Karlsruhe Institute of Technology

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

Robust Reception for a Satellite-based Global Rescue System

European GNU Radio Days 2023

Felix Artmann, Marcus Müller

Overview

- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

COSPAS-SARSAT

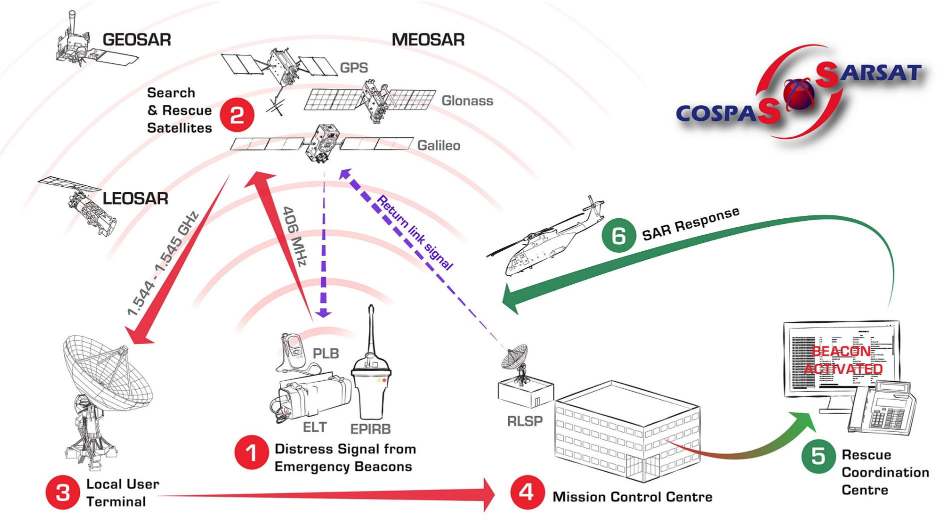


Image source: INTRODUCTION TO THE COSPAS-SARSAT SYSTEM, C/S G.003, Issue 7, November 2019

Project Setup

- Joint development effort with Becker AG
  - Manufacturer of aeronautical equipment
  - Had gen. 1 COSPAS-SARSAT devices, but no way to support gen. 2
- Project coordination: German Aerospace Center (DLR),
  financial support bei German federal Ministry of Economy Affairs and Climate Action (BMWK)
- CEL Goals:
  - Assist Becker in transition to SDR
  - Develop reference implementation
  - Value-add functionality through overlay system and awareness
- CEL Theses:
  - **Reference transceiver** (Elena Schütz, Felix Artmann)
  - Overlay in satellite uplink (Messmer)
  - Overlay in auxiliary chirp homing signal (Gölz, Manz, Messmer, . . .)

Overview

- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

COSPAS-SARSAT – System Characteristics

Karlsruhe Institute of Technology

- Information bit stream: $300\,\mathrm{bit\,s^{-1}}$
  - Message length = $300\,\mathrm{bit}$
  - Preamble length = $50\,\mathrm{bit}$
- **Offset-QPSK**
- **Direct Sequence Spread Spectrum**
  - Spread using Pseudo Random Noise (PRN)
  - Two different sections of an **m-Sequence** for in-phase and quadrature components
  - **I** : PRN_1
  - **Q**: PRN_2
- Properties
  - Spread factor $L = 256$
  - Output stream: 38400 chips/second
  - Signal hidden from others

Overview

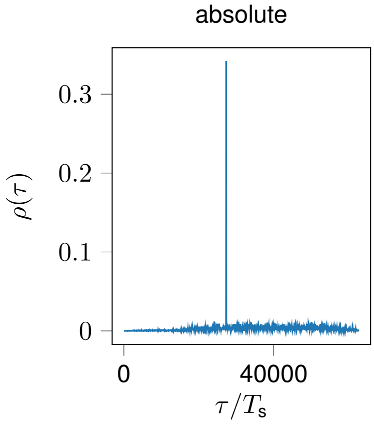
- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

Overview

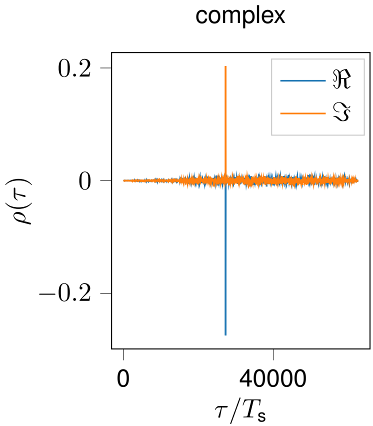
Karlsruhe Institute of Technology

- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

Receiver Detection and Phase Correction



(a) Time



(b) Phase

- Correlation with preamble (6400 chips)
- Sent signal

$$\Re\{A_{\text{Tx}}\} = \text{PRN}_1$$
$$\Im\{A_{\text{Tx}}\} = \text{PRN}_2$$

- Received signal

$$\Re\{A_{\text{Rx}}\} = \Theta_1 \cdot \text{PRN}_1 + \Theta_2 \cdot \text{PRN}_2$$
$$\Im\{A_{\text{Rx}}\} = \Theta_2 \cdot \text{PRN}_1 - \Theta_1 \cdot \text{PRN}_2$$

$$A_{\text{corr}} = A_{\text{Rx}} \cdot e^{-j \cdot \varphi_{\text{peak}}}$$

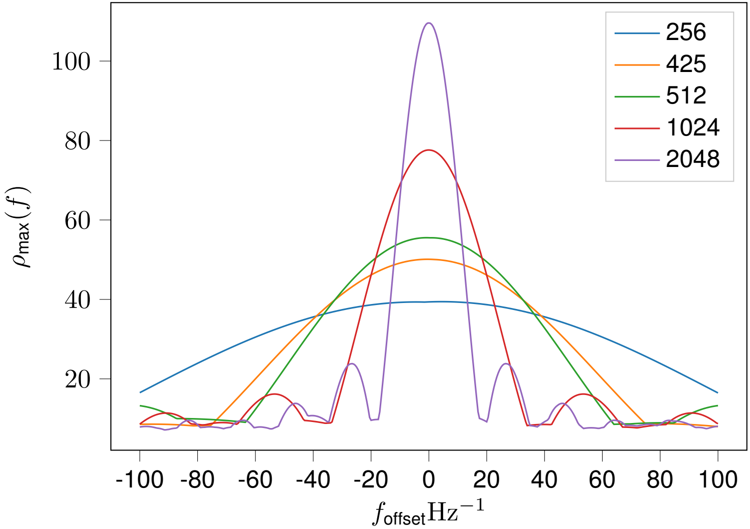
Overview

Karlsruhe Institute of Technology

- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

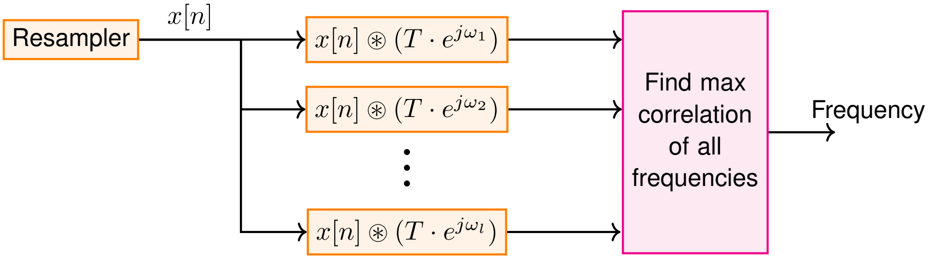
Frequency Offset

- Same procedure as on slide before but **truncated** preamble
- Deviation expected in the range of at least $-400\,\mathrm{Hz}$ to $400\,\mathrm{Hz}$
- Peak gets barely visible
- Need for **Frequency Detection**



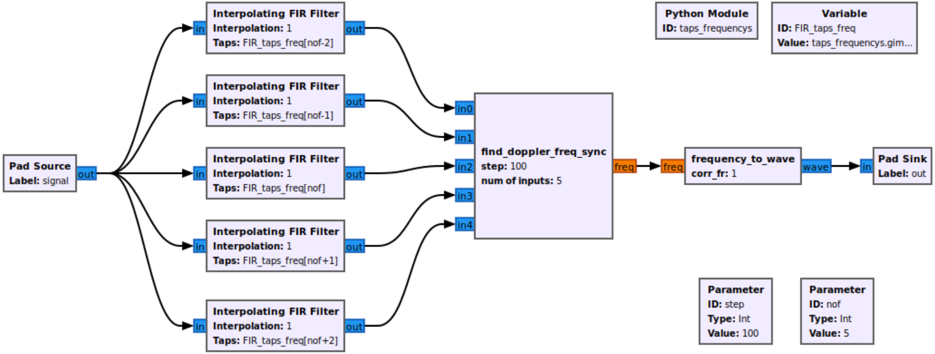
Signal Detection: Correlator Bank

- Correlation with several frequency shifted versions of the preamble (T)
- Eventually reducing the susceptibility for frequency variations by only using fraction of the preamble
  - By that: possible to increase $\Delta\omega$



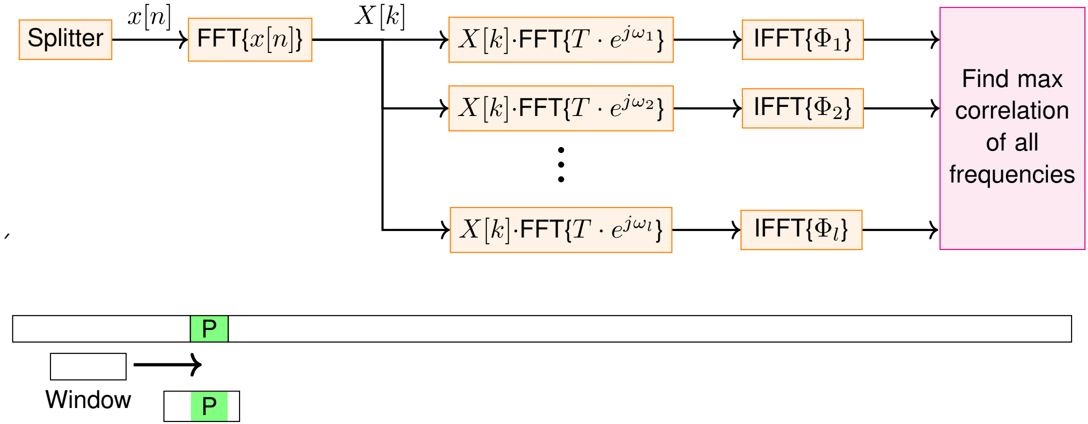
Signal Detection: Correlator Bank – GRC

- Using FIR filters
- First stage; $f_{\text{grid}} = 100\,\text{Hz}$; covered spectrum: $-250\,\text{Hz} < f < 250\,\text{Hz}$

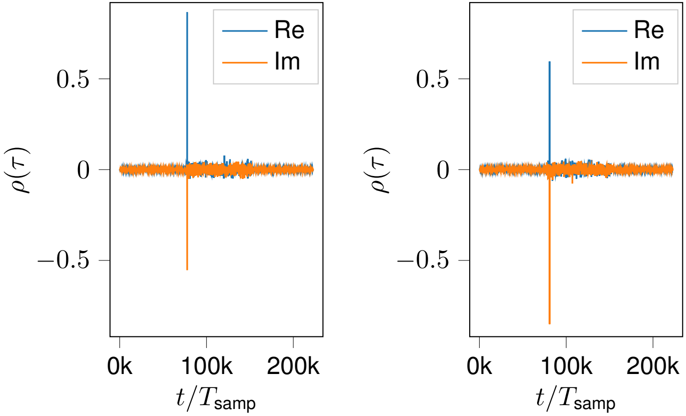


Signal Detection: Filters in DFT Domain

- Use Fast Fourier Transform



Fine Frequency Sync: Split Preamble Method



(a) first half of preamble   **(b)** second half of preamble

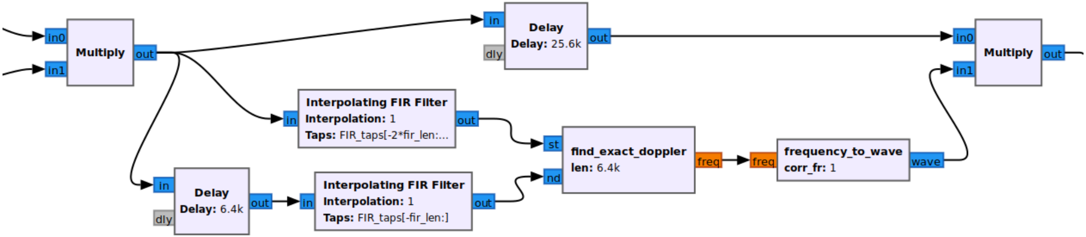
- **So far:** Coarse estimation of frequency
- **Now:** Exact determination by evaluating the phase shift
  - Split preamble
  - Difference of phase angles of correlation peaks

$$\varphi_{\text{diff}} = \varphi_B - \varphi_A \quad (1)$$

$$t_{\text{delay}} = \frac{3200}{38400\frac{1}{s}} = \frac{1}{12}s = 0.08333s \quad (2)$$

$$f_{\text{diff}} = \frac{\varphi_{\text{diff}}}{t_{\text{delay}} \cdot 2 \cdot \pi} \quad (3)$$

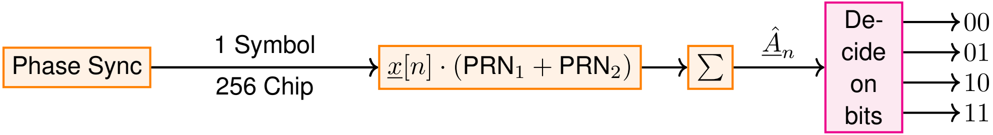
Fine Frequency Sync: Split Preamble Method (GRC)



Overview

- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

Despreading: $\sum$-PRN



- Despreading by multiplication of BPSK-symbols with BPSK-preamble
- Computationally advantageous
- Quadrature cross-talk if phase not perfect

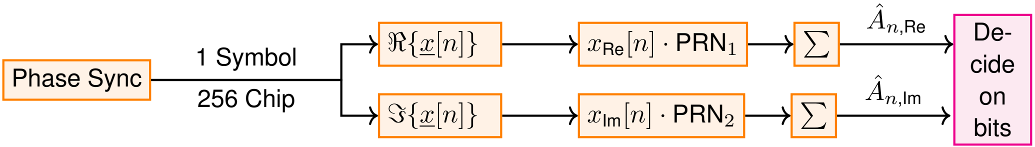
$$\underline{x}[n] = a[n] + jb[n]$$

$$P[n] = a[n] \cdot (\mathrm{PRN}_1 + \mathrm{PRN}_2) + jb[n] \cdot (\mathrm{PRN}_2 + \mathrm{PRN}_1)$$

$$\lim_{\mathrm{SNR}\to\infty} P \approx \sum_{n=1}^{256} a[n] \cdot \mathrm{PRN}_1 + jb[n] \cdot \mathrm{PRN}_2$$

Despreading: Split-IQ PRNs

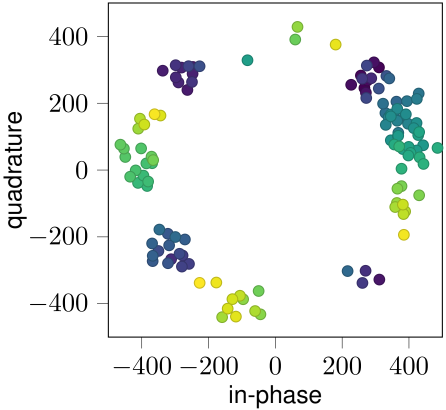
Karlsruhe Institute of Technology



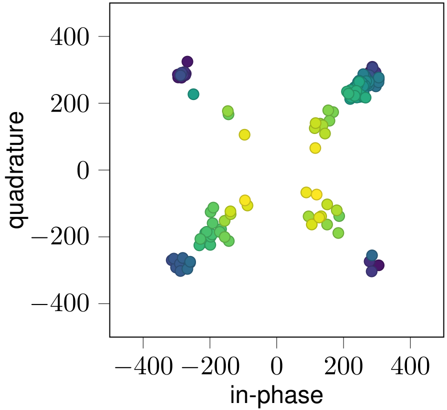
- Despreading separately for PRN_1 and PRN_2
- Two multiplications in real domain
- Eliminates quadrature cross-talk, halves noise power

Despreading: Comparison

- Frequency error can change after preamble
- Compare constellation diagrams with error of $0.3\,\mathrm{Hz}$ blue $\xrightarrow{\text{time}}$ yellow



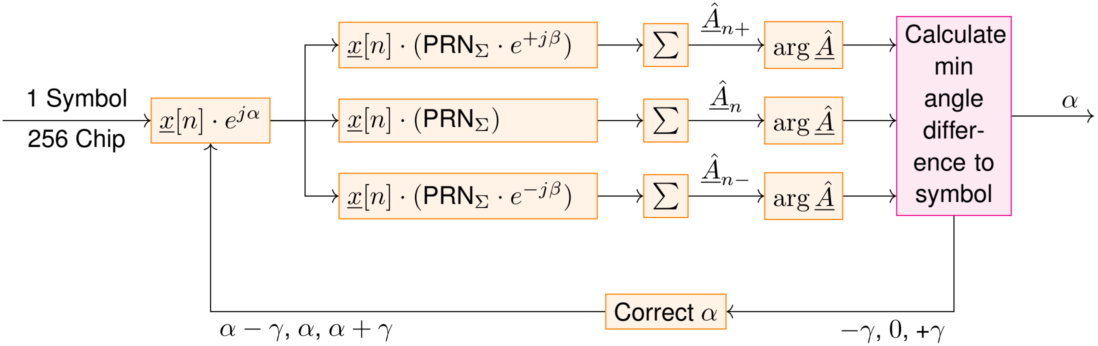
(a) $\sum$-PRN despreading



(b) Split-IQ despreading

Adaptive Despreading: Phase Error Feedback

- Despreading with feedback of phase error based on $\sum$-PRN method
- $\text{PRN}_\Sigma = \text{PRN}_1 + \text{PRN}_2$

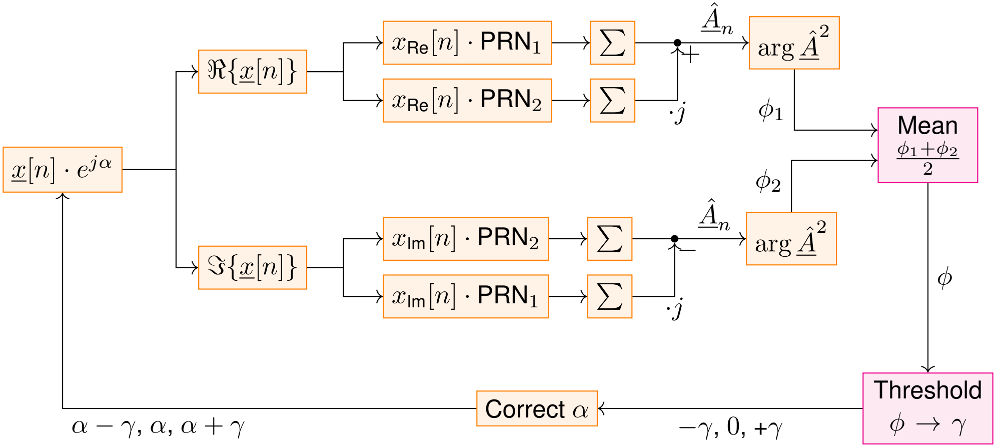


Problem: Still using the worse sum-PRN for despreading.

Adaptive Despreading: Split-IQ with Phase

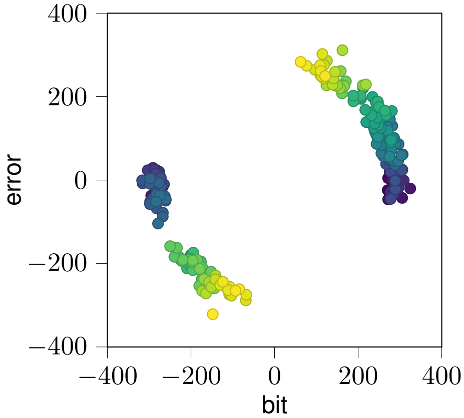
Karlsruhe Institute of Technology

- Method to use Split-IQ and still correct evolving phase error?

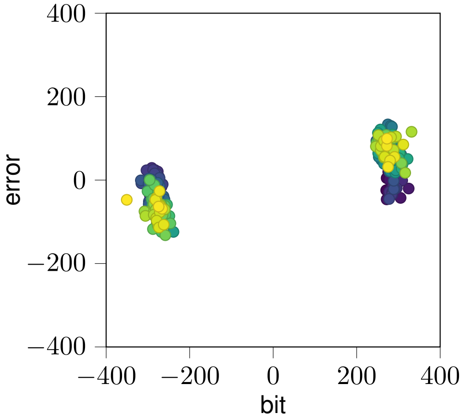


Adaptive Despreading: Results

Simulated frequency error of $f_{\text{off}} = -0.3\,\text{Hz}$



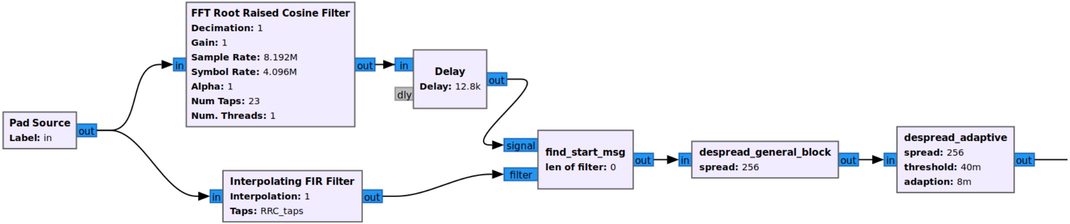
(a) without correction



(b) correction w. $\phi_{\text{thres}} = 2\pi \cdot 0.05$ and $\gamma = 2\pi \cdot 0.01$

Adaptive Despread Implementation

- Adaptive Despreading also implemented



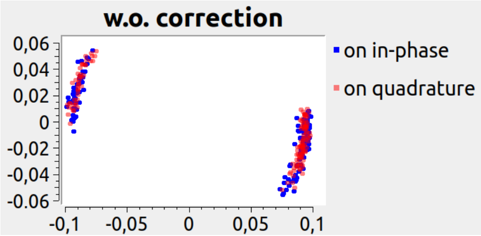
Overview

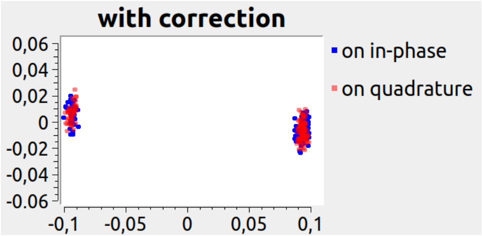
- Introduction
  - COSPAS-SARSAT
- Techniques and Algorithms
  - Signal Detection: Time and Phase
  - Signal Detection: Frequency Offset
  - Despreading
- Evaluation Over-the-air
- Conclusion & Outlook

Over-the-air results

- Tests using two different USRPs over the air
- Detected frequency offset around $100\,\mathrm{Hz}$
- Detection and synchronization **successful**

- Adaptive despread
- Constellation diagrams from GNU Radio GUI with real-world data and identical stream





Overview

Karlsruhe Institute of Technology

Conclusion & Outlook

Take-Away

- Creation of (as far as we know) first functional transceiver for 2nd gen COSPAS-SARSAT
- Usage of improved frequency correction methods pushes beyond standard
- Over-the-air proven, suitable for deeply embedded implementation

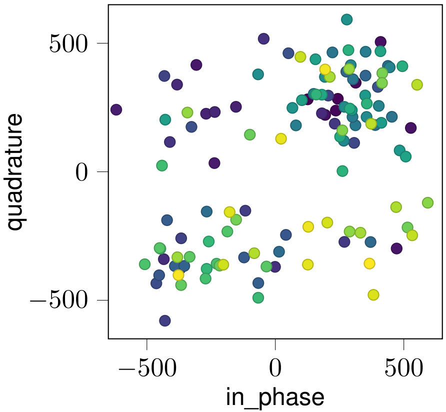
Next up

- Integration with overlay systems
- GNU Radio through MEO
- Shrink-Down to microcontroller (Becker)

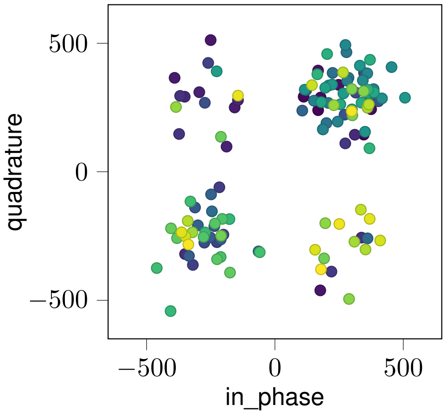
FIN

Karlsruhe Institute of Technology

Questions?



(a) $\sum$-PRN method



(b) Split-IQ method

Implementation in GNU Radio

- Using **GNU RADIO**
- Communication via USRPs

THE FREE & OPEN SOFTWARE RADIO ECOSYSTEM

- **GNU RADIO** is a Toolkit

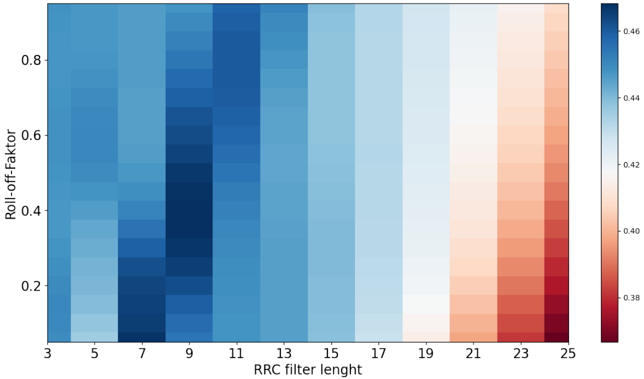
Image source: https://www.gnuradio.org/

Optimization of RRC Filter Length and Roll-off-Factor

Karlsruhe Institute of Technology

- Simulation of different output and mf filters
- Normalization of power
- Adding AWGN
- Compare correlation[1]

- Optimum at around $\beta = 0.35$ and $N = 9$ Taps[2]

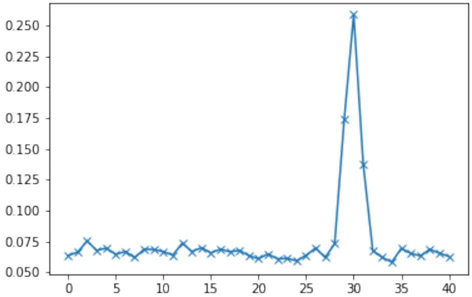


[1] The result is not yet deterministic as it includes randomness
[2] Simulation with SNR=-10dB

Doppler Shift Correction

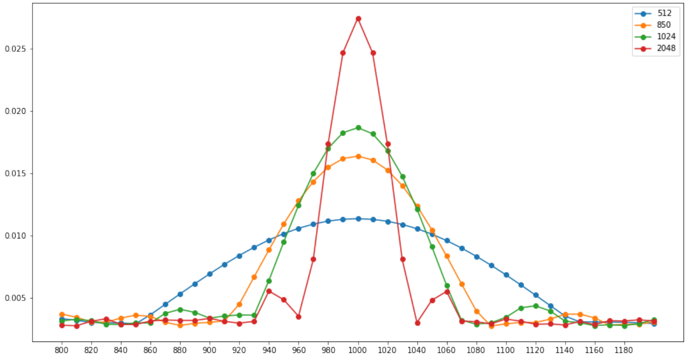
- What can be done?
  - Correlation with several frequency shifted versions of the preamble
  - Reducing the susceptibility for frequency variations by only using fraction of the preamble (next slide)

- Using only 512 chips of preamble
- Vary over a range of -2000 Hz to 2000 Hz
- Raster of 100 Hz



Optimization of Doppler Shift Correction

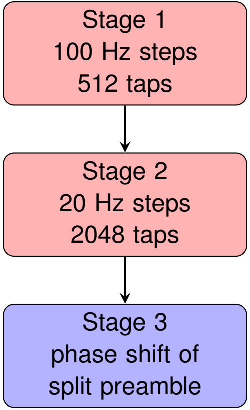
- By shortening the length of the correlated preamble frequency sensitivity gets smaller but peak also gets lower
  - Frequency raster can be higher
  - **But:** Risk of not finding the peak
- Simulation of different lengths



Implementation of Receiver (Previous Version)

- Which method will be used?
- Consideration of least possible resource usage but also reliable detection

- Use three-stage doppler correction
  - Frequency-shifted preamble taps over whole spectrum[3]: grid of 100 Hz; 512 taps
  - Frequency-shifted preamble taps over narrow range: grid of 20 Hz; 2048 taps
  - Time shifted preamble taps with accurate detection detection by phase shift calculation



[3] expected doppler range from -400Hz to 400Hz