On-board ODTS for Large Constellations of Satellites by means of a Distributed EKF and ISL Scheduling Optimization Algorithms

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Contents

Introduction

Introduction

Traditional satellite constellations heavily depend on frequent communications with globally distributed ground stations for monitoring, orbit estimation and time synchronization.

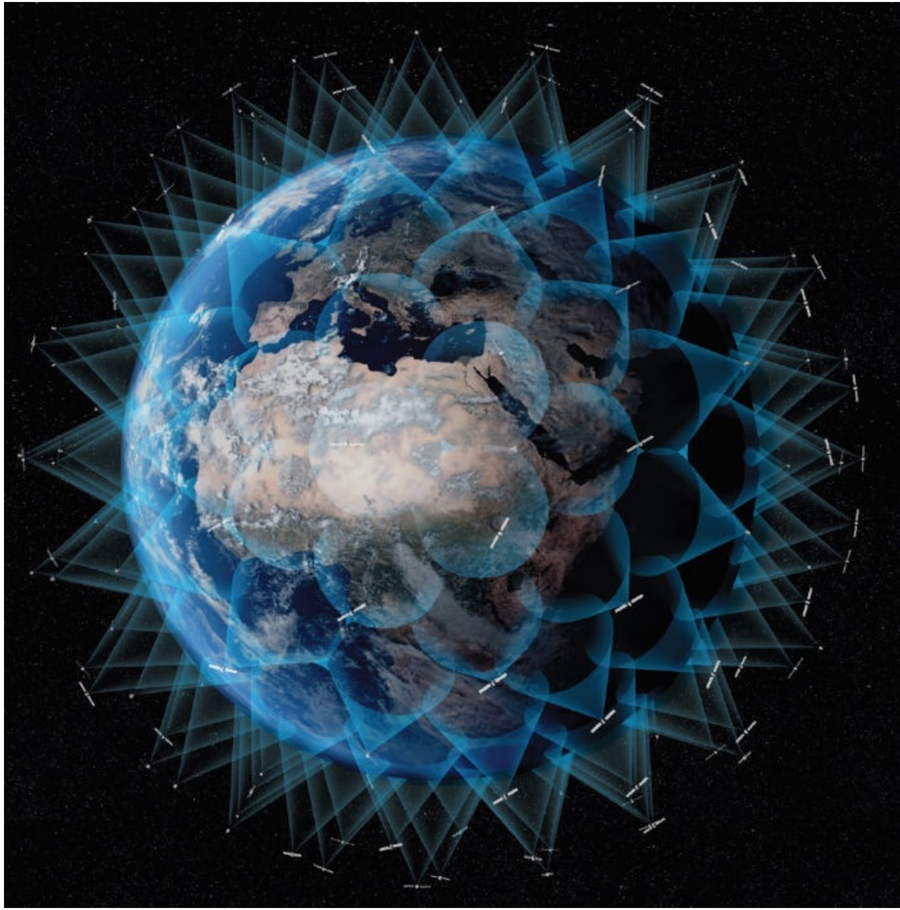
New systems such as Galileo Second Generation (G2G) or BeiDou (BDS-3) introduce Inter-Satellite Links (ISLs)

↓

Capability to perform communications and ranging measurements between satellites, minimizing the dependency on ground stations

Objective: increase the **autonomy** of satellite constellations

- **Distribution of the ODTS process**
- **Optimization of the ISL scheduling**



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TaRDIS Project

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TaRDIS

Trustworthy and **R**esilient **D**ecentralized **I**ntelligence for Edge **S**ystems

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Activity timeline

Baseline

- Use case definition
- Development of a centralized EKF and a random ISL scheduling generator
- Improvement nº1: **Distributed EKF**
- Improvement nº2: **Optimized ISL Scheduling**

Development and integration of TaRDIS

- Development and training of a **Federated Learning model** for ODTS
- Development and training of a **Reinforcement Learning model** for ISL Scheduling optimization
- Integration of **TaRDIS** tools within the baseline software

Use case definition

1 **Constellation configuration:**
- 170 satellites
- 10 uniformly distributed orbital planes
- At least 4 satellites always in view from the Earth surface

2 **Orbit characteristics:**
- Sun-Synchronous (SSO)
- Altitude: 1200 km
- Inclination: 100.4º

3 **Satellite communications:**
- 2 ISL antennas per satellite
- 1 antenna for links with GS
- 4 GS around the globe

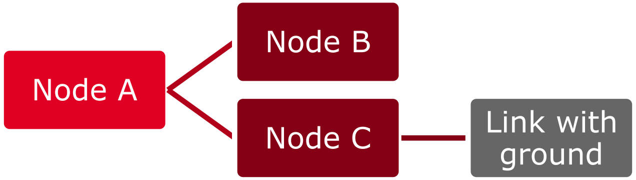
4 **Time Division Multiple Access** scheme:
- Measurements and communications are scheduled in timeslots of 10s
- Each satellite can establish up to 2 ISLs and 1 link Earth every timeslot

Distributed EKF

Distributed EKF

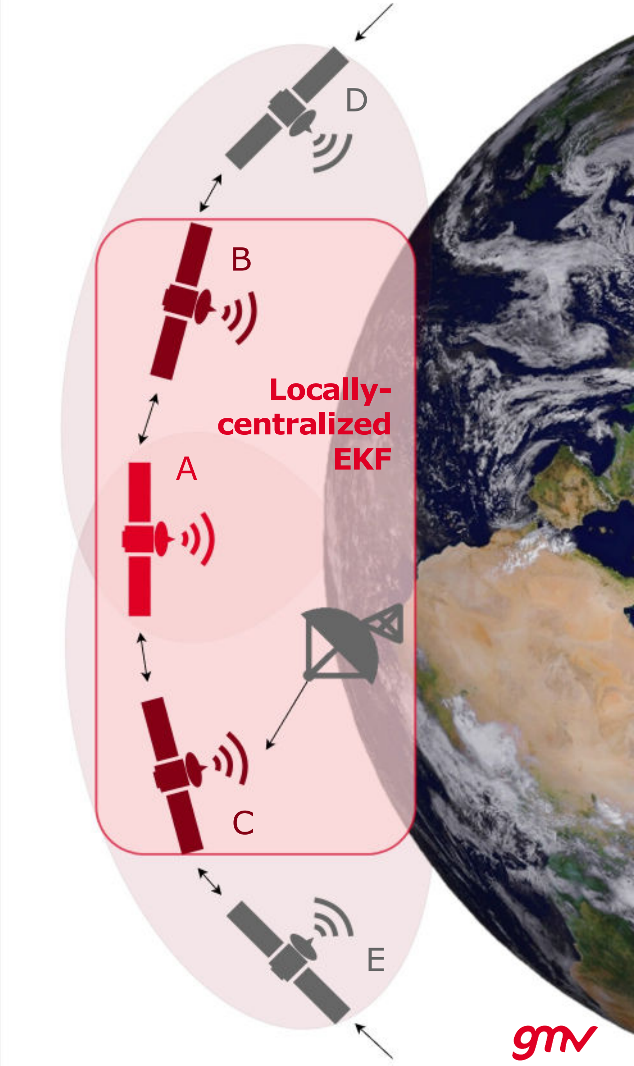
Each satellite estimates its own state vector with a **locally-centralized EKF** based on observables (pseudorange and Doppler) from:

- Direct links (ISL and with GS)
- Links between adjacent nodes and GS



With this configuration:

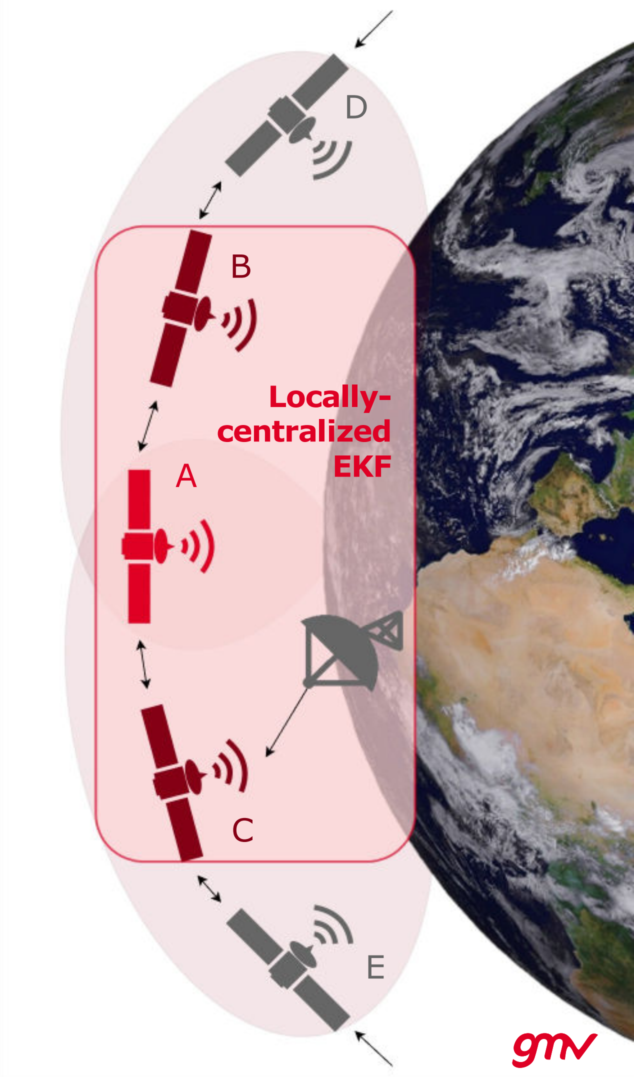
- Covariance from satellites **B** and **C** affects satellite **A** state vector calculation
- Reduction of the state vector uncertainty provided by links with ground **propagates effectively** through the constellation



Distributed EKF

This approach allows to:

- Decentralize the ODTS computation for each satellite → **autonomy**
- Reduce the **computational load**
- Include the uncertainty of all the involved satellites in the measurement covariance calculation → **resilience**
- Avoid an iterative process to achieve rapid convergence: **lower latency in data transfer between satellites**.



ISL Scheduling

ISL Scheduling

Visibility Matrix → Anchors definition → Grouping of invisible satellites → Anchors Scheduling → Minimum PDOP Scheduling → Scheduling Completion

Definition of **superframe** (set of timeslots)

Obtention of all **visibilities** through the superframe (ISL and GS-sat), considering:

- Earth occultation
- Maximum distance

Definition of **anchors**:

- Satellites that have visibility with GS through the entire superframe
- They are the only satellites allowed to link with ground

Links with ground **reduce the uncertainty** of the state vector considerably

ISL Scheduling

Visibility Matrix → Anchors definition → Grouping of invisible satellites → Anchors Scheduling → Minimum PDOP Scheduling → Scheduling Completion

Invisible satellites are divided into groups: each timeslot, only **one group** can link with anchors

To avoid conflict, invisible satellites are grouped based on **visibility correlation minimization**

- Satellites within a group must have the most diverse visibilities
- A Discrete Differential Evolution (DDE) approach is followed

Each timeslot, links between anchors and invisible satellites from one group are orchestrated

Priority is given to **new** links

Once an invisible satellite has linked with all visible anchors, priority is given to the links that occurred **longer ago**

ISL Scheduling

Visibility Matrix → Anchors definition → Grouping of invisible satellites → Anchors Scheduling → Minimum PDOP Scheduling → Scheduling Completion

For each satellite:

- **four links** are defined with a geometry as contrasting as possible
- Link availability is checked, and its scheduling at the beginning of the superframe is prioritized
- It is ensured that every satellite receives information from **diverse directions**, reducing the dilution of precision

Final step: fill the link gaps. Several criteria are considered in a weighted approach:

- Priority is given to **new links** that did not occur in the past
- Priority is given to **nearer satellites**, therefore links with lower noise
- Interest in establishing a chain that allows **interconnectivity** of all the constellation

Results

Results

Figures in this section show the 3D position error between the output of the EKF (estimated navigation solution) and the *real world* data (simulated reference truth considering all significant orbital perturbations).

Some considerations about the simulations performed:

- Timeslot duration of 10s
- Simulation time of 110 min, statistics are taken for the last 25% of the simulation period
- Orbit propagator in EKF based on reduced dynamic orbit determination up to J2 perturbations
- Thermal noise model used to simulate ISL measurements including realistic ranging performances
- Representative measurements with ground stations including atmospheric effects

Optimized Scheduling vs **Random Scheduling**

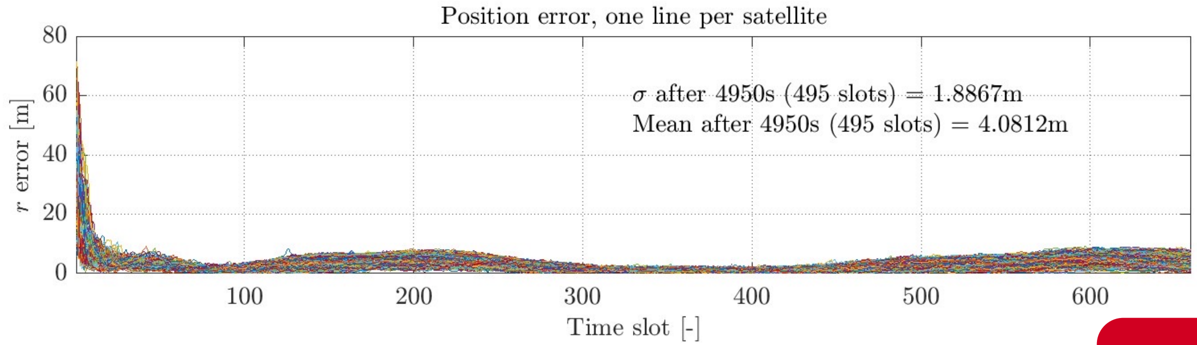
Following the approach presented in previous slides

Anchors are still defined, but all ISLs are orchestrated in a random fashion only ensuring visibility

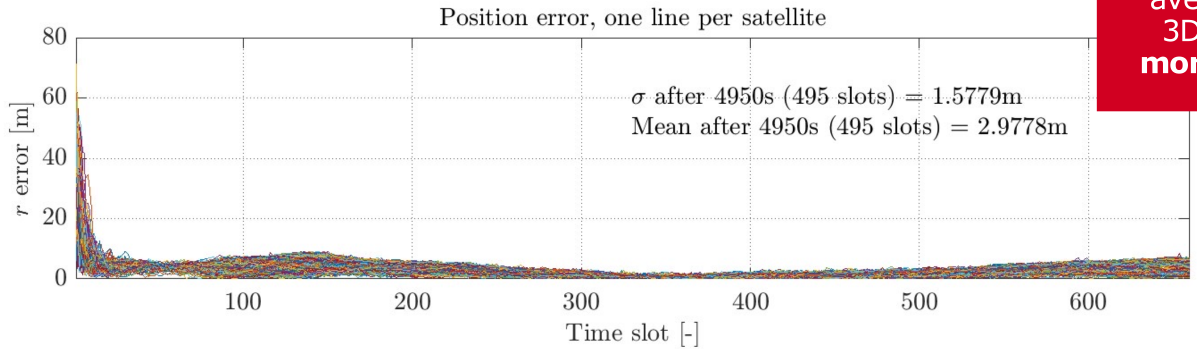
Results

Initial position uncertainty of 20m (1-sigma):

Random Scheduling



Optimized Scheduling

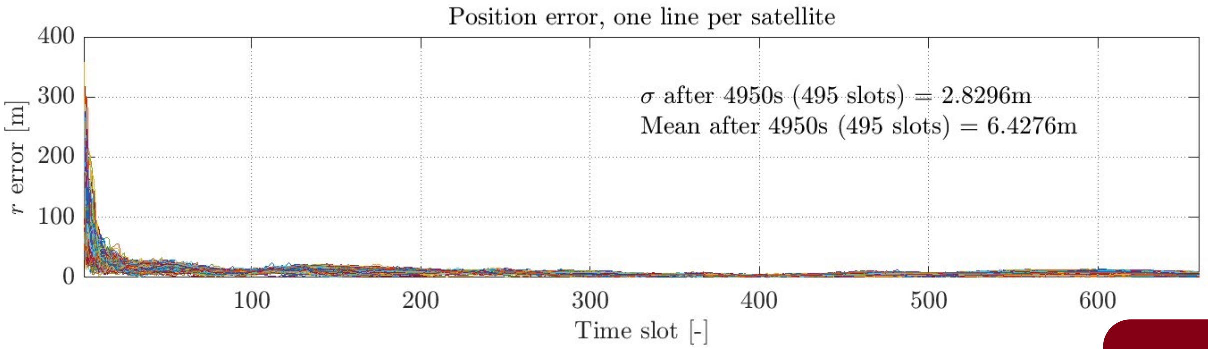


Reduction of the average error in 3D position by **more than 25%**

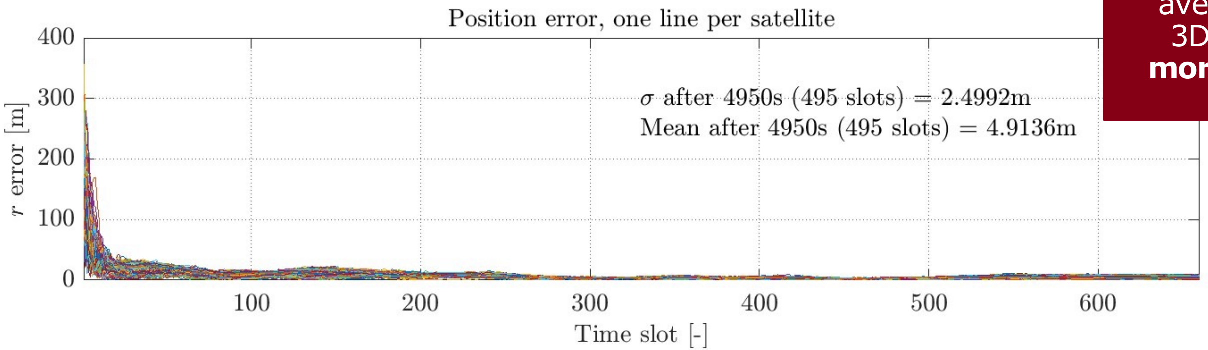
Results

Increasing it now to 100m (1-sigma):

Random Scheduling



Optimized Scheduling



Reduction of the average error in 3D position by **more than 23%**

TaRDIS vision

Machine Learning

Federated Learning for decentralized ODTS

- In development
- Goal is to replace/assist on-board models with lightweight techniques that enhance accuracy and promote decentralization
- Application of Physics-Informed Neural Networks (PINNs) to ensure model predictions are consistent with the physical constraints of orbital mechanics

Reinforcement Learning for ISL Scheduling

- Still to be developed
- Goal is to implement on-board re-scheduling capability to prevent communication gaps caused by potential failures
- Trade-off with the performance achieved by the proposed algorithm

Thank you

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