τau - A formation of CubeSats for GNSS-Reflectometry Earth Observation

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Outline

- Theoretical Introduction
- University of Luxembourg ISM GNSS-R **Mission τau Design Overview**
  - Mission **requirements and constraints**
  - MATLAB **Astrodynamics model overview**
  - **System overview**
- UCLouvain's Formation Flight Model Overview
  - Assumptions
  - Illustration
- **Satellite distribution changes**
- **Position uncertainties**
- **Frequency changes**
- Conclusion
- Future Work

Theoretical Introduction

Theoretical Introduction

GNSS-R Overview

- **GNSS Reflectometry** (GNSS-R) is a **remote sensing technique** that captures **geophysical properties of the Earth's surface** by analyzing **GNSS signals reflected from it.**
- The **specular point** is the point on the **Earth's surface** where the **reflected GNSS signal is the strongest, where incident and reflected angles are equal.**
- Lies at the center of the **glistening zone,** the **area** over which the signal is **reflected toward the receiver.**
- **All that is needed is a receiver, perfectly suited for CubeSat.**

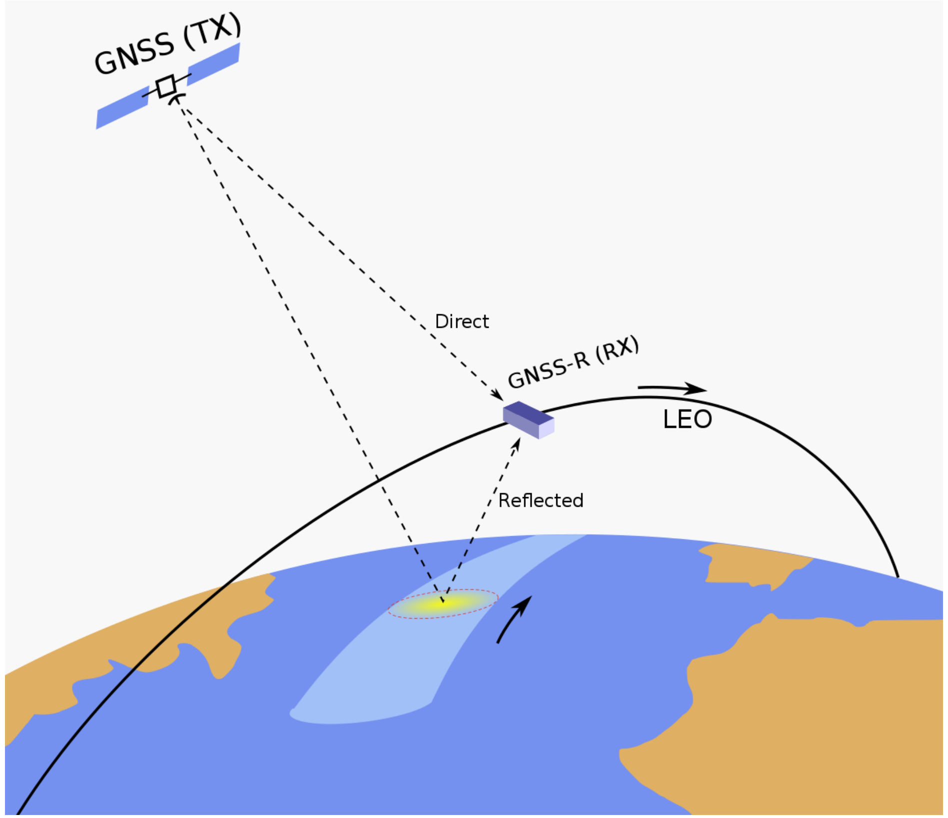

Figure 1: GNSS-R visualization

Image credit: https://en.wikipedia.org/wiki/GNSS_reflectometry#/media/File:GNSS-R_system_diagram.svg

Theoretical Introduction

CubeSat formation flight: Resolution

- CubeSats deployed in formation **would use beamforming**, a technique that focuses signals from an array of antennas **towards specific directions.**

- This creates a main lobe, **directly pointing towards the Earth's observation point.**

- **A coordinated satellite formation reduces the beamwidth**, yields a **higher resolution.**

- More efficient, cost-effective, and easier to deploy **compared to using a single, larger antenna.**

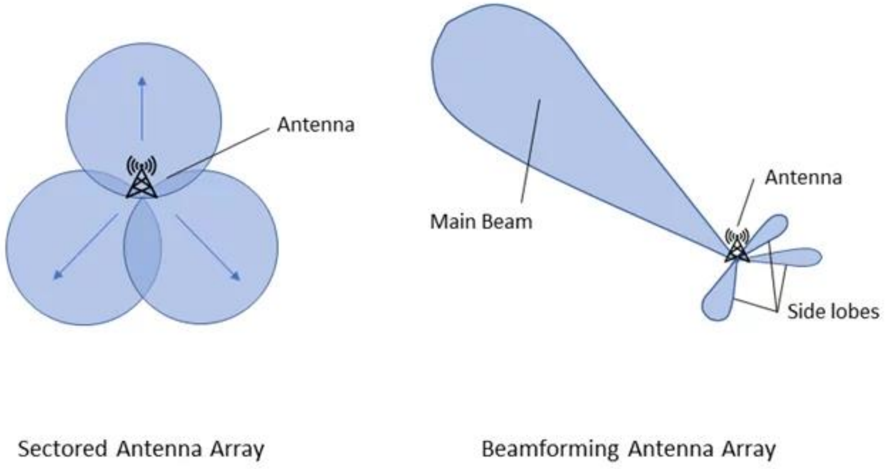

Figure 2: Beamforming

Image credit: https://verkotan.com/2021/beamforming-antennas-how-they-work-and-are-tested/

Theoretical Introduction

Beamforming byproducts: Side lobes

- Side lobes are unintentionally generated areas of signal reception from directions outside the main lobes. **Byproducts of the beamforming process.**

- Side lobes **can cause interferences** in the glistening zone, **crucial to manage their presence effectively.**

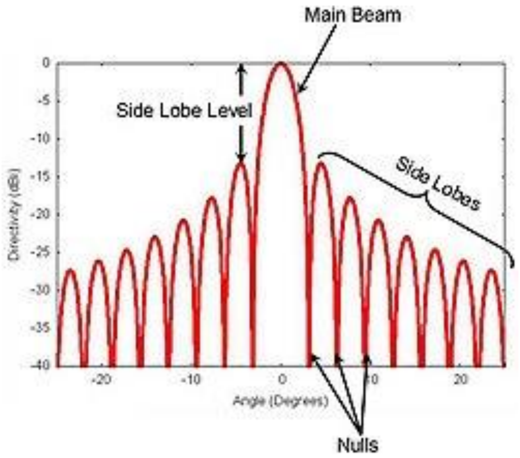

Figure 3: Main lobes and side lobes

- To **minimize interferences** and maintain signal clarity, **sidelobes should be kept low enough.** This ensures that the main beam remains focused and effective for high-resolution observation.

Image credit: https://en.wikipedia.org/wiki/Sidelobes#/media/File:Typical_Antenna_Pattern.jpg

τau Mission Design

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Mission Design

Requirements and constraints

- Project divided in teams, **Astrodynamics**, **Communication Subsystem**, **Power Subsystem** and **P/L.**
- The following **mission requirements and constraints** were given.

ID	Mission Requirements
MR 01	Remote sensing data of at least 1 km resolution shall be obtained
MR 02	Measurements shall be between latitudes -80° and +80°
MR 03	At least 3x8640 data points shall be measured over land mass per day
MR 04	Data shall be provided to users within one week
MR 05	Data shall be provided for a duration of 5 years

Table 1: Mission Requirements

ID	Mission Constraints
MC 01	A 20 satellite formation in a circular geometry shall be used
MC 02	Satellite formation shall be a 2U CubeSat with at least 2U deployable solar panels
MC 03	Altitude shall be 450 km < altitude < 550 km
MC 04	Orbit shall be: SSO 10:30 LTAN/LTDN
MC 05	Measurement technique shall be GNSS-reflectometry

Table 2: Mission Assumptions

Mission Design

Phases 0/A: Astrodynamics

- Astrodynamics model made through **MATLAB Aerospace toolbox.**
- Formation is considered as **a single point,** all perturbations are neglected.
- **Completed with STK** to mitigate **MATLAB limitations: Eclipse Time & Solar AER**
- Overall, model **outputs data for system and subsystem design**
- For P/L, need **specular point positions** as a **function of the inputted orbits**

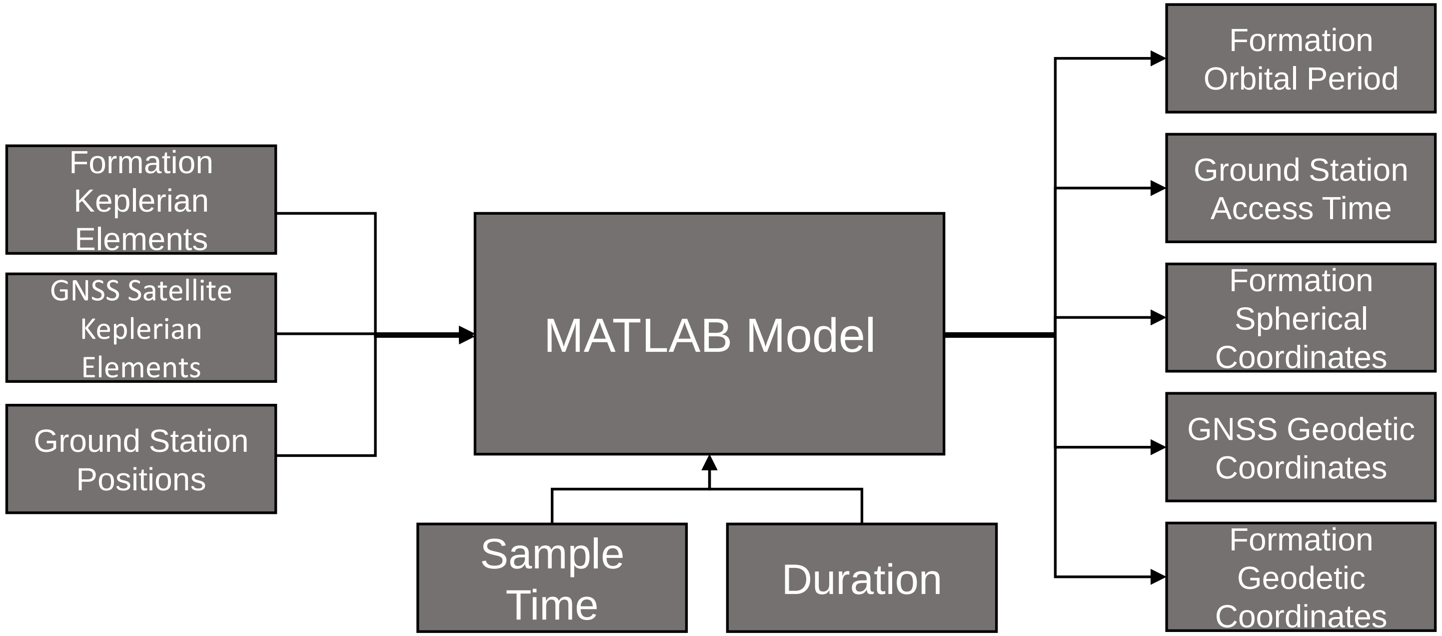

Figure 4: Astrodynamics Model Overview

Specular Point Determination Model

Phases 0/A: Specular point determination via the Minimum Path Length Method

- ➢ Minimize the sum of distances from the GNSS satellite to the specular point and from the specular point to the formation.
- ➢ Ensure the specular point lies on the Earth's surface modeled by the WGS84 ellipsoid.
- ➢ Optimization within the Earth's surface constraint.
- ➢ Validate physical reality of the specular point through geometric checks against the Earth's tangent plane.
- ➢ See ref [2] for precise derivation.

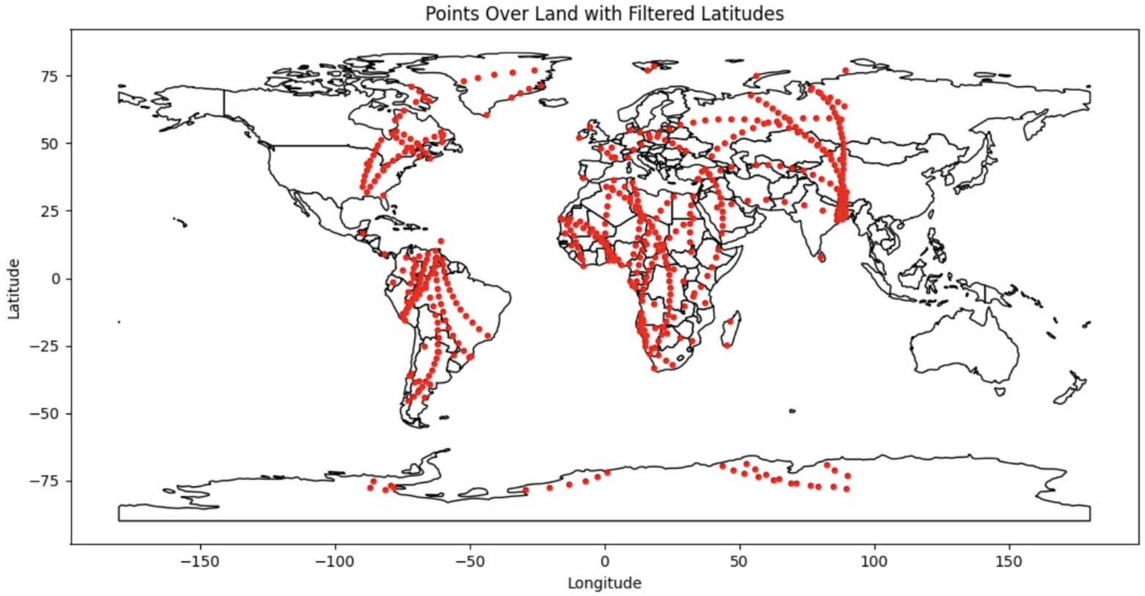

Figure 5: Specular points over land for GSAT0101, altitude 450km.

CubeSat Main Subsystems

Phase B1: System preliminary design

- Subsystems choice based on **astrodynamics model outputs**, **mission requirements and constraints**
- P/L:
  - **RHCP antenna for direct signal, zenith pointing , LHCP antenna for reflected signal nadir pointing, both GCA01- Compact GNSS Active Patch Antenna**
  - **Space GNSS Receiver SGR-Ligo**
  - **ISIS On-Board Computer**
- COM:
  - **Endurosat S-Band Transceiver**
  - **Monopole S-Band Antenna NanoCom AM2150-O**
  - **S-Band diplexer DSA-FM made by WiRan**
- POW:
  - **Li-ion Batteries**
  - **GaAs EXA DMSA/1 Arrays**
  - **Spacemanic model SM-PSUAMUN EPS**

Conclusion

Mission τau Phases 0/A/B1

- Mission design **aligns with current EO research and is physically feasible**
- Covers **design phases up to early phase B**, with **subsystem preliminary design**
- **Satellite formation shape and number requires further analysis**

Problem Statement

Scope of the project

- **Resolution** and **Side Lobes Amplitude** are the two main **Key Performance Indicators** (KPIs) for assessing **the efficacy** of the satellite formation.

- UCLouvain colleagues built a model and compared formations based on a **central chief satellite** and **deputy satellites. Candidate is a 4 arms spiral formation.**

- **Based on those KPIs and this model:**

- Are there opportunities to **refine the candidate formations** to further **improve resolution** and to **reduce side lobes amplitude**?

- How **positional uncertainties** affect the resolution and side lobes amplitude?

- How **frequency changes** affect the resolution and side lobes amplitude?

UCLouvain Model Overview

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Model Assumptions

Assumptions

- The model was built with **the following assumptions:**

ID	Assumption
MA 01	Earth shall be considered as a sphere of radius 6371 km
MA 02	The glistening zone shall be considered as a disk of 5km radius
MA 03	All atmospheric disturbances on electromagnetic waves shall be neglected
MA 04	The specular point position was determined through the Minimum Path Length Method, see ref. [2]
MA 05	The chief body and the GNSS satellite shall be considered in a perfect circular orbit around the Earth
MA 06	All astrodynamics disturbances shall be neglected

Table 3: Model assumptions

Model Illustration

Satellites' orbit

- In the model, the following orbits have been chosen

Keplerian Elements	a (m)	ε	i (°)	Ω (°)	ω (°)
CubeSat Chief Body	6 771 000 (400km altitude)	0	90	0	0
GNSS Satellite	29 593 000 (23 222km altitude)	0	56°	0	0

Table 4: Satellite's Keplerian Elements

- From chief satellite, **Clohessy-Wiltshire equations** used to determine **deputy satellites positions**, which is **what induces ellipses**

Model Illustration

Visualization

- KPIs also vary over the orbit **due to formation's static inclination**
- The KPIs changes will be observed fixed in time to ensure the **implication of the intended changes are the only thing seen**
- Final set-up overview:

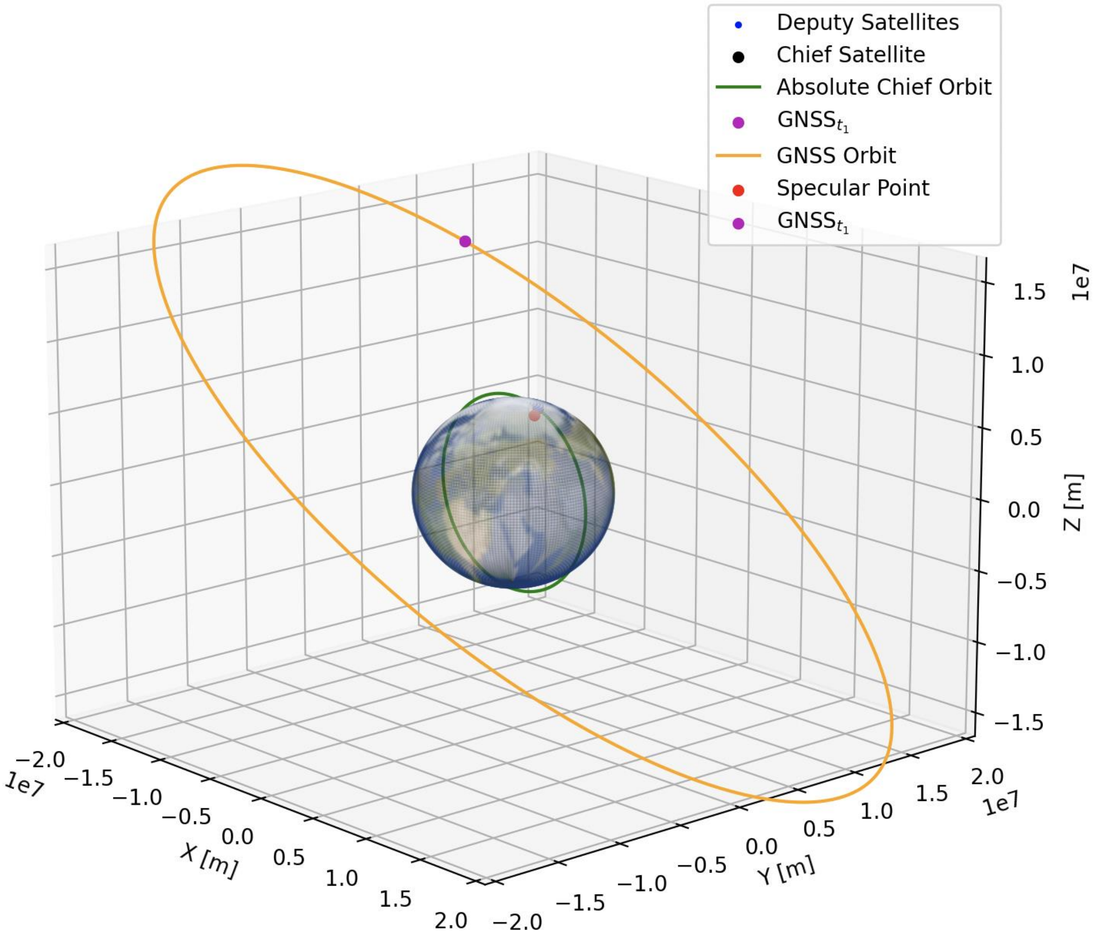

Figure 6: Model set-up overview

Satellite distribution changes

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Satellite Distribution Changes

Initial model flight formation

- ➢ Model initial satellite distribution: **a 4-arm spiral formation spread across concentric ellipsoids.**
- ➢ Outer semi minor axis radius constrained to 35m in this configuration.
- ➢ Inner semi minor axis radii **adjusted** to meet KPI requirements from UCLouvain project (R = 1km, side lobes -10dB).
- ➢ **Initial model's flight formation**

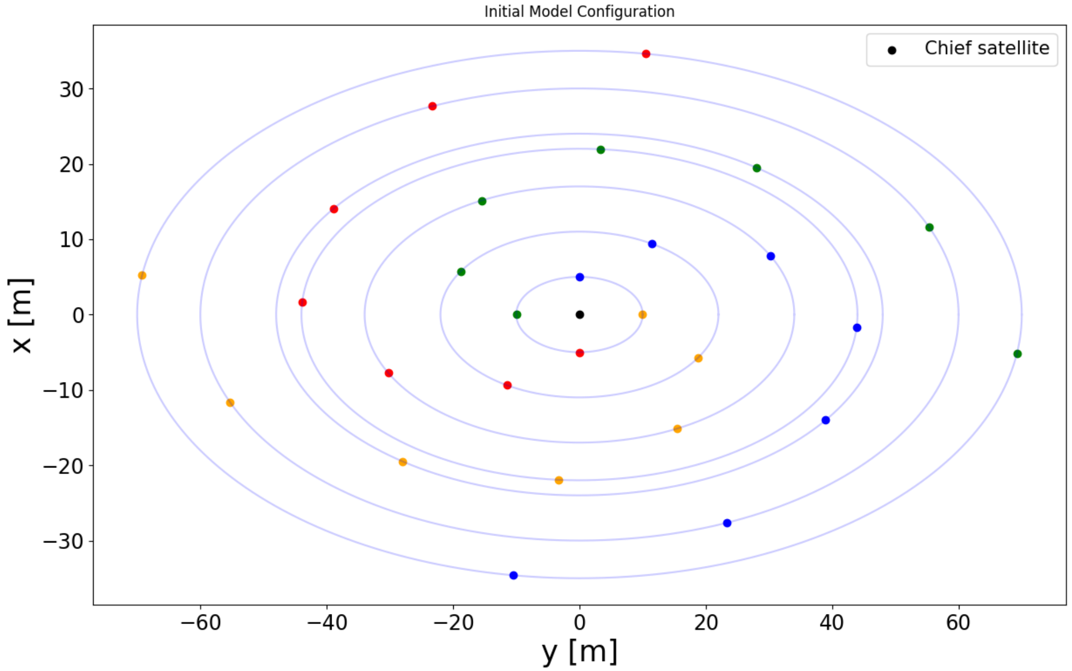

Figure 7: Initial Model Configuration

- ➢ **Model's initial frequency fixed at f = 1498.962 MHz**
- ➢ **No position uncertainties**

Satellite Distribution Changes

Initial model flight's formation KPIs

- The previous configuration leads to the following **radiation pattern, with side lobes in the glistening zone around -6dB**
- **And a resolution $R_{Initial}$ ≈ 0.92 km.**

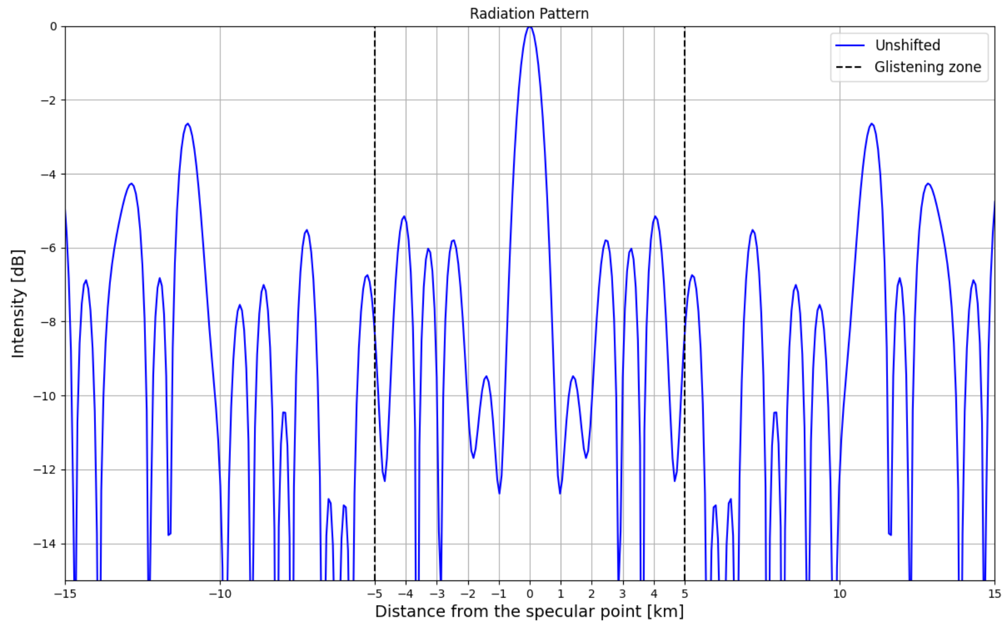

Figure 8: Initial Radiation Pattern

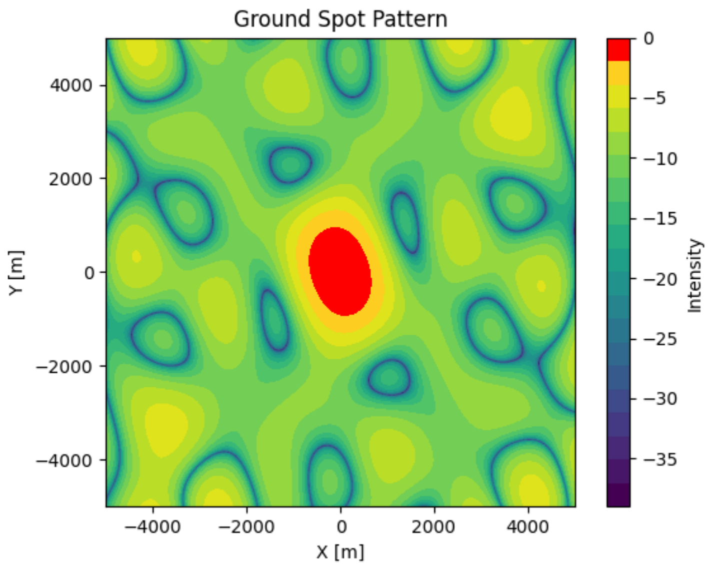

Figure 9: Initial ground spot

- **Ground spots** visualize the power distribution on **Earth's surface.**
- **Aids in assessing the array's directional signal reach.**

Satellite Distribution Changes

Outer radius increase impact

- Explore alternative configurations; **what if the outer radius is not constrained to 35m?**

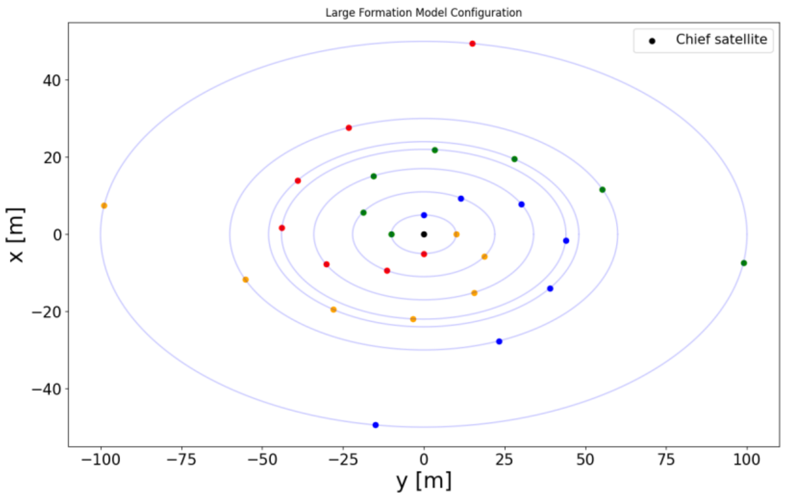

Figure 10: Large formation configuration

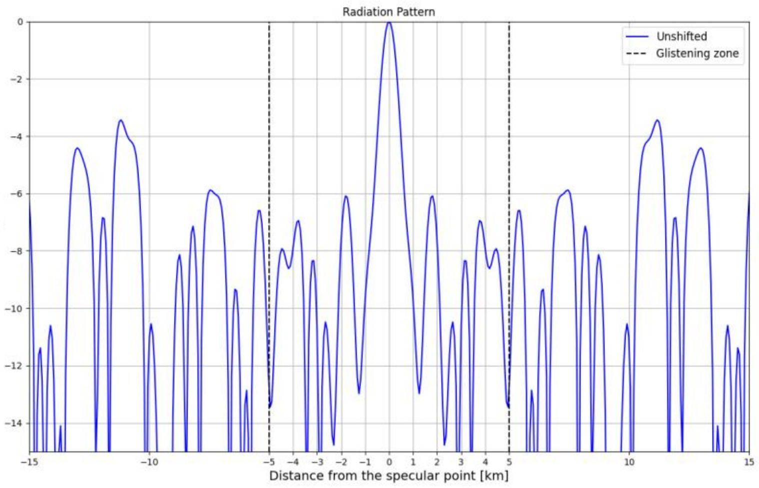

Figure 11: Large formation radiation pattern

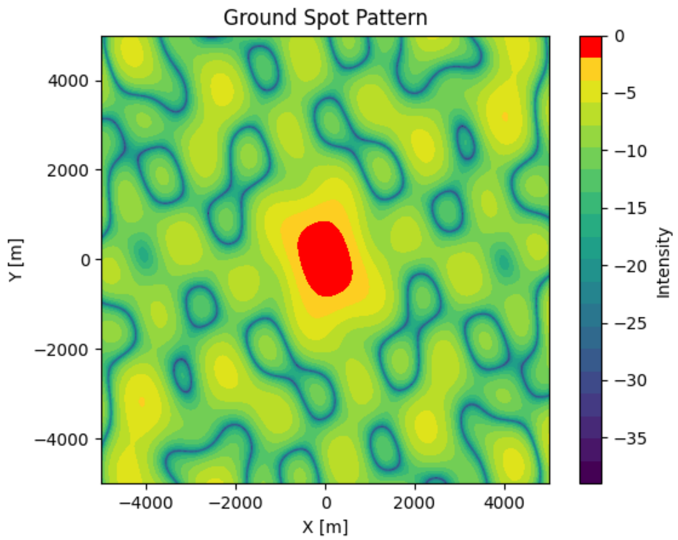

Figure 12: Large formation ground spot

- The large formation configuration leads to **side lobes in the glistening zone still around -6dB**
- **And a resolution R_{Large} ≈ 0.83 km, an enhancement of 9.34% compared to $R_{initial}$.**

Satellite Distribution Changes

Conclusion

- Adjusting **the formation's outer radius could yield better resolution,** **room for improvement.**
- Insights from my University of Luxembourg colleagues at **SIGCOM lab** indicate that a **Gaussian distribution of 5G satellites in a linear array can improve resolution.**
- However those distributions **don’t account for positional uncertainties**.
- Investigate how position uncertainties **impact KPIs.**

Position uncertainties

Position Uncertainties

Initial model flight formation

- ➢ Return to the **initial formation flight** configuration
- ➢ Still at the same **f = 1498.962 MHz**

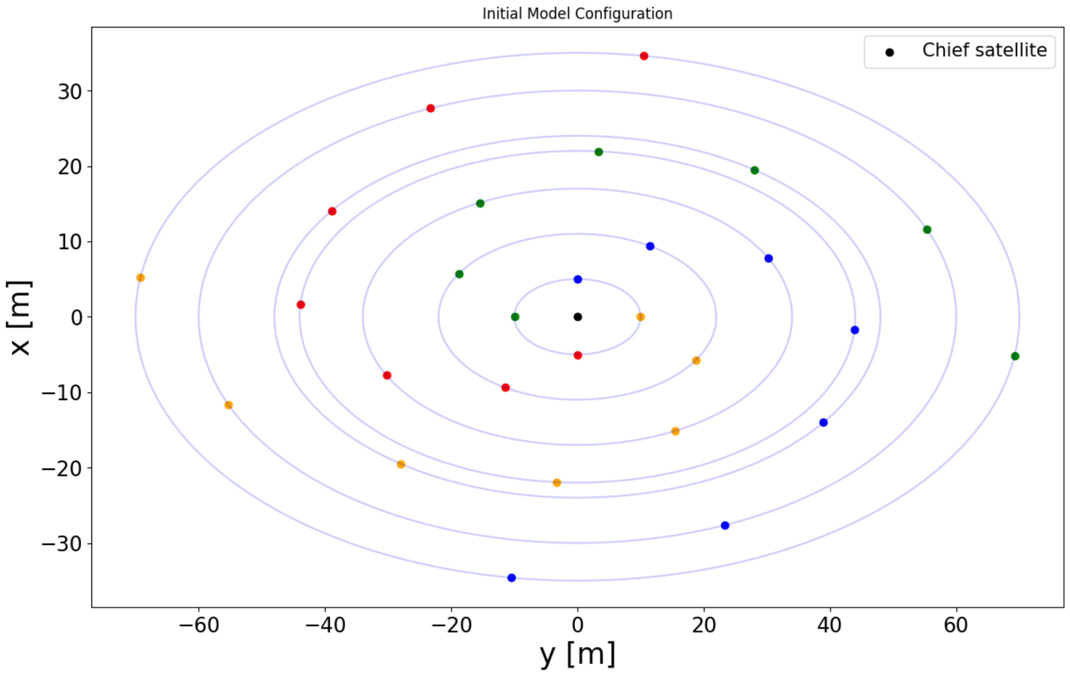

Figure 13: Initial Model Configuration

Position Uncertainties

Minimum achievable error implication on the KPIs

- **0.7m** the **minimum achievable** error according to ref [4].
- Implies an error shift of **Δ = ± 0.35m for each satellite positions**
- **Direct implication on the KPI**

- Error is **randomly generated**
- KPIs are computed **N = 100 times,** then **averaged**

- **Unshifted Resolution: 0.9158229277 km**
- **Averaged shifted resolution: 0.9152861423 km**
- **Relative difference of 0.0586%, negligible!**

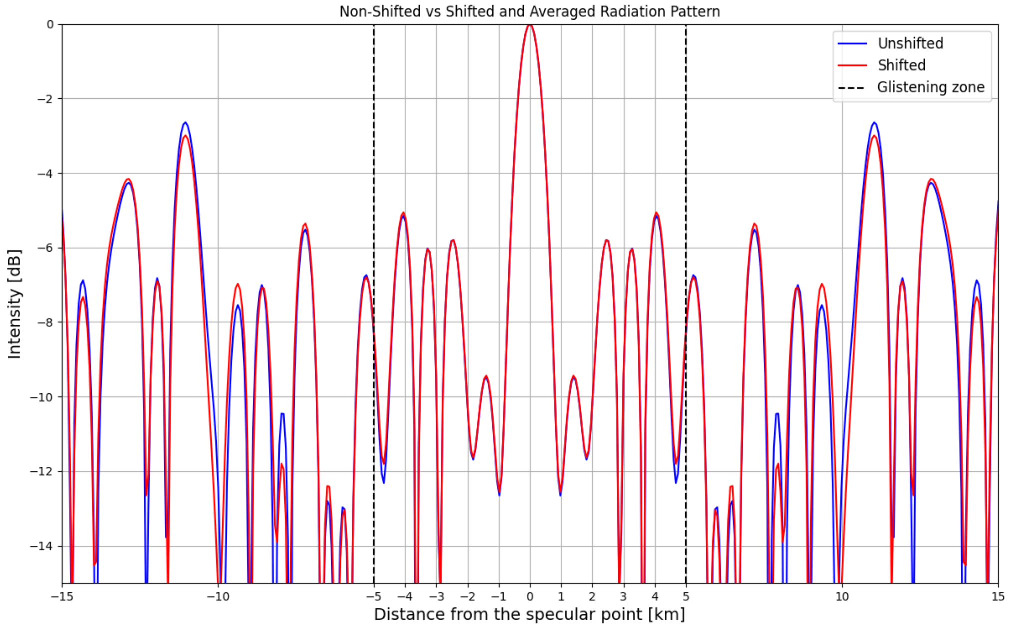

Figure 14: Shifted and Non-Shifted Radiation Pattern

- **Side lobes are approximately around -6dB**
- **No notable variations**

Position Uncertainties

Minimum achievable error implication on the ground spots

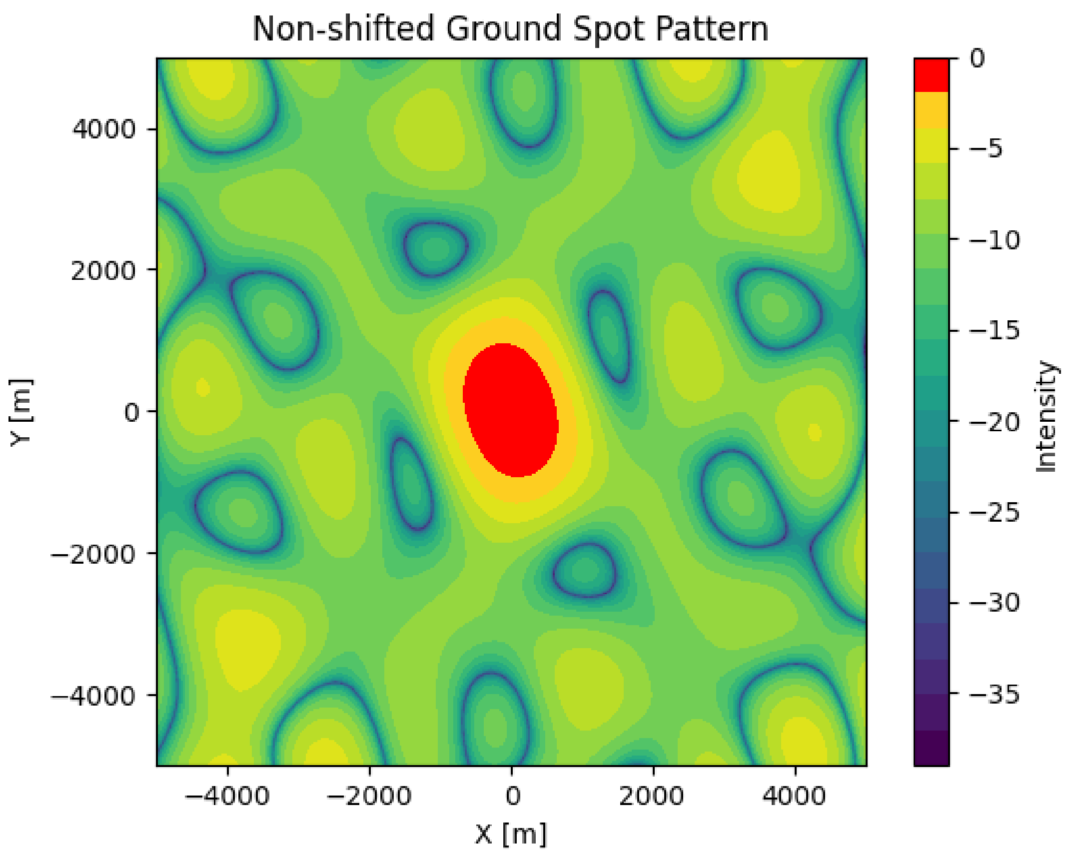

Figure 15: Non-shifted Ground Spot

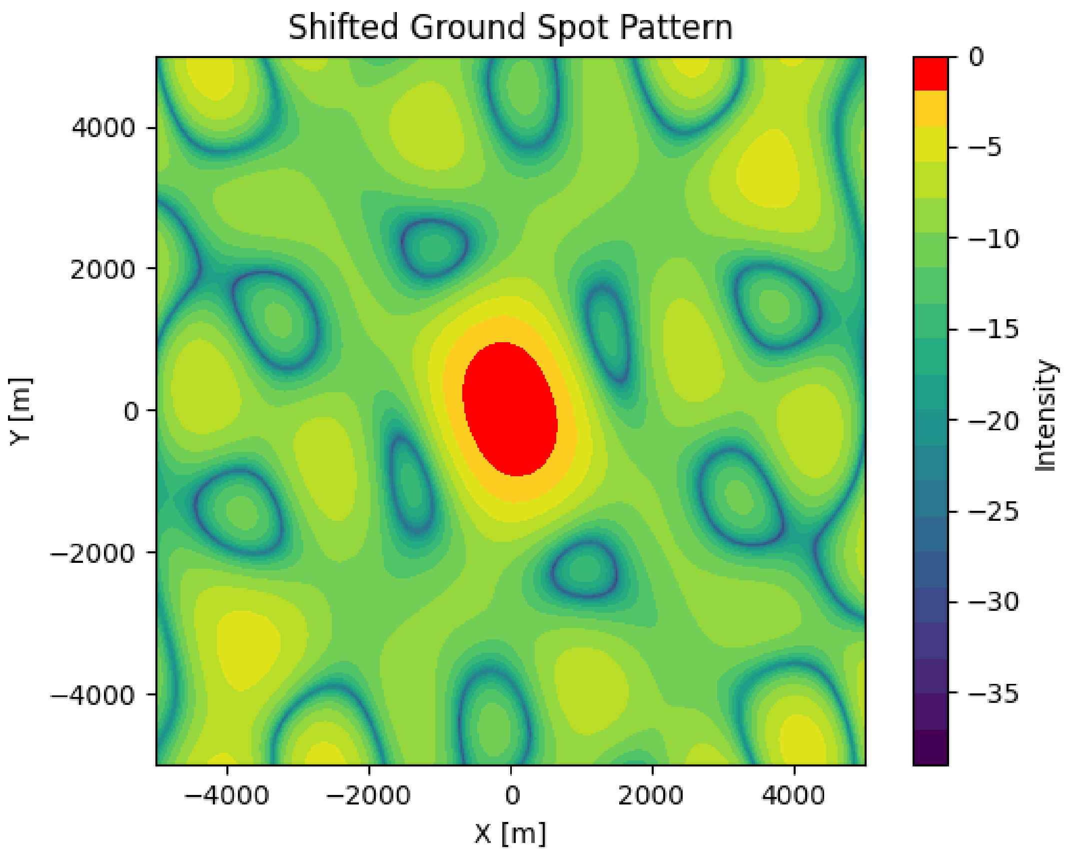

Figure 16: Shifted Ground Spot

- **No notable changes**

Position Uncertainties

Growing error implication on the KPIs

- **One can be skeptical about the achievability of .7m precision.**
- Precision within a **few meters** is more realistic.
- Same as before with **Δ growing from ± 1 to ± 5m.**
- Above **± 5m, the formation will be considered broken.**

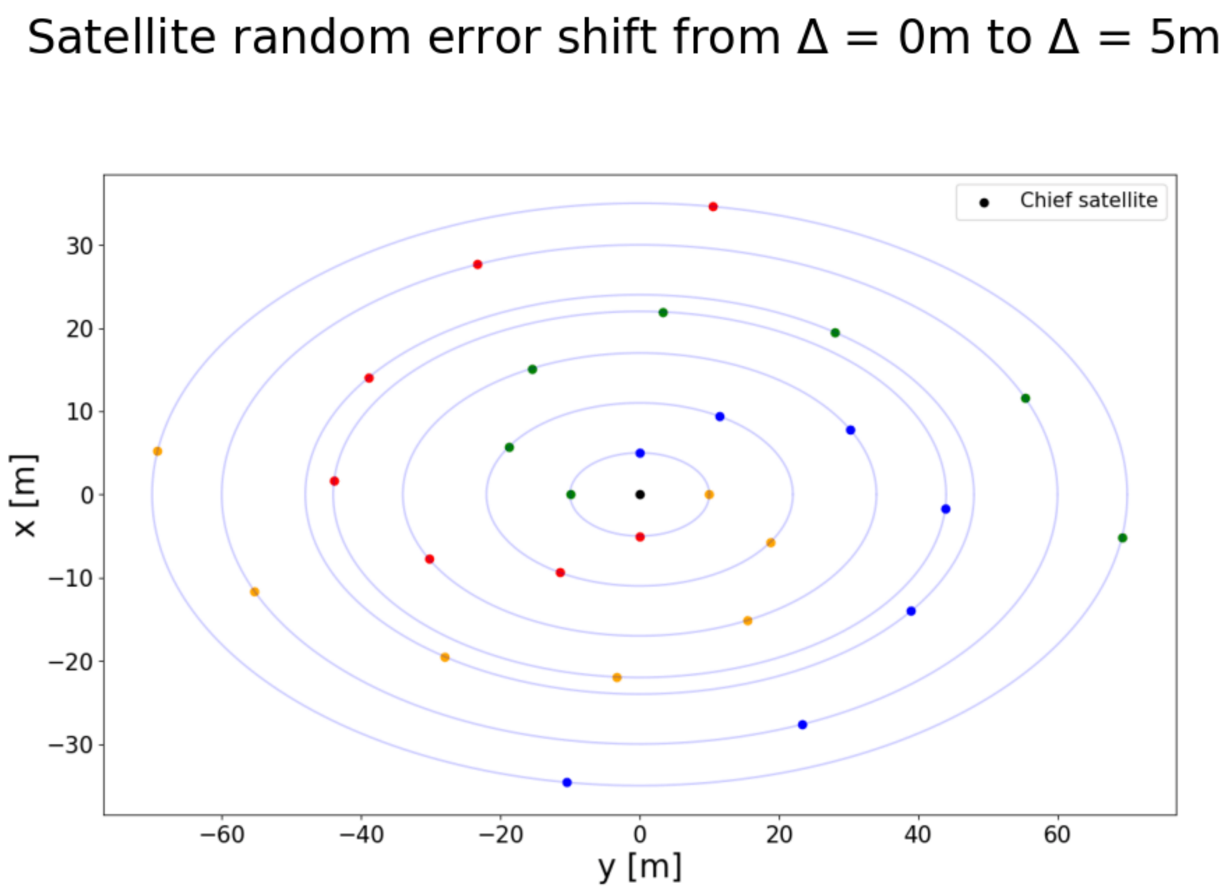

Figure 17: Increasing error shift animation

Position Uncertainties

Growing error implication on the KPIs

- **As the error increase:**
  - **Direct side lobes are being slightly shifted**
  - **Outer side lobes are being strongly shifted**

Error (m)	Resolution (km)	Relative Difference (%)
Δ = 0	0.9158229277	0
Δ = 1	0.9143847773	0.16
Δ = 2	0.8830666090	3.64
Δ = 3	0.9195090607	0.40
Δ = 4	0.8947533265	2.33
Δ = 5	0.9092744566	0.72

Table 5: Resolution as a function of the error

Non-Shifted vs Shifted and Averaged Radiation Pattern from Δ = 0m to Δ = 5m

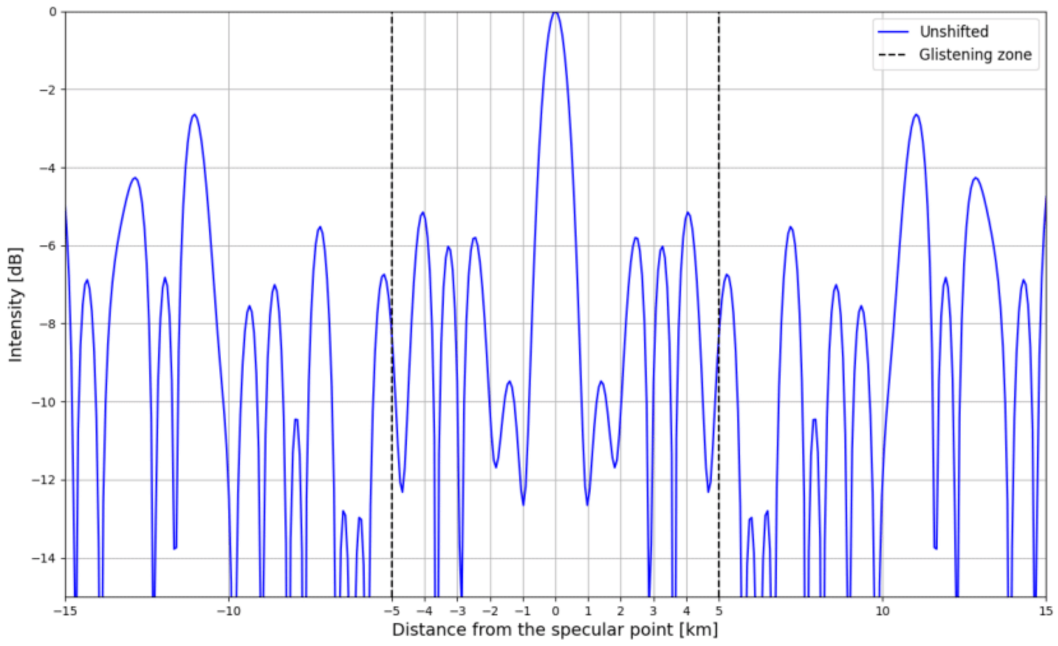

Figure 18: Increasing error shift animation impact on Radiation Pattern

- **No visible trend on the resolution, in fact, resolution look random**
- **Room for improvement**

Position Uncertainties

Growing error implication on the ground spot

- As the error Δ increases:
    - No notable trend on the central spot
    - Surroundings get blurry

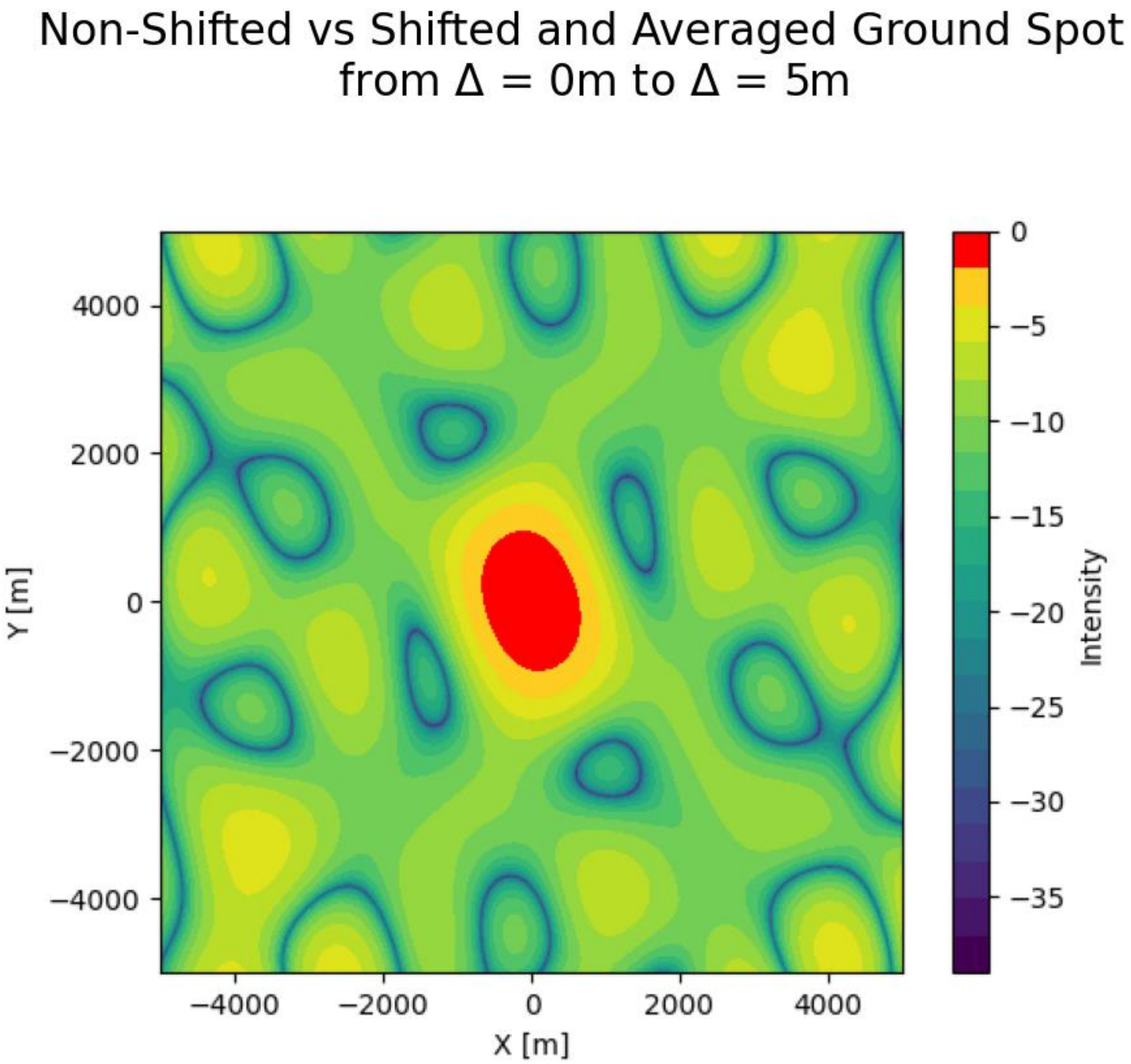

Figure 19: Increasing error shift animation impact on Ground spot

Position Uncertainties

Conclusion

- **Uncertainty has been randomly generated and** KPI's are computed **N = 100 times,** then **averaged. Probably not enough iterations.**

- **The initial minimum achievable uncertainty of .7m implies no notable changes on the KPI's.**

- **While growing the randomly generated uncertainty;**
  - **Direct side lobes amplitude were slightly altered with no particular trend.**
  - **Outer side lobes amplitude were strongly altered with no particular trend.**
  - **Resolution variation and associated relative difference were showing no particular trend, however random positioning increased resolution, again room for formation enhancement**

- However here, no phase shift error but only **positional chaos added with beamforming still in phase.**
- Next step: check what would imply roughly known position **within the beamforming process itself.**
- **Position in space known, but no possibility to have them in their intended position.**

Frequency changes

Frequency changes

Initial model flight formation

- **No uncertainty**, following distribution;
- Changes in frequency, tests **with L1, L2 L5 GPS frequencies**

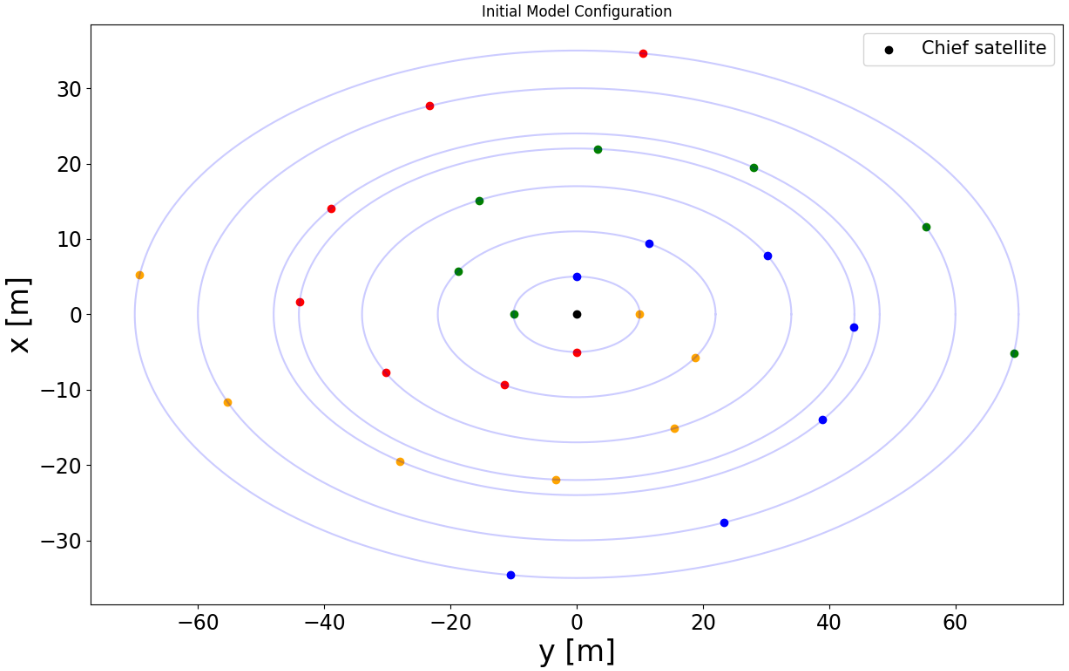

Figure 20: Initial Model Configuration

Frequency changes

GPS frequencies

- GPS set of frequencies
  - L1, **1575.42 MHz**
  - L2, **1227.60 MHz**
  - L5, **1176.45 MHz**

- Impact of **frequency changes on the KPI** is the following:

Frequency	Resolution (km)	Relative Difference (%)
Initial; 1498.962 MHz	0.9158229277	0
L1	0.8718546206	4.92%
L2	1.1218274626	20.22%
L5	1.1685743131	24.25%

Table 6: Resolution as a function of the frequency

- **As frequency decreases, resolution gets worse**

GNSS Frequency variation, GPS L1 (1575.42 MHz), GPS L2(1227.60 MHz) and GPS L5(1176.45 MHz)

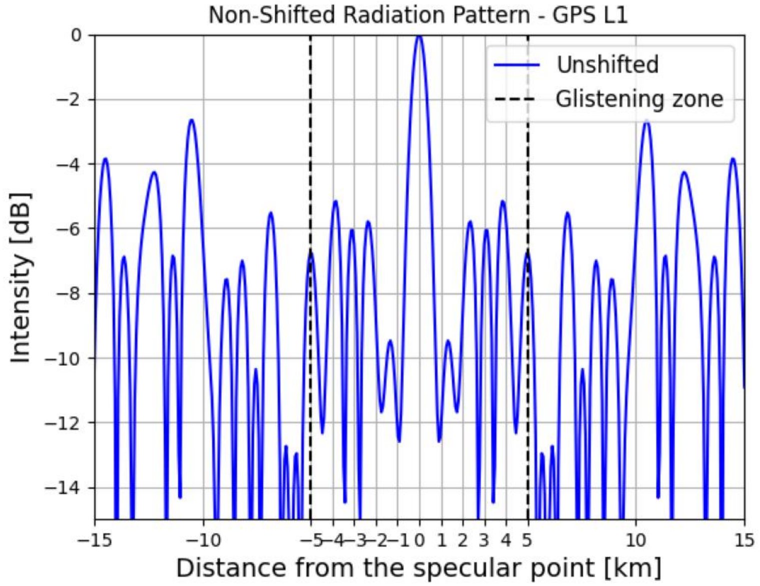

Figure 21: Frequency changes impact on the Radiation Pattern

- **As frequency decreases, the overall radiation pattern spreads out**
- **Main lobe AND side lobes**

Frequency changes

GPS frequencies

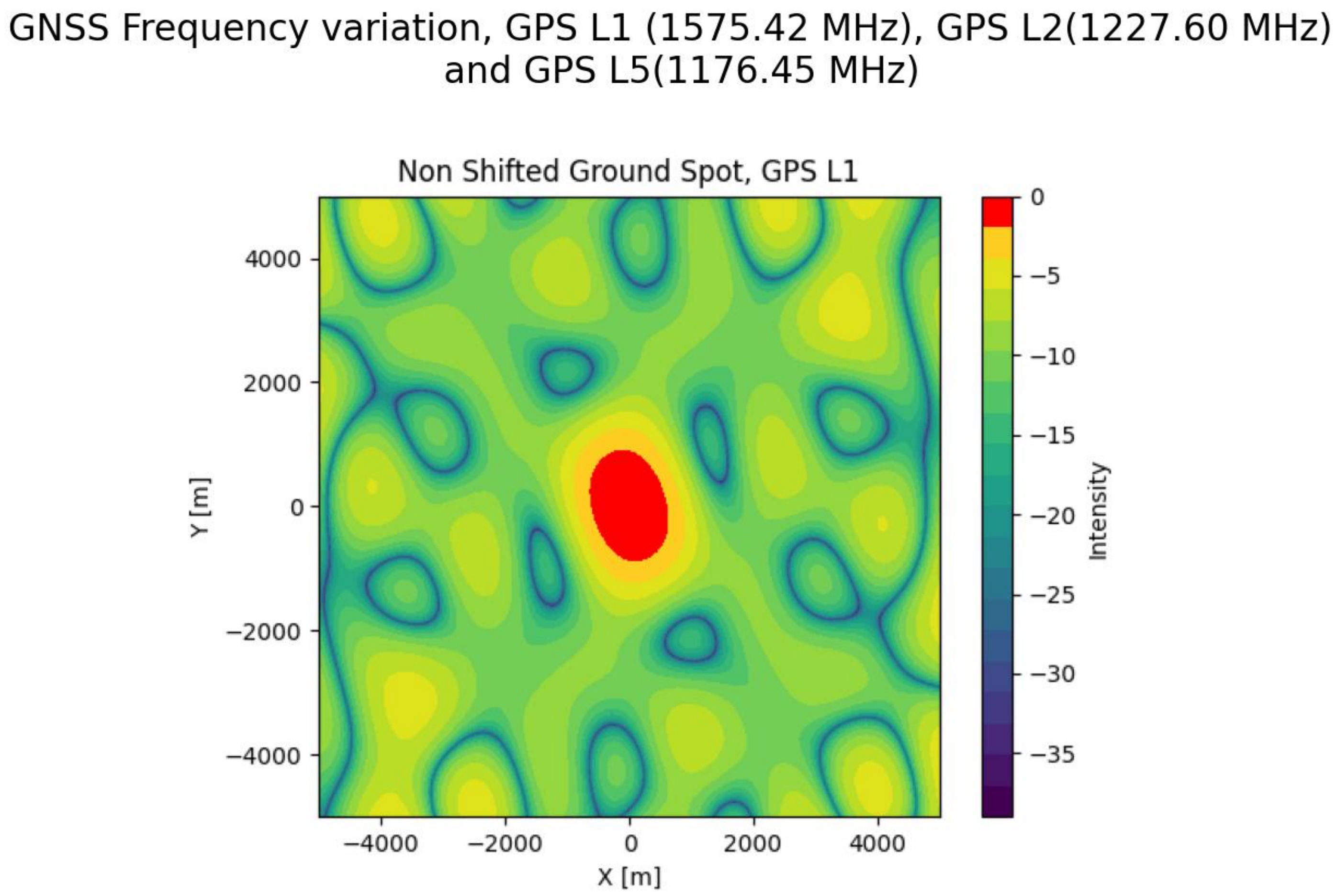

Figure 22: Frequency changes impact on the Ground Spot

➢ **As frequency decreases, ground spot is spread out/zoomed-in**

Frequency changes

Conclusion

- As frequency changes, **KPI’s are critically altered**
- Resolution **gets worse (increases) as frequency decreases**, and **gets better (decreases) as frequency increases**
- Overall radiation pattern spreads out:
  - **Main lobe** spreading is what implies **the changes in resolution**
  - **Side lobes** spreading is an interesting phenomenon as it could be looked for.
  - Ideally, **sidelobes could be moved out of the glistering zone for a certain frequency range.**

General Conclusion

Conclusion

General conclusion

- **Feasibility and preliminary design has been assessed for a GNSS-R Mission**

- **Room for formation flight improvements although the work performed by UCLouvain is an incredible step further in the domain**

- **Strategies must be developed to mitigate uncertainties that surpass an established accuracy threshold, implementation of a dynamic flight system could be an option**

- **Potential to enhance EO area through cost-effective mission multiplication, based on CubeSats formation flights**

- **Potential for broad applications and advantages in diverse sectors**

Future work

CubeSats formation flight future

- **Improve the model to consider additional external factors, especially the ones affecting electromagnetic waves.**
- **Aim for an ideal tool that would be modulable through mission requirements (observation points, resolution, frequency).**
- **Such a tool would help to transition from observed trends to actionable engineering data.**

References

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- [2] Southwell, B. J., & Dempster, A. G. (2018). "*A New Approach to Determine the Specular Point of Forward Reflected GNSS Signals*". IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, DOI: 10.1109/JSTARS.2017.2775647.
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Thank you for your attention

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