High-Sensitivity Adaptive GNSS Acquisition Schemes

Supervisors:
Dr. Mohamed SAHMOUDI
Prof. Marie-Laure BOUCHERET

Toulouse, May 27th 2014

Presentation Outline

I. Introduction to GNSS and Signal Acquisition

II. Thesis Contributions

A. Analysis and Compensation of Doppler Effect

B. Characterization of Differential Detectors

C. Multi-Constellation Collective Acquisition

III. Conclusions and Future Work

GNSS – Global Navigation Satellite System

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GNSS – Global Navigation Satellite System

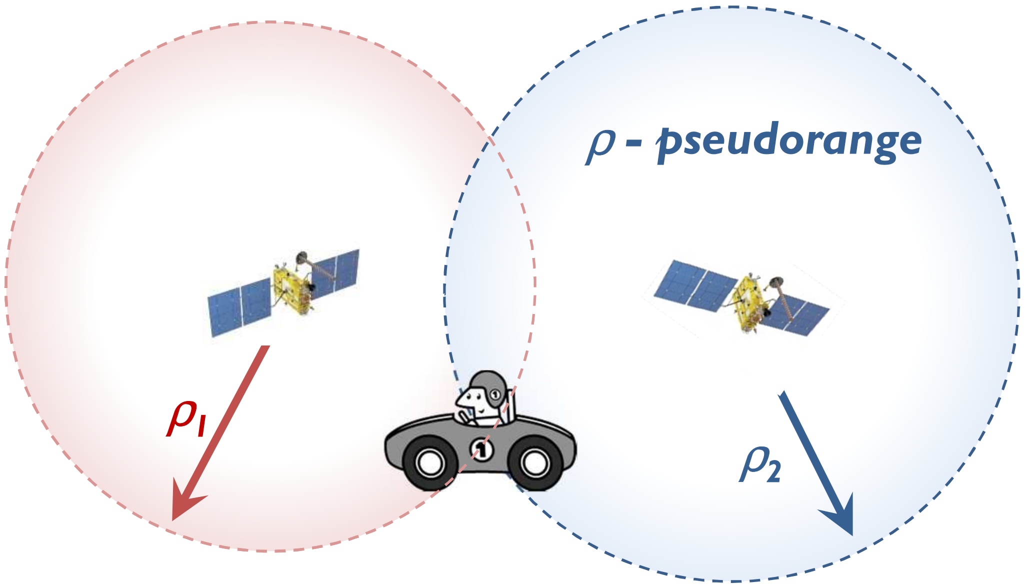
GNSS Working Principle

- The underlying principle of GNSS systems is ***trilateration***:

An unknown position can be inferred from distances to points with known positions

- ✓ Satellites position can be established accurately
- ✓ User pseudorange to satellites can be estimated

➡ **User position and clock bias (with respect to GNSS system time) can be determined**

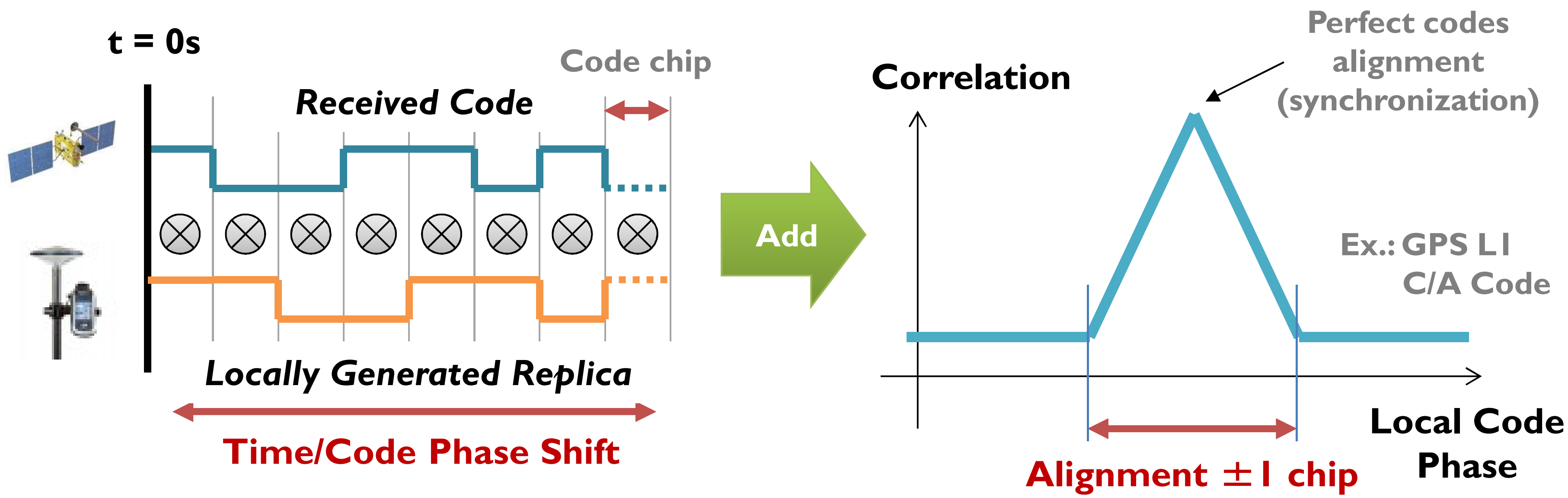


- Number of unknowns = 4 ➡ A ***minimum of 4 satellites*** is required to determine user ***navigation solution***

Acquisition Role

Goal: Trilateration → Requires → Distance ↔ GNSS ↔ Time = Distance / Speed-of-Light

How to estimate the signals time of travel accurately? Correlation!



- Besides ***code phase*** also ***Doppler offset*** needs to be estimated
- First phase of (coarse) estimation of both parameters is **ACQUISITION**

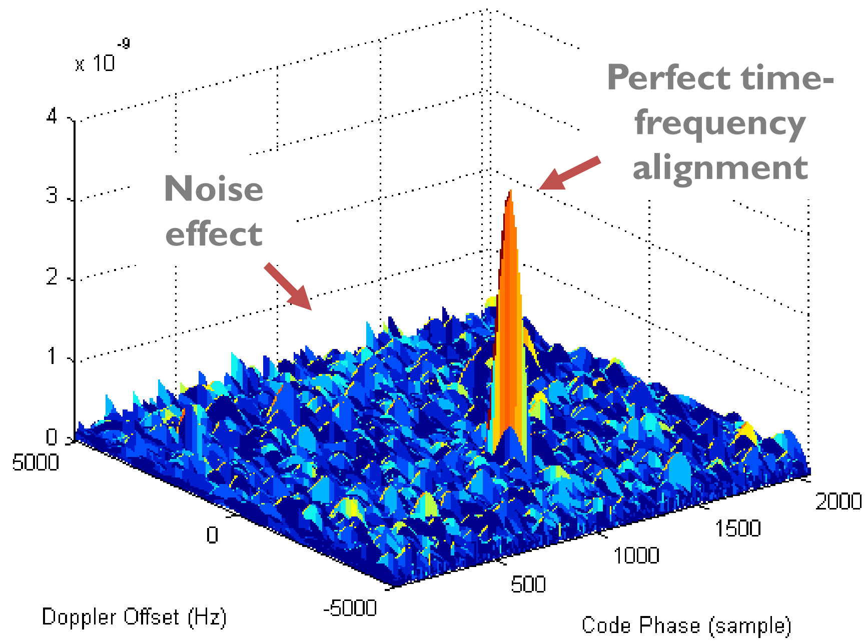
Acquisition Role

- Acquisition output example for **GPS L1 C/A** signal:

Outdoor
- ✓ Line-of-sight visibility

Standard Acquisition
- ✓ 1 code period

Comput. Complexity
- ✓ Search Points: 1E3
- ✓ Number of Operations Required ~ 1E5



➡ Acquisition is a combined ***estimation and detection*** problem

Why a PhD thesis in acquisition?

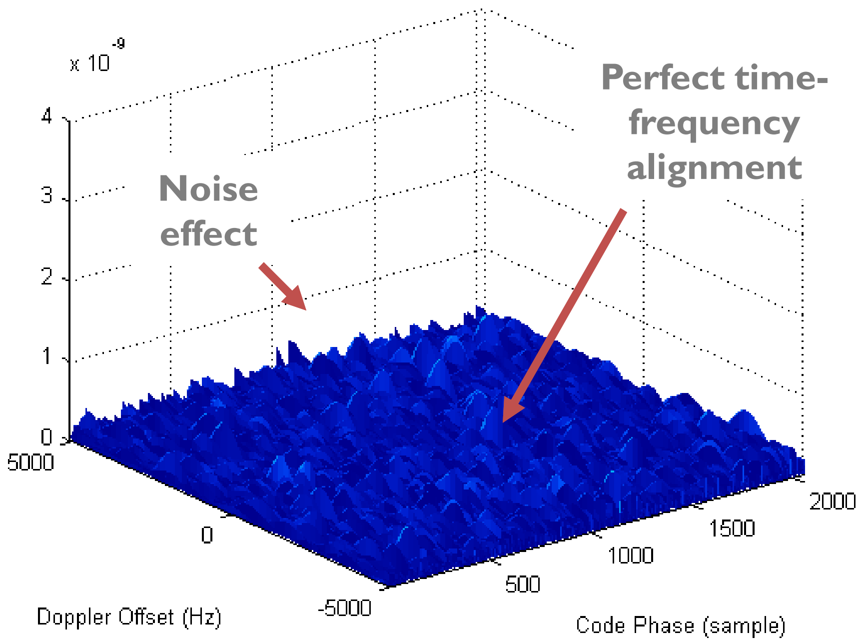
Acquisition Challenges

- Acquisition output example for **GPS L1 C/A** signal:

~~Outdoor~~ Indoor
- ✓ Non line-of-sight

Standard Acquisition
- ✓ 1 code period

Comput. Complexity
- ✓ Search Points: 1E3
- ✓ Number of Operations Required ~ 1E5



Standard GNSS Acquisition is not capable of satisfying current user expectations!

Acquisition Challenges

- Acquisition output example for **GPS L1 C/A** signal:

~~Outdoor~~ Indoor

- ✓ **Non line-of-sight**

~~Standard Acquisition~~

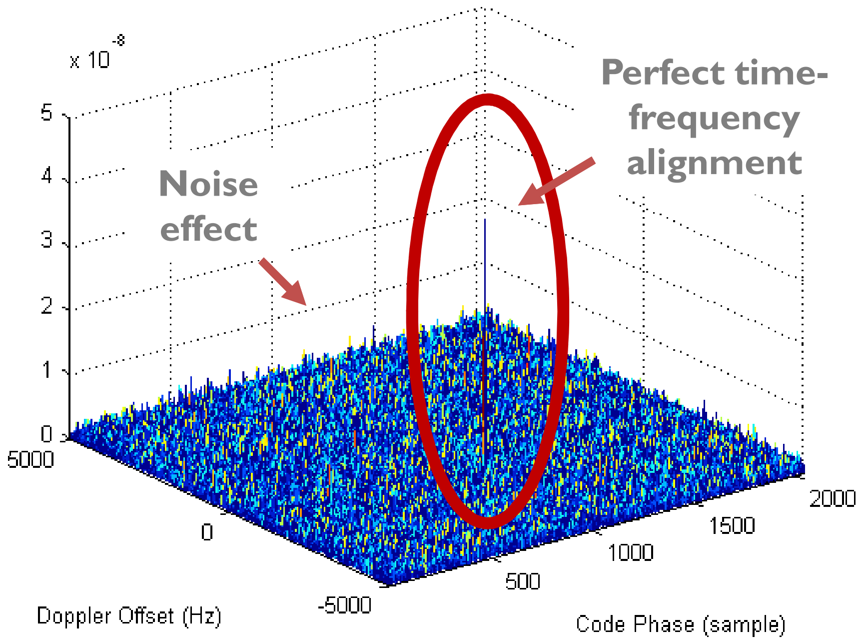
High-Sensitivity Acquisition

- ✓ **100 code periods**

Comput. Complexity

- ✓ **Search Points: 1E5**
- ✓ **Number of Operations Required ~ 1E9**

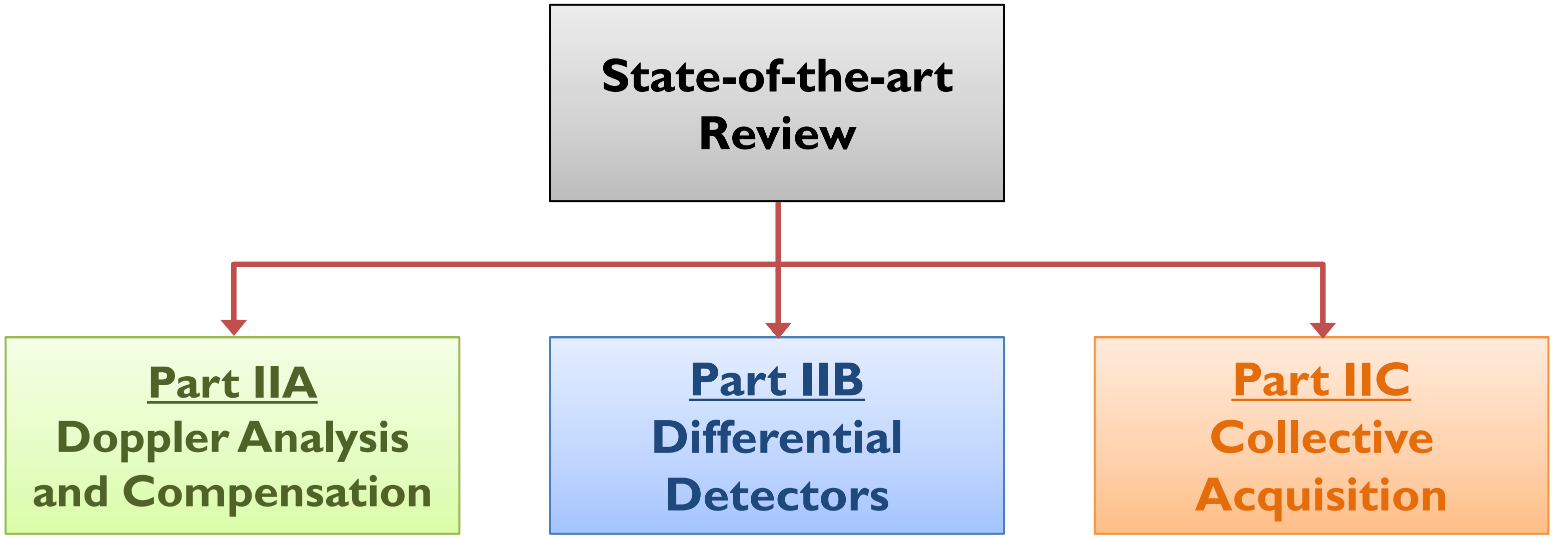
10.000 times higher than standard acquisition!



➡ High-sensitivity acquisition involves a ***sensitivity vs complexity*** trade-off

Thesis Objectives

- **Propose innovative solutions to the current challenges of acquisition**
  - ✓ Current challenges and innovation opportunities: identified through **state-of-the-art review**



  - ✓ Analysis carried always considering the ***sensitivity vs complexity*** trade-off of High-Sensitivity GNSS acquisition

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GNSS – Global Navigation Satellite System

Part II: Thesis Contributions

Part IIA: Analysis and Compensation of Doppler Effect in GNSS Acquisition

Part II: Thesis Contributions

Part IIA: Analysis and Compensation of Doppler Effect in GNSS Acquisition

Contents:

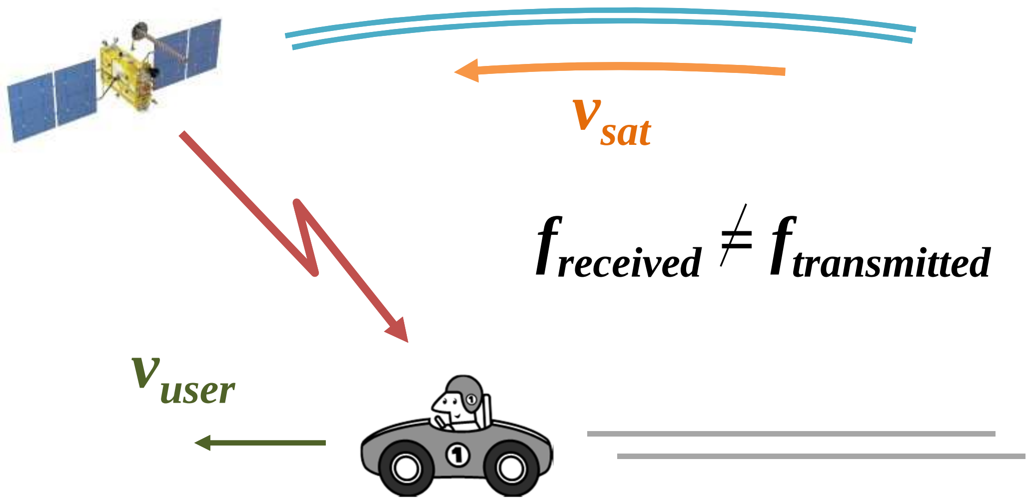
1. Introduction
2. Compensation of Doppler Effect in Low-Dynamics
3. Analysis of Doppler Effect in Medium-Dynamics
4. Compensation of Doppler Effect in High-Dynamics
5. Conclusion

Introduction

- Doppler shift is unavoidable in GNSS given the significant (relative) user-satellite motion

- The Doppler shift experienced by a land-based user is mainly due to **3** sources:

  1. **Satellite Motion**
  2. **User Motion**
  3. **User Receiver Oscillator**



- **High-sensitivity** signal processing techniques require **long observation times**

➡ Doppler **variation** throughout signal observation time is also important!

Introduction

- **Three Doppler-related scenarios can then be defined:**

1. **Low-Dynamics**

   Doppler offset remains approximately **constant** during acquisition time

2. **Medium-Dynamics**

   Doppler offset **changes slightly** and does not impact the acquisition process

3. **High-Dynamics**

   Doppler offset **changes significantly** and impacts the acquisition process

✓ **Conclusion and Possible scenarios of application**

Part II: Thesis Contributions

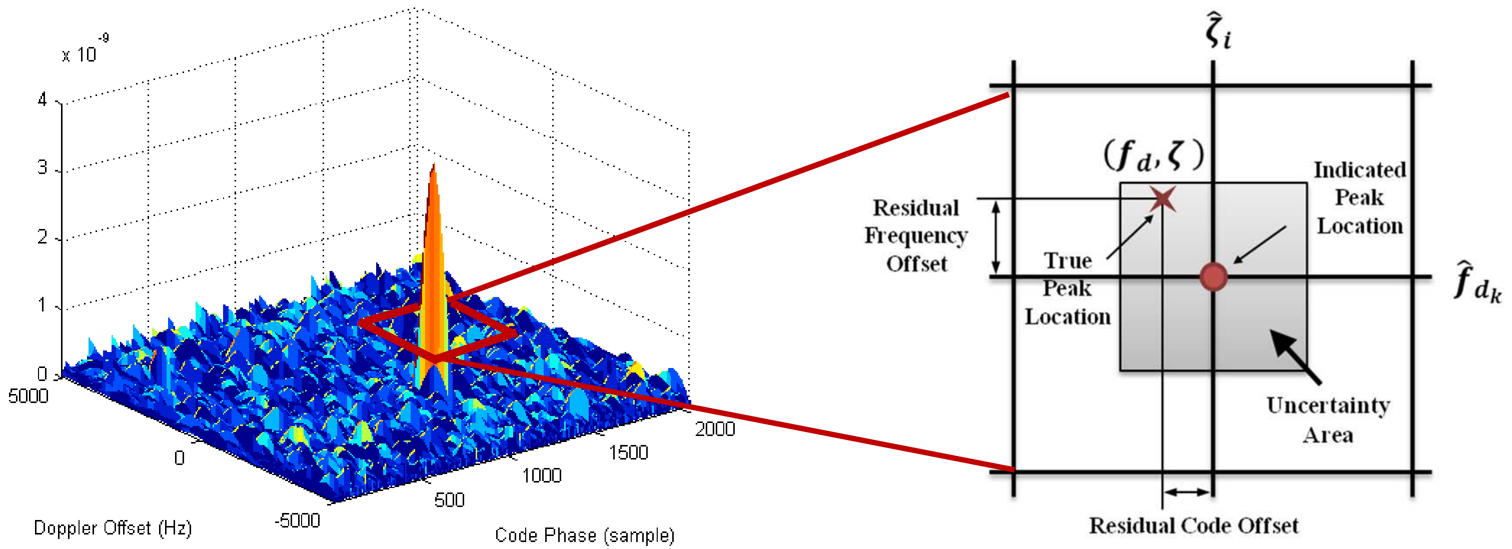
Part IIA: Analysis and Compensation of Doppler Effect in GNSS Acquisition

Contents:

1. Motivation

- Acquisition involves a search over a **finite** number of **candidate** frequencies (Doppler offsets) and code phases

➡ **Residual code and frequency estimation offsets are inevitable**

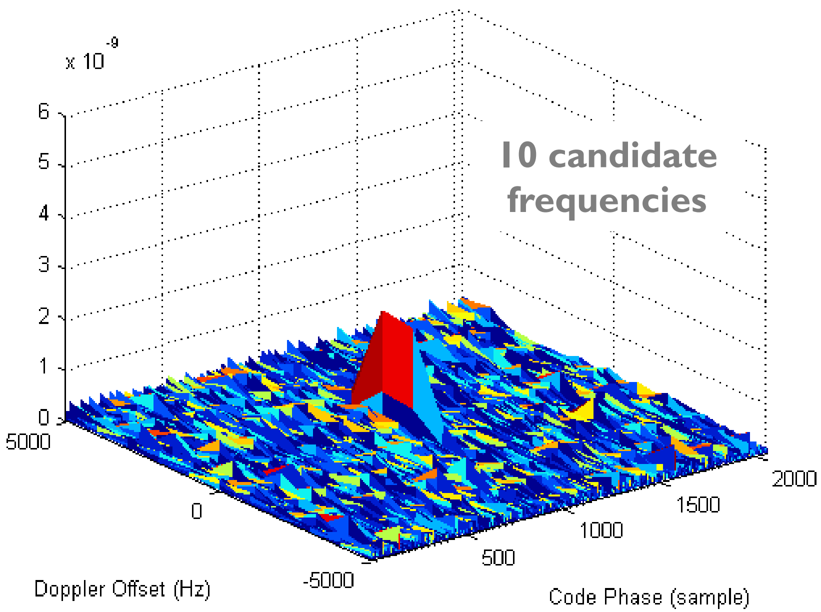


What is the impact on acquisition of a residual frequency estimation error?

1. Motivation

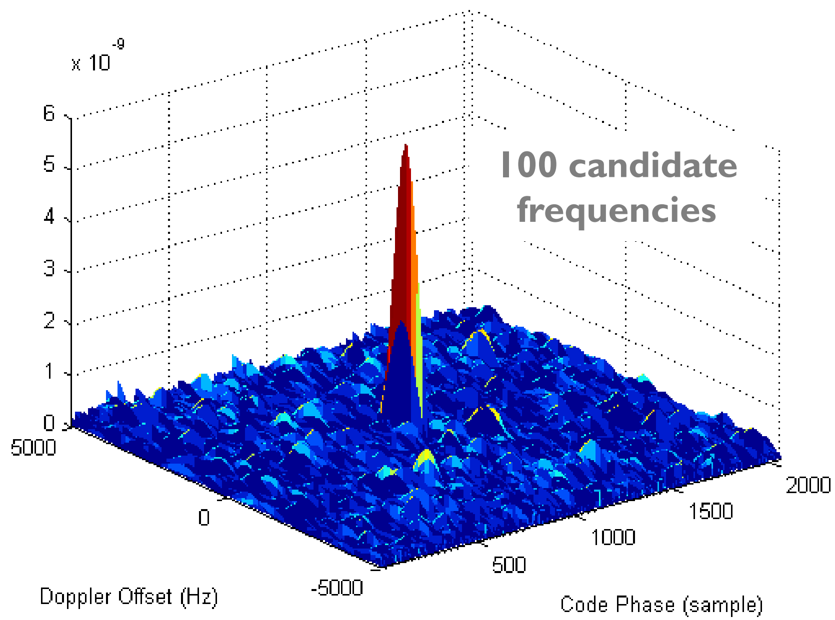
- **Coarse vs Fine Search Grid comparison** (worst-case scenario)

Coarse Acquisition Grid



- ✓ « Low » computational cost
- ✓ Potentially « high » frequency-derived losses

Fine Acquisition Grid

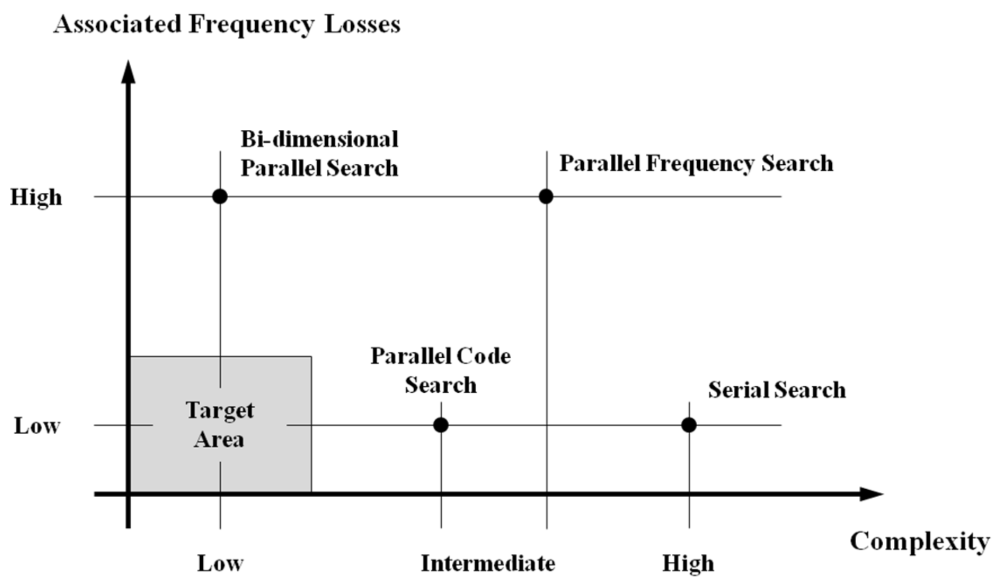


- ✓ « High » computational cost
- ✓ « Limited » frequency-derived losses

1. Motivation

- Most computationally efficient GNSS acquisition methods employ Fast Frequency Transform (FFT) for computation optimization

➡ **FFT imposes coarse frequency grid** ⚠

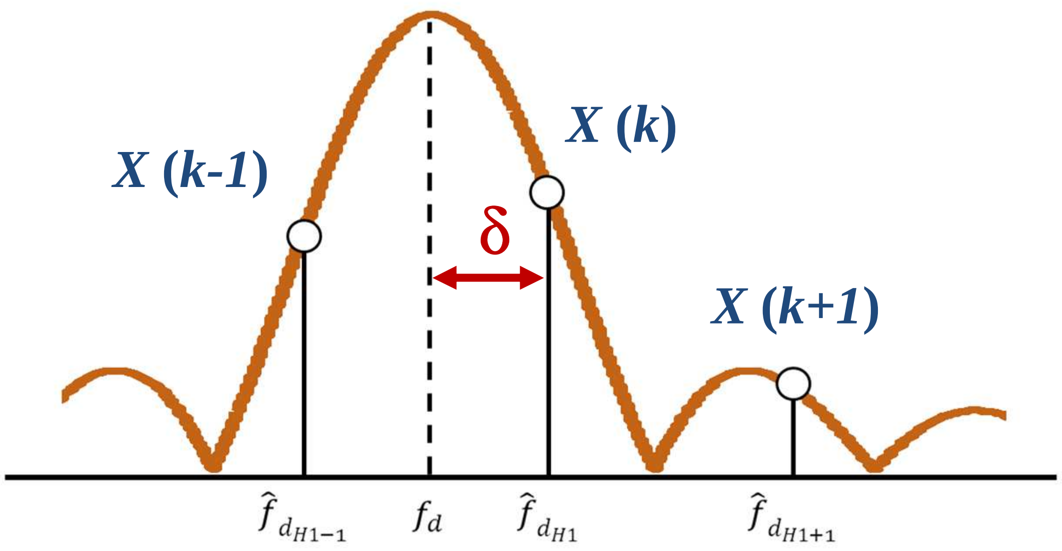


Objective: **Adapt the most computationally efficient methods in order to reduce the maximum frequency attenuation losses!**

2. Proposed Approach

- How to counteract the coarse FFT frequency resolution?

Spectral Peak Location algorithms (from Digital Signal Processing literature)



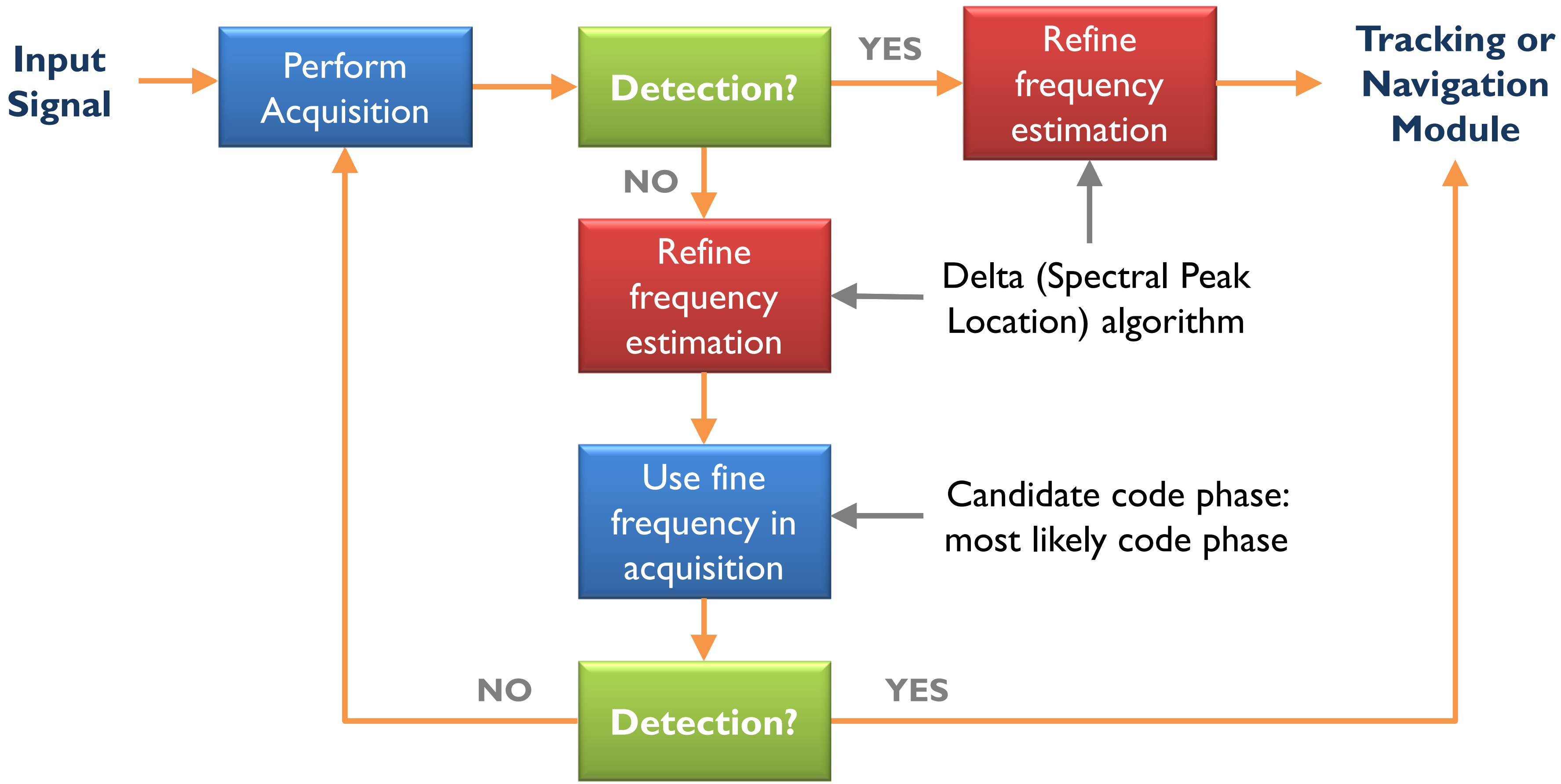
FFT output profile known (*sinc* function)

Interpolate the FFT outputs to calculate δ

$\delta = f\,(\text{correlation outputs})$ ➡ $f_{\textit{delta corrected}} = f_{\textit{simple}} + \delta$

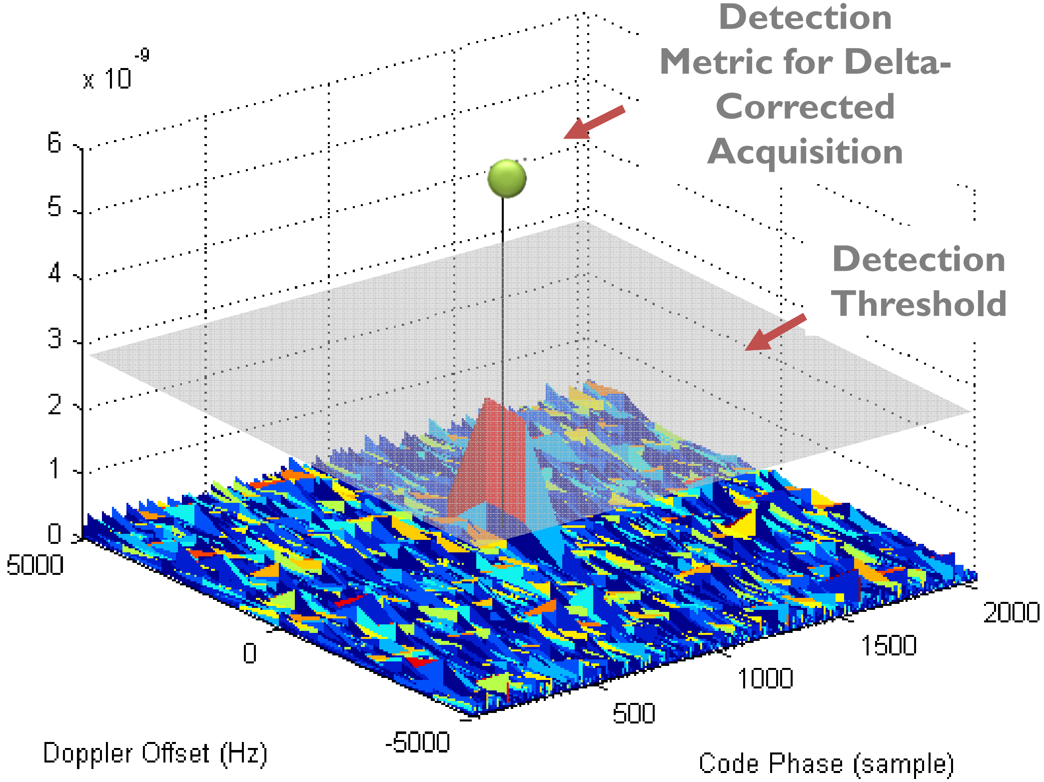
2. Proposed Approach

- New **delta-corrected** acquisition methodology



2. Proposed Approach

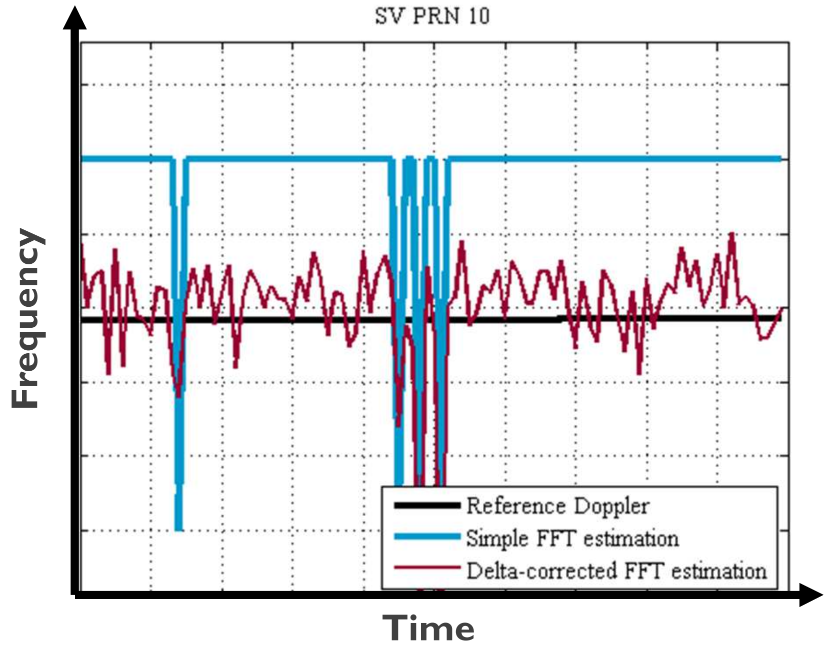
- New **delta-corrected** acquisition methodology



3. Results

- Analysis of real data collected with test and reference receivers (1ms GPS L1 C/A signal)

Doppler offset estimation: simple vs delta-corrected frequency estimator

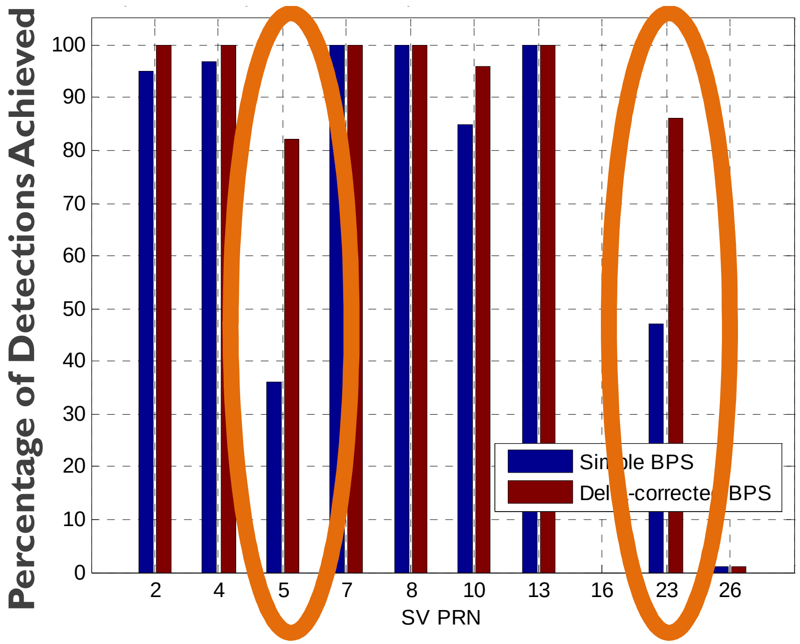


- **Simple FFT Doppler estimation**
- **Delta-corrected Doppler estimation**
- **Reference Doppler value**

3. Results

- Analysis of real data collected with test and reference receivers (1ms GPS L1 C/A signal)

Satellites Detection: **simple** vs **delta-corrected** acquisition scheme



SV PRN	Mean Doppler Offset (Hz)	Mean C/N_0 (dB-Hz)
2	1450	48.1
4	-1570	48.1
5	4480	46.7
7	1930	48.1
8	4080	48.9
10	1550	47.1
13	-1020	48.6
23	-1550	46.4

Part II: Thesis Contributions

Part IIA: Analysis and Compensation of Doppler Effect in GNSS Acquisition

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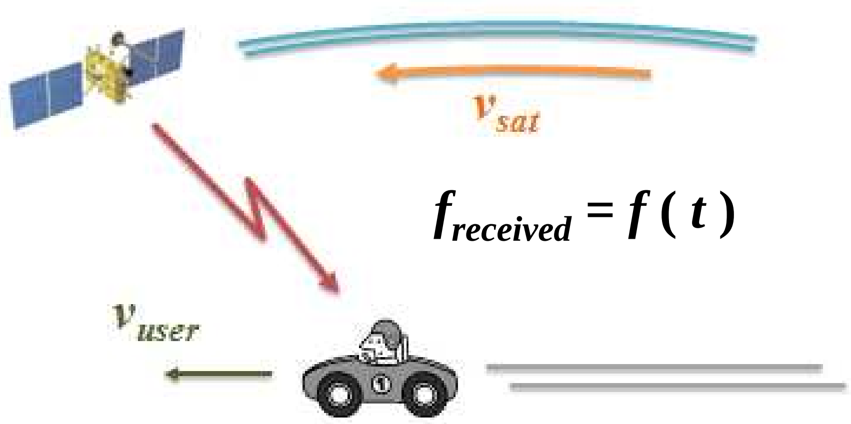
1. Motivation

- For detection of weak signals (very) long signal observation times are required

Assumption of a constant Doppler offset is no longer valid!



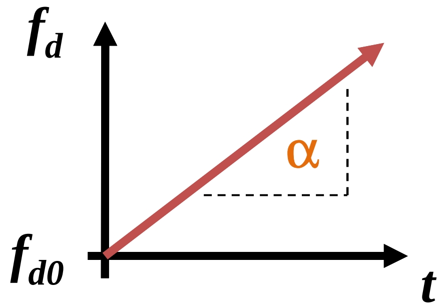
Source	Maximum Expected Variation (Hz/s)
Satellite Motion	± 10
User Motion	± 50
Receiver Oscillator	Variable
Total	**± 60 Hz/s**

How does a changing Doppler offset impact the acquisition process?

2. Proposed Approach

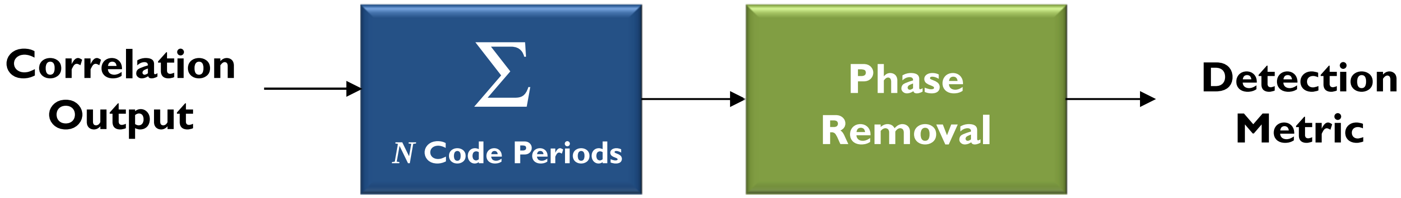
- **Chosen model:** frequency ramp (linear variation)

$$f_d = f_{d0} + \alpha\, t\,, \quad \alpha \equiv \text{Doppler change rate (Hz/s)}$$

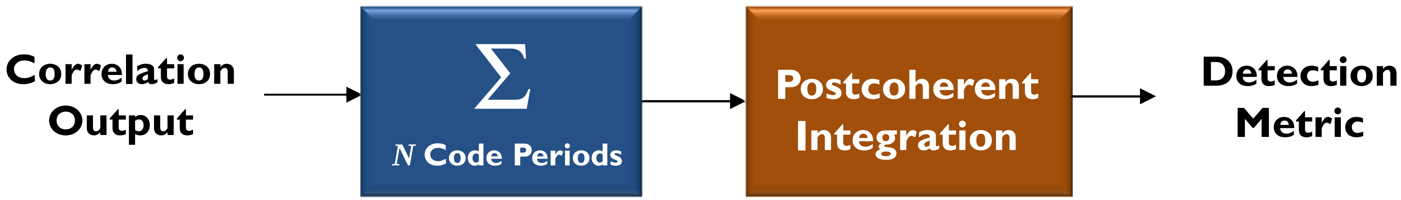


- **2 different analysis conducted:**

1. **Detector employing exclusively coherent integration:**



2. **Detectors employing coherent and postcoherent integration:**



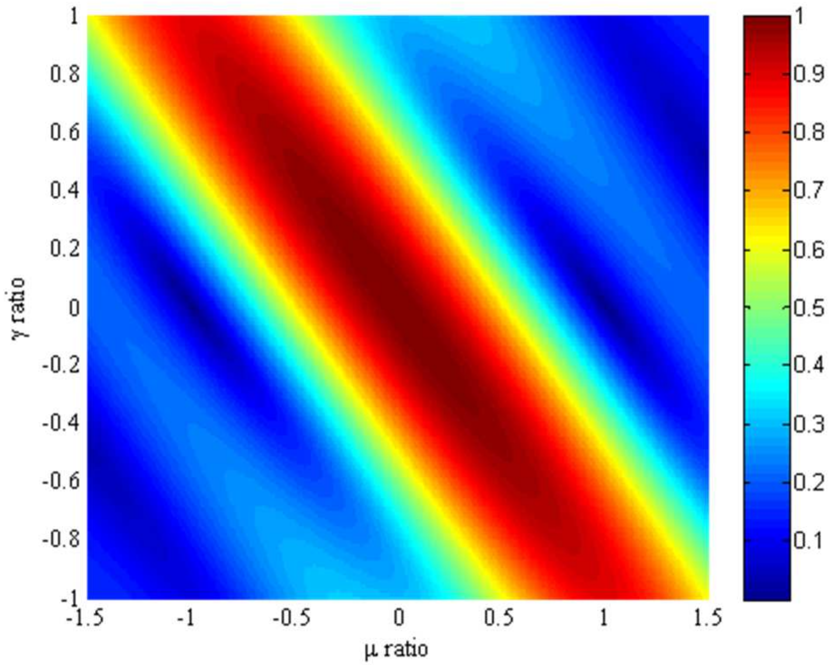
3. Results

1. Detector employing exclusively coherent integration

- Percentage of Doppler bin «swept» by the Doppler frequency during coherent integration - **Sweep factor (γ)**

$$\gamma = \alpha \cdot T_{coh}^2$$

  - ✓ Simulation analysis of effect of γ in coherent integration



- **Conclusions:**
  - ✓ For γ < 100% worst-case detection metric attenuation equal to FFT coarse grid loss
  - ✓ Coherent integration time adjusted according to expected dynamics (α)

Part II: Thesis Contributions

Part IIA: Analysis and Compensation of Doppler Effect in GNSS Acquisition

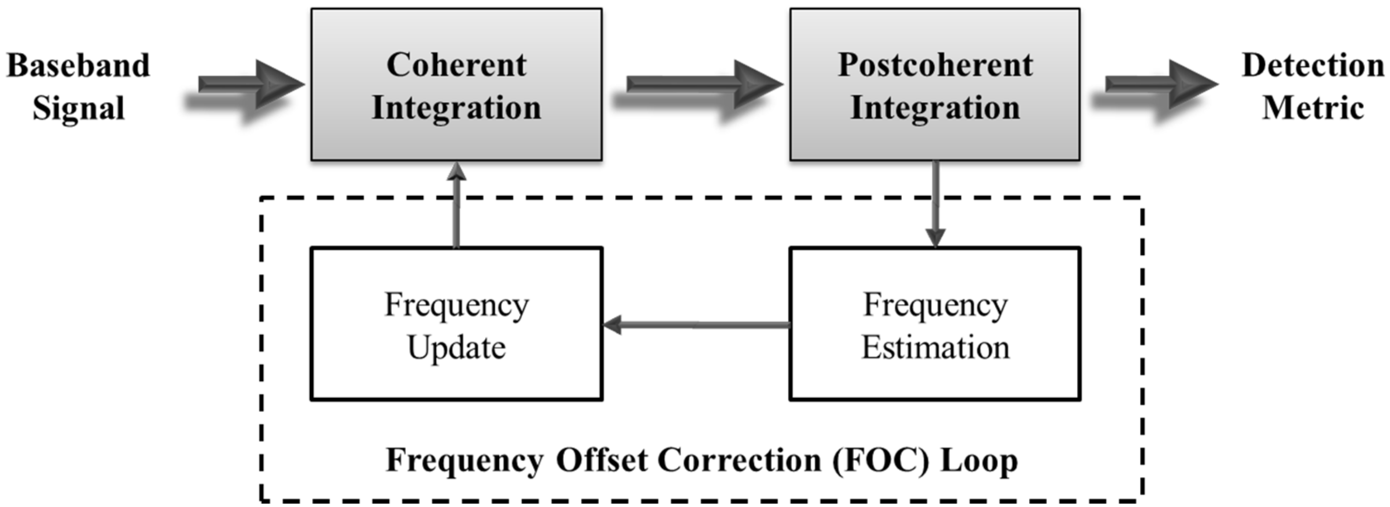
Contents:

2. Proposed Approach

- **For Medium-Dynamics:** proposed formulas adapt integration times only, implying no design changes

- **For High-Dynamics:** application scenarios and involved dynamics require new design!

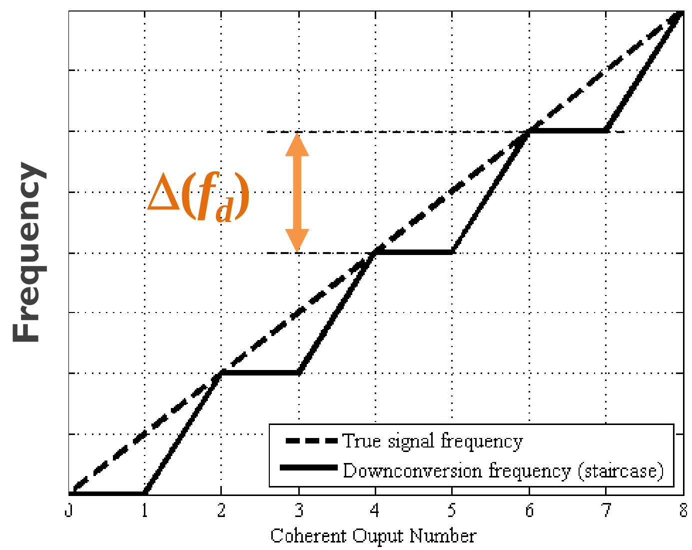
Proposed approach: Frequency Offset Correction Loop



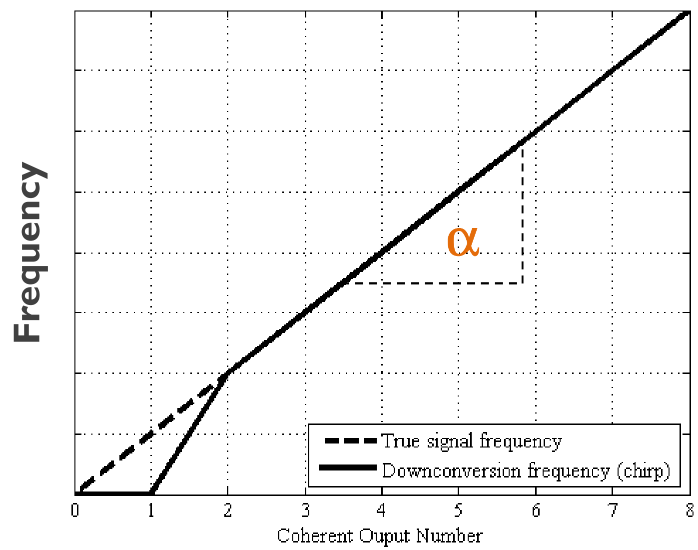
3. Results

- Two different frequency compensation approaches analyzed:

Staircase compensation



Chirp compensation



- Chirp compensation **more efficient** than staircase approach
- Chirp-compensated acquisition **limited by α estimation** at low input signal powers

Part II: Thesis Contributions

Part IIA: Analysis and Compensation of Doppler Effect in GNSS Acquisition

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Conclusions

- **Three different Doppler scenarios were defined and evaluated:**

1. ***Low-Dynamics***
   - ✓ Improve sensitivity/complexity trade-off of GNSS Acquisition
   - ✓ **Proposed for mass-market applications**
2. ***Medium-Dynamics***
   - ✓ Adapt acquisition schemes parameters according to expected level of dynamics
   - ✓ **Proposed for urban receivers and LEO and GEO satellite receiver**
3. ***High-Dynamics***
   - ✓ Inclusion of a dynamic Frequency Offset Correction loop for enhanced robustness
   - ✓ **Proposed for receivers targeting indoor acquisition**

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GNSS – Global Navigation Satellite System

Part II: Thesis Contributions

Part IIB: Sensitivity Characterization of Differential GNSS Detectors

Contents:

1. Introduction
2. Sensitivity Characterization of Nonoptimal Detectors
3. Noncoherent Differential Detector Sensitivity
4. Comparison with Noncoherent Detector
5. Conclusion

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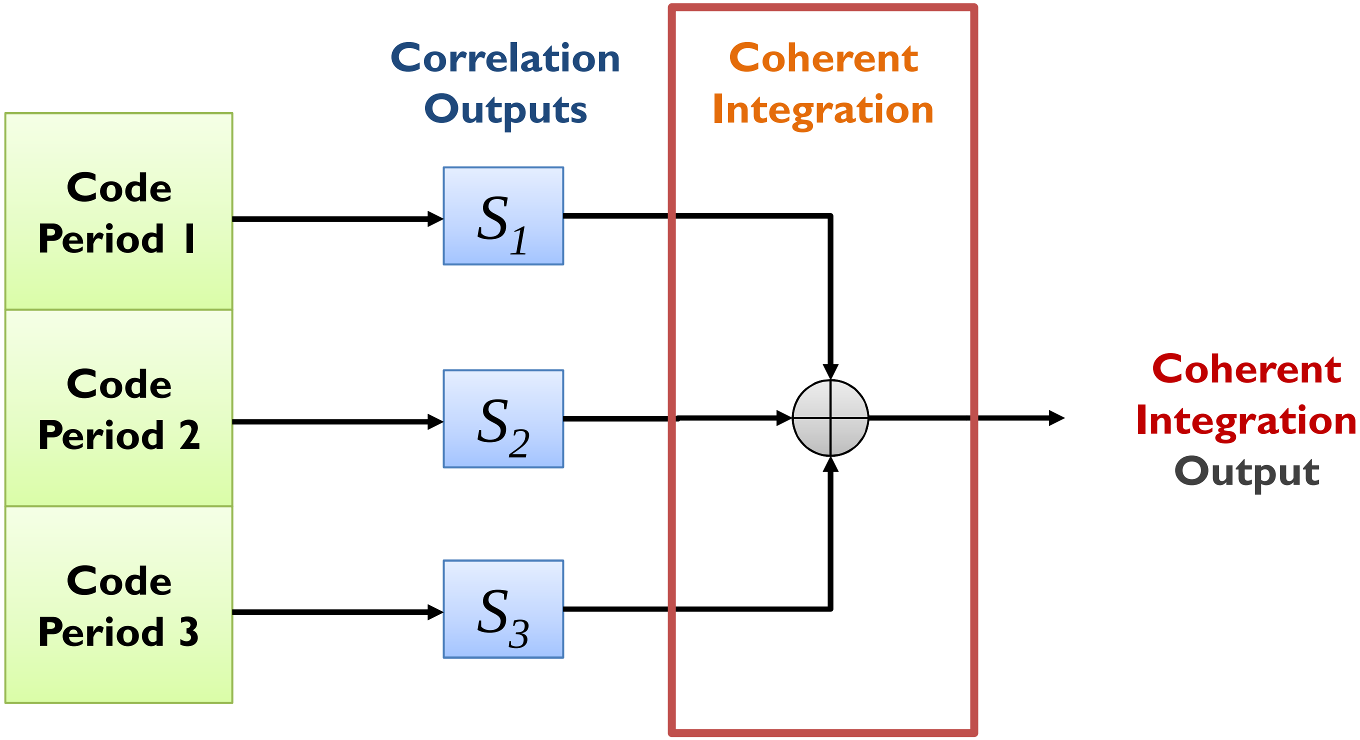
Introduction

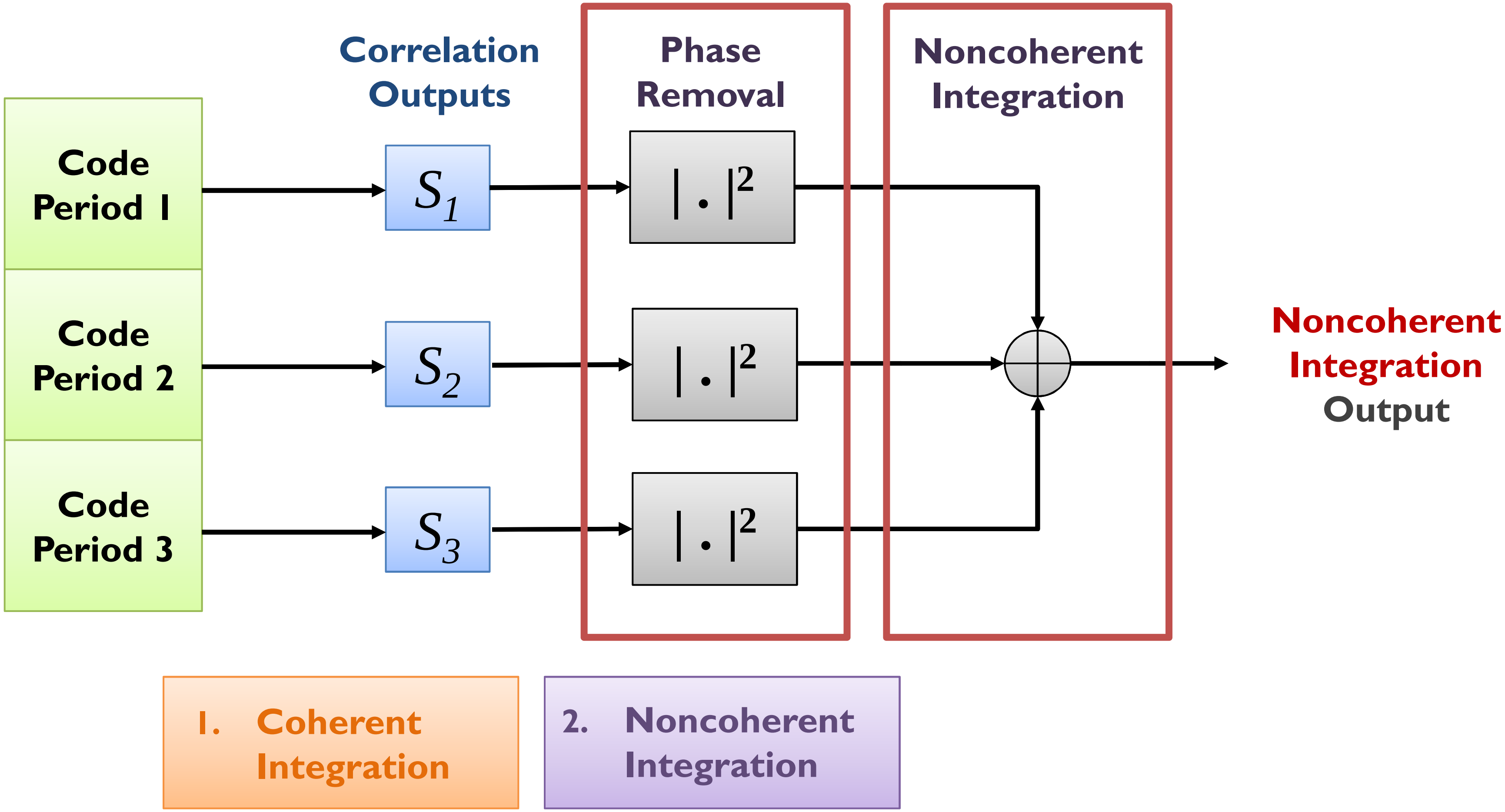
- **GNSS signal integration techniques**



I. Coherent Integration

Introduction

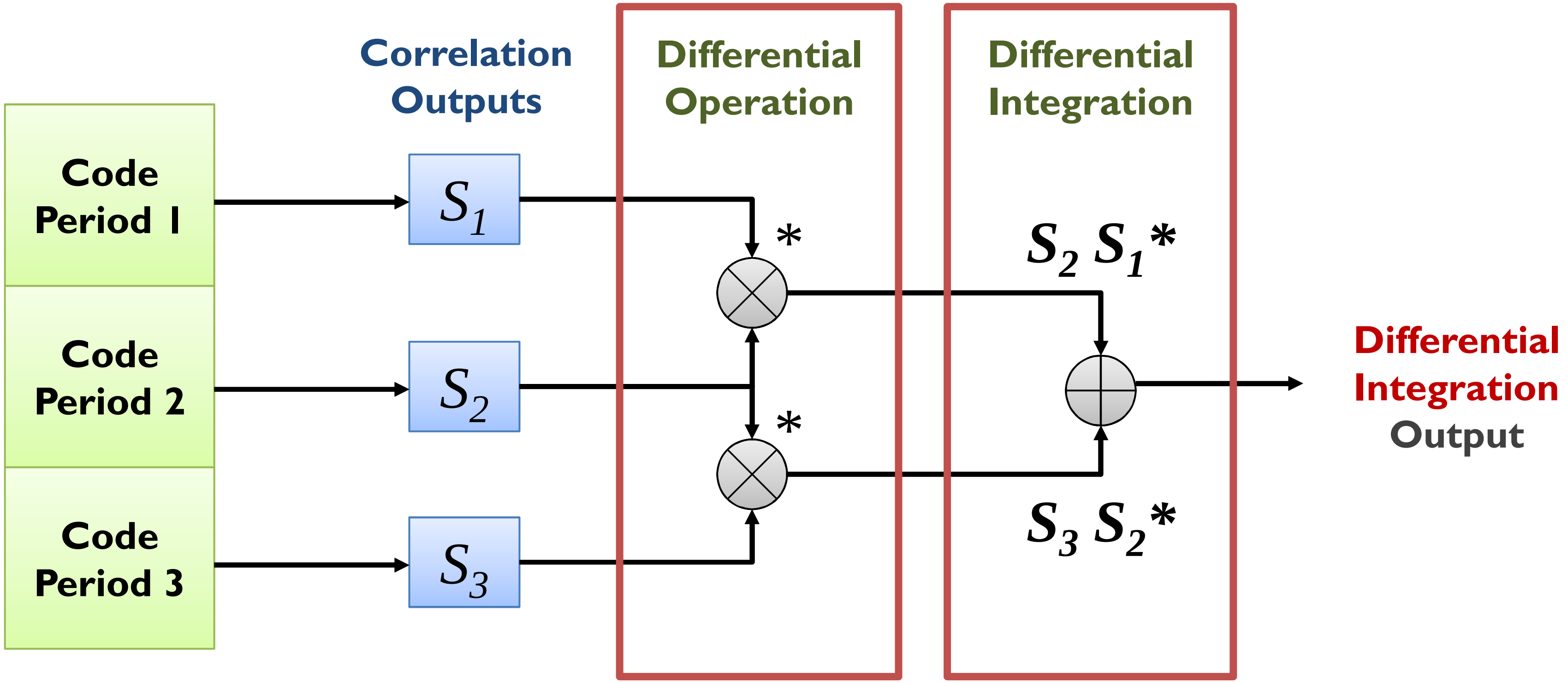
- **GNSS signal integration techniques**



Introduction

- **GNSS signal integration techniques**

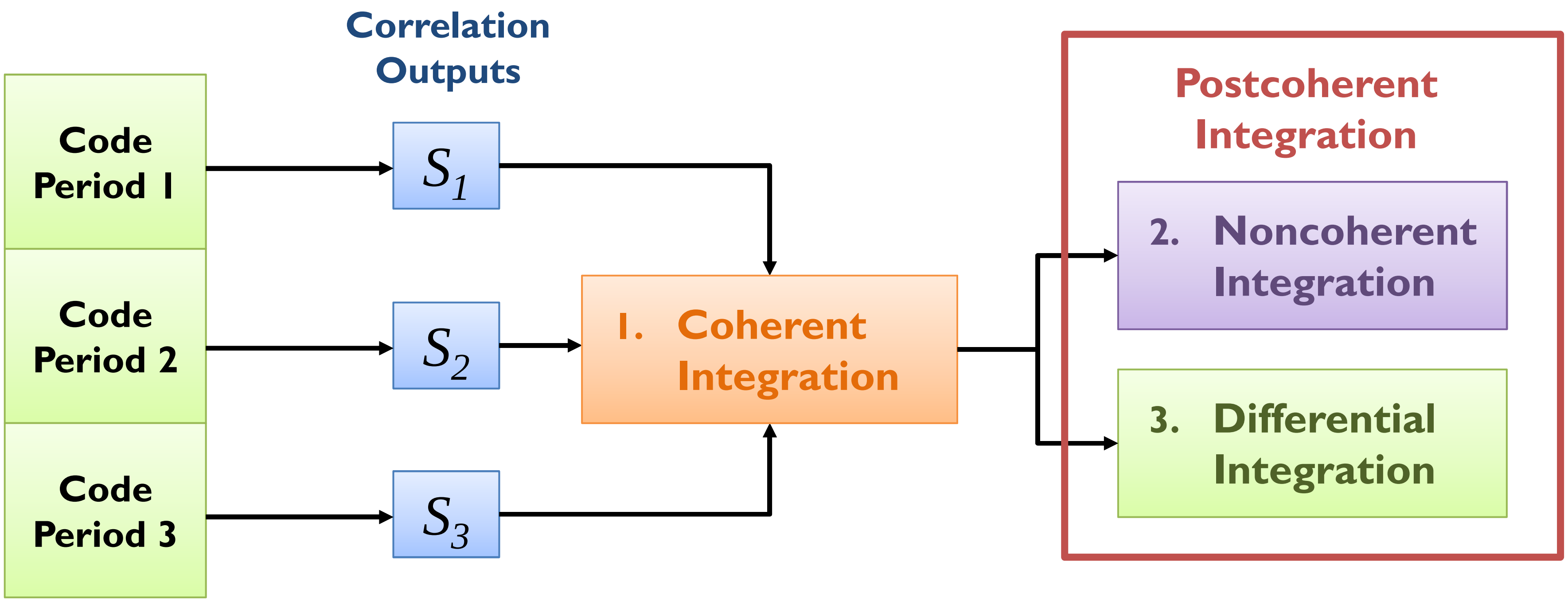
* - Complex conjugate



1. Coherent Integration
2. Noncoherent Integration
3. Differential Integration

Introduction

- **GNSS signal integration techniques: coherent and postcoherent**



1. Coherent Integration

2. Noncoherent Integration

3. Differential Integration

Introduction

- **Coherent and Postcoherent integration techniques comparison**

	Coherent	Postcoherent
Sensitivity Improvement	+	−
Robustness to Signal Phase (Doppler and data bit)	−	+
Impact on Computational Complexity	−	+

➡ **Given limitations of coherent integration, transition to postcoherent integration is usually required**

What is preferable: transition to noncoherent or differential?

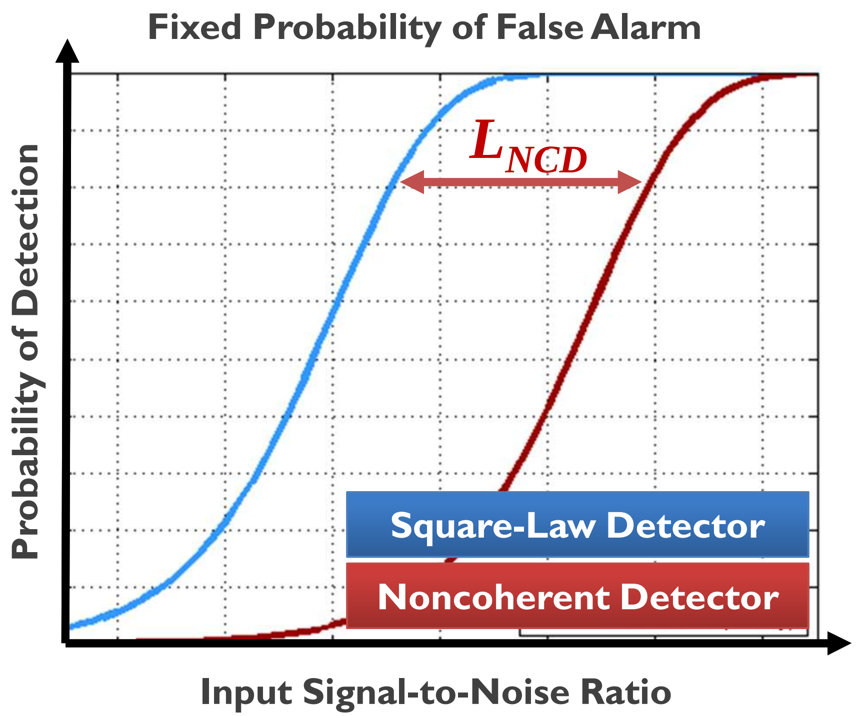
Introduction

Noncoherent integration

- ✓ Most commonly employed approach (standard technique since radar)
- ✓ The ***sensitivity loss*** of performing N ***noncoherent*** integrations instead of N ***coherent*** integrations has been expressed as:

$$L_{NCD} = f\,(N, P_d\,, P_{fa})$$

- P_d **– Probability of Detection**
- P_{fa} **– Probability of False Alarm**



Objective: **Propose a similar formula for most suitable differential detector**

Part II: Thesis Contributions

Part IIB: Sensitivity Characterization of Differential GNSS Detectors

Contents:

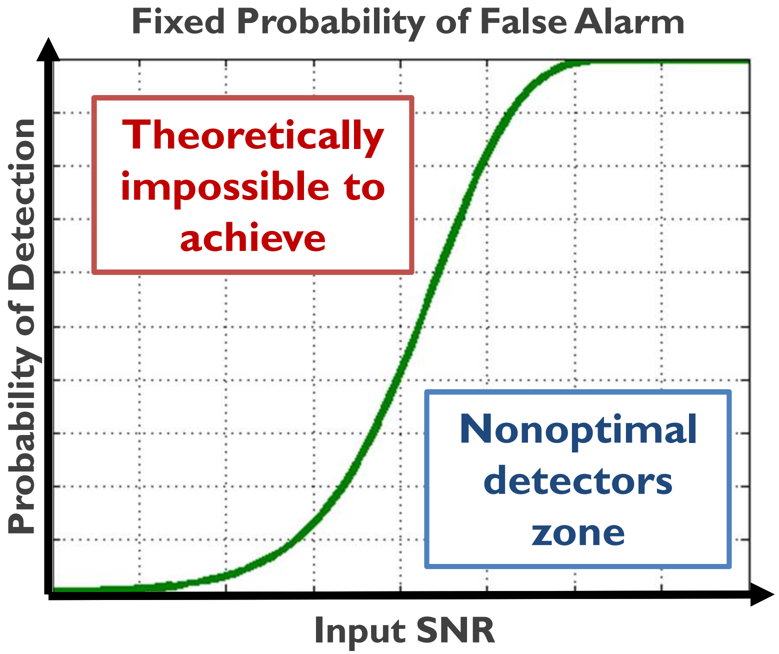
Sensitivity Characterization of Nonoptimal Detectors

- **Optimal Detector: Coherent Integration exclusively**

- ✓ Through its statistical characterization it is possible to express the required input Signal-to-Noise Ratio (SNR) to achieve a given working point (P_d, P_{fa}):

$$SNR_{in} = f\,(P_d, P_{fa}, N) = SNR_{in,min}$$

- ✓ Theoretical minimum SNR required to achieve target working point



Sensitivity Characterization of Nonoptimal Detectors

- **Nonoptimal Detector: Coherent Integration + Nonoptimal Operation(s)**

Correlation Output → Σ **N Code Periods** → **Nonoptimal Operation** → **Detection Metric**

✓ Given its nonoptimality, the SNR required to achieve the same working point as the optimal detector is higher than $SNR_{in,min}$:

$$SNR_{in,req}\,(P_d\,,\,P_{fa}) > \; SNR_{in,min}\,(P_d\,,\,P_{fa})$$

✓ The sensitivity loss of the nonoptimal detector can then simply expressed as:

$$L_{detector} = \frac{SNR_{in,req}\left(P_d, P_{fa}\right)}{SNR_{in,min}\left(P_d, P_{fa}\right)}$$

From statistical characterization of nonoptimal detector!

From statistical characterization of optimal detector

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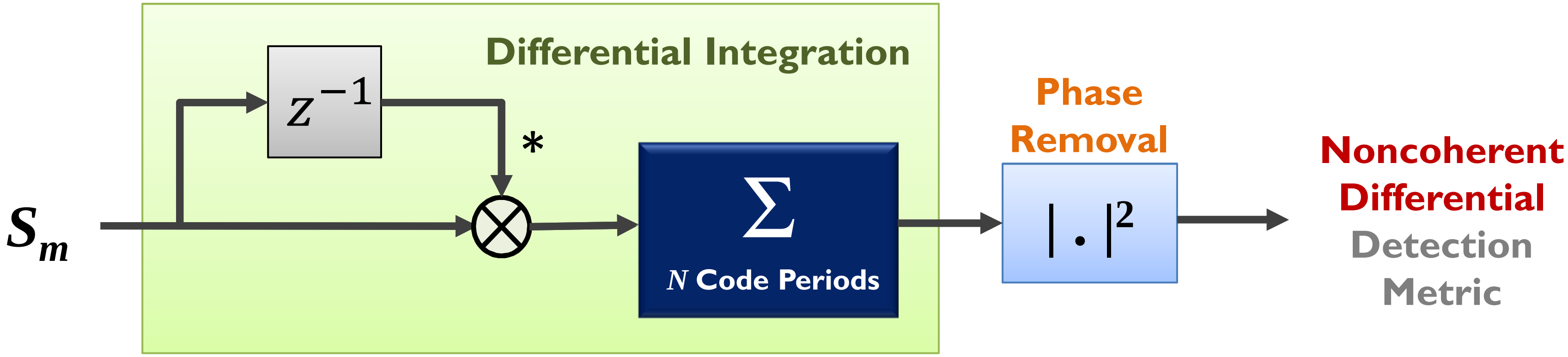
Noncoherent Differential Detector Sensitivity

- **Noncoherent Differential Detector (NCDD)**
  - ✓ Most appropriate differential detector for GNSS applications



- NCDD sensitivity loss: combination of ***differential*** and ***squaring*** losses!
  - ✓ Squaring loss is known from noncoherent integration

How to find the sensitivity loss of differential integration?

➡ **Statistical characterization of differential operation!**

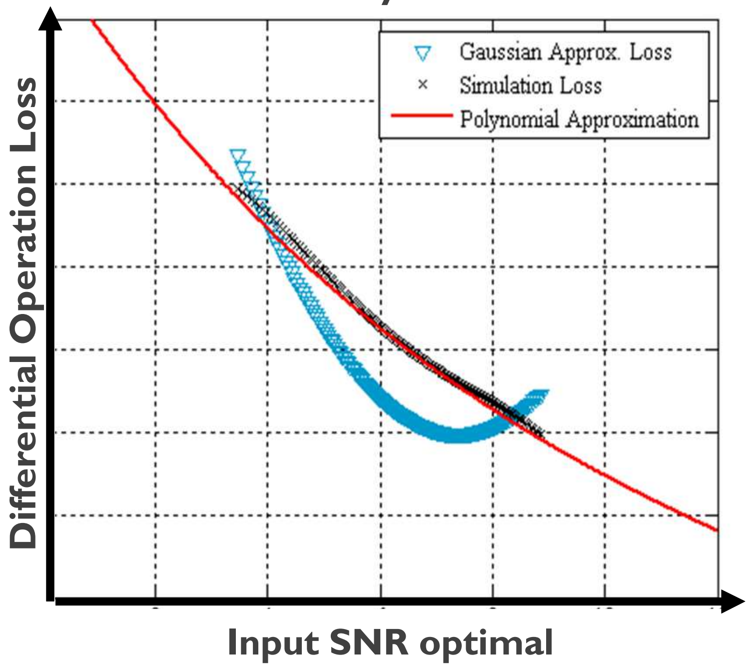
Noncoherent Differential Detector Sensitivity

Sensitivity Loss of Differential Operation

- ✓ Statistical characterization of differential operation:
  - Apparently « good » fit between theory and simulation results
  - Not good enough **to propose a model for the sensitivity loss** given the significantly different profile

Model proposed based on simulation results exclusively

Fixed Probability of False Alarm



- **Theoretical Loss**
- **Simulation Loss**
- **Proposed Approximation**

Noncoherent Differential Detector Sensitivity

Sensitivity Loss of NCDD Detector

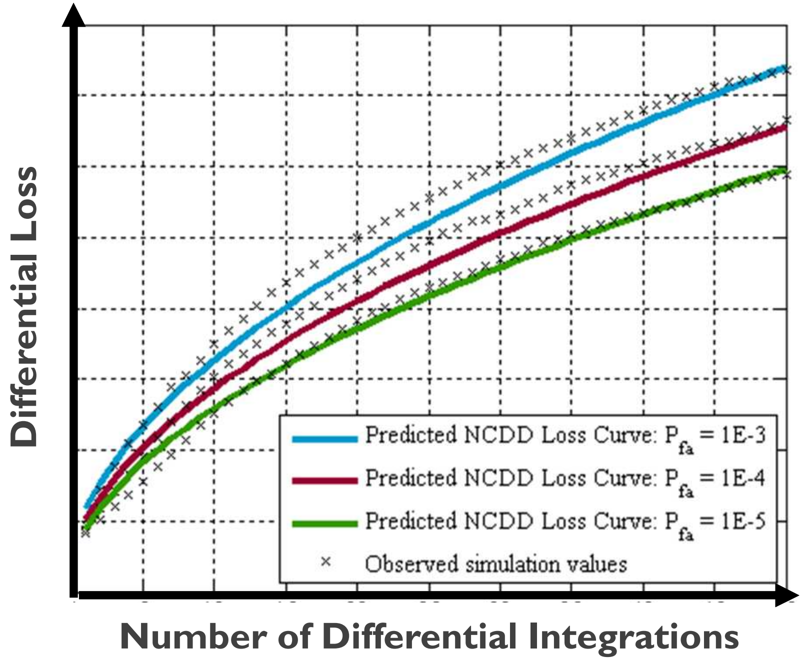
- Mathematical « subtility » to extend proposed model from **1** to **N** differential integrations

- Proposed formula includes all targeted parameters:

$$L_{NCDD} = f\,(N, P_d\,, P_{fa})$$

$$\approx 1 + \frac{0.2 \cdot\ (N+1)}{SNR_{diff}} + \frac{0.45 \cdot\ \sqrt[3]{(N+1)}}{\sqrt[3]{SNR_{diff}}}$$

$$SNR_{diff} = f\ (P_d\,, P_{fa})$$



- Simulation analyses show ***very good fit*** of proposed formula in predicting NCDD sensitivity

Part II: Thesis Contributions

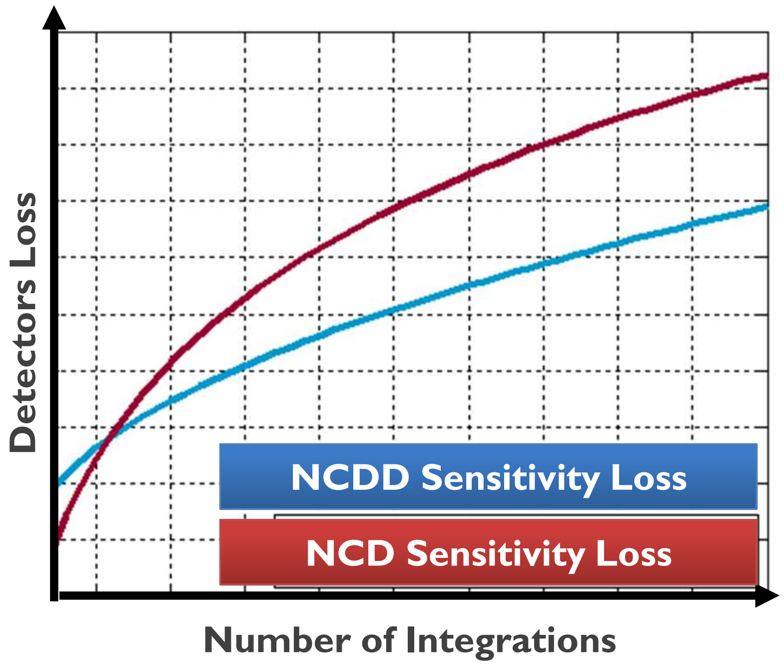
Part IIB: Sensitivity Characterization of Differential GNSS Detectors

Contents:

Comparison with Noncoherent Detector

- The proposed formula allows the objective of comparison of the **NCDD** with the Noncoherent Detector (**NCD**)

  Example: Sensitivity loss of NCDD and NCD detectors for $(P_d, P_{fa}) = (0.9, 1E\text{-}5)$



- Examples of application of proposed formula described in the thesis

- Theoretical conclusions validated by acquisition of **real GPS data**

- In case of **medium-** or **high-dynamics**, NCD shown to be more robust than NCDD

Part II: Thesis Contributions

Part IIB: Sensitivity Characterization of Differential GNSS Detectors

Contents:

Conclusions

- Given **limitations of coherent integration**, transition to **postcoherent integration** is typical for acquiring weak signals
  - ✓ **Noncoherent integration** - standard and well-characterized technique
  - ✓ D**ifferential integration -** still required full characterization
- Theoretical and simulation results enabled proposal of a formula for the **sensitivity characterization of the NCDD detector**
- The objective of formal comparison between the **NCDD** and the **NCD detectors** can now be conducted

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Part IIC: Systematic and Efficient Collective Acquisition of Multi-Constellation GNSS Signals

Contents:

1. Introduction
2. Systematic and Efficient Collective Acquisition
3. Hybridization with Sequential Acquisition
4. Multi-Constellation Collective Acquisition
5. Conclusions

Part II: Thesis Contributions

Part IIC: Systematic and Efficient Collective Acquisition of Multi-Constellation GNSS Signals

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Introduction

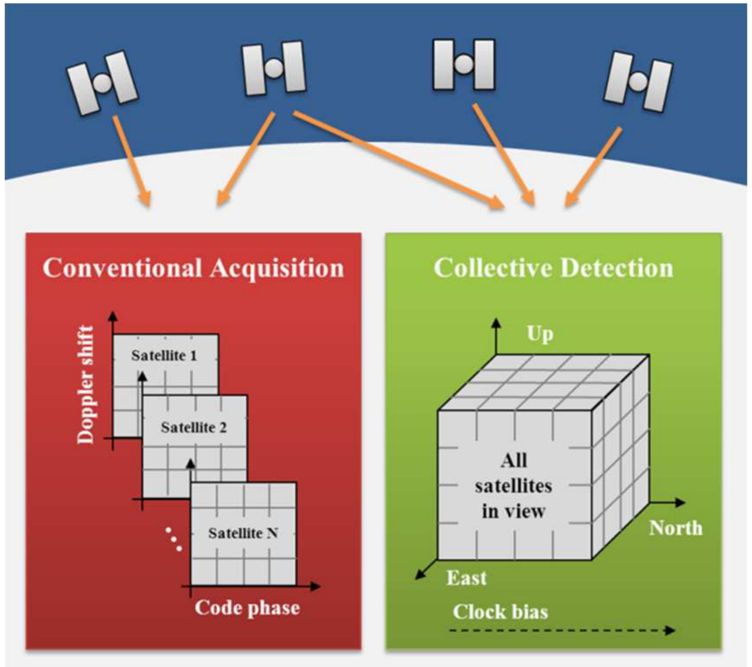
- GNSS signals are usually acquired independently from one another
- New acquisition techniques (***combined acquisition***) recently developed in which signals are ***combined to improve overall acquisition sensitivity***

→ **New Approach: Collective Detection / Collective Acquisition**

Individual satellites (**2D**) **code phase** and **Doppler** search

mapped into

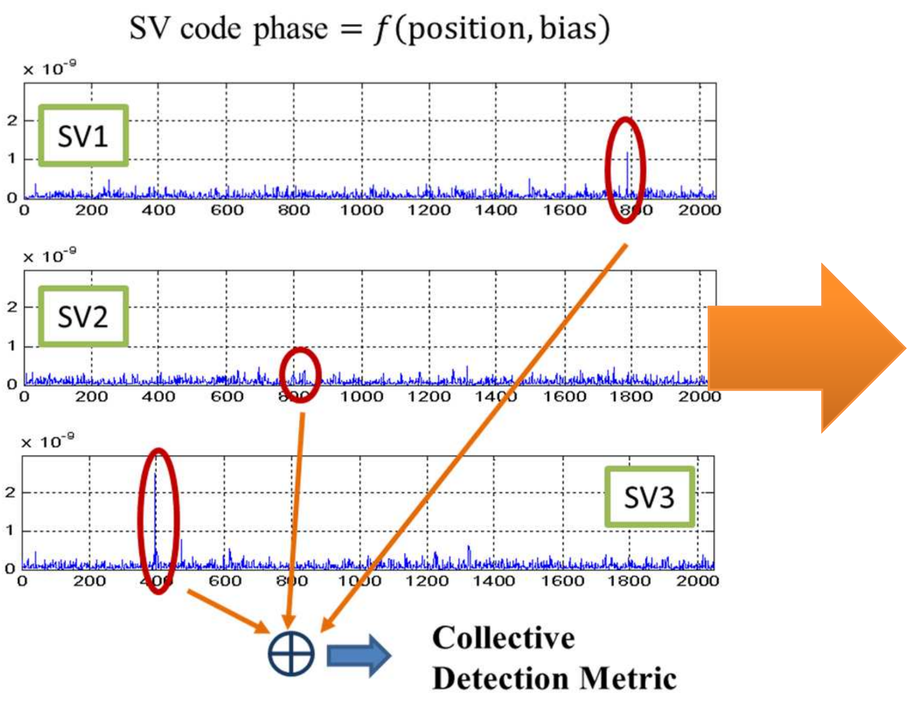
User (**4D**) **position** and **clock bias** domain

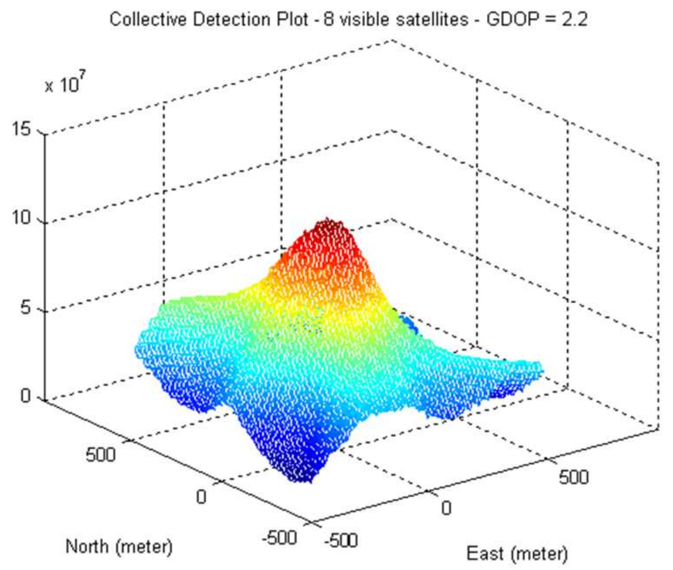


Objective: **Acquire all visible satellites at the same time (collectively)**

Introduction

- **Collective Detection principle:** estimate signal code phases based on candidate position and clock bias
  - ✓ **Doppler offset can be removed to a great extent through Assistance information**





Collective Detection output at correct estimated clock bias

Introduction

- Biggest drawback in Collective Detection ➡ **Complexity**

Example search grid found in literature [Axelrad 2011]

Item	Rough (m)	Medium (m)	Fine (m)
North/East	±10.000	±2.000	±900
North/East Step	1.000	100	30
Clock Bias	±150.000	±1.200	±300
Clock Bias Step	1.000	100	30
Number of Points	**132.741**	**42.025**	**182.329**

+350.000 points

- Search grid impacts not only **complexity** but also **sensitivity**!

First Objective: **Propose a methodology for the systematic and efficient application of Collective Detection**

- ✓ **Systematic** – Search steps are determined by a set of input parameters
- ✓ **Efficient** – Avoid excessively fine and computationally heavy search grids

Part IIC: Systematic and Efficient Collective Acquisition of Multi-Constellation GNSS Signals

Contents:

Systematic and Efficient Collective Acquisition

How to ensure a Systematic and Efficient Collective Detection search process?

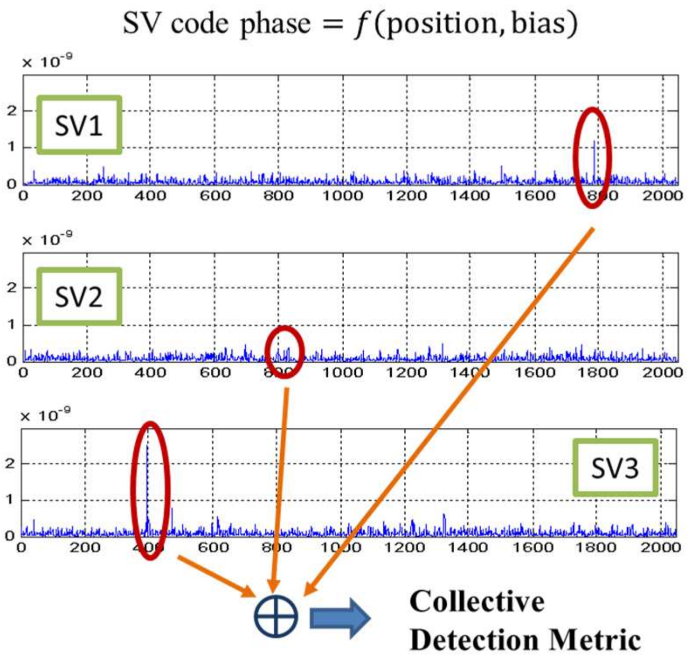
Satellite **code phase** is function of:

1. **User position** 2. **User clock bias**

Satellite **code phase search resolution** is function of:

1. User position **search resolution**
2. User clock bias **search resolution**

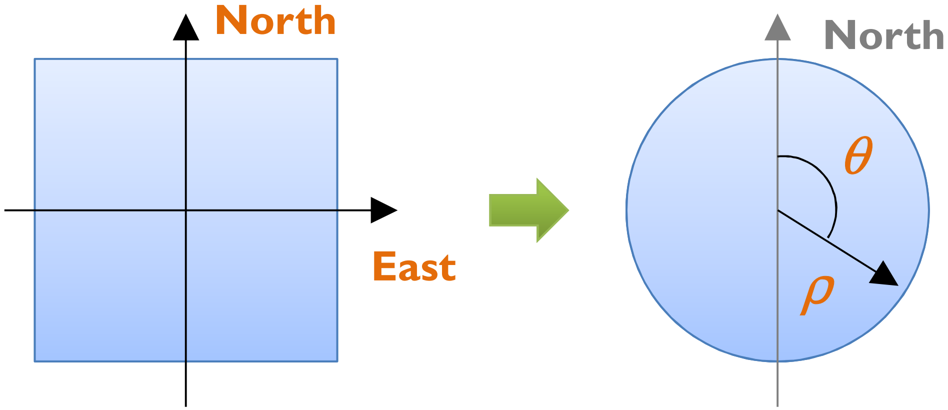
The inverse is also applicable!



Maximum allowable code phase estimation error →

- **Position search step**
- **Clock bias search step**

Proposed Approach: redefinition of horizontal search from North-East to Rho-Theta coordinates



- ✓ More intuitive
- ✓ Simplifies mathematics involved

Maximum allowable code phase estimation error, β

Radius search step	$\delta R = f\,(\,\beta, w_{position}\,)$
Angular search step	$\delta\theta = f\,(\,\beta, w_{position}\,)$
Clock bias search step	$\delta B = f\,(\,\beta, w_{bias}\,)$

Systematic and Efficient Collective Acquisition

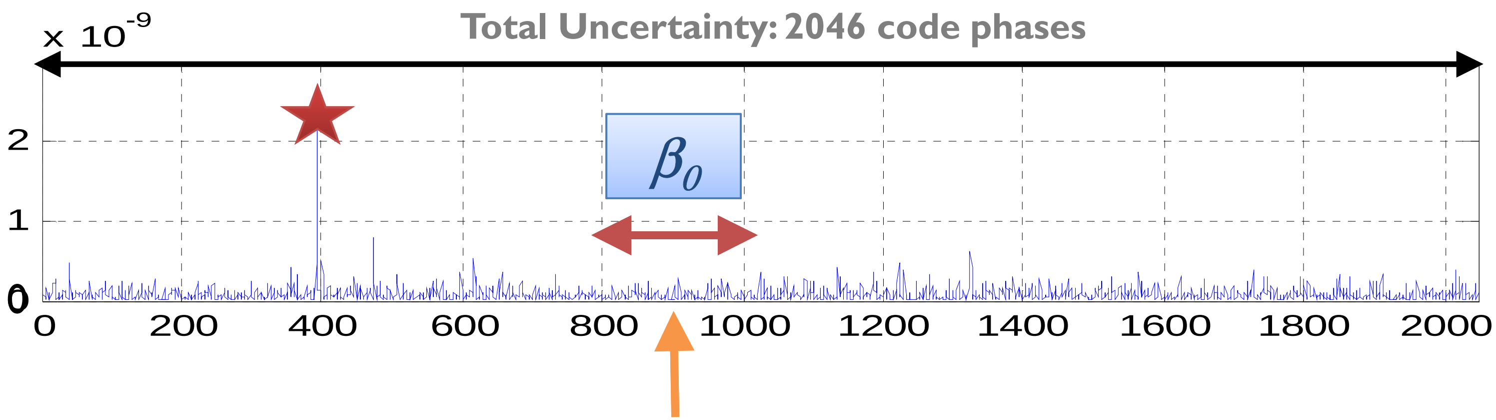
- The **lower** the maximum allowable code phase estimation error is…

  … the **higher** the number of search points to consider!

1. **Iterative search process**
2. **Code phases considered are a range around the central code phase**

First Iteration

β_0 – **initial maximum tolerable code phase estimation error**



Systematic and Efficient Collective Acquisition

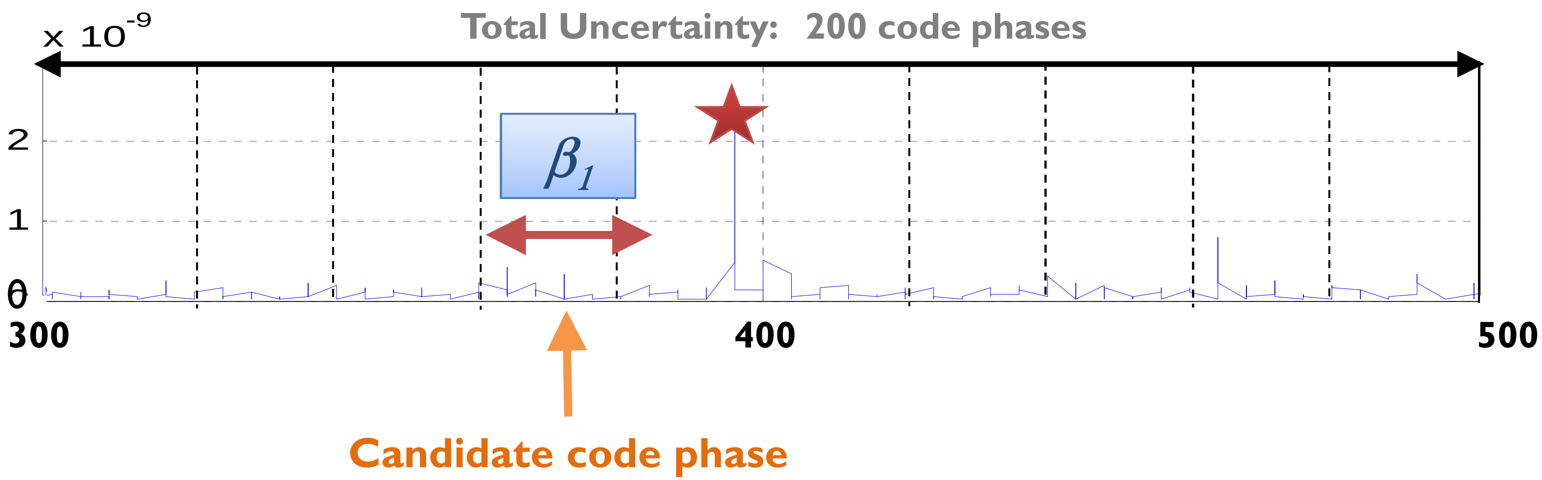
- The **lower** the maximum allowable code phase estimation error is…

  … the **higher** the number of search points to consider!

1. **Iterative search process**
2. **Code phases considered are a range around the central code phase**

Second Iteration

$\beta_1 = \beta_0$ / **division factor**



Systematic and Efficient Collective Acquisition

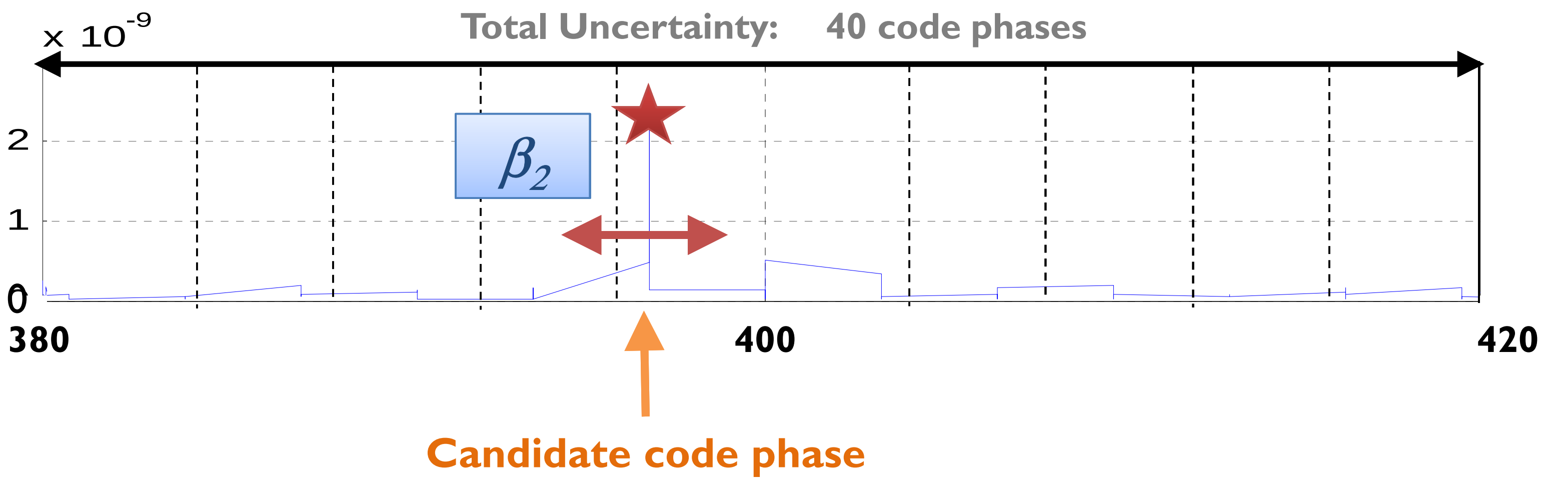
- The **lower** the maximum allowable code phase estimation error is…

  … the **higher** the number of search points to consider!

1. **Iterative search process**
2. **Code phases considered are a range around the central code phase**

Third Iteration

$\beta_2 = \beta_1$ / division factor



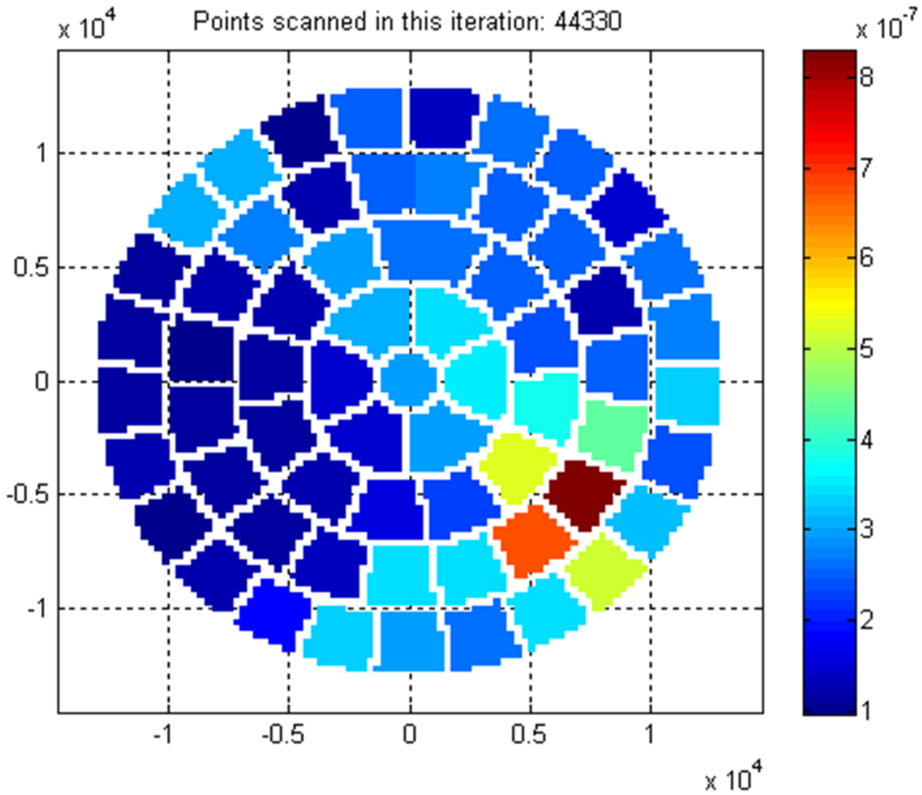
Systematic and Efficient Collective Acquisition

Example of application

- ✓ **6 nominal power satellites**
- ✓ **True user position:** $(\Delta N, \Delta E) = (-4000, 7000)$
- ✓ **Radial uncertainty:** 10km
- ✓ $\beta_0 = 5$ chips, $\beta_i = \beta_{i-1} / 10$
- ✓ **3 iterations**

Iteration	Number of search points
1	44330

First Iteration

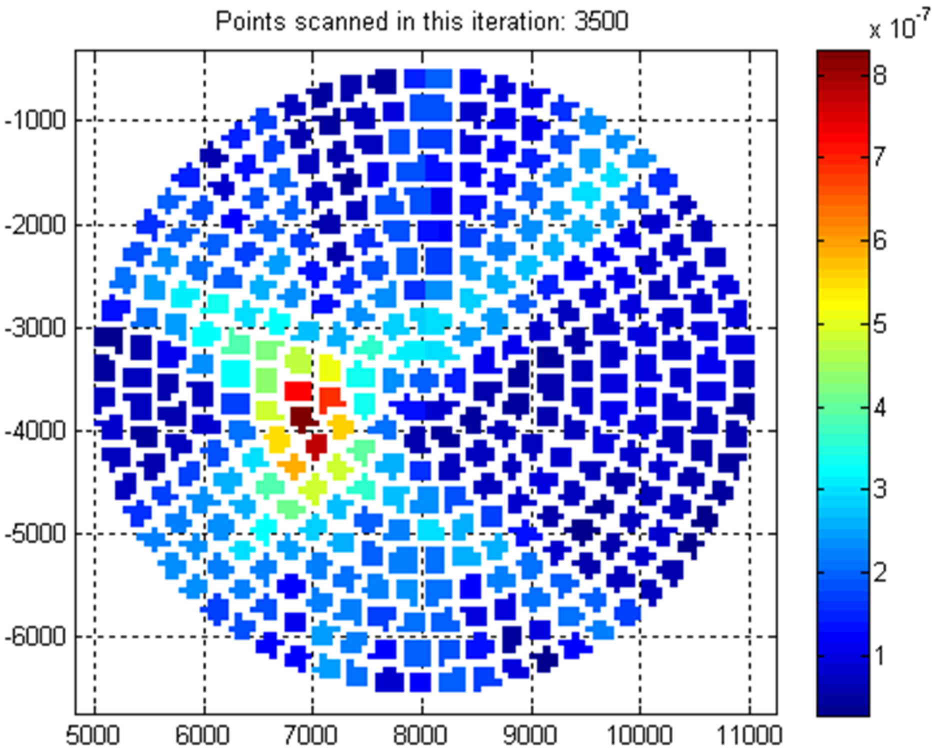


Systematic and Efficient Collective Acquisition

- **Example of application**
  - ✓ **6 nominal power satellites**
  - ✓ **True user position:** $(\Delta N, \Delta E)$ = (-4000, 7000)
  - ✓ **Radial uncertainty:** 10km
  - ✓ β_0 = 5 chips, $\beta_i = \beta_{i-1} / 10$
  - ✓ **3 iterations**

Iteration	Number of search points
1	44330
2	3500

Second Iteration

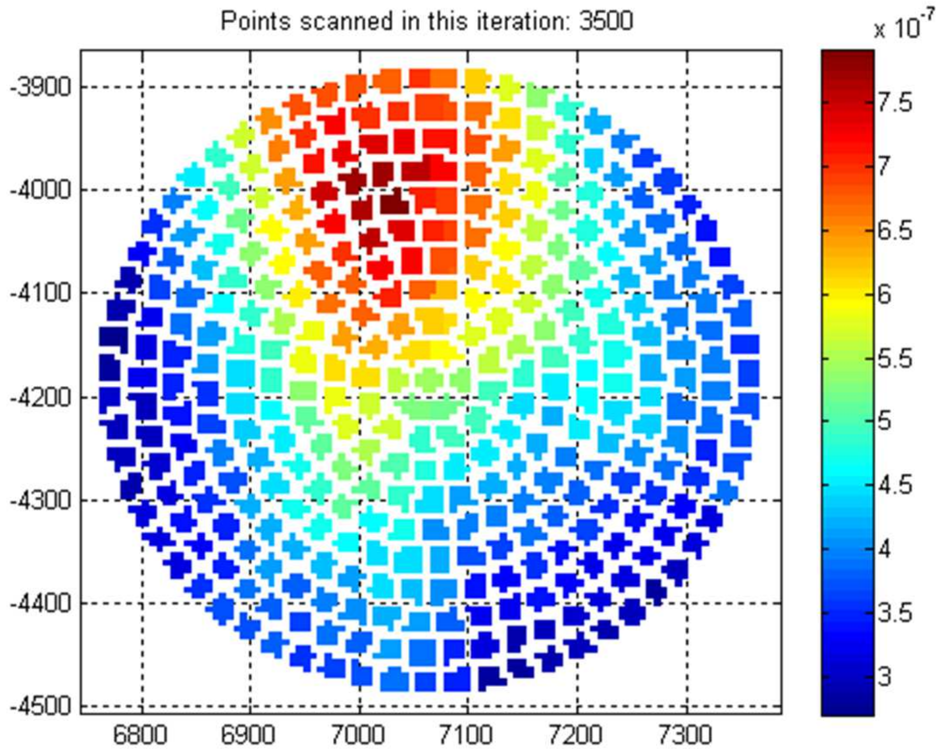


Systematic and Efficient Collective Acquisition

- **Example of application**
  - ✓ **6 nominal power satellites**
  - ✓ **True user position:** $(\Delta N, \Delta E)$ = (-4000, 7000)
  - ✓ **Radial uncertainty:** 10km
  - ✓ β_0 = 5 chips, $\beta_i = \beta_{i-1} / 10$
  - ✓ **3 iterations**

Iteration	Number of search points
1	44330
2	3500
3	3500
Total	**52030**

Third Iteration



1+ orders of magnitude more efficient than fixed step search grids found in literature

Part II: Thesis Contributions

Part IIC: Systematic and Efficient Collective Acquisition of Multi-Constellation GNSS Signals

Contents:

1. Introduction
2. Systematic and Efficient Collective Acquisition
3. Hybridization with Sequential Acquisition
4. Multi-Constellation Collective Acquisition
5. Conclusions

Hybridization with Sequential Acquisition

- Collective Detection is intended for acquisition of weak signals

➡ **In the visible satellite set both strong and weak signals may exist!**

How to profit from strong signals presence in Collective Detection?

1. **Reduce search dimensions** (in particular clock bias)
2. **Establish dependency between search dimensions**

No strong satellites			1 strong satellite			2 strong satellites		
Clock bias (full)	Azimuth	Radius	Clock bias (reduced)	Azimuth	Radius	Clock bias	Azimuth	Radius
↻	↻	↻	↻	↻	$f(x)$	$f(x)$	↻	$f(x)$

➡ **Enhanced sensitivity and complexity (depending on algorithm parameters)**

Part II: Thesis Contributions

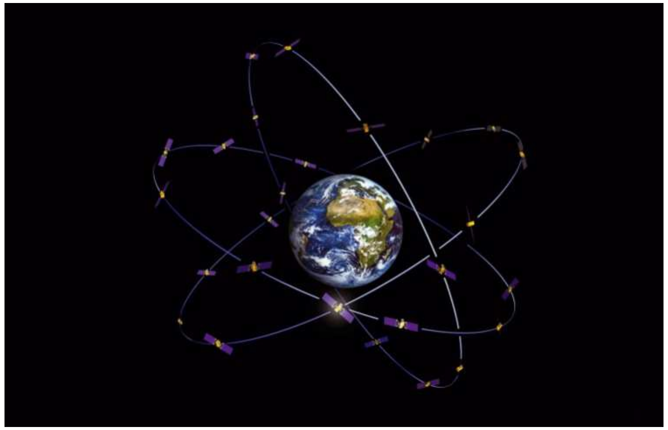
Part IIC: Systematic and Efficient Collective Acquisition of Multi-Constellation GNSS Signals

Contents:

Multi-Constellation Collective Acquisition

- GNSS systems are not limited to GPS!

How to adapt Collective Detection for multi-constellation GNSS signals?



Artist's impression of the Galileo Constellation [European Space Agency website]

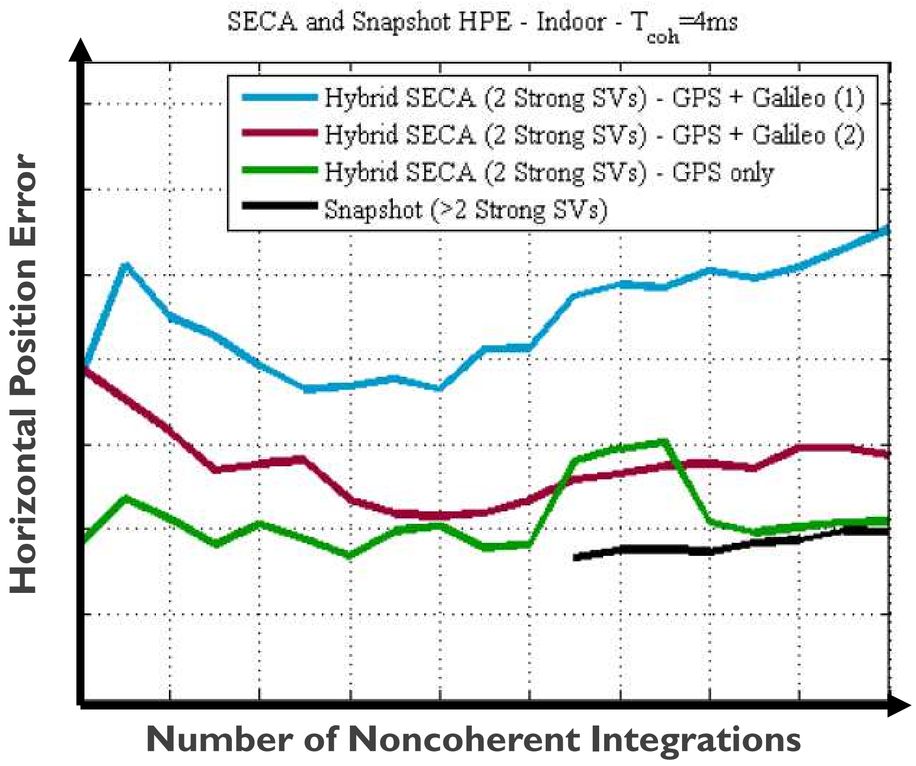
- Multi-Constellation Collective Detection considerations
  - ✓ Time offset between constellations
  - ✓ Difference in code lengths
  - ✓ Difference in clock bias magnitude

➡ **Development of proposals to handle these issues in a combined GPS and Galileo context**

- Preliminary results ***not very promising*** but further assessments are required

Multi-Constellation Collective Acquisition

- **Preliminary assessments carried on Indoor data collection**



- **Combined GPS+Galileo (1)**
- **Combined GPS+Galileo (2)**
- **GPS-Only**

Part II: Thesis Contributions

Part IIC: **Systematic and Efficient Collective Acquisition of Multi-Constellation GNSS Signals**

Contents:

Conclusions

- Collective Detection is an innovative approach capable of improving GNSS signal acquisition sensitivity
- **Biggest drawback** in Collective Detection is the **computational complexity** of approaches found in literature
- A methodology for the **Systematic and Efficient** application of **Collective Detection** has been proposed
- **Hybridization with sequential acquisition** has also been addressed and shown as capable of **improving sensitivity and complexity** of Collective Detection
- The application of Collective Detection in a **multi-constellation GNSS receiver** has also been addressed with the acquisition of both real **GPS** and **Galileo** signals

Presentation Outline

GNSS – Global Navigation Satellite System

Conclusions

- **High-sensitivity GNSS acquisition** is necessary to fulfill current user expectations
- A thorough **state-of-the-art review** allowed identifying possible axes of research
- In this thesis **three different aspects** of high-sensitivity GNSS acquisition were considered for improvement:
  1. **Analysis and Compensation of Doppler effect**
     - Low, Medium, and High-dynamics
  2. **Sensitivity Characterization of Differential Detectors**
  3. **Systematic and Efficient multi-constellation Collective Detection**
- Solutions were proposed for enhancing the overall acquisition process keeping in mind the key **sensitivity-complexity trade-off**

Future Work Recommendations

- ***Doppler***
  - Dynamic scenarios analysis carried **only with linearly changing Doppler** and not validated with real data
  - More complete research of **Doppler change rate estimators** is required for high-dynamics scenario
- ***Differential***
  - Analysis carried assumes that **data bit effect** is aptly mitigated which is not necessarily the case
- ***Collective Detection***
  - Complementary study required for assessing **best parameters** for tuning the proposed methodology
  - More analysis required to assess true potential of Collective Detection for **Indoor scenarios** in a **multi-constellation** receiver context

Published Works

- **5 conference articles:**
  - ✓ Sahmoudi, M., Esteves, P. et al. – **ION GNSS 2011**
  - ✓ Esteves, P., Sahmoudi, M. et al. – **ION GNSS 2012**
  - ✓ Esteves, P., Sahmoudi, M. et al. – **ENC 2013** ***Best student presentation award***
  - ✓ Esteves, P. – **ION GNSS 2013** ***Best student paper award***
  - ✓ Esteves, P., Sahmoudi, M. et al. – **SIGNALS 2013**
- **1 journal article** (accepted, under second revision)**:**
  - ✓ Esteves, P., Sahmoudi, M. and Boucheret, M.-L. – **IEEE TAES**
- **1 magazine article** (to be published in next issue)**:**
  - ✓ Esteves, P., Sahmoudi, M. and Ries, L. – **Inside GNSS**

Thank you!

Questions?