Other error sources including jamming and spoofing

NKG Summer School 2016

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Error Sources

- Significant errors present in pseudorange measurements

$$P^k(t) = \rho^k(t, t-\tau) + \delta\rho + c[\delta t_u(t) - \delta t^k(t-\tau)] + I^k(t) + T^k(t) + \varepsilon^k(t)$$

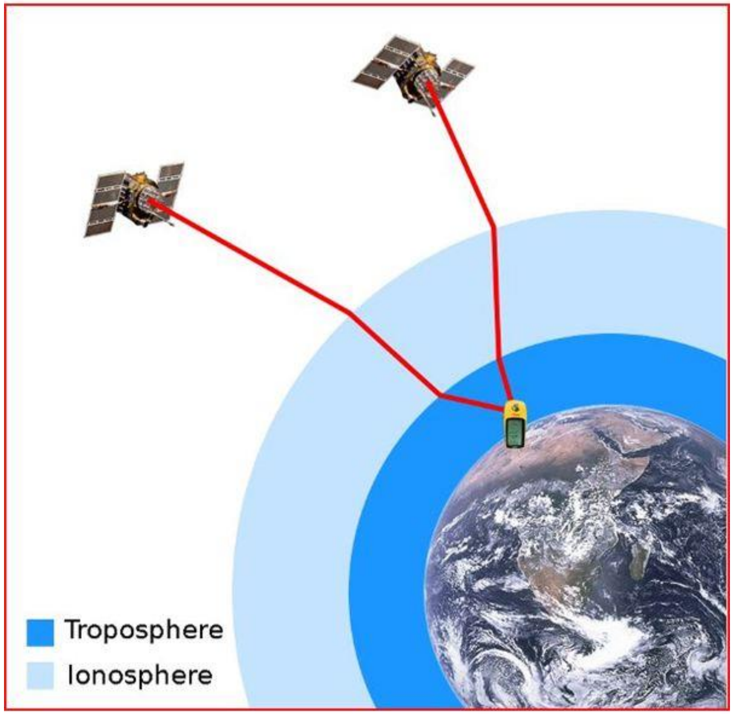
  include
  - Orbital errors
  - Satellite clock errors
  - Ionosphere errors
  - Troposphere errors
  - Receiver noise and multipath errors

+ Other sources

GNSS Error budget

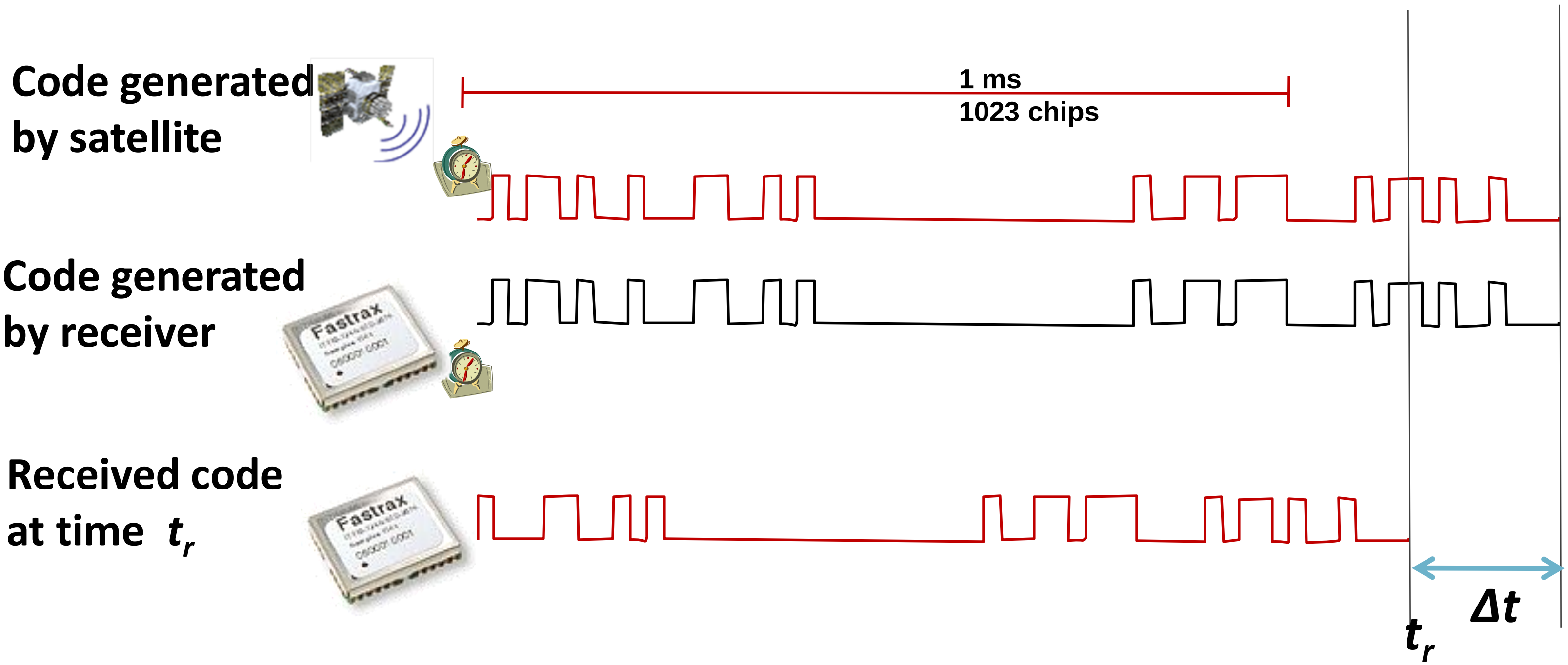
Standard error model - L1 C/A (sources: Samuel J. Wormley http://edu-observatory.org/gps/, E. Kaplan and J. Hegarty: GPS Principles and Applications, 2nd edition, 2006)

Error source	One-sigma error, m
Ephemeris data	1.1 - 2.1
Satellite clock	1.1 - 2.1
Ionosphere	4.0 - 7.0
Troposphere	0.2 - 0.7
Multipath [1]	0.2 - 1.4
Receiver measurement	0.1 - 0.5



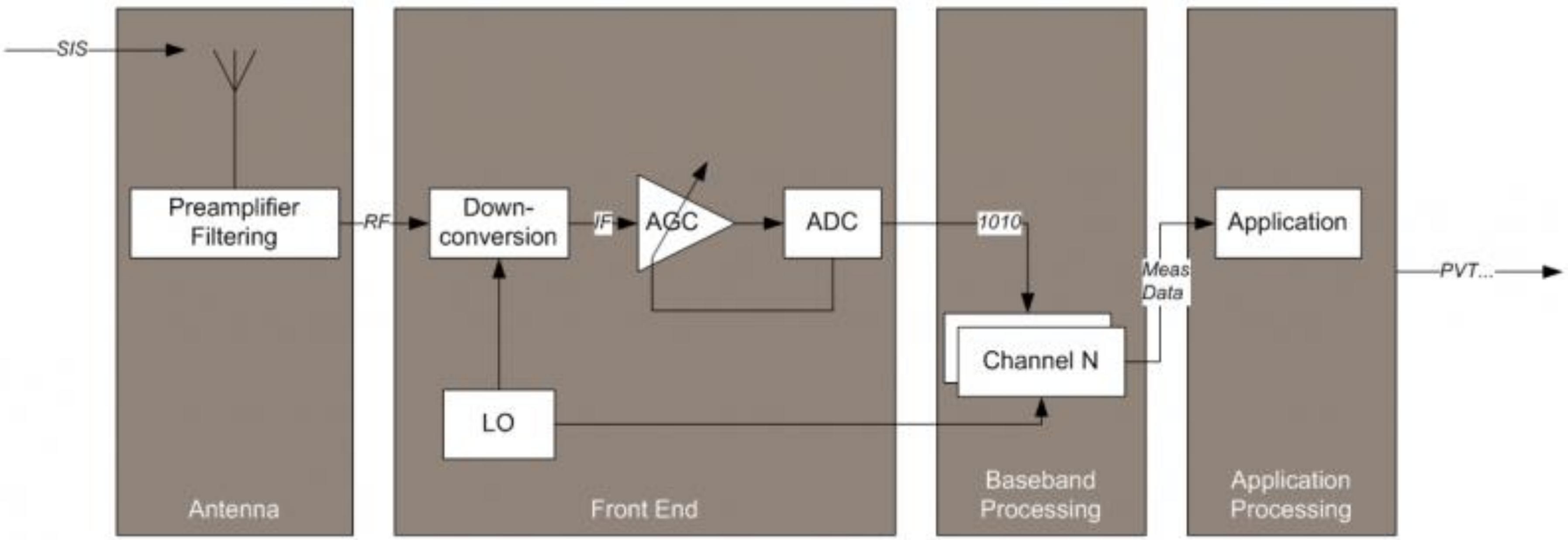
- **Ionospheric effects are the main error source for line-of-sight signals**
- **[1] Much more in e.g. challenging urban environments**

GNSS Receiver (1)



The received code from the satellite is delayed by Δt with respect to the code generated in the receiver that replicates the satellite transmitted code. This delay is the signal time of flight from the satellite to the receiver.

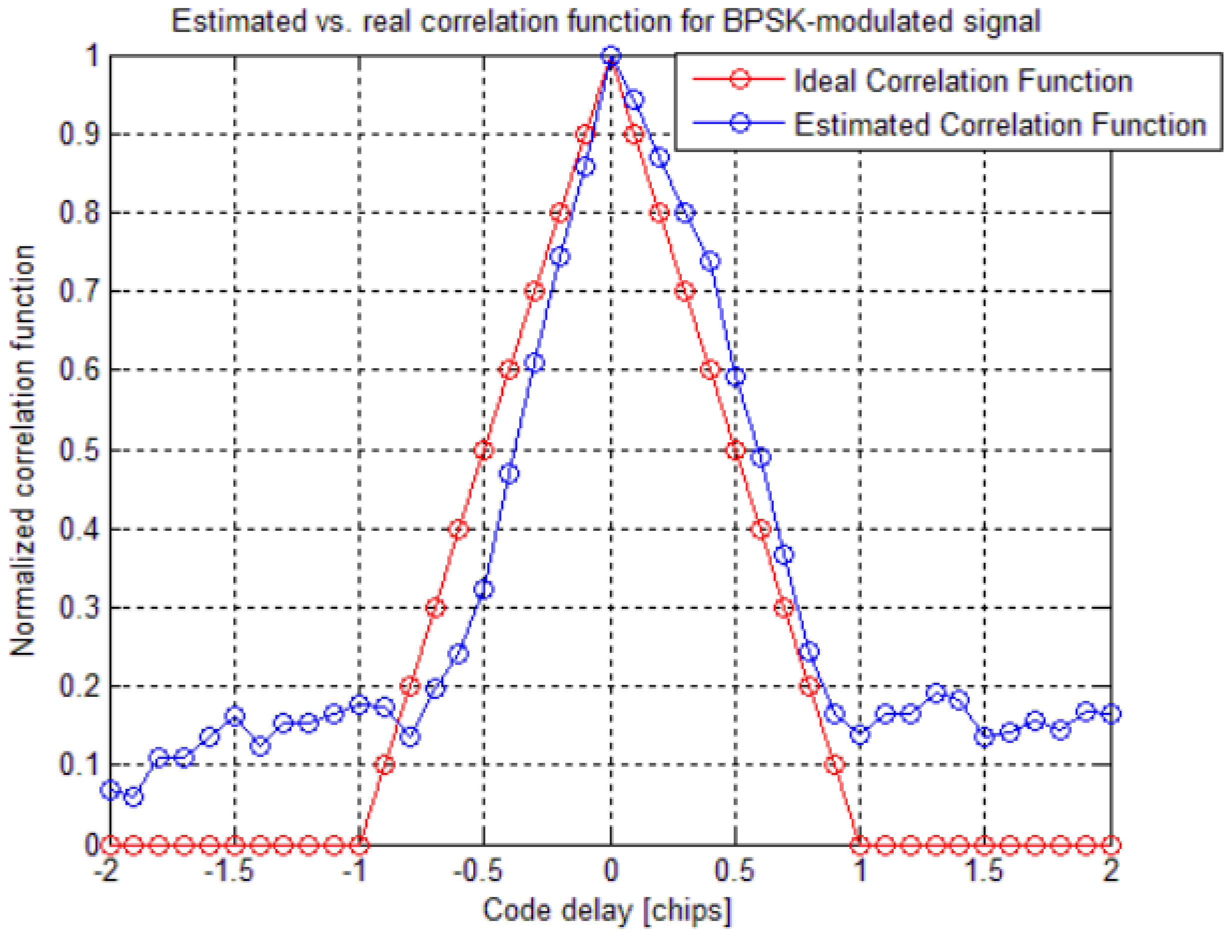
GNSS Receiver (2)



Picture: Navipedia
www.navipedia.net

NCO – Numerically Controlled Oscillator forms the replica signal

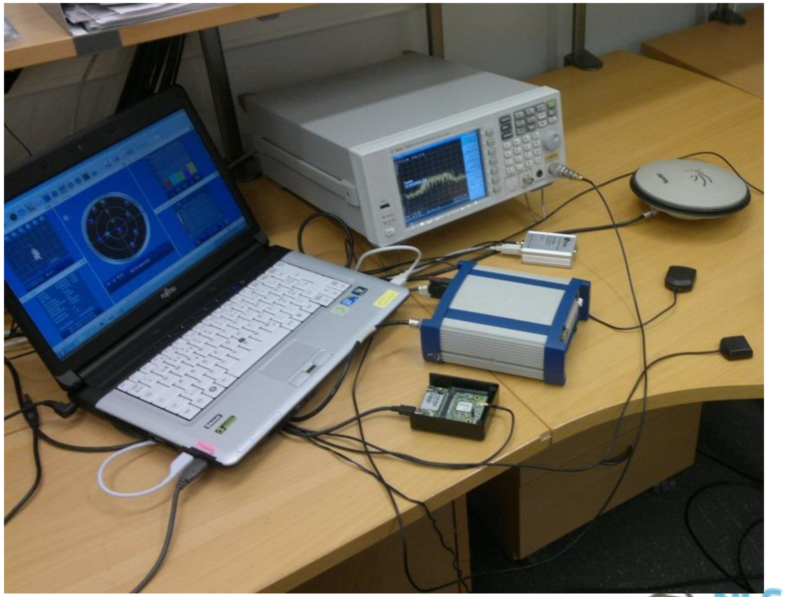
GNSS Receiver (3)



Received signal and replica signal are correlated and when they are perfectly aligned a correlation peak with value 1 is found

Error Sources – Receiver noise

- Noise added as part of the down-conversion and tracking of the signals when computing measurements is inevitable
  - Thermal noise jitter
  - Interference
- With modern receivers receiver noise can usually be kept to manageable levels
  - Pseudorange: ~0.1m (one-sigma error)
  - Carrier phase: ~1.2 mm (one-sigma error)



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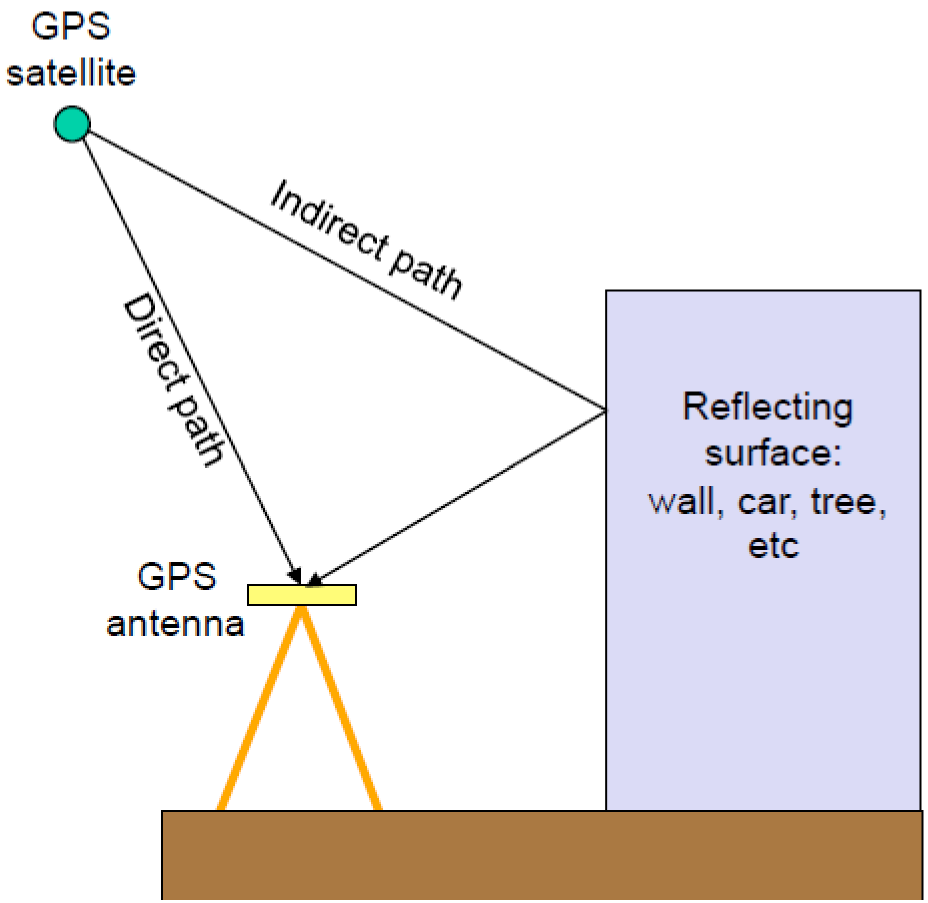
Error Sources – Multipath (1)

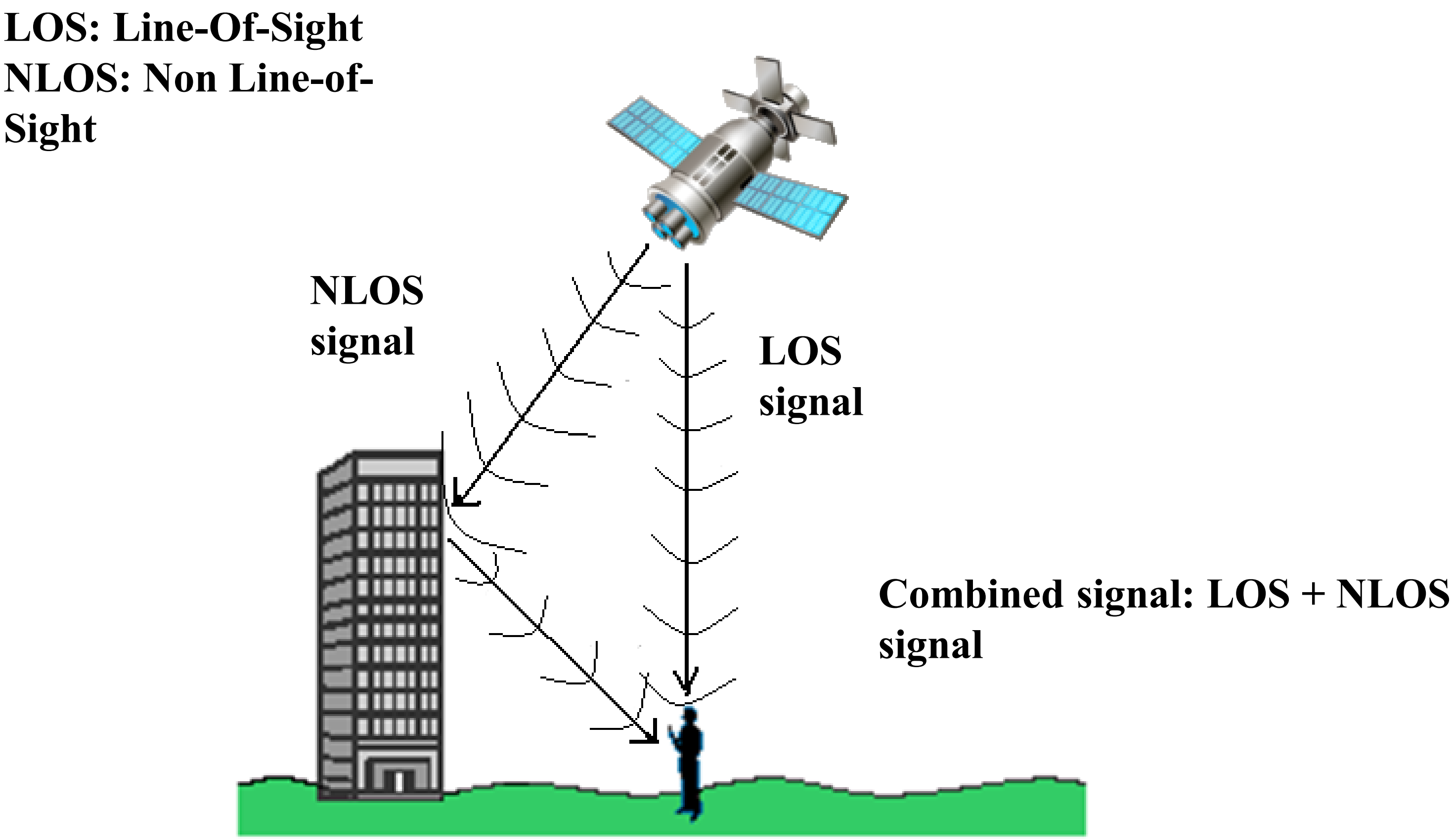
- Multipath propagation:
  - A GNSS signal may be reflected by surfaces near the receiver => direct and reflected signals
  - Echo-only signal reception pose a significant threat to position accuracy
  - Can't be corrected with Differential GNSS (DGNSS)



Source: E. Calais, GPS Geodesy, Purdue University, 2009.

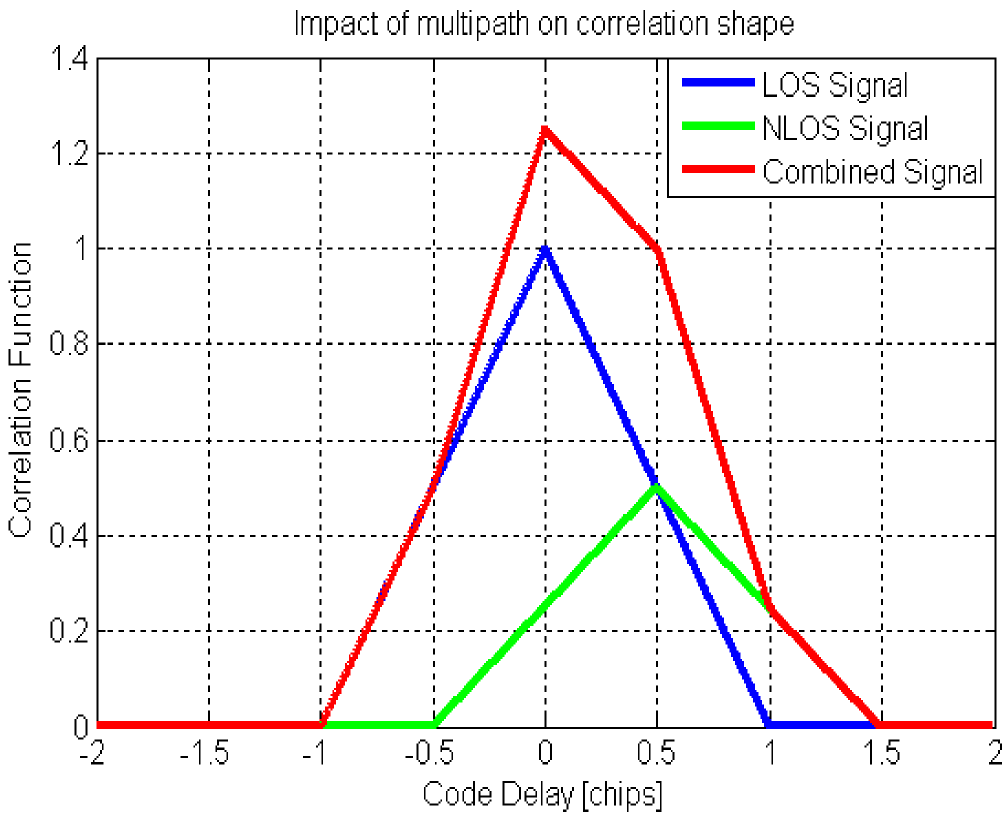
Error Sources – Multipath (2)

- Multipath propagation: How does it occur?



Error Sources – Multipath (3)

- Impact of Multipath on Navigation Receiver
- Effect of the multipath may be mitigated at the signal processing level
  - Narrow Early-Minus-Late discriminator (nEML)
  - Multipath Estimating Delay Lock Loop (MEDLL)



Lectio Praecursia © Zahidul Bhuiyan

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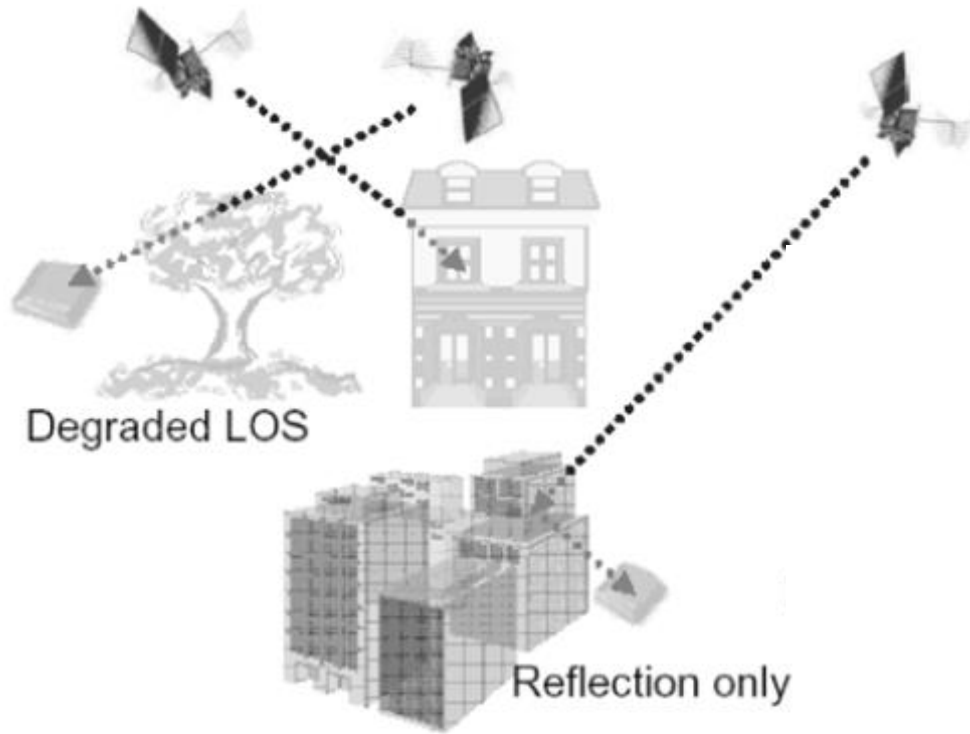
Error Sources – Multipath (4)

- Mitigation techniques:
  - Selecting the site carefully, minimum obstructions, no water
  - Use of chokering antennas
  - Use of correlators described before

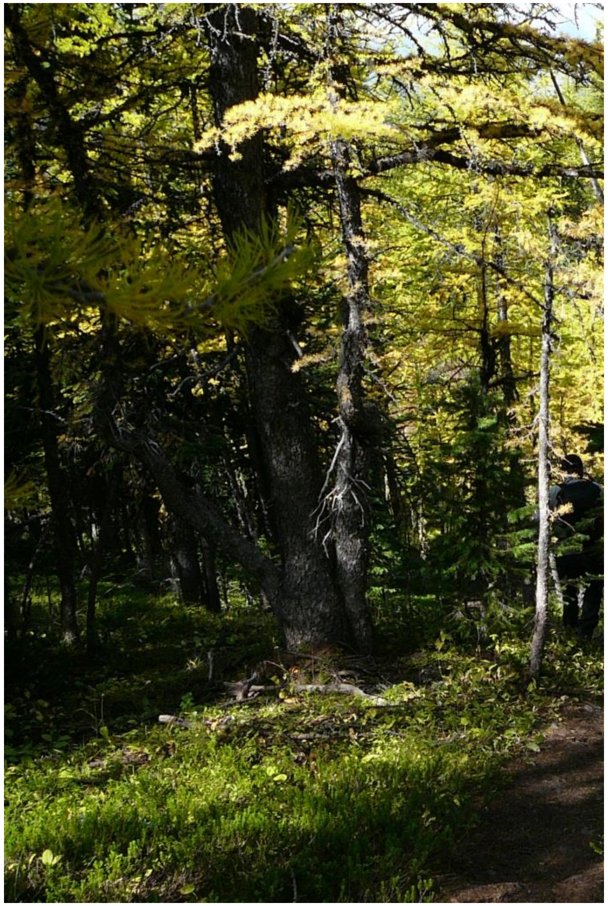
Challenging environments (1)

- In GNSS challenging environments the obtained solution is deteriorated or completely unvailable
  - Forests
  - Urban areas
  - Indoors



Challenging environments (2)

- **Foliage** degrades GNSS positioning. Consequences on availability, signal quality and position accuracy depend on
  - Thickness of leaves and branches
  - Density of foliage
  - Humidity



(Lachapelle et al. Seasonal effect of tree foliage on GPS signal availability and accuracy for vehicular navigation, ION GPS'94)

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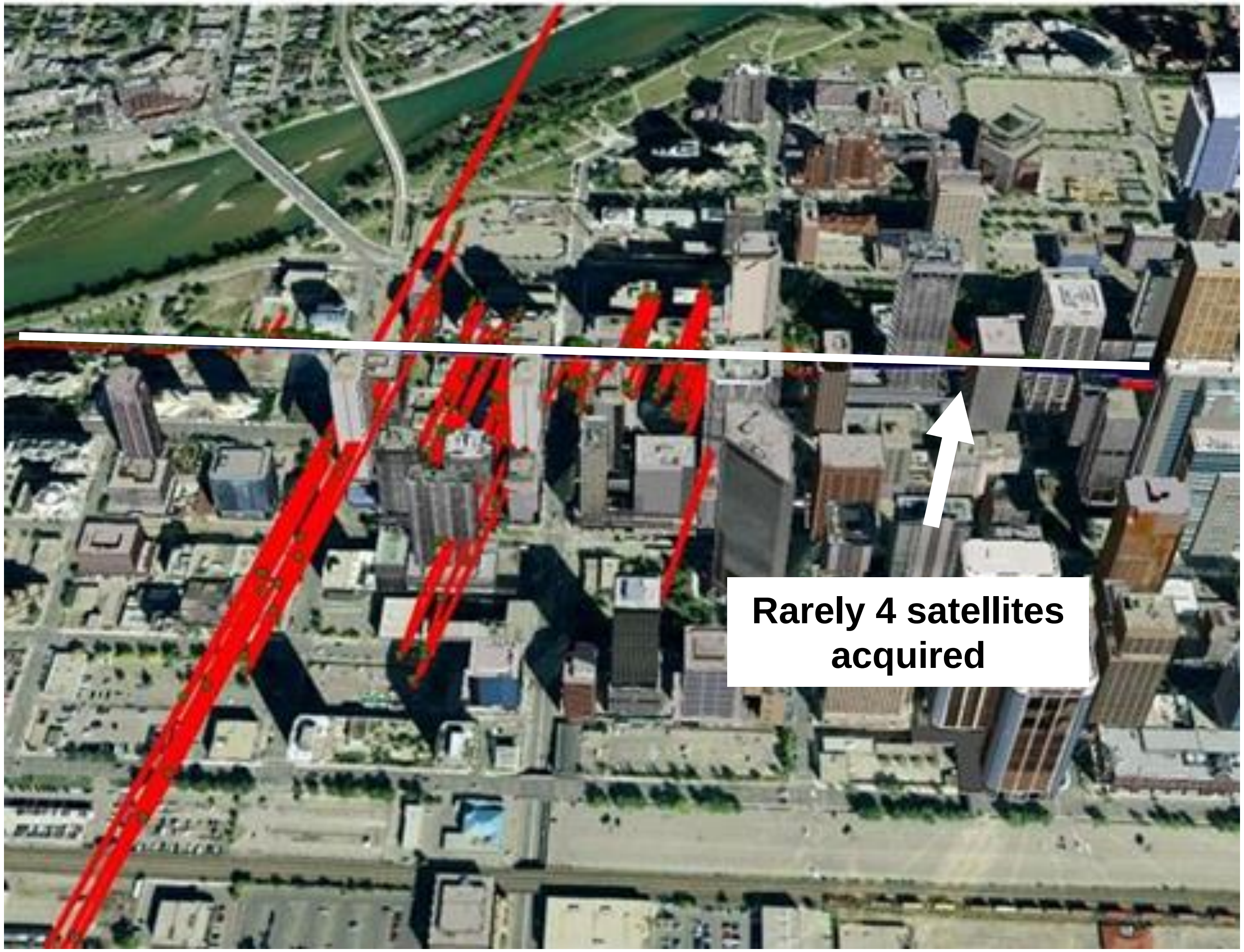
Challenging environments (3)



White = true path, Green = GPS positions, Red = Path with GPS

Urban canyons, degraded accuracy and availability due to signal obstruction and multipath

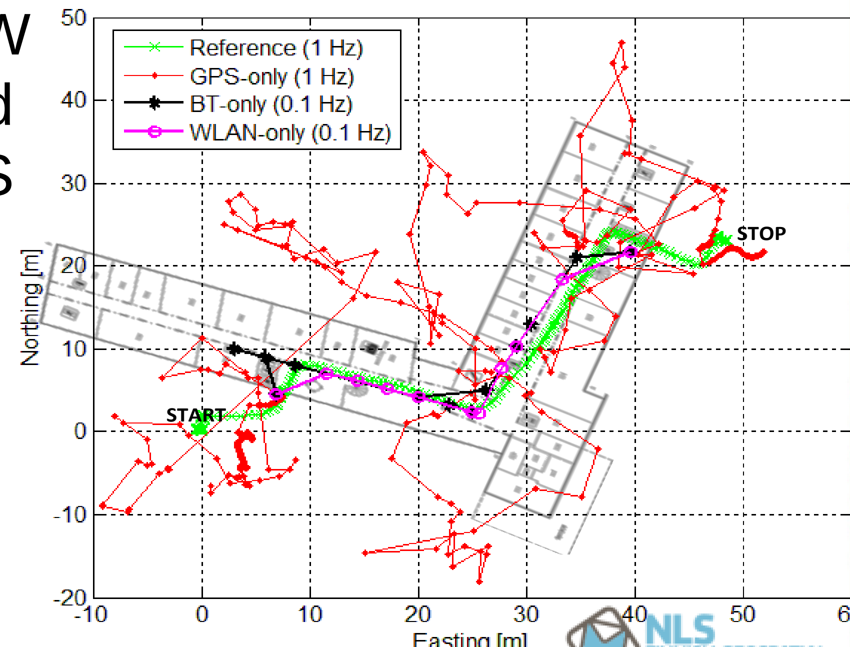
- Figure: Calgary downtown
- In Helsinki downtown also deep urban canyons

Ruotsalainen, Vision-aided Pedestrian Navigation for Challenging GNSS Environments, Doctoral dissertation, 2013

Challenging environments (4)

Indoors

- GNSS is heavily degraded or not available at all
  - Although High Sensitivity GNSS (HSGNSS) is used, reliability and accuracy is degraded
  - Minimum received power for GNSS position computation has to be -160 dBW (-186 for HGNSS) and is around that in normal Line-of-Sight LOS conditions
  - However e.g. concrete and steel fade the signal ranges 19-23 dB, depending on the elevation angle of the satellite



Error Sources – Interference(1)

- Interference is any unwanted disturbance causing degradation in C/N_0 (Carrier-to-Noise ratio, often referred as Signal-to-Noise ratio)
- GNSS is very vulnerable for interference
  - Radio waves disperse energy as they propagate
  - Satellites are > 20 000 km away
  - Signal emitted at about 30W
  - Signal strength proportional to 1/ distance => signal reduced by a factor of about 10^{18}
- ➢ Signal levels are below the natural background radiation

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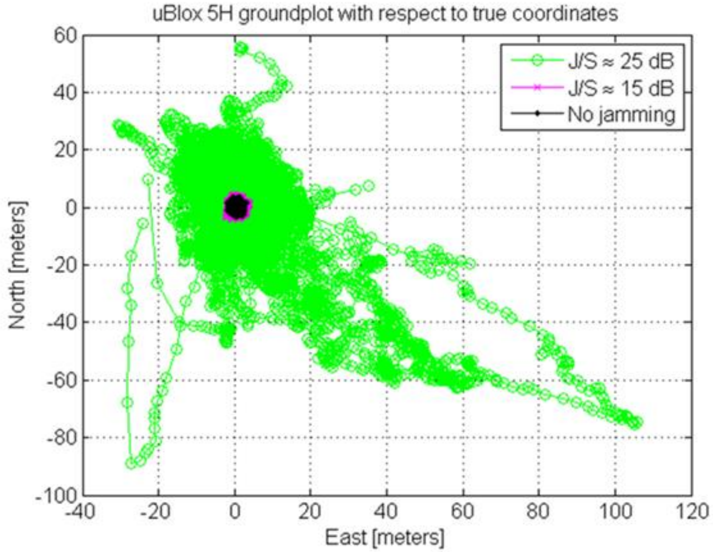
Error Sources – Interference(2)

- Other RF systems on GNSS spectrum
  - Mobile Satellite Service
  - Ultra-Wide Band Service
- ➢ Forunately these problems are usually solvable by spectrum management
- Masking
  - Buildings, foliage
- Intentional interference
  - Jamming
  - Spoofing

Error Sources – Interference(3)

Deliberate GNSS interference

- **Jamming**: transmission of signals at GNSS frequencies
  - Deteriorates or denies GNSS position
  - Illegal in most countries, however observed increasingly
  - ”Personal Privacy Devices”
- **Spoofing**: transmission of fake GNSS signals
  - Deludes the receiver to be in wrong position



S. Pullen, G. Gao, “GNSS Jamming in the Name of Privacy”, Inside GNSS, March/April 2012, 34-43.

Intentional Interference(1)

Jammers	US	RU	China	EU
manufacture	illegal	illegal	illegal	Nation-by-nation
sell	illegal	illegal	illegal	illegal
export	illegal	illegal	illegal	Nation-by-nation
purchase	Undefined (consumer import illegal)	illegal	illegal	illegal
own	legal	Undefined	Undefined	legal
use	illegal	illegal	illegal	illegal

http://www.unoosa.org/oosa/en/ourwork/icg/activities/2015/icg-experts-meeting_presentations.html

Intentional Interference(2)

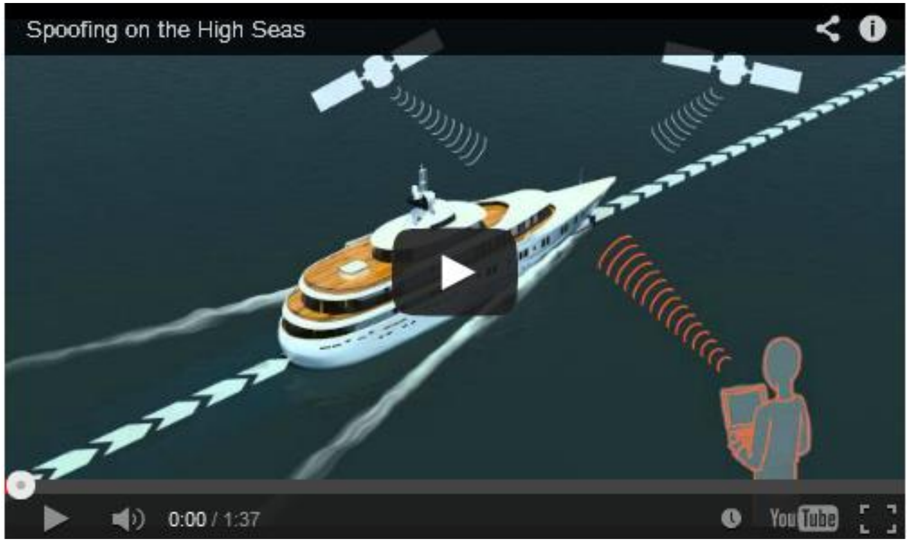
Reported cases of intentional interference

2009 Newark airport – daily GPS outages

GPS jamming: No jam tomorrow", The Economist , 2011

University of Texas at Austin spoofed a luxurious private yacht

KVH Mobile World, 2014



- US port disruption due to interference
- Spoofing / interference of border drones

Nation State

Intentional High-Power GPS Jamming

[The Central Radio Management Office, South Korea]

Dates	Aug 23-26, 2010 (4 days)	Mar 4-14, 2011 (11 days)	Apr 28 – May 13, 2012 (16 days)
Jammer locations	Gaesong	Gaesong, Mt. Gumgang	Gaesong
Affected areas	Gimpo, Paju, etc.	Gimpo, Paju, Gangwon, etc.	Gimpo, Paju, etc.
GPS disruptions	**181 cell towers, 15 airplanes, 1 battle ship**	**145 cell towers, 106 airplanes, 10 ships**	**1,016 airplanes, 254 ships**

Prof. Jiwon Seo -Yonsei University, South Korea Resilient PNT Forum II, Dana Point, California - January 26, 2015

http://www.unoosa.org/oosa/en/ourwork/icg/activities/2015/icg-experts-meeting_presentations.html

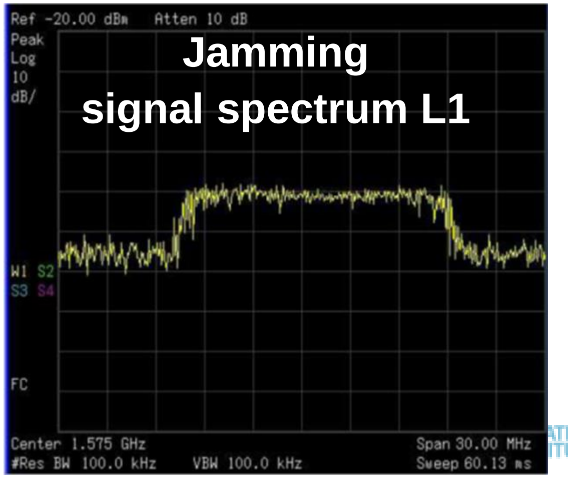
Intentional Interference (3)

- How does a jammer affect the GNSS receiver?
- Special permission from the Finland’s communications authority
  - Covert GPS L1 jammer (< 100 $): attenuated under -30 dBm (nominal 18 dBm)
  - GPS L2-L5 TG-120D jammer (130 $):

  attenuated under -30 dBm

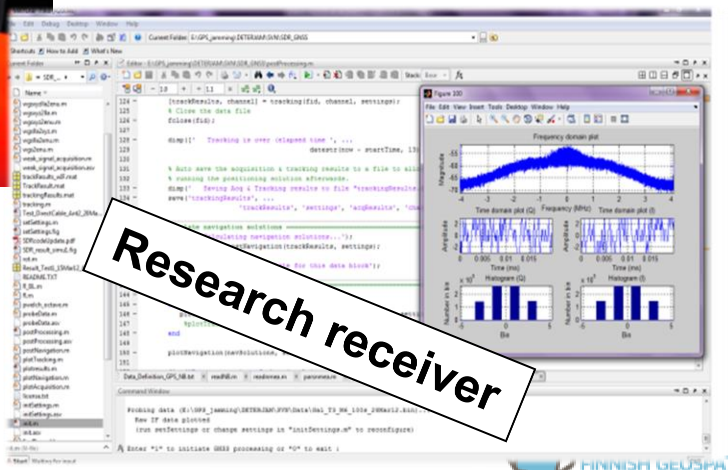
  (nominal 33 dBm)

Navigation lab



Intentional Interference (4)

- Receivers:
  - uBlox 5H ja 5T
  - Fastrax IT500 ja IT600
  - GPS Nokia N8
  - GPS Samsung Galaxy Nexus
  - NovAtel OEM 4 (L1/L2)
  - Leica 1230 L1/L2
- Radios
  - GNSS SiGe4120 L1/E1 radio
  - GNSS NSL L5-L1 radio
- Signal simulator
- Matlab- software receiver FGI-GSRx



Intentional Interference (5)

- How does jamming affect commercial receivers?
- L1-signal
- 24-h static test
- Positioning error increased and availability of positioning decreased

		Mean (m)	Std (m)	Max (m)	%
uBlox 5H	no jam	1.0	0.6	3.8	100
	max J/S≈15 dB	1.4	0.7	4.6	100
	max J/S≈25 dB	9.2	8.7	129.3	16
uBlox 5T	no jam	1.0	0.6	4.0	100
	max J/S≈15 dB	1.5	0.8	6.5	100
	max J/S≈25 dB	4.2	5.5	94	26
Fastrax IT500	no jam	2.2	1.0	5.3	100
	max J/S≈15 dB	2.3	1.0	6.5	100
	max J/S≈25 dB	3.7	5.2	85.4	16
Fastrax IT600	no jam	1.3	0.6	3.2	100
	max J/S≈15 dB	1.3	0.7	3.2	100
	max J/S≈25 dB	5.9	3.6	16.4	100
Nokia N8 GPS	no jam	2.6	2.4	32.4	100
	max J/S≈15 dB	3.1	3.8	34.0	100
	max J/S≈25 dB	3.9	2.2	22.4	16
NovAtel	no jam	1.0	0.7	4.8	100
	max J/S≈15 dB	2.4	3.9	90.5	30
	max J/S≈25 dB	5.4	7.3	92.1	8

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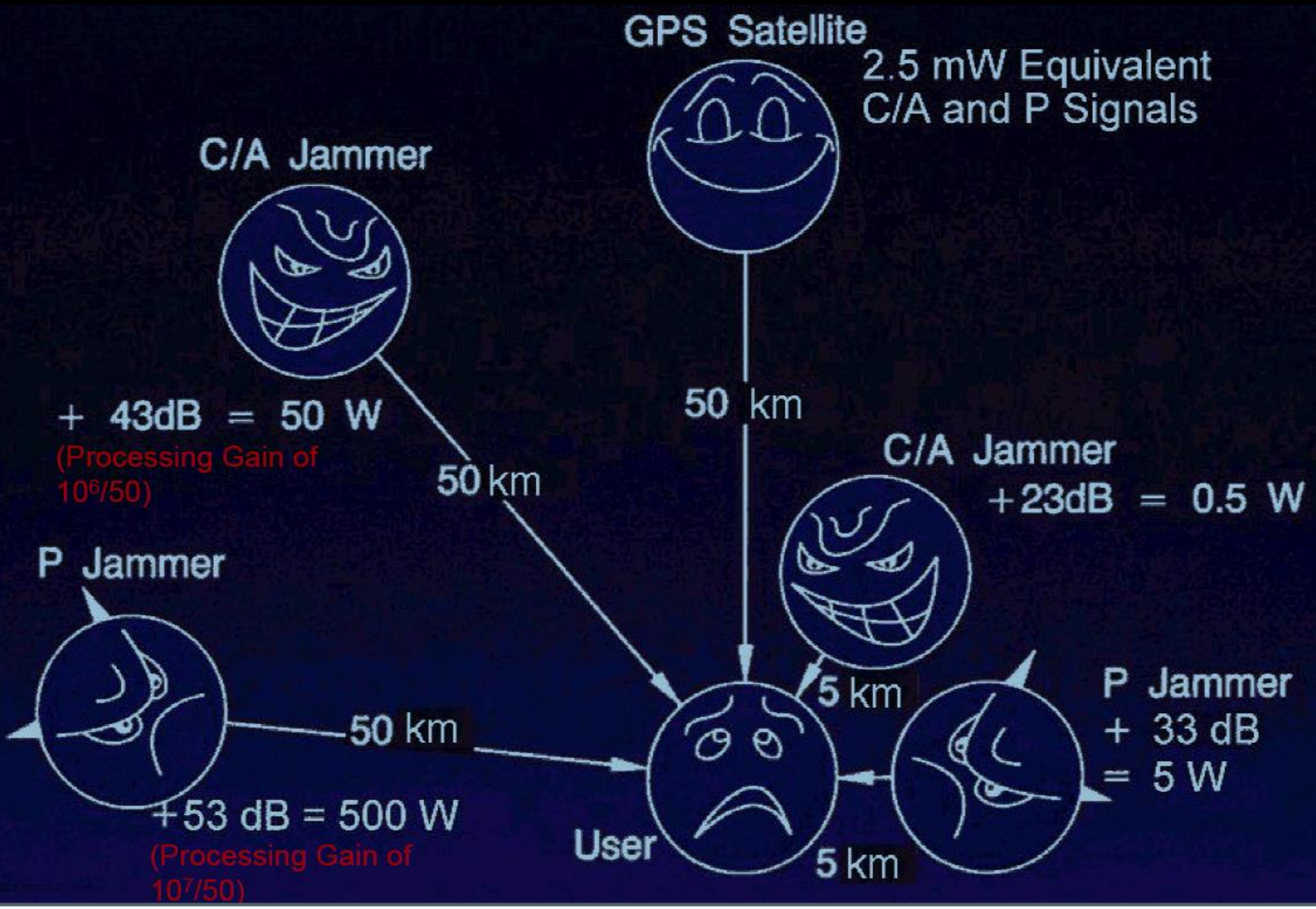
The Near/Far Problem

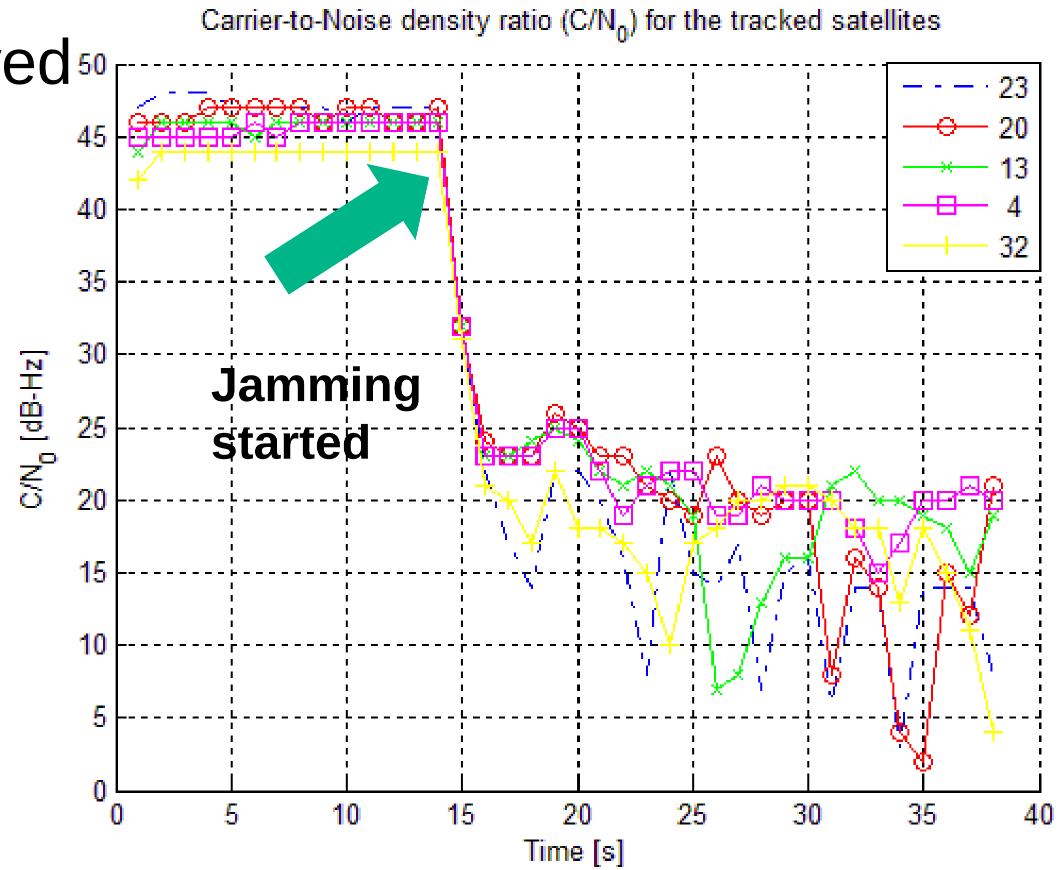


Tom Stansell – ICG Experts meeting 2016,

http://www.unoosa.org/oosa/en/ourwork/icg/activities/2015/icg-experts-meeting_presentations.html

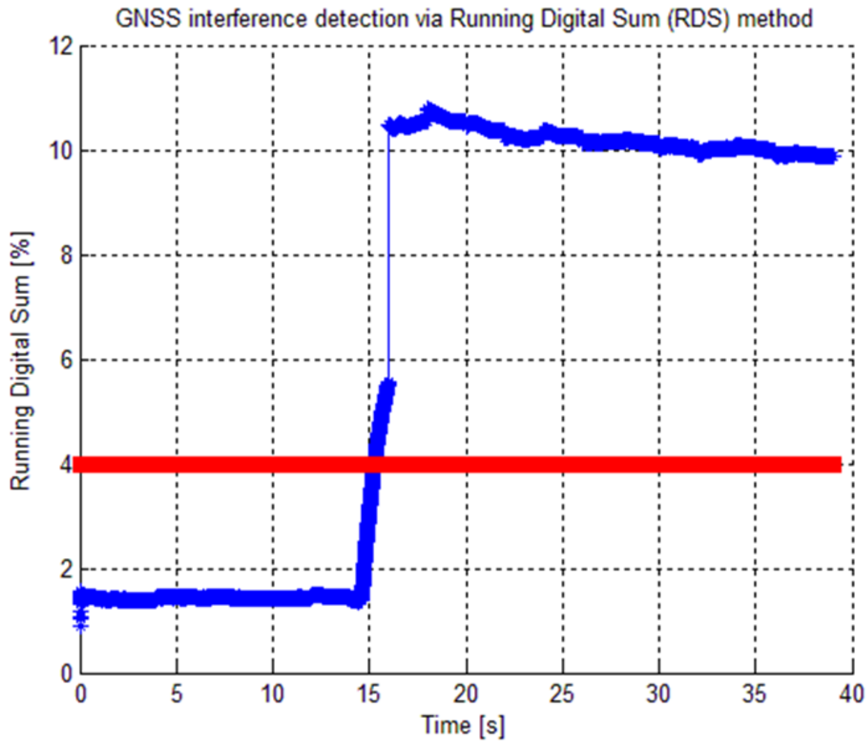
Interference Detection (1)

- Jamming may be observed from the signal quality drop
- Interference detection may be difficult: signal quality decreases, but the same happens when entering indoors



Interference Detection (2)

- New methods developed, e.g. based on the digitalization of the signal
- Running Digital Sum: digitalized signal should be uniform => if not, jamming present



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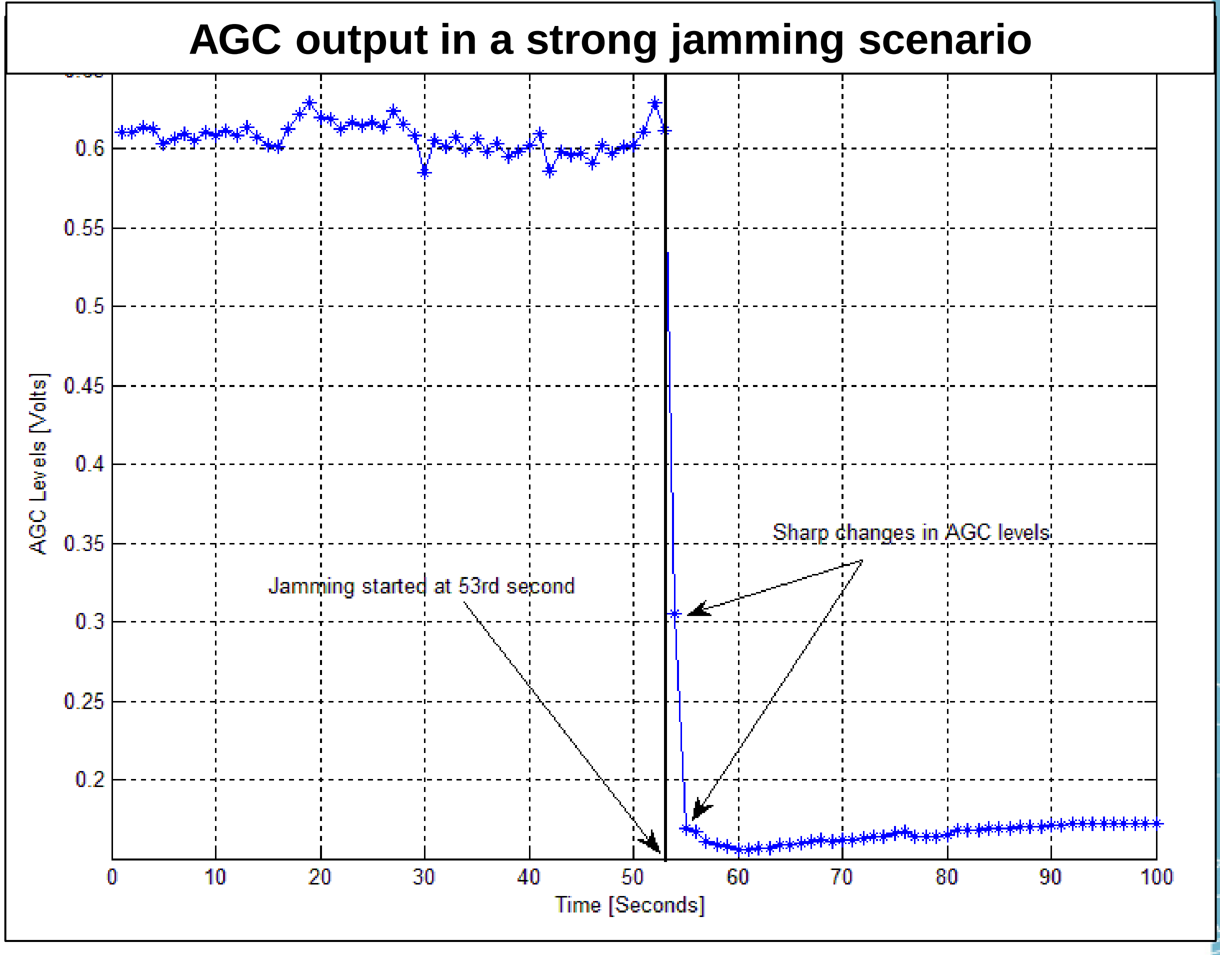
Interference Detection (3)

- Jamming may also be observed from the behaviour of the front-end processes
- When GNSS signal power suddenly increases due to jamming, AGC value drops
- Unfortunately commercial receivers don’t always provide the users with all information needed



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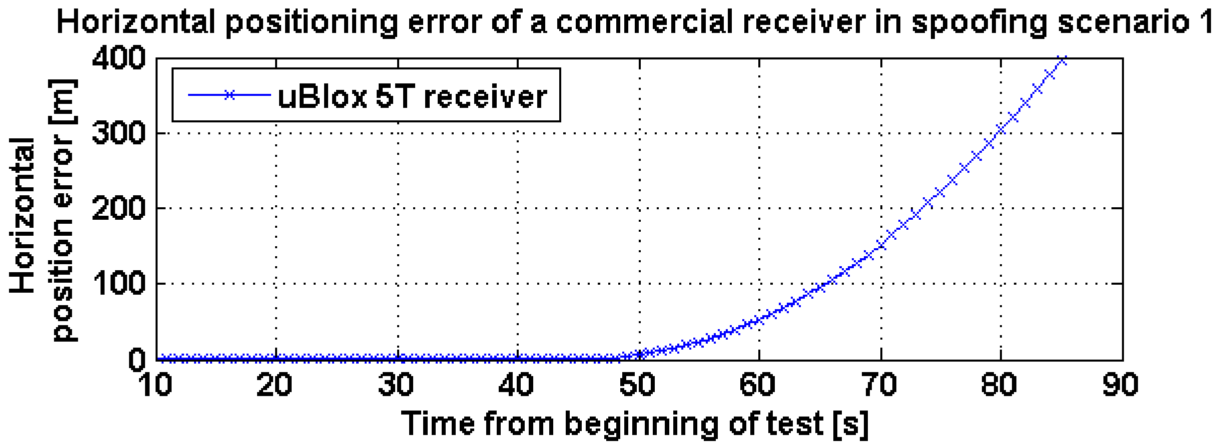
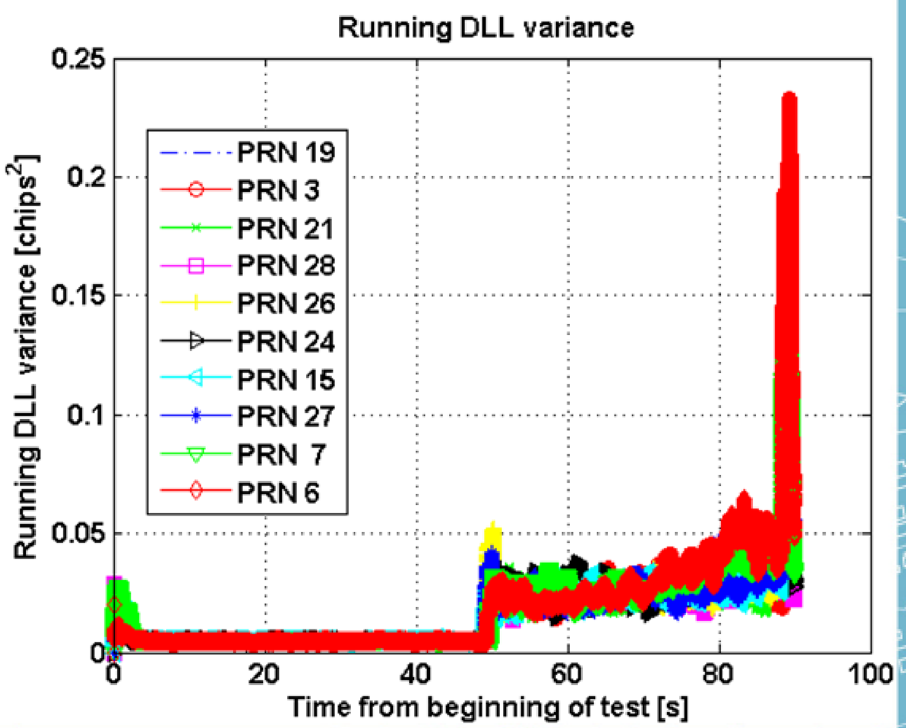
Interference Detection (4)

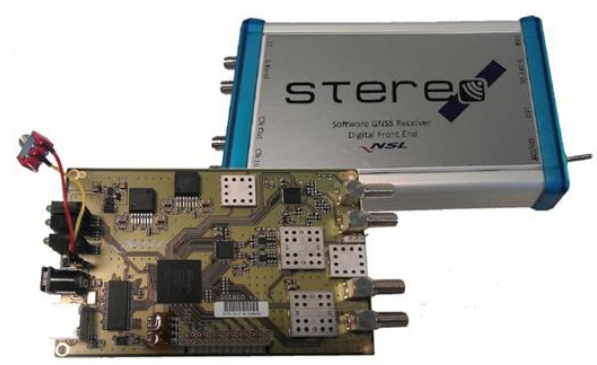


- Spoofing is even more difficult to be detected
- Above the receiver was static, spoofing was started at 48 seconds
- Looking at the signal shows that the receiver is spoofed (on right)



Interference mitigation (1)

- Mitigation:
  - Encryption of codes prevents spoofing
    - GPS L2 P(Y) codes
    - Future Galileo PRS (Public Regulated Service)
  - Use of multi-GNSS for jamming mitigation, signals on different frequency bands
  - Deeply-coupled integration with inertial and other self-contained sensors
  - Signal processing methods
  - Antenna arrays



Interference mitigation (2)

- Galileo PRS (Public Regulated Service) for authorities of EU countries
- Improved interference resistance
  - Encrypted Signal
  - Higher transmission power
  - Signals on two frequency bands
- Each EU country has an CPA (Competent PRS Authority) who controls the distribution and use of encryption keys

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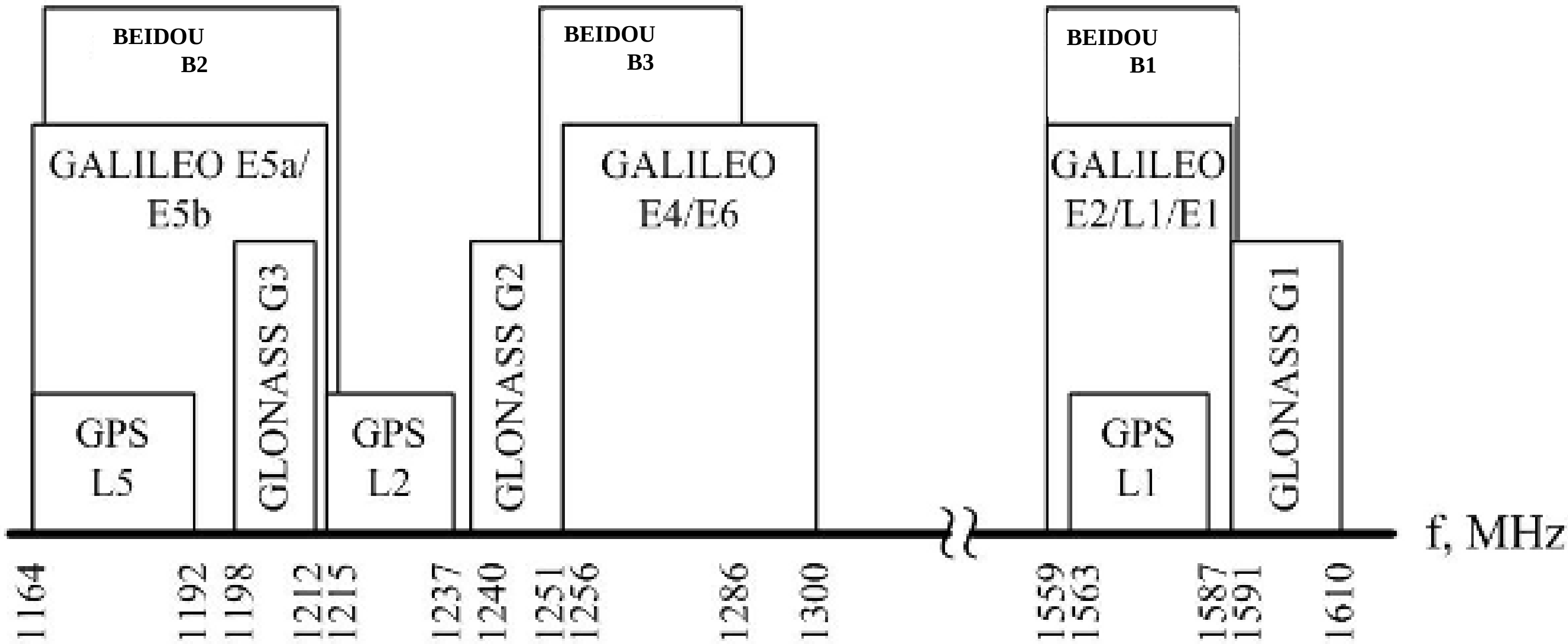
Interference mitigation (3)

- Use of multiple GNSS systems for forming the navigation solution will enable the use of signals on different frequency bands

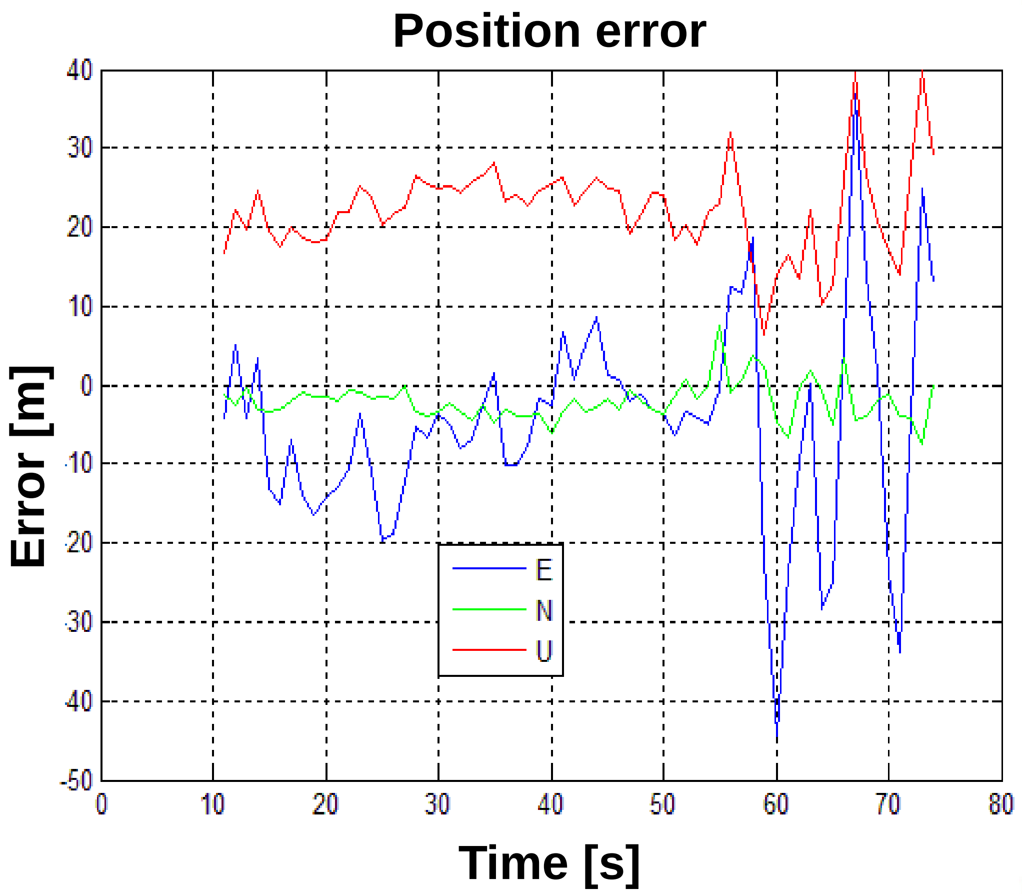


Interference mitigation (4)

- Use of multiple GNSS systems for forming the navigation solution will enable the use of signals on different frequency bands
- Receiver Autonomous Integrity Monitoring (RAIM) algortihms check, if all obtained pseudoranges are consistent and discard the ones that are not
- When one frequency is jammed, others may still be used
- However, the computation is complicated in multi-GNSS receivers => a good balance should be found

Interference mitigation (5)

- Jamming using a GPS-jammer (bandwidth 16 MHz)
- Difference of 14 MHZ between BeiDou and GPS central frequencies
- GPS signal was blocked, no position solution available
- Jamming may be seen in BeiDou signal, but positioning possible



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Interference mitigation (6)

- Deeply-coupled integration:
  - Deeply coupled Kalman filter algorithm integrating GNSS and Inertial Navigation System (INS) measurements
- Inertial sensors in INS, accelerometers and gyroscopes, continuously measure specific force (from which acceleration can be deduced) and rotation rates, from which position, velocity, and attitude can be computed
- INS measurements are used to aid the signal processing algorithms
- Sensors are not affected by radio interference
- INS errors degrade the accuracy => other sensors needed to constrain the error growth

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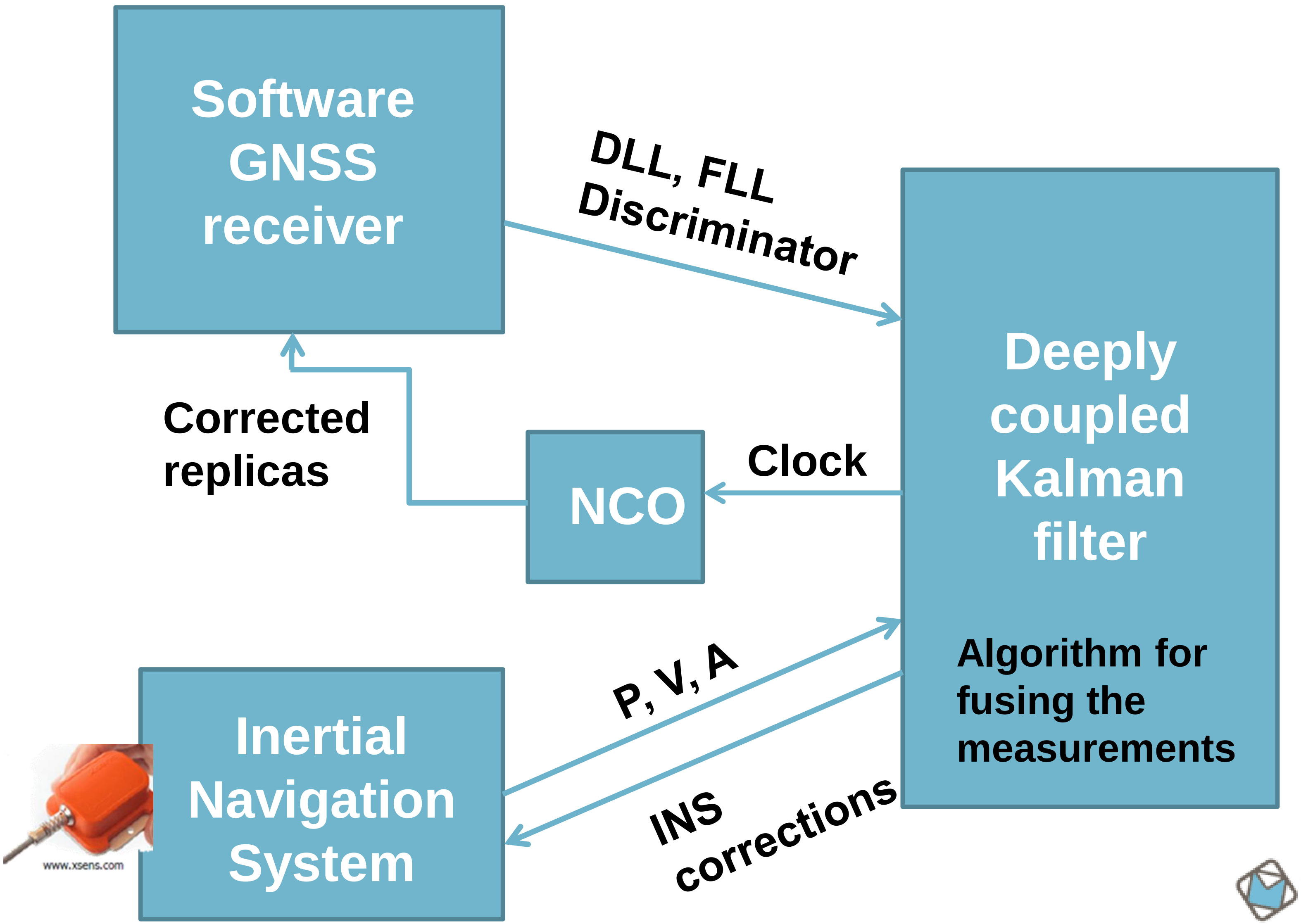
Interference mitigation (7)



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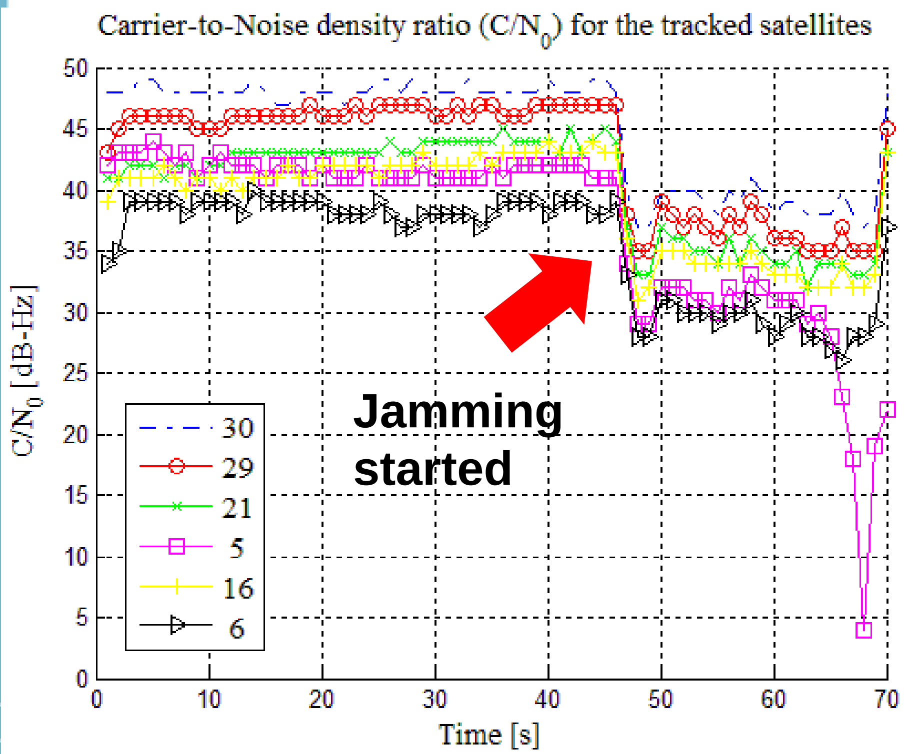
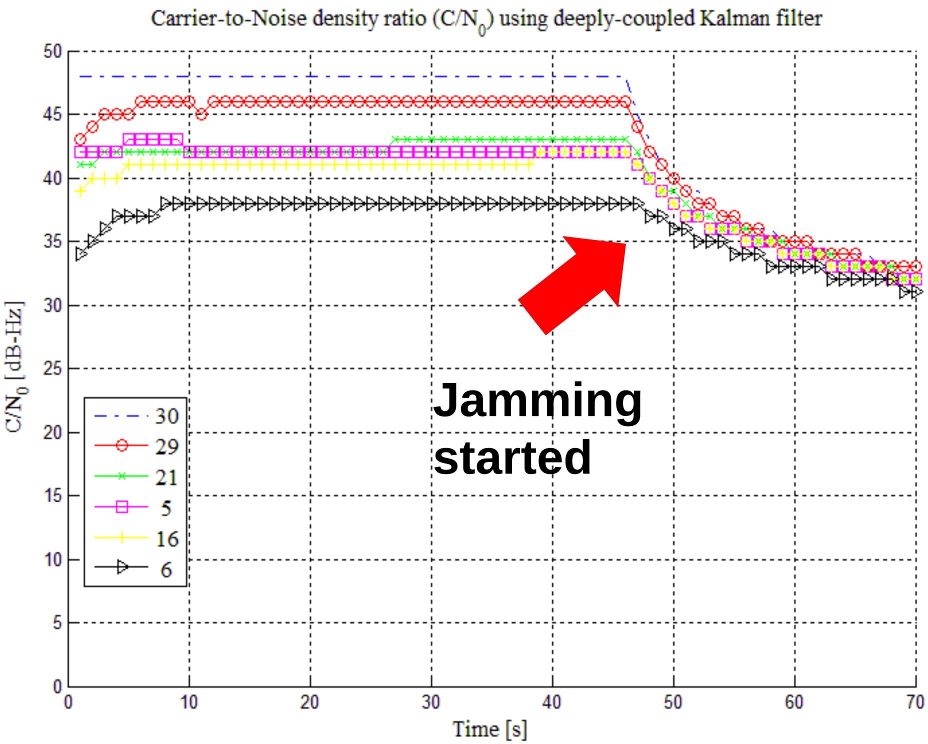
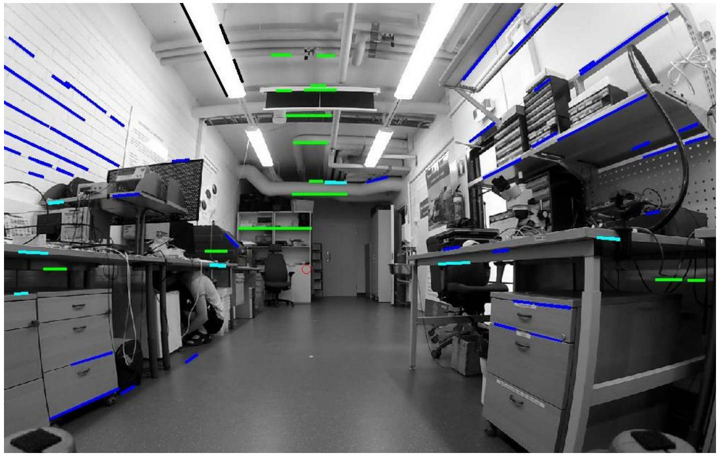
Interference mitigation (8)





Interference mitigation (9)

- Use of other self-contained sensors would keep the solution good for longer time
  - Camera => vision-aided navigation
  - Magnetometer
  - …..



Tackling interference – Strike3

- Interference detection, localization and mitigation are important research subjects
- e.g. H2020- project STRIKE3: Standardisation of GNSS Threat reporting and Receiver testing through International Knowledge Exchange, Experimentation and Exploitation
  - http://www.fgi.fi/fgi/research/research-projects/standardisation-gnss-threat-reporting-and-receiver-testing-through
  - DETECTOR-tool
    - http://www.spirent.com/Products/GSS100D-Detector

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GNSS LABS
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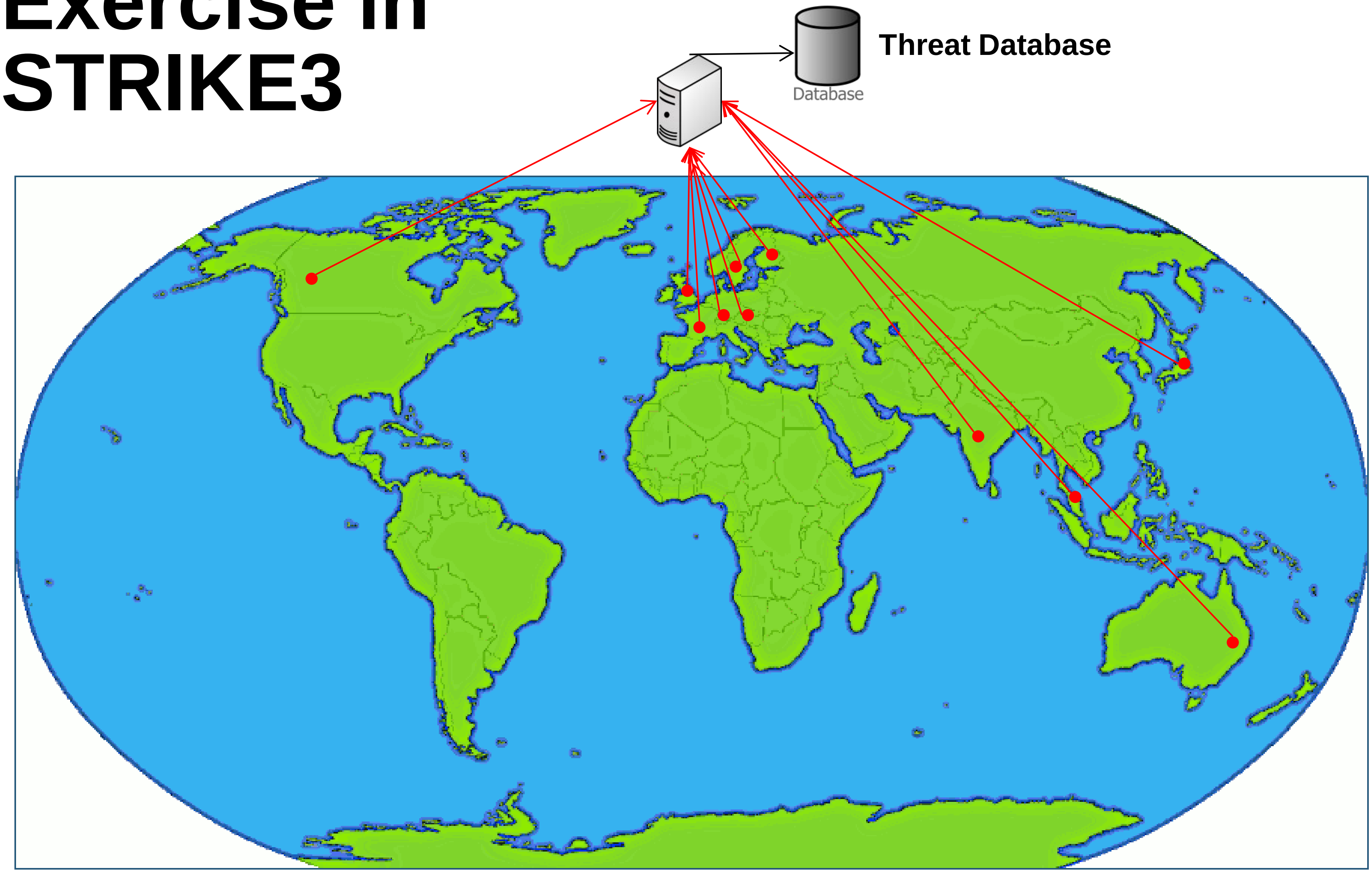
Overview of Threat Collection Exercise in STRIKE3



Interference publications by FGI

- D. Borio, F. Dovis, H. Kuusniemi and L. Lo Presti, "Impact and Detection of GNSS Jammers on Consumer Grade Satellite Navigation Receivers," in Proceedings of the IEEE, vol. 104, no. 6, pp. 1233-1245, June 2016.
- M. Z. H. Bhuiyan, Kuusniemi, H., Söderholm, S., and E. Airos (2014). The Impact of Interference on GNSS Receiver Observables – A Running Digital Sum Based Simple Jammer Detector. *Radioengineering*, Vol. 23, No. 3: 898-906, September 2014, ISSN 1805-9600.
- Bhuiyan, M.Z.H., Söderholm, S., Thombre, S., Ruotsalainen L. and H. Kuusniemi (2014). Over-coming the Challenges of BeiDou Receiver Implementation, Sensors, MPDI.
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