"Higher Robustness of GNSS Receiver through Interference Mitigation Techniques for Single-Element Antenna Concepts"

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Structure of this presentation

1. Objectives of my PhD
2. ESA project TERMINATE
3. Interference suppression unit (ISU) with a SDR/USRP
4. Types of interferences and the RFI impact to GNSS receivers
5. Maximum theoretical mitigation capability based on the hardware parameter
6. Overview of mitigation methods
7. Influence on timing applications
Objectives of the PhD

1. **RFI Mitigation: Consideration of the full signal chain**
   - Hardware and software
   - Maximum theoretical mitigation capability based on the hardware parameter (assumption of a perfect DSP mitigation)

2. **Finding a solution, which handles the overall complexity of various DSP algorithms**
   - There are many papers and solution proposed, but which methods are better and more flexible under manifold RFI conditions?
   - What is the optimum parametrization for this methods?
     - e.g. filter depth, thresholds, windowing
   - Which ones are real-time capable?
     - in general: CPU/GPU
     - for: FPGAs?

3. **Real-time demonstration (development platform) with a interference suppression unit for existing GNSS receivers/infrastructures**

4. **Definitions of a metrics, which quantifies the RFI robustness of the GNSS receivers and/or mitigation techniques** (improved comparability)
   - includes appropriate test scenarios

5. **How is the influence to applications?**
   - like timing, RTK, PPP
Starting point for my PhD:
ESA project “TERMINATE” (from 2012 to 2015)

Concept Demonstrator
Novel Signal Processing Interference Cancellation

- Objective was to investigate a future GNSS receiver design offering a visibly superior interference detection and rejection capability compared to that typically achieved by state of the art commercial GNSS receivers
- Validation of the enabling techniques and features by means of an IDM concept demonstrator based on a commercial receiver (IFEN GmbH, SX-NSR Software Receiver)
- RF-FE: 8bit, 10 MHz band width
- RF-FE also provides a very high out-of-band signal rejection
- Algorithms are based on:
  - AGC (fast/slow mode, Pulse Blanking)
  - Statistical Tests
  - FIR and IIR filter (for time-stationary “standard” and time-varying “adaptive”)
  - Fourier Transform (FT)
  - Short-Time Fourier Transform (STFT)
  - Fractional Fourier Transform (FrFT)
  - Wavelet Transform (WT)
  - Signal Tracking and Suppression
  - Karhunen-Loève-Transform (KLT)

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1 “Interference Mitigation based on Novel Signal Processing Cancellation and RF-Front-End (TERMINATE)”, funded by ESA-ESTEC (Netherlands)
Consortium of the University FAF Munich, IFEN GmbH and WISER S.r.l.
(ESA Project Officer: Francisco Amarillo Fernandez)
Concept of the ISU (1)

any GNSS antenna

any GNSS receiver
Concept of the ISU (2)

any GNSS antenna

NI USRP RIO

any GNSS receiver

PC for signal analysis and control of the DSPs

FPGA Kintex7

ADC

FIFO

FIFO

DAP Mitigation

DAC

RF Cable

PXLe-x4

GNSS Receiver
Potential Interference Sources

- **in-band signals**
  - Military/Civil Aeronautical Communication Systems
    - tactical air navigation (TACAN)
    - distance measuring equipment (DME)
  - Ultra-Wideband Signals (UWB)
  - Personal Privacy Devices (PPDs) / Jammer
  - Amateur TV

- **out-of-band signals**
  - Analog TV Channels
  - DVB-T Signals
  - VHFCOM
  - FM Harmonics
  - Personal Electronics Devices (PED)
  - SATCOM
  - VOR and ILS Harmonics
  - Mobile Satellite Service (MMS)
  - Mobile Phone Interference

- **Focus on PPDs**
  - reported by T. Kraus and R.H. Mitch at ION GNSS 2011 [Kra][Mit]

- **Additionally to RFI projected GNSS receivers, the PPD issue can be controlled by the government**
  - Latest example: “FCC Fines Chinese Retailer $34.9 Million for Marketing Illegal ‘Jammers”, Mai 2016 [FCC]
**Question:**
How robust are GNSS signals against RF interferences?

**Answer, which you usually get:**
- “GNSS signals are very weak on earth and that’s why they are not robust against RF interferences”

→ Is this “phrase” correct?
GNSS signals and RFI

- GNSS signals are buried under the thermal noise.
- The noise floor is defined by the overall noise figure of the GNSS receiver and antenna.
  - Any increase of the noise floor, which can also be caused by RFI, is degrading the SNR of the GNSS signal.

\[
\frac{C}{N_0} = \frac{S}{N + I}
\]
GNSS Signal Degradation (RFI Power) and RFI Tolerance

Test setup and RFI power level:
- Initial RFI power at the antenna:
  - $P_{init,ant} = -116.5\text{dBm}$
- Initial RFI power at the GNSS receiver:
  - $P_{init,receiver} = -91.0\text{dBm}$
- Receiver:
  - Septentrio PolaRx4
- RFI:
  - CW
  - $f_{CW} = f_{\text{GPS}, L1} + 1.023\text{MHz}$

\[
\frac{C}{N_0} = \frac{S}{N + I} = \frac{S}{N + P_{init} + P_{Normalized}}
\]

- **Tolerable Jamming Power** is “here” defined as power of the RFI, which is not or only slightly affecting the SNR.
  - equals to the end of “Region I” (see one slide before)
  - Other methodology used by “GPS Adjacent-Band Compatibility Assessment Plan” of the U.S. Department of Transportation (DOT):
    “1dB reduction of the $C/N_0$ defines the tolerable jamming power”
RF Signal Chain of the ISU Setup
(for the calculation of the maximum mitigation capability)

- **Active antenna:**
  - LNA: $NF\ 1.5\,dB$, $G \approx 50\,dB$

- **SDR/USRP**
  - the full chain of RF components
    (appears at the running order)
    - Amplifier: $G=13.2\,dB$
    - Switch (Selection of the Input Channel)
    - Digital attenuator
    - Amplifier: $G=13.2\,dB$
    - Digital attenuator
    - RF transformer
    - Demodulator: $G=6.8\,dB$
    - ADC Driver
    - ADC: 14-bit
Maximum Theoretical Mitigation Capability

- **Maximum Theoretical Mitigation Capability (MTMC)** is the maximum regain we can get, because of the hardware conditions
  - based on the hardware parameter under the assumption of a perfect DSP-suppression of the RFI
- Tests have shown that the **MTMC for RFIs with constant power** can be calculated by the **third-order intercept point IP₃ minus the power of the noise floor**
  - \( G_{MTMC} = IP_3 - N \)
- The **noise floor at the input of the SDR** is determined by the antenna and cable (gain of the LNA of the antenna \( G_{ant} \) and \( NF_{ant} \))
  - \( N[\text{dBm/Hz}] = N_0 + NF_{ant} + G_{ant} \)
  - The minimum gain of the antenna (including the loss of the cable) is given through the Friis formular
    - **given**: \( NF_{ant} = 1.5\text{dB}, \) \( NF_{SDR} = 5\text{dB}, \) \( BW_{ant} = 130\text{MHz}; \) **design traget**: \( NF_{system} = 1.5\text{dB} \)
    - \( \rightarrow G_{ant,min} = 25.5\text{dB} \)
    - \( N_0 = k \cdot T_{eq} [\text{W/Hz}] = -174\text{dBm/Hz} (@ NF = 0\text{dB}) \)
    - \( N[\text{dBm}] = N[\text{dBm/Hz}] \cdot 10 \log (BW_{ant}) = -65.9\text{dBm} \)
  - \( G_{MTMC} = IP_3 + 65.9\text{dBm} = ??\text{dB} \)
ETTUS SBX RF Board
(Part of NI USRP 29x2R)

- IP3 = -15dB
- NF = 5dB

Gain of the USRP [dB] →
Maximum Theoretical Mitigation Capability

- **Maximum Theoretical Mitigation Capability**
  - \( G_{\text{MTMC}} = \text{IP}_3 + 65.9\,\text{dBm} = ??\,\text{dB} \)
  - \( G_{\text{MTMC}} = -15\,\text{dBm} + 65.9\,\text{dBm} = 50.9\,\text{dB} \)

- **Dynamic range of an A/D-Converter**
  - \( DR[\text{dB}] = 20 \cdot \log_2^n = 6.02 \cdot n \)
  - The SDR (USRP) has a 14-bit ADC
  - \( \rightarrow DR = 84.3\,\text{dB} \)

- **Effective number of bits (ENOB)**
  - \( ENOB = \frac{\text{SINAD} - 1.76}{6.02} = \frac{50.9 - 1.76}{6.02} = 8.2 \)
  - SINAD is the ratio indicating the quality of the signal
  - The 6.02 term in the divisor converts decibels to bits
  - The 1.76 term comes from quantization error in an ideal ADC
RFI mitigation
RFI Mitigation Methods (Groups)

• There are various methods to mitigate RFI:
  (each with pro and cons; combined solutions possible or desired)
  • on hardware side or digital domain
  • Pre- or post-correlation
  • Single aperture antenna
    ▪ one port: e.g. RHCP
      – Digital Signal Processing (DSP)
        » Destructive: filtering (time- or frequency domain)
        » Non-Destructive: subtraction of the “perfect” RFI replica
    ▪ two port: e.g. RHCP+LHCP or vertical/horizontal
  • Array antenna (CRPA)
    ▪ Analog: Phase-shifters and amplifiers/attenuators
    ▪ Digital beamforming
Pre- and Post-Correlation Mitigation

- **Pre-Correlation Mitigation:**
  - DSP occurs before the correlation process
  - Signal stream modification usually common to all GNSS signals

- **Post-Correlation Mitigation:**
  - Implemented after the correlation process
  - allows (or even forces) satellite specific processing
Destructive and Non-Destructive

- **Destructive** RFI mitigation
  - Filter is also reducing part of the energy of the GNSS signal

- **Non-Destructive** RFI mitigation
  - non-destructive in an ideal situation → but, can also become destructive
Front-end Modifications (Recommendations)

- **Improved analog filter** to avoid that out-of-band RFI is saturating the RF components or mirroring into the in-band

- **High fidelity ADCs** to get a linear representation of the RFI
  - ADCs (and analog RF components), which are operating in the non-linear region because of RFI, are “destroying” the noise floor where the GNSS signals are buried.

- **Modification of the ADC methodology**

- **Reduction of the overall “analog” gain**
  - Possible because of the multi-bit ADCs (at least 8-bit)
List of DSP mitigation techniques
(primarily for signal aperture antenna solutions)

- Pulse Blanking
- FIR and IIR filter
  - Notch-Filter
- Fourier Transform (FT)
  - Short-Time Fourier Transform (STFT)
- Fractional Fourier Transform (FrFT)
- Wavelet Transform (WT)
  - Wavelet-Packet-Decomposition
- Suppression with a RFI replica
- Karhunen-Lòeve-Transform (KLT)
- Mitigation via Polarization

increase of the data processing requirements

low DSP requirements, but at least the double amount of hardware resources
Mitigation of a FM Signal and the Maximum Signal Dynamic of the ISU

RFI:
- FM
- $f_C = f_{GPS} + 2\text{MHz}$
- Waveform: Sine
- Waveform Frequency: 25 kHz
- Deviation: 1 MHz

Mitigation:
- FDAF/STFT
- Overlapping factor: 0.5
- FFT depth: $N = 4096$
- Windowing: Hann

- Initial RFI power at the ISU input $P_{\text{init,ISU}} = -98.9\text{dBm}$
- Initial RFI power at the antenna $P_{\text{init,ant}} = -124.4\text{dBm}$
- Regain of GPS: $G \approx 49\text{dB}$ @ $P_{\text{ant}} = -49.4\text{dBm}$
  - $I/S(\text{GPS}) = -49.4\text{dBm} + 127.5\text{dBm} = 78\text{dB}$
Personal Privacy Device (1)

**RFI:**
- **PPD**
- \( f_{\text{center}} = f_{\text{GPS}} \)
- **BW** = 12.18 MHz
- \( T_{\text{SW}} = 14.48 \mu s \)
- \( T_{\text{SW,up}} = 6.83 \mu s \)
- \( T_{\text{SW,down}} = 7.65 \mu s \)

**Mitigation:**
- FDAF/STFT
- Overlapping factor (OLF): 0.5
- FFT depth: \( N = 1024 \) or 4096
- Windowing: Hann

Initial RFI power at the ISU input: \( P_{\text{init,ISU}} = -92.3 \text{dBm} \)
Initial RFI power at the antenna: \( P_{\text{init,ant}} = -117.8 \text{dBm} \)
Maximum regain of GPS with FDAF/STFT (\( N = 4096 \)): \( G \approx 20 \text{dB} \)

\[
\begin{align*}
  f_S &= 10 \text{MHz} = 10 \text{MS/s} \quad \rightarrow t_S = 100 \text{ns} \\
  t_{\text{FFT},N} &= t_S \cdot N \quad t_{\text{FFT,1024}} = 102 \mu s \quad t_{\text{FFT,4096}} = 410 \mu s \\
  Z_{N,\text{OLF}} &= \frac{t_{\text{FFT}}(1-\text{OLF})}{t_{\text{SW}}} \quad [\# \text{ chirp repetitions}] \\
  Z_{1024,0.5} &= 3.52 \quad Z_{4096,0.5} = 28.31
\end{align*}
\]
Initial RFI power at the ISU input $P_{\text{init,ISU}} = -92.3\,\text{dBm}$

Initial RFI power at the antenna $P_{\text{init,ant}} = -117.8\,\text{dBm}$

Maximum regain of GPS with FDAF/STFT ($N = 4096$): $G \approx 20\,\text{dB}$

- $f_s = 10\,\text{MHz} = 10\,\text{MS/s} \rightarrow t_s = 100\,\text{ns}$
- $t_{FFT,N} = t_s \cdot N \quad t_{FFT,1024} = 102\,\mu\text{s}$
  $t_{FFT,4096} = 410\,\mu\text{s}$

$$Z_{N,OLF} = \frac{t_{FFT\cdot(1-OLF)}}{t_{SW}} \quad \text{[# chirp repetitions]}$$

$Z_{1024,0.5} = 3.52 \quad Z_{4096,0.5} = 28.31$
Personal Privacy Device (2)

- Initial RFI power at the ISU input $P_{\text{init,ISU}} = -92.3\,\text{dBm}$
- Initial RFI power at the antenna $P_{\text{init,ant}} = -117.8\,\text{dBm}$
- Maximum regain of GPS with FDAF/STFT ($N = 4096$): $G \approx 20\,\text{dB}$
- Maximum regain of GPS with “Filter + Blanking”: $G \approx 40\,\text{dB}$ @ $P_{\text{ant}} = -47.8\,\text{dBm}$
  - $I/S(\text{GPS}) = -47.8\,\text{dBm} + 127.5\,\text{dBm} = 79.7\,\text{dB}$

RFI:
- PPD
- $f_{\text{center}} = f_{\text{GPS}}$
- $\text{BW} = 12.18\,\text{MHz}$
- $T_{\text{SW}} = 14.48\,\mu\text{s}$
- $T_{\text{SW,up}} = 6.83\,\mu\text{s}$
- $T_{\text{SW,down}} = 7.65\,\mu\text{s}$

Mitigation:
- FDAF/STFT
- Overlapping factor: 0.5
- FFT depth: $N = 1024$ or 4096
- Windowing: Hann

\[ \text{PPD} = f_{\text{center}} = f_{\text{GPS}} - \text{BW} = 12.18\,\text{MHz} \]
\[ T_{\text{SW}} = 14.48\,\mu\text{s} \]
\[ T_{\text{SW,up}} = 6.83\,\mu\text{s} \]
\[ T_{\text{SW,down}} = 7.65\,\mu\text{s} \]
**RFI:**
- PPD
- $f_{\text{center}} = f_{\text{GPS}}$
- $\text{BW} = 12.18 \text{ MHz}$
- $T_{\text{SW}} = 14.48 \mu\text{s}$
- $T_{\text{SW,up}} = 6.83 \mu\text{s}$
- $T_{\text{SW,down}} = 7.65 \mu\text{s}$

**Mitigation:**
- FDAF/STFT
- Overlapping factor: 0.5
- FFT depth: $N = 1024$ or $4096$
- Windowing: Hann

- Initial RFI power at the ISU input $P_{\text{init,ISU}} = -92.3 \text{ dBm}$
- Initial RFI power at the antenna $P_{\text{init,ant}} = -117.8 \text{ dBm}$
- Maximum regain of GPS with FDAF/STFT ($N = 4096$): $G \approx 20 \text{ dB}$
- Maximum regain of GPS with “Filter + Blanking”: $G \approx 40 \text{ dB}$ @ $P_{\text{ant}} = -47.8 \text{ dBm}$
  - $I/S(\text{GPS}) = -47.8 \text{ dBm} + 127.5 \text{ dBm} = 79.7 \text{ dB}$

[Kra15]
Personal Privacy Device (3)

RFI:
- PPD
- $f_{\text{center}} = f_{\text{GPS}}$
- BW = 12.18 MHz
- $T_{\text{SW}} = 14.48 \mu s$
- $T_{\text{SW,up}} = 6.83 \mu s$
- $T_{\text{SW,down}} = 7.65 \mu s$

Mitigation:
- FDAF/STFT
- Overlapping factor: 0.5
- FFT depth: N = 1024 or 4096
- Windowing: Hann

- Initial RFI power at the ISU input $P_{\text{init,ISU}} = -92.3 \text{dBm}$
- Initial RFI power at the antenna $P_{\text{init,ant}} = -117.8 \text{dBm}$
- Maximum regain of GPS with FDAF/STFT (N = 4096): $G \approx 20 \text{dB}$
- Maximum regain of GPS with “Filter + Blanking”: $G \approx 40 \text{dB} @ P_{\text{ant}} = -47.8 \text{dBm}$
  - $I/S(\text{GPS}) = -47.8 \text{dBm} + 127.5 \text{dBm} = 79.7 \text{dB}$
Mitigation

by using the polarization of the signals
to distinguish between the GNSS and the interference signals

Advantage:
- the only algorithm with a single-aperture antenna, who can mitigate broadband noise RFI
Mitigation with…

- a “two-port” single antenna
  - Using the *polarization* of the signals to distinguish between the GNSS and the interference signals (*any type – even broadband noise*)

RHCP/LHCP antenna

- **RHCP**
  - GNSS signal
  - halve of the interference power

- **LHCP**
  - halve of the interference power


Demonstration (of the concept)

\[ \Delta \theta \approx 0^\circ \]

\( \text{RHCP} \rightarrow \text{Filter}^{(1)} \rightarrow \text{LHCP} \)

\( \Delta \theta \)

Note:
The purpose of this demonstration is to provide a simplified explanation. It is not reflecting a realistic time-domain signal!
Test results (filtered noise, GPS C/A)

Interference Scenario:
- **Filter Noise** centered at GPS L1
- **BW = 1 MHz (3dB) and 1.8 MHz (20dB)**

GPS C/A (PRN 29, elevation ≈ 39°, azimuth ≈ 78°)

- The “Polar Algorithm” is the only algorithm, which can mitigate for GPS C/A in this scenario
- The algorithm starts to become effective at **J/N ≈ 5dB** \(^{(1)}\)
- Systematic loss of **ΔC/N₀ ≈ 6dB**

\(^{(1)}\) = 23dB (Gain of Interference by Attenuator)
ISU and the influence on timing applications

- The latency (group delay) of the USRP transceiver with the software framework of National Instruments is dependent on the setting of the data rate (bandwidth).
  - The USRP has a latency of 108.6 μsec with a 10 MHz bandwidth (measured in our laboratory)
- Additional delay comes with the DSP mitigation:
  - Our FDAF(STFT) implementation with a FFT depth of 1024 increases the delay with further 390 μsec.

**Group Delay:**
- The switching between DSP methods leads to different group delays
- Different coefficient for FIR/IIR filter causes also variable group delays
  - At least for timing applications, any compensation should be done.
Conclusion / Summary

- **Objectives of my PhD**
- „Natural“ robustness of GNSS signals (vulnerability)
- Real-time **Interference Suppression Unit** with SDR/USRP
  - \((I/S)_{\text{max}} = 78\,\text{dB}\); Regain: \(G_{\text{max}} = 49\,\text{dB}\)
- Calculation of the **Maximum Theoretical Mitigation Capability (MTMC)**
  - \(G_{\text{MTMC}} = 50.9\,\text{dB}\) (with the setup of the ISU)
  - ENOB = 8.5 of the ISU (14-bit converter)
- **Mitigation techniques** and test results
  - Each technique has advantage and disadvantages
  - Receivers should be equipped at least with:
    - selectable out-of-band filters (hardware), digital filter and filter banks, pulse blanking and FDAF(STFT)
- **Influence on timing applications**
  - Additional latency (group delay) can not be neglected
References

Books:

Paper:

Presentations:

Internet and websites:
Listed at the website: http://www.gps.gov/spectrum/jamming/
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