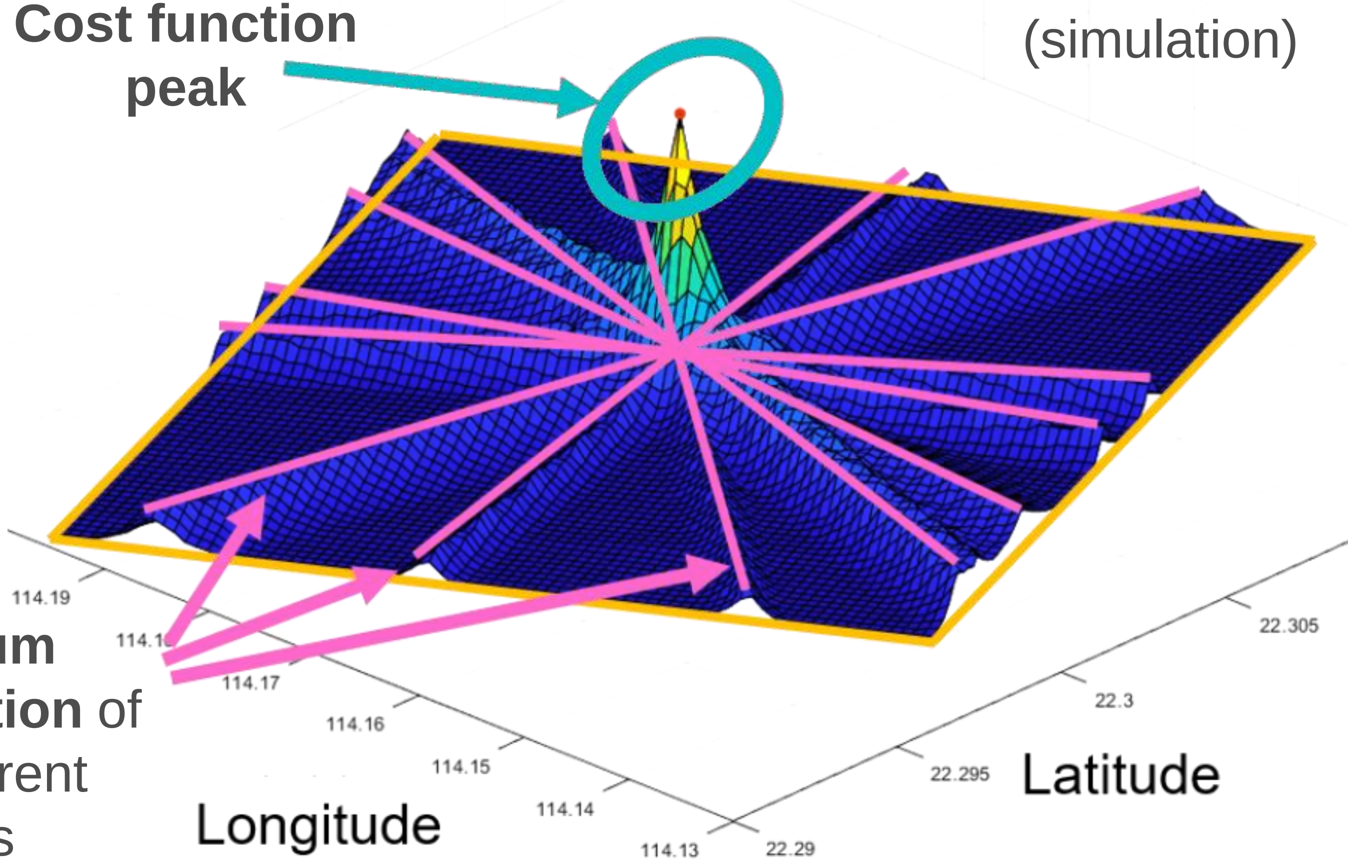
P. Closas and A. Gusi-Amigo (2017), "Direct Position Estimation of GNSS Receivers: Analyzing main results, architectures, enhancements, and challenges," in IEEE Signal Processing Magazine

DPE Optimization

- Fully exploit the **relationship between signals** from different satellites
- Increased **resilience to multipath errors** (on a limited number of signals)
- **Active field of research**: reduce computational complexity (parallelization, search domain decoupling, ...)
- Multi-frequency, multi-constellation solutions, integration with other sensors

DPE cost function (simulation)

Cost function peak



Lines of **maximum correlation** of the different satellites

Figure from:
Sergio Vicenzo et al. "Experimental Investigation of GNSS Direct Position Estimation in Densely Urban Area", ION GNSS+ 2023

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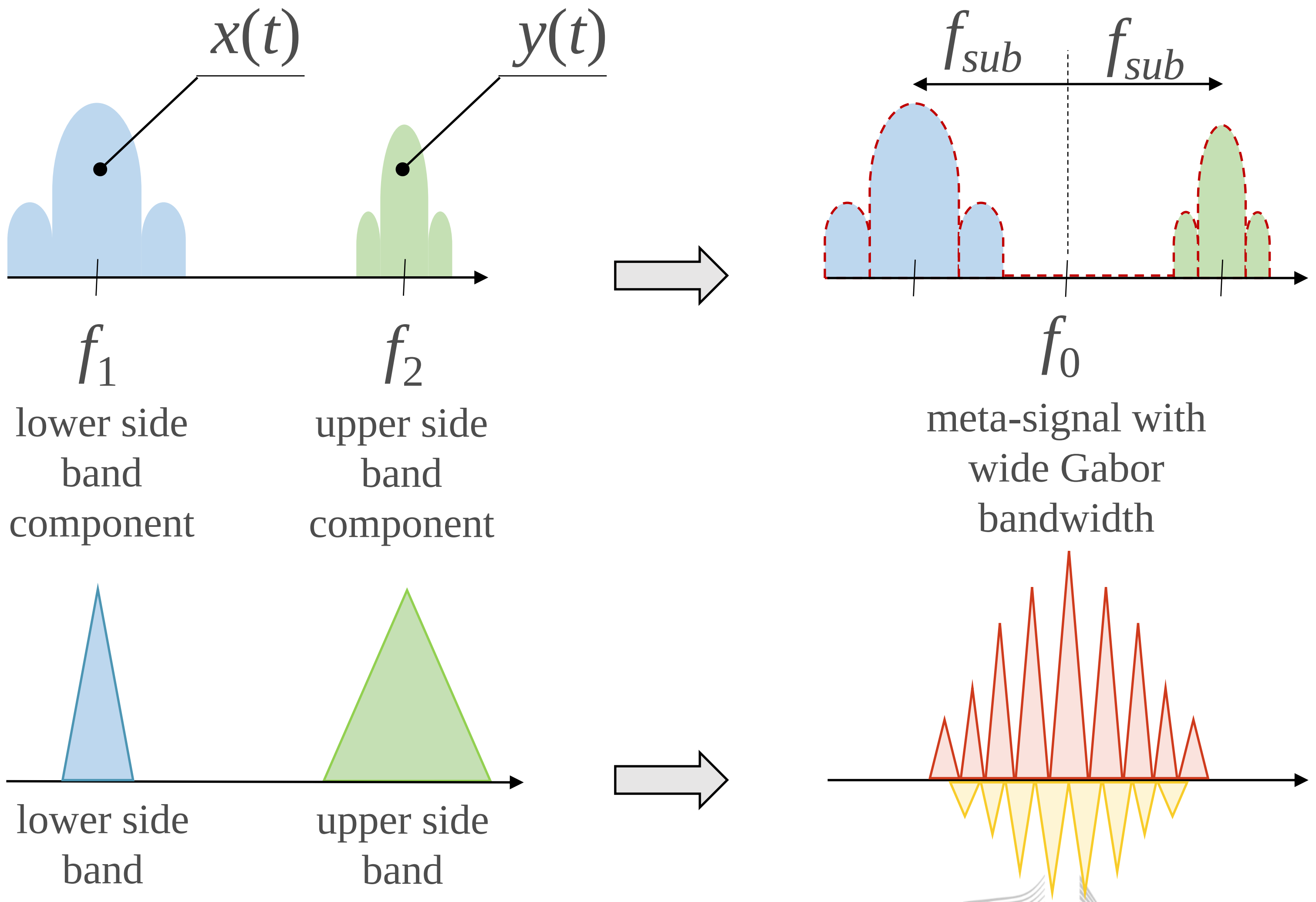
GNSS Meta-Signals

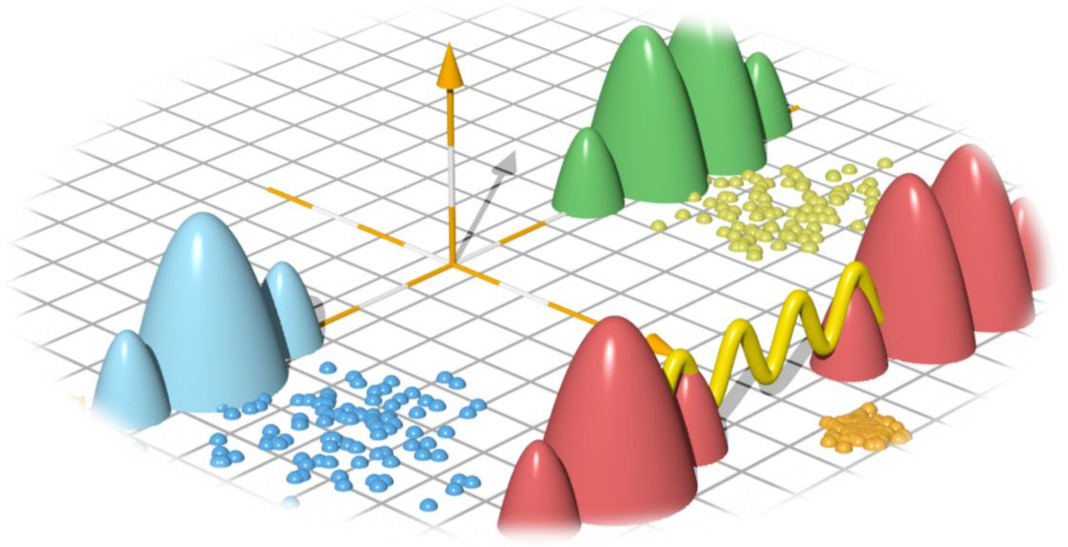
frequency coherency

Principle:

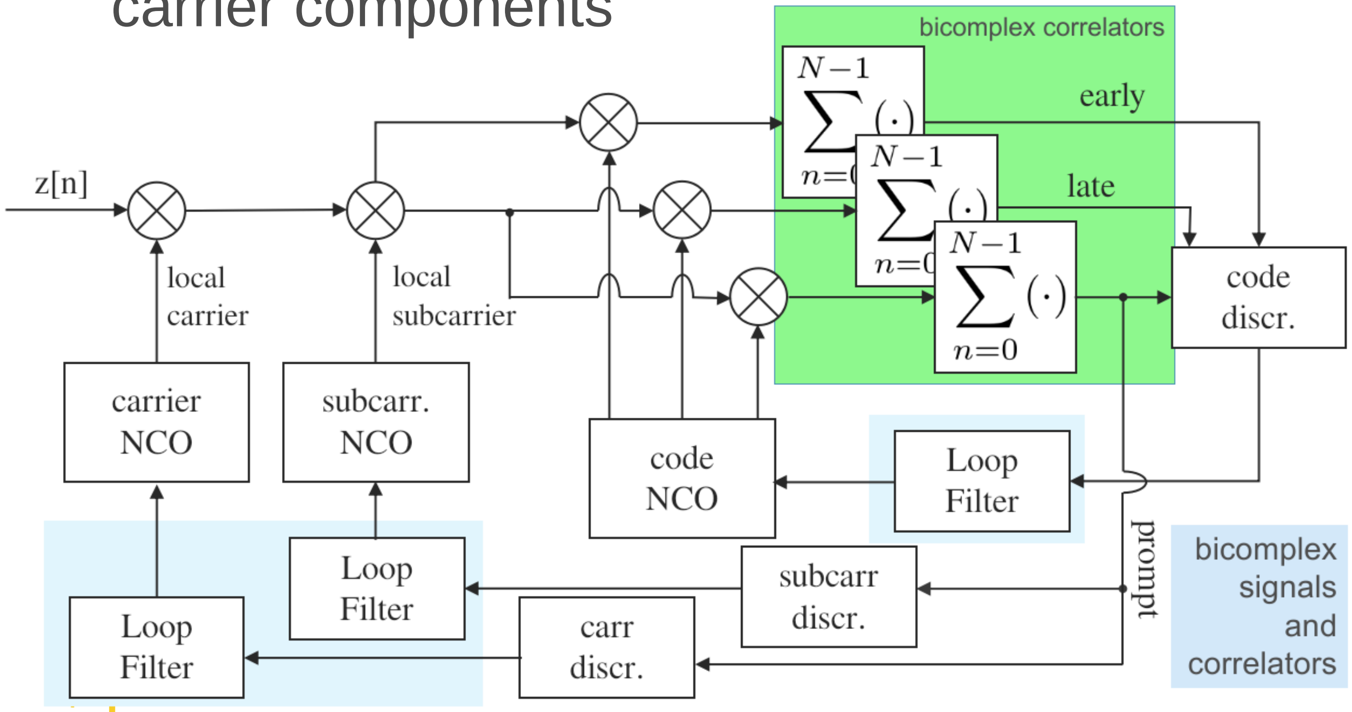
- consider two (or more) GNSS signals **together**: obtain a composite signal with a wide **Gabor bandwidth** (**high code accuracy**)
- signals from **different frequencies**
- generalized **Binary Offset Carrier** (BOC) modulation with **different side-band components**
- **ambiguous** (and complex) **correlation function**



Meta-Signal Approaches



- **Advanced signal processing approaches**
- **E.g.: triple-loop architectures** with code components processed jointly (DLL), PLL and **Subcarrier Phase Look Loop** (SPLL) to process carrier components



- **Subcarrier concept:** side-band components **away** from a **common centre frequency**
- **Synthetic meta-signal observations**: reconstruction from side-band measurements
- ***code-carrier dual-frequency combinations***

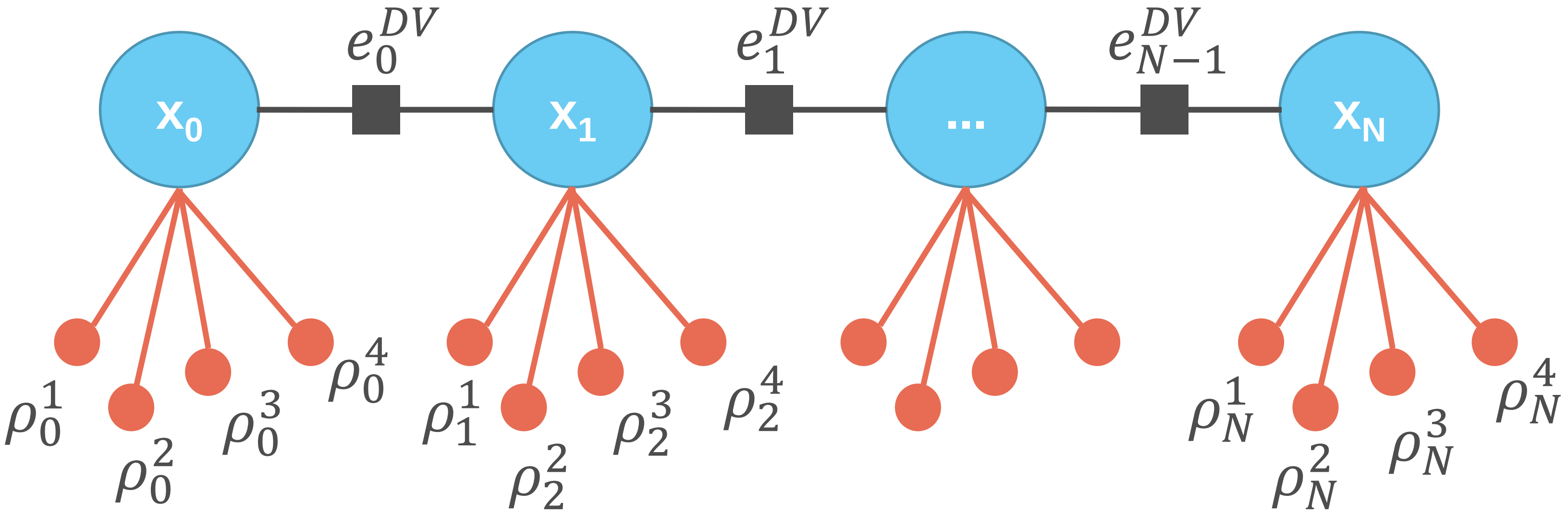
Factor Graph Optimization (I/II)

time and model coherency

State nodes: unobserved variable to be estimated (e.g., position/clock)

Measurement unary factors

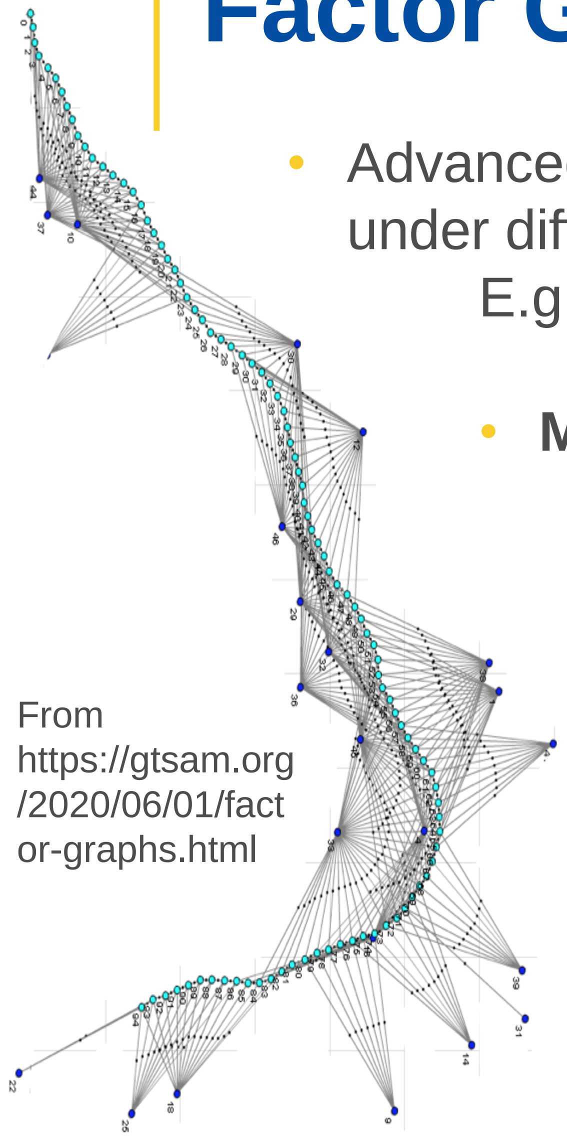
Binary factors



- **Probabilistic graph models**, widely used in robotics, increased popularity in GNSS over the last decade
- **Position domain, cooperative location** and **sensor fusion**
- **Maximization** of **cost functions** which can be **factored**

Example from W. Wen and L. -T. Hsu, "Towards Robust GNSS Positioning and Real-time Kinematic Using Factor Graph Optimization," 2021 IEEE International Conference on Robotics and Automation (ICRA)

Factor Graph Optimization (II/II)



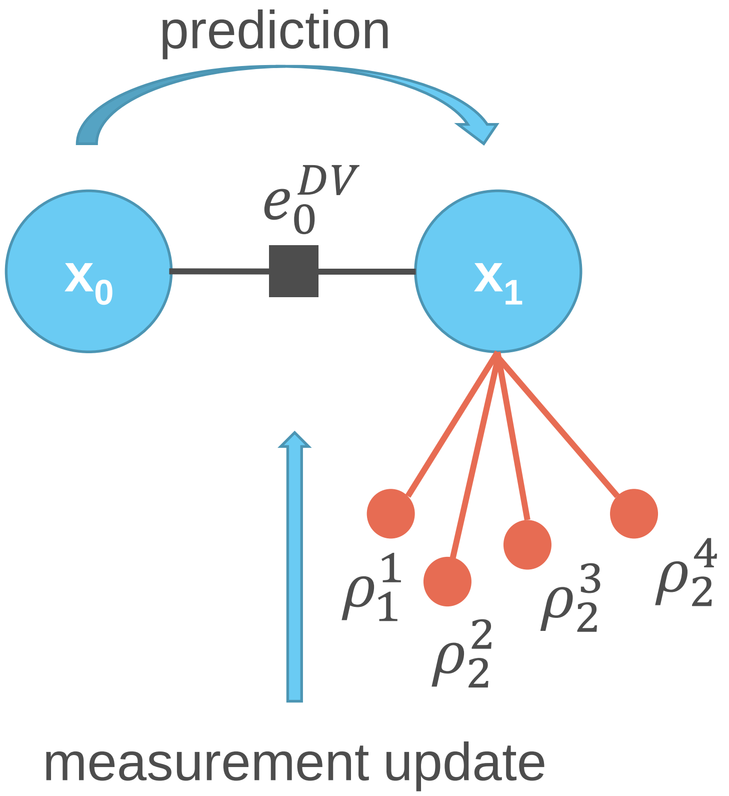
From https://gtsam.org/2020/06/01/factor-graphs.html

- Advanced and flexible models: **improved performance** under difficult conditions.
  E.g., urban navigation

- **Multi-epoch** and **batch processing**

- **Optimization on graphs**: several algorithms available (Gauss-Netwon/gradient descent, Levenberg-Marquardt optimization, SAM...)

- **Message passing** and **error correction** (e.g. LDPC codes on GPS L1C and Beidou B1C)



generalization of the Kalman Filter
(first order Markov property)

Xiwei Wu et al. (2022) “Factor graph based navigation and positioning for control system design: A review, Chinese Journal of Aeronautics

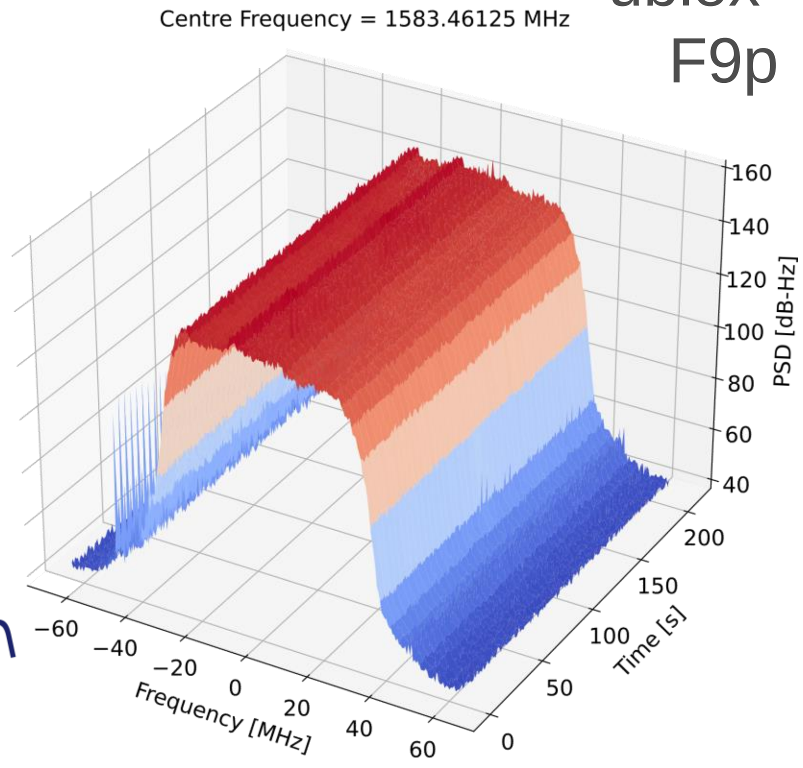
Weisong Wen et al. (2021) "Factor graph optimization for GNSS/INS integration: A comparison with the extended Kalman filter" NAVIGATION: Journal of the Institute of Navigation

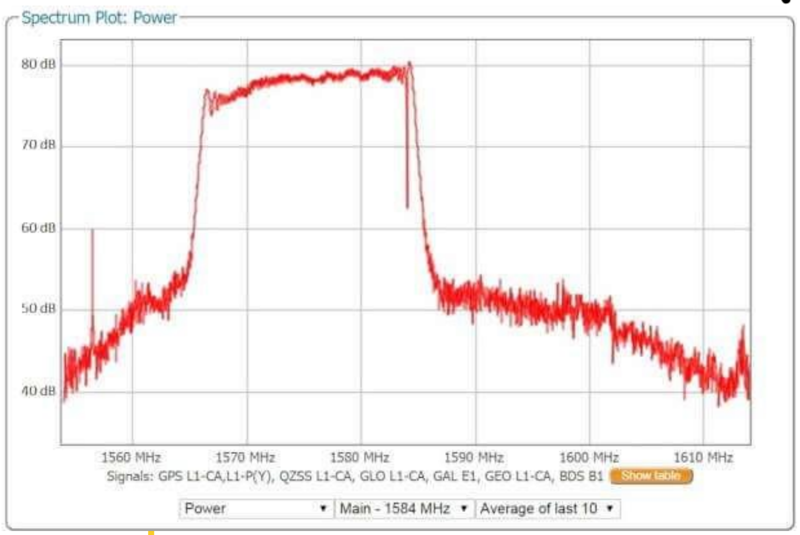
Receiver Resilience

- Interference detection and mitigation: **reality** in many **professional** and **mass-market** receivers

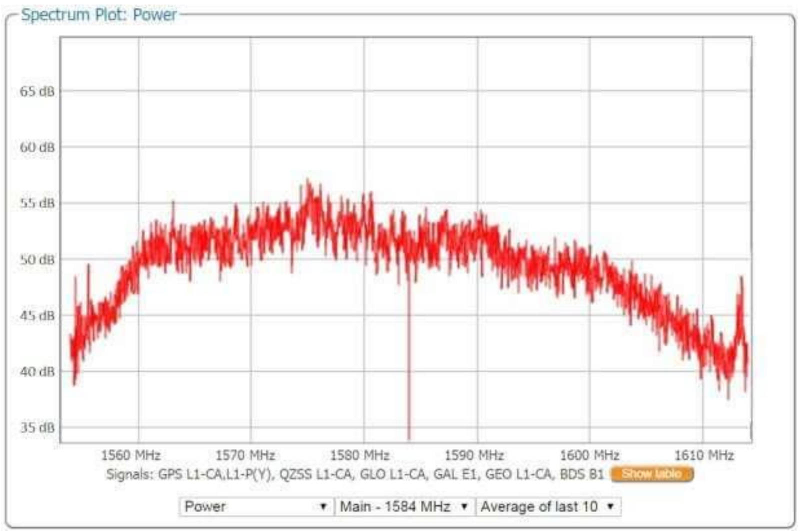
- **Smartphones** (through Android API)

ublox F9p





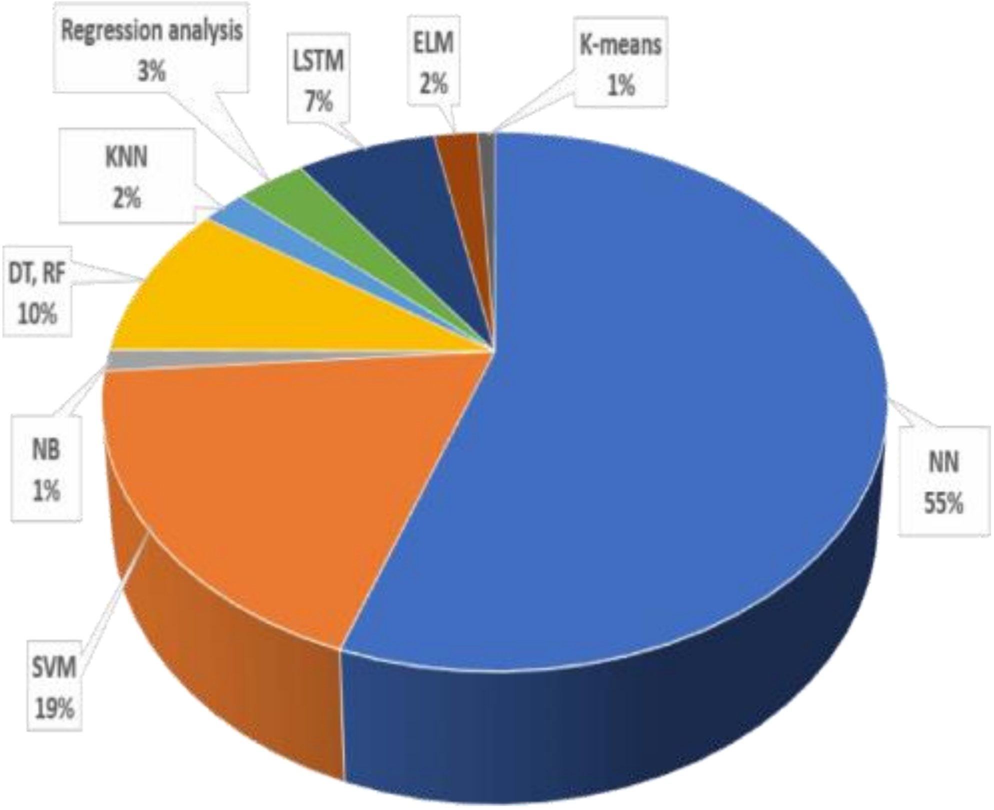
Example from: https://www.septentrio.com/en/learn-more/advanced-positioning-technology/aim-jamming-protection



Machine Learning and Neural Networks

- Processing (acquisition/tracking/position solution) under **non-nominal conditions**: e.g., multipath mitigation, NLOS conditions, urban and indoor navigation
- **Anomaly detection**: e.g., ionospheric disturbances, clock anomalies, interference effects
- **Sensor fusion** and **high-accuracy applications** (see Google competition 2022)
- **Scientific/remote sensing applications**: height estimation (sea, crops, ...), weather prediction, ...

large variety of approaches!



From Siemuri et al. (2022) “A Systematic Review of Machine Learning Techniques for GNSS Use Cases”

ML&ML’s

Maximum Likelihood

- **probabilistic model**
- **no need for training data**
- **observations**: what is observed is the most likely event
- **generally, computationally efficient**
- **model mispecification**: robustness

old school

sexy

Machine Learning

- **no need for a model**
- **training data:** learn the model from the data
- **test data:** classification/estimation based on the learned model
- **computationally intensive**
- **model generalization/overfitting**

ML Ingenuity (Maximum Likelihood)

- The **art** of defining the **most appropriate model**

- ML still **at the hearth** of a GNSS receiver: **acquisition**, standard **tracking**, **MMSE** solutions, **interference mitigation**, ...

- Extensions: non-Gaussian and Bayesian models, MAP estimation, **Kalman filters**, **graphical models**

- **Active field of research:** e.g., Direct Position Estimation, GNSS meta-signals, Factor Graph Optimization

image from https://www.linkedin.com/pulse/6-ai-implementation-challenges-how-overcome-them-pappas-/

ML Ingenuity (Machine Learning)

- Select the **right application** and the **right machine learning technique** or **network**
- Several **toolboxes** already implementing ML algorithms: **how to apply them?** **“Applied machine learning”** e.g., migration from vision/image processing
- **Data curation**: building the **training/testing** datasets
- **Training** and **computational load** (**transfer learning** for GNSS)

image from https://www.linkedin.com/pulse/6-ai-implementation-challenges-how-overcome-them-pappas-/

Long Live the Kalman Filter

Search in the ION GNSS+ 2023 proceedings

- **Still a very trendy tropic!** Either as a main subject or as a comparison term (the standard!)
- **New models:** robustness, outlier detection and exclusion, different processing domains, ...
- **New applications:** tracking of LEO satellite signals, lunar navigation, ...
- **Computationally efficient** and well suited for real-time applications

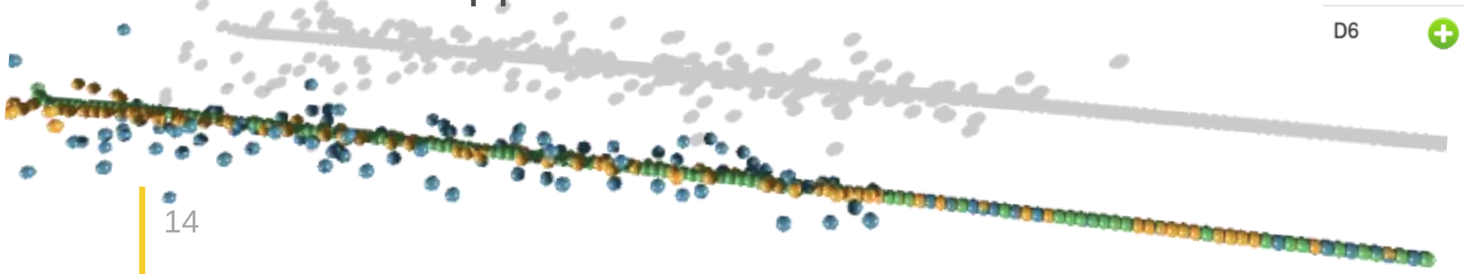
Search Results

RETURN TO SESSION LIST

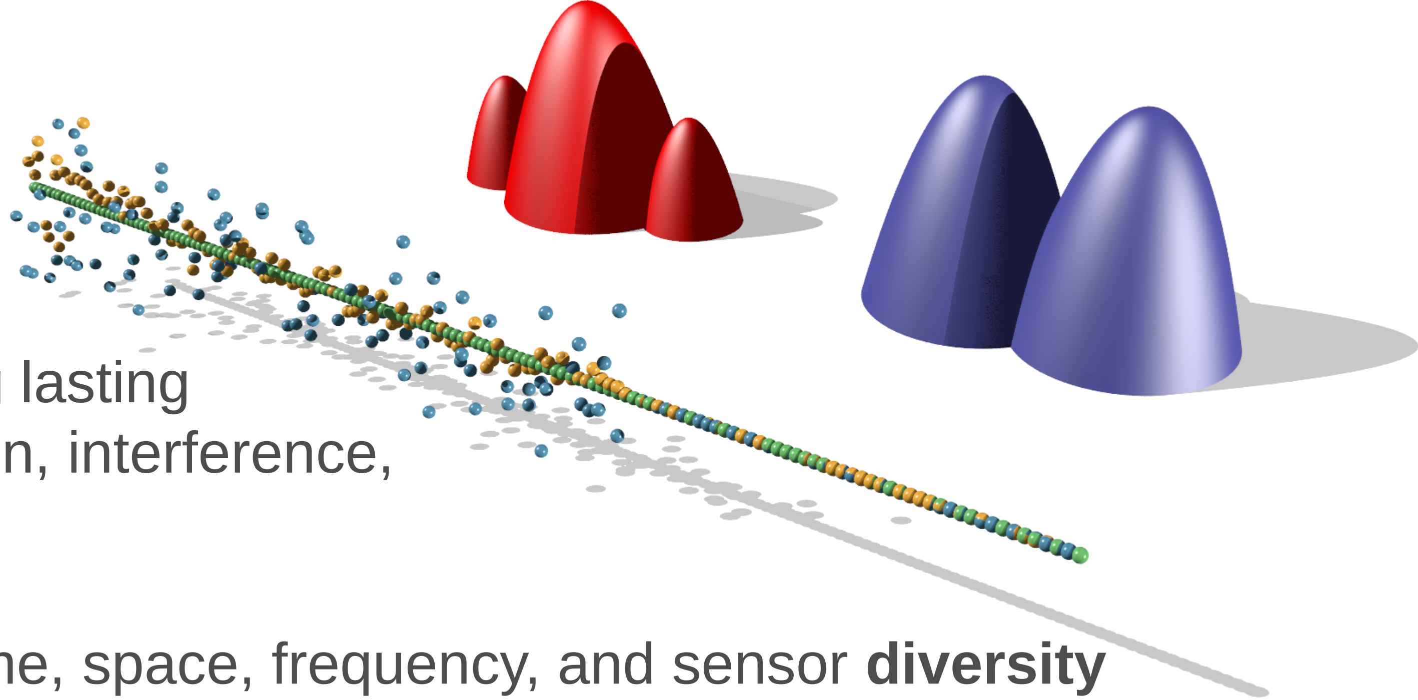
The term “neural network” scored 25

53 papers found.

Session		Title/Author
D1	+	Improving Land Vehicle Navigation: A Study on RIDR and Kalman Filters: *Paulo Ricardo Marques de Araujo, Queen's University; Eslam Mounier, Queen's University, Kingston, and Ain Shams University; Mohamed Elhabiby, Micro Engineering Tech Inc.; Sidney Givigi, Queen's University; Aboelmagd Noureldin, Royal Military College, Kingston, and Queen's University*
D3	+	Mitigating the Impact of Inaccurate State Variance-Covariance Matrix in Kalman filtering for Real-Time PPP with Low-Cost GNSS Devices: *Yan Zhang, Yang Jiang, Yang Gao, Department of Geomatics Engineering, University of Calgary*
F3	+	Analysis of PNT Algorithms and Related Performance for Lunar Navigation Service Users: *Filippo Rodriguez, Alessio Martinelli, Luca Spazzacampagna, Carlo Albanese, Telespazio SpA; Giovanni B. Palmerini, Marco Sabatini, Scuola di Ingegneria Aerospaziale, Sapienza Universita di Roma*
E1	+	Joint Doppler and Azimuth DOA Tracking for Positioning with Iridium LEO Satellites: *Shaghayegh Shahcheraghi, Forough Gourabi, Mohammad Neinavaie, Zak (Zaher) M. Kassas, The Ohio State University*
D4	+	GNSS/INS Positioning in Dense Urban Environment with Adaptive Choice of Process Noise Covariance Based on Satellite Geometry: *Yoji Takayama, FURUNO ELECTRIC CO., Ltd.; Takateru Urakubo, Hisashi Tamaki, Kobe University*
D6	+	GNSS Satellite Fault Detection and Exclusion for Integrated GNSS/INS Systems: *Birendra Kujur, Samer Khanafseh, and Boris Pervan, Illinois Institute of Technology*



Putting All Together



- **Advanced techniques** to solve long lasting problems (multipath, urban navigation, interference, ...)

- Exploit all **information available**: time, space, frequency, and sensor **diversity** Build the most appropriate model

- The different techniques can be **combined**: e.g., **meta-signal direct position estimation**

- **Theory** is nice but it is **only the first step**: **implementation complexity**, **computational load**, **real-time capabilities**, ... important factors determining actual algorithm uptake

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Thank you

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