grammar
Galileo Ready Advanced Mass Market Receiver

Challenges in Multi-System Multi-Frequency GNSS Receiver Design — Introduction

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Tutorial Outline

» Introduction: GRAMMAR, Satellite navigation basic principles, existing and emerging GNSS satellite constellations and augmentation systems (30 minutes): Stephan Sand, DLR

» Antennas and RF front-ends for multi-frequency GNSS receivers (30 minutes): Marco Detratti, ACORDE

» Advanced receiver algorithms for baseband processing (30 minutes): Simona Lohan, TUT/DCE

» Baseband hardware solutions for multi-system, multi-frequency reception (30 minutes): Heikki Hurskainen, TUT/DCS

» Issues in PVT solution software for GNSS (20 minutes): Francescantonio Della Rosa, TUT/DCS

» Hybridization with other sensor data (30 minutes): Stephan Sand, DLR

» Wrap-up and conclusions (10 minutes): Stephan Sand, DLR

Introduction — Outline

» Motivation

» Satellite navigation principles

» Global navigation satellite systems (GNSS)

» Space and ground based augmentation systems

» GNSS positioning receiver

» Galileo Ready Advanced Mass Market Receiver (GRAMMAR)

» Summary

Motivation

» New Galileo signals:
  » Improved accuracy, integrity and authentication
  » Massive wave of new applications in key downstream markets

» Total market of upstream and downstream European GNSS based industry:
About €300bn in 2020 [L.E.K. Consulting]

» Now time to build a successful European GNSS industry

» R&D in GRAMMAR:
Boost Galileo downstream industry by providing IP for future Galileo mass market receivers

Satellite Navigation Principles

Radio wave propagation:

» Waves travel at known speed of light c

» Measure signal propagation time from transmitter to receiver, i.e., time-of-flight

  ➔ Distance between transmitter and receiver

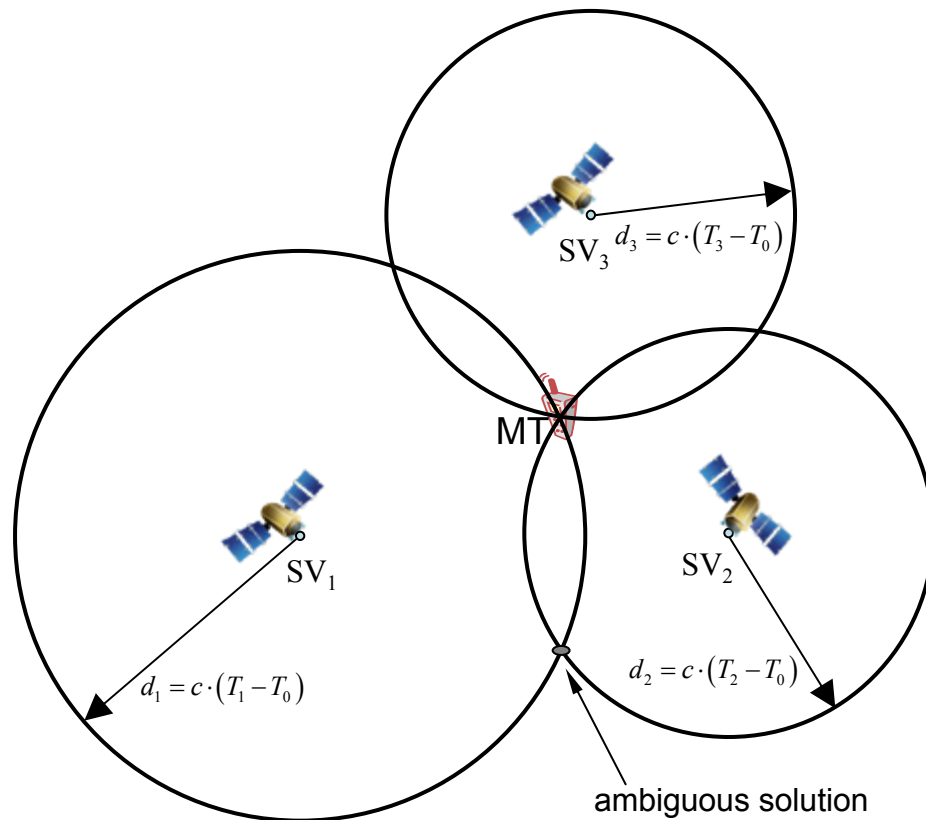 $$d_\mu(\boldsymbol{x}) = c \cdot \left(T_\mu - T_0\right)$$

  T_0 time at which navigation signal was sent synchronously

  T_μ time at which navigation signal from SV μ was received at receiver position $\boldsymbol{x} = \begin{pmatrix} x & y & z \end{pmatrix}^{\mathsf{T}}$

» Three transmitters with known positions

  ➔ Unambiguous position

$$d_3 = c \cdot (T_3 - T_0)$$

SV$_3$

MT

SV$_1$

SV$_2$

$$d_1 = c \cdot (T_1 - T_0)$$
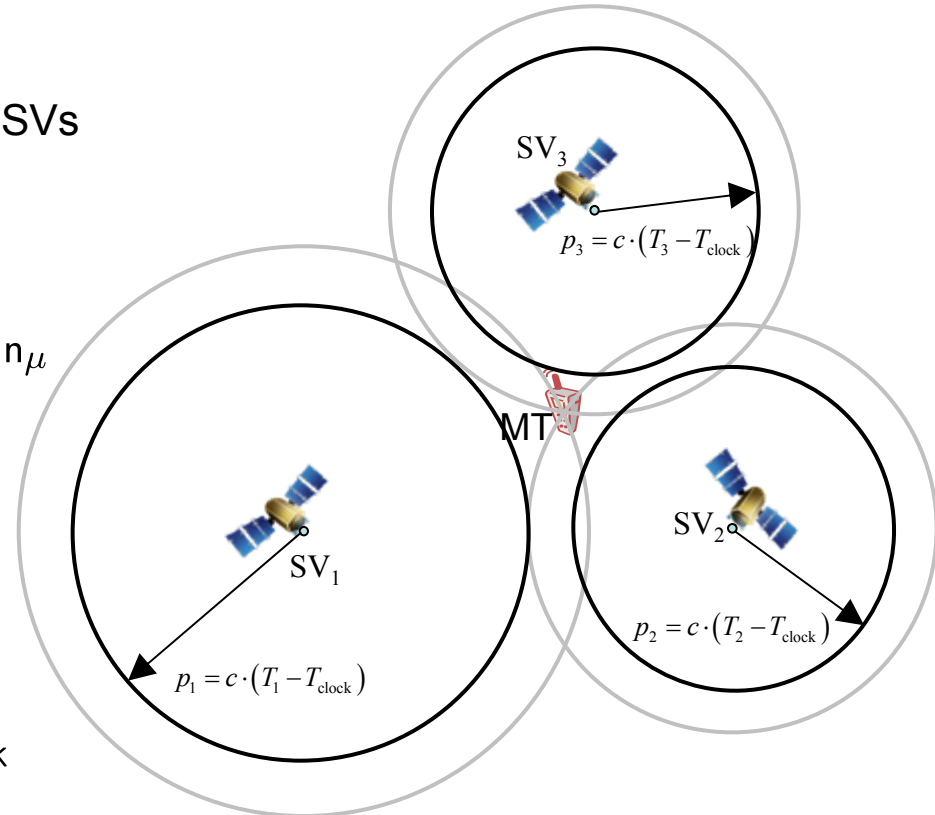
$$d_2 = c \cdot (T_2 - T_0)$$

ambiguous solution

Satellite Navigation Principles

Global navigation satellite systems (GNSS)

» Propagation time measurements between receiver and fully synchronized SVs

» Receiver clock T_{clock} not synchronized to SVs

» Pseudorange measurements for SV μ

$$p_\mu = c \cdot \left(T_\mu - T_{\text{clock}} \right) + n_\mu$$
$$= c \cdot \left(T_\mu - T_0 \right) + c \cdot \left(T_0 - T_{\text{clock}} \right) + n_\mu$$
$$= d_\mu(x) + b_{\text{clock}} + n_\mu,$$

» True distance $d_\mu(x)$ between SV μ and receiver position $x = \begin{pmatrix} x & y & z \end{pmatrix}^{\mathsf{T}}$

» At least 4 pseudorange measurements
  ➜ receiver position x and clock bias b_{clock}

SV$_3$

$p_3 = c \cdot (T_3 - T_{\text{clock}})$

MT

SV$_2$

$p_2 = c \cdot (T_2 - T_{\text{clock}})$

SV$_1$

$p_1 = c \cdot (T_1 - T_{\text{clock}})$

Global Navigation Satellite Systems (GNSS): Global Positioning System (GPS)

» Space segment: 24 satellites (SVs)
  » Orbits: 6 planes with 4 SVs
  » Inclination: 55°
  » Orbit radius: 26560 km
  » Orbit time: 11h 58 min
» Control segment
  » Master control station(s)
  » 4 ground antennas
  » 6 monitor stations
  » Update of SV's:
    » Clock synchronization
    » Ephemeris
   » Change of orbit
» User segment: GPS receivers
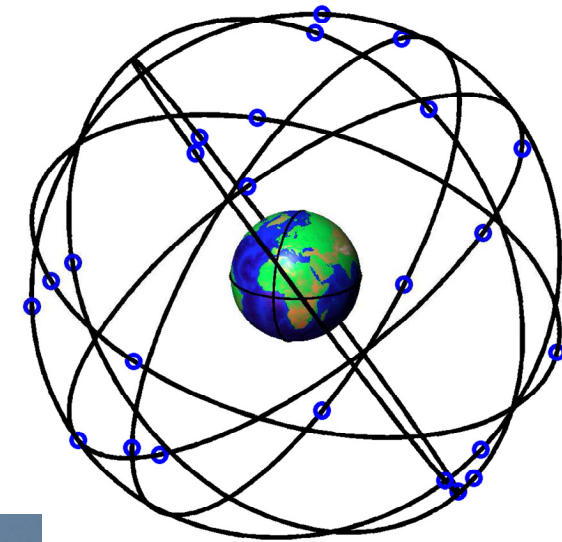
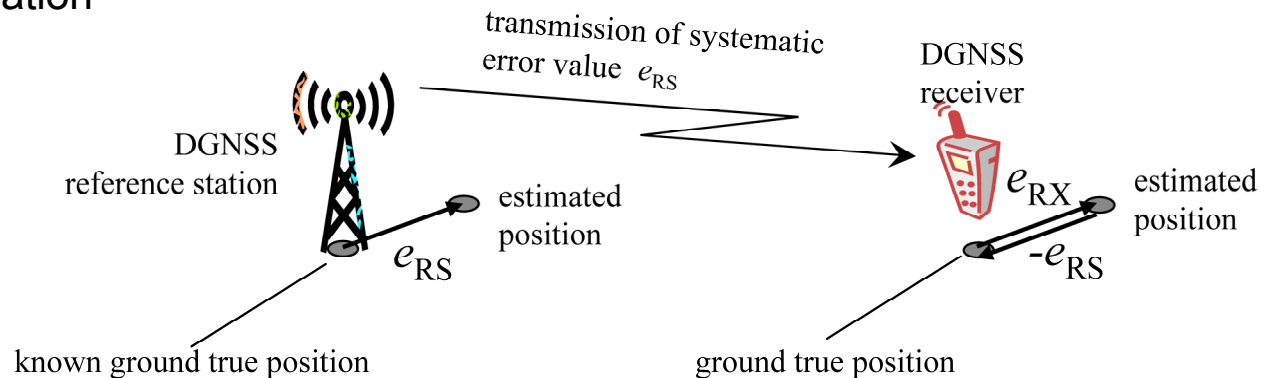# Global Navigation Satellite Systems (GNSS): GPS, GLONASS, Galileo, Compass

GNSS	GPS	GLONASS	Galileo	Compass
Number SVs	24	24	30	35
Orbits	6	3	3	?
Orbit radius [km]	26560	25440	29620	MEO+GEO
Orbit time	11 h 58 min	11 h 15 min 40 s	14 h 5 min	?
Inclination	55°	64.8 °	56 °	?
Multiplex	**CDM**	**FDM**	**CDM**	**CDM**
Code type	Gold (C/A), Tiered	M-sequence (C/A)	Tiered	?
Code length	1023, 10230	511 (C/A)	4092, 10230	2046, 10230?
Chip rate [Mchips/s]	1.023, 10.230	0.511	1.023, 10.230	2.046, 10.230?
Modulation	BPSK	BPSK	BPSK, BOC	QPSK, BOC
Carrier frequency (GHz)	L1 1.575, L2 1.227, L5 1.176	L1 1.602, L2 1.246	E1 1.575, E5a 1.1176, E5b 1.207, E6 1.278	B1 1.575, B2 1.191, B3 1.268
Transmit power [dBW (EIRP)]	23-25	25-27	?	?

Global Navigation Satellite Systems (GNSS): GPS, GLONASS, Galileo, Compass
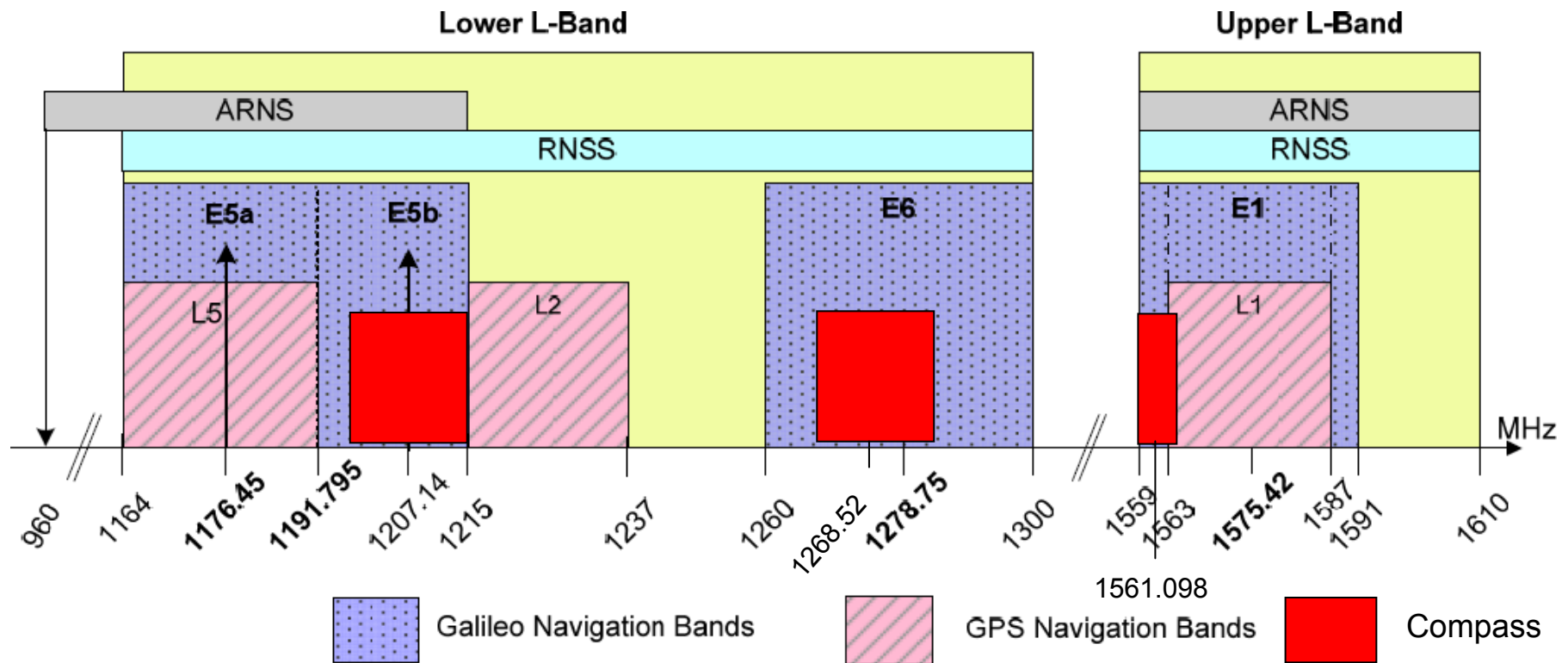
Space and Ground Based Augmentation Systems: SBASs and GBASs

» Improve GNSS receiver accuracy, reliability, availability through external information

» Systematic errors in modeling

  » Satellite clocks and ephemerides

  » Ionospheric and tropospheric delays

  » Code and carrier phase due to multipath and receiver noise

» Ground-based reference stations communicate to GNSS receiver

 » Measured systematic errors

  » Unavailable information

transmission of systematic error value e_{RS}

DGNSS receiver

DGNSS reference station

estimated position

e_{RS}

known ground true position

e_{RX}

estimated position

$-e_{RS}$

ground true position

Space and Ground Based Augmentation Systems: SBASs and GBASs

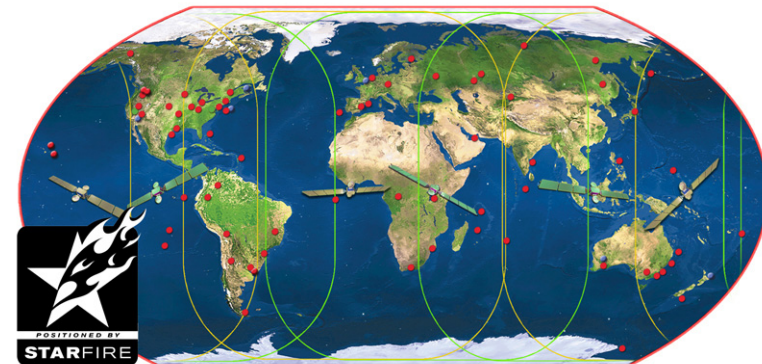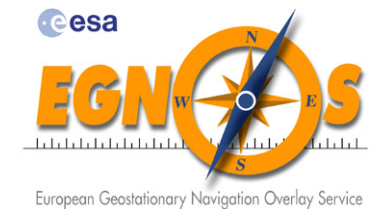Space based augmentation systems (SBAS)

» Wide Area Augmentation System (WAAS)

» GPS SBAS for North America

» North American reference stations

» Two geostationary communication satellites

» Accuracy requirement: 7.6 m for 95% of the time

» Measurements: 1 m lateral and 1.5 m vertical accuracy

» GPS like modulated signals:
No additional overhead for radio frequency (RF) part of GNSS receiver
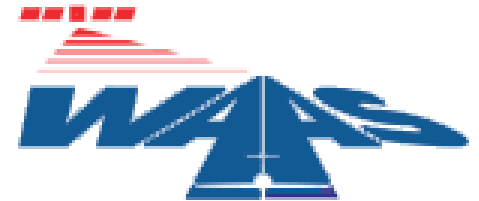
Space and Ground Based Augmentation Systems: SBASs and GBASs

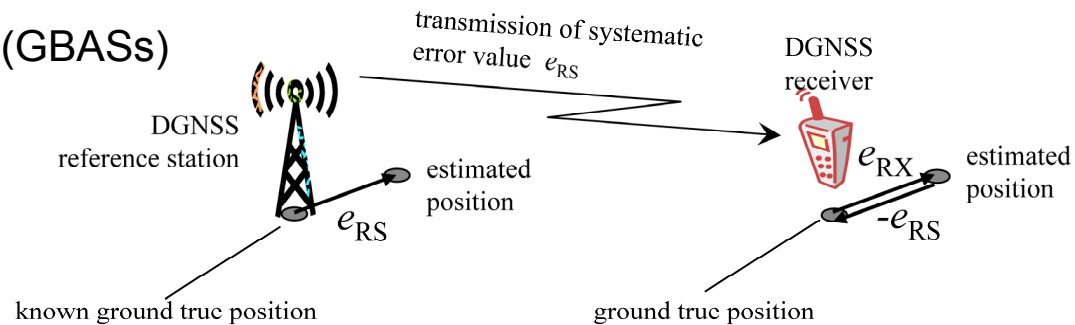Space based augmentation systems (SBAS)

» European Geostationary Navigation Overlay Service (EGNOS)

    » GPS, GLONASS, and Galileo SBAS for Europe

    » European reference stations

    » Three geostationary communication satellites

» Multi-functional Satellite Augmentation System (MSAS): Japanese SBAS

» GPS Aided Geo Augmented Navigation or GPS and Geo Augmented Navigation system (GAGAN) : Indian SBAS

» StarFire navigation system:
Global, commercial SBAS by John Deere

» Starfix DGPS System and OmniSTAR system:
Global, commercial SBAS by Fugro

Space and Ground Based Augmentation Systems: SBASs and GBASs

Ground based augmentation systems (GBASs)

» Differential GNSS (DGNSS)

» Terrestrial broadcast
of pseudorange errors

transmission of systematic error value e_{RS}

DGNSS reference station

DGNSS receiver

estimated position

e_{RS}

e_{RX}

estimated position

$-e_{RS}$

known ground true position

ground true position

» Local Area Augmentation System (LAAS)

» All-weather aircraft landing system:
Real-time differential correction of the GPS signal in airport vicinity

» VHF radio

» Real Time Kinematic (RTK) satellite navigation

» Broadcasts carrier phase measurements

» UHF radio

» Assisted GNSS (A-GNSS)

» Assistance data from reference receiver to cellular handset:
DGNSS, acquisition assistance, sensitivity assistance

GNSS Positioning Receiver

» Radio frequency front-end (RF-FE):
Bandpass filter, low-noise amplifier (LNA), down converters, amplifiers, analog-to-digital converter (ADC)

» Baseband (BB): For each satellite:

    » Acquisition, tracking ➔ pseudorange measurements

    » Data demodulation

» Position-Velocity-Time (PVT) estimation:

    » PVT solution from pseudoranges and received data

» Graphical user interface (GUI)

GNSS

Antenna

| RF-FE | → | BB | → | PVT | → | GUI |
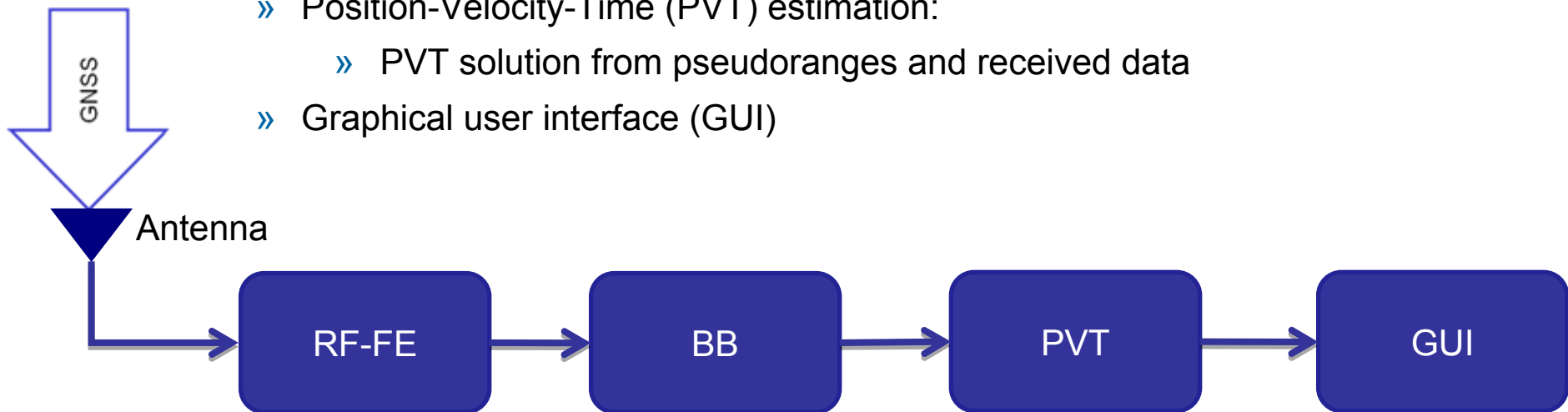
Galileo Ready Advance Mass Market Receiver
WP1 Market, Commercial and Exploitation

» Market study for GNSS products

  » Cellular: Largest market

    » Emerging applications with demanding requirements

  » Automotive: Second largest market

    » Legislated services

    » High accuracy and reliability for safety related apps

» GRAMMAR Mass Market Navigation Receiver Survey

  » Cellular handset market: Key for the GNSS mass market

  » Smart-phones: Highest impact on the adoption of GNSS

  » Mass market applications: Navigation and route planning

  » Market pull for advanced features (multi-frequency, Galileo, …):
   Costs remain low and clear benefits over state-of-the-art

Galileo Ready Advance Mass Market Receiver
WP2 Advanced Hardware

» Hardware prototype GNSS receiver targeted at mass market

  » Dual-frequency low power single chip GNSS radio front-end

  » FPGA based baseband
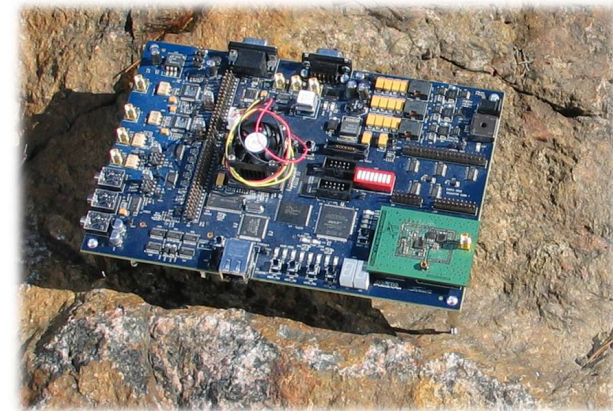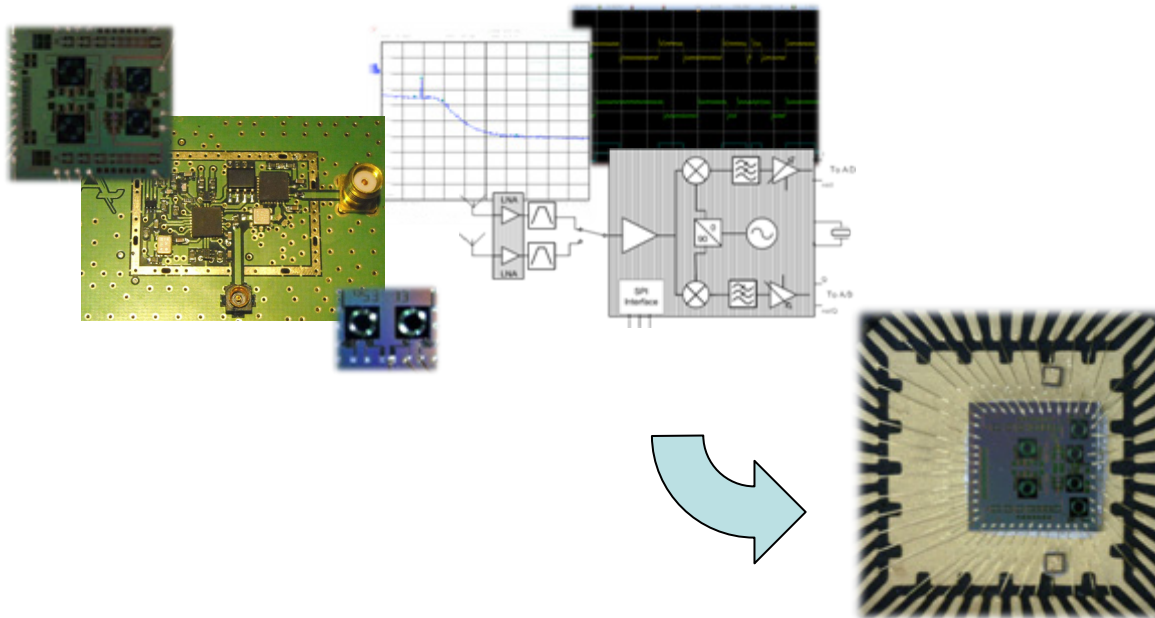
Galileo Ready Advance Mass Market Receiver
WP3 Advanced Algorithms

» Prototyping advanced algorithms

  » FPGA prototype GNSS receiver

  » FPGA prototype navigation receiver for 3GPP-LTE

» Advanced baseband algorithms

  » Acquisition and tracking for dual frequency GNSS receiver

  » Multi-correlator tracking and complexity reduced multipath mitigation

  » Non-line-of-sight detection and mitigation

» Hybrid data fusion (HDF):

  » Combine information from inexpensive sensors for indoor and urban positioning

  » GNSSs, communication systems (3GPP-LTE, Wi-Fi), and navigation sensors (accelerometers, barometers, magnetometers, gyroscopes)

  ➔ Improved accuracy, robustness, and availability
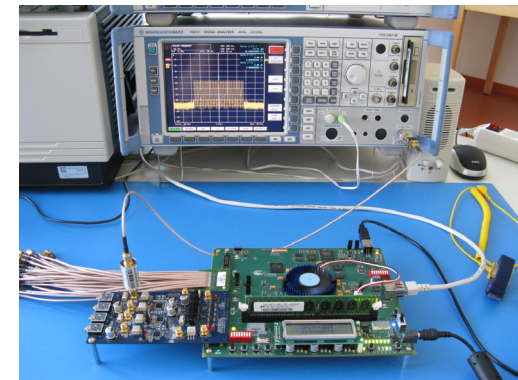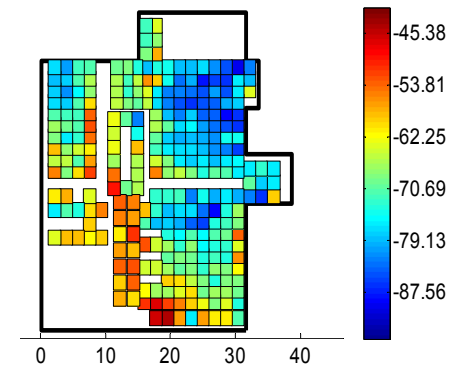
Galileo Ready Advance Mass Market Receiver Consortium

» EU FP7 collaborative project, Feb 2009 – Jul 2011

» Budget: 2,6 Mio. €

» Partners

  » German Aerospace Center (DLR)

    » Coordinator, LTE prototype navigation receiver and advanced algorithms

  » ACORDE TECHNOLOGIES S.A. (ACORDE)

    » Radio frequency front-end integrated circuit development, market and commercial exploitation

  » Tampere University of Technology (TUT)

    » Department of Communication Engineering (DCE): Advanced algorithms

    » Department of Computer Systems (DCS) FPGA baseband prototyping and advanced algorithms

TAMPERE UNIVERSITY OF TECHNOLOGY

DLR

ACORDE

Summary

» Satellite navigation principles

   » Measure signal propagation time from transmitter to receiver
      → Distance between transmitter and receiver

   » Three transmitters with known positions

      → Unambiguous position

   » GNSS measures pseudoranges
      → At least 4 pseudoranges for x,y,z and receiver clock bias b

» Global navigation satellite systems (GNSS)

   » GPS: 24 SVs, CDM, multi-frequency

   » GLONASS: 24 SVs, FDM, multi-frequency

   » Galileo: 30 SVs, CDM, multi-frequency, GPS compatible

   » Compass: 35 SVs, CDM, multi-frequency, GPS compatible

Summary

» Space and ground based augmentation systems

  » Improved GNSS receiver accuracy, reliability, availability through communicating to GNSS receiver

  » Communications measured systematic errors and unavailable information to GNSS receiver

  » SBAS: WAAS, EGNOS, MSAS, GAGAN, StarFire, Starfix, Omnistar

  » GBAS: DGNSS, LAAS, RTK, A-GNSS

» GNSS positioning receiver

  » RF-FE, BB, PVT, GUI

» Galileo Ready Advanced Mass Market Receiver (GRAMMAR)

  » Dual-frequency low power single chip GNSS RF-FE and FPGA BB prototype GNSS receiver targeted at mass market for rapid prototyping of advanced algorithms and techniques

  » Identification, evaluation and simulation of enhanced algorithm concepts for next generation mass market receivers

References

1. Pratap Misra and Per Enge, "Global Positioning System: Signals, Measurements, and Performance", Ganga-Jamuna Press, 2006
2. Global Navigation Satellite Systems http://en.wikipedia.org/wiki/Global_navigation_satellite_system
3. GPS Modernization http://www.navcen.uscg.gov/gps/modernization/default.htm
4. Galileo OS SIS ICD (Open Service Signal-In-Space Interface Control)

   http://ec.europa.eu/enterprise/policies/space/galileo/files/galileo_os_sis_icd_revised_3_en.pdf
5. GLONASS ICD http://www.glonass-ianc.rsa.ru/docs/ICD02_e.pdf
6. Compass Status http://scpnt.stanford.edu/pnt/PNT09/presentation_slides/3_Cao_Beidou_Status.pdf
7. Galileo Ready Advance Mass Market Receiver (GRAMMAR) http://www.gsa-grammar.eu

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» Wrap-up and conclusions (10 minutes): Stephan Sand, DLR

Antennas and RF front-ends for multi-frequency GNSS receivers

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13th June 2010

Outline

» The GRAMMAR Goal: Multi-frequency GNSS for the consumer market

» Multi-frequency RF Front Ends

» Multi-frequency Antenna solutions

» Conclusions & references

Multi Frequency in GNSS

» Today's consumer/mass market GNSS…

  → *Single frequency GPS, assisted, augmented*

  → *Enough for present user needs*

» …but what is the expected future with GNSS modernization [1] ?

  » **_End-user demand_** *for better performance will increase due to increasing number of new applications →The future of the GNSS market is associated with highly accurate and reliable GNSS applications.*

  » **_Advanced features_** *will be driven by the need to maximise the perceived reliability and accuracy of the solution to encourage user adoption and meet increasing user demands*

  » **_There is a Market pull_** *for advanced features (multi-frequency and Galileo, multipath…) if cost remains low or if solution clearly outperforms actual implementations*

Multi Frequency in GNSS

» GRAMMAR is addressing gaps identified as obstacles for producing high quality advanced GNSS receivers

» What is pursued is a solution which could bring real advantages targeting specific user needs (low TTFF, accuracy, availability,…) independently of the specific ("killer") application considered. → ***An enabling technology for future high performance receivers.***

» It is essential that the total solution and product **cost** will be kept **low** while achieving high accuracy and reliability. If multi-frequency receivers can demonstrate sufficient improvements in performance (visible to mass market user) with minimal increased cost over single frequency receivers then there may be an opportunity for multi-frequency to be used as a differentiation feature in the mass market.

Multi Frequency in GNSS

» Galileo and GPS Open Service (OS)
» CDMA Type Modulation→ Receiver compatibility

Standard	GPS L1	GPS L2	GPS L5	Galileo E1	Galileo E5a	Galileo E5b
Frequency (MHz)	1575.42	1227.6	1176.45	1575.42	1176.45	1207.40
Allocated BW (MHz)	20.46	20.46	20.46	24.552	25.575	25.575
First zero BW (MHz)	2.046	2.046	20.46	4.092	20.46	20.46
Modulation	BPSK	BPSK	BPSK	BOC(1,1)	BPSK	BPSK
Data rate	50bps	25bps	100bps	250bps	50bps	250bps
Chip rate (Mcps)	1.023	1.023	10.23	1.023	10.23	10.23

Multi Frequency in GNSS

» Something to enhance the capability of European GNSS industry:

  » *Multiple Standard→ sharing of information between GPS and Galileo, increased availability*

  » *Multiple Frequencies → better accuracy and multipath mitigation, faster reception of navigation data*
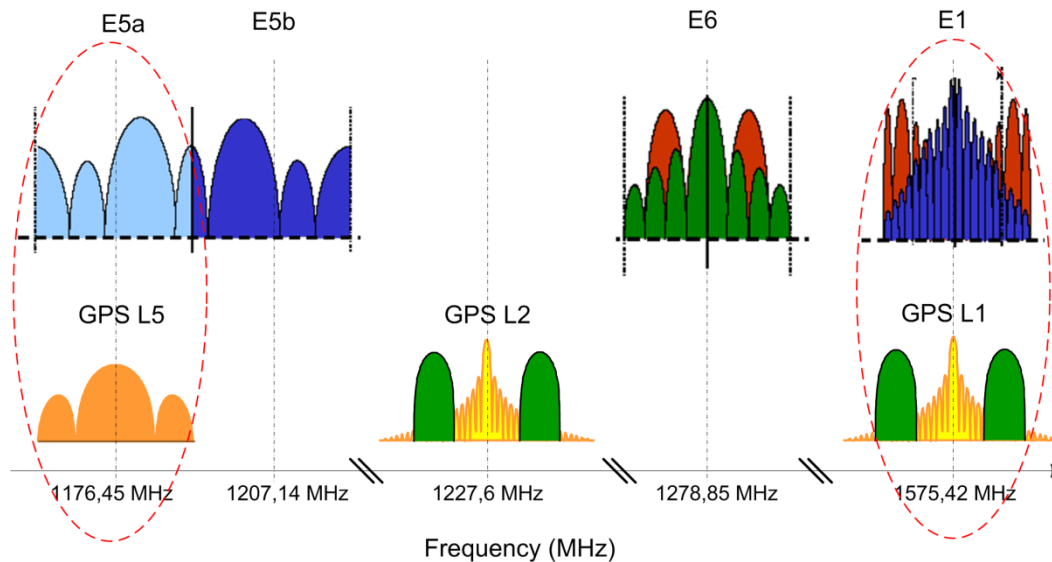
Galileo E1/E5a
GPS L1/L5

- *Same frequencies*
- *Low Spectral Separation Coeff.*
- *Optimal for BB implementation [2]*

Multi Frequency in GNSS

» RF System Specifications and Technology Gaps:

  » *Operating frequencies: 1.1-1.6 GHz multi-band in a single hip*
  » *Optimal Channel BW (3dB): 3MHz (E1-L1) and 13MHz (E5a/L5)* [3]
  » *Low NF→ Best sensitivity for weak signal detection*
  » *Compactness*
  » *Power consumption / Performance Trade-off*
  » *Flexibility for multiple platform integration*

» Strongly Affected by antenna performance

  » *→ Need characterization of multi-frequency environment*

RF Front Ends

» Current State-of-the-art (COTS): **only single frequency chips**

Parameter	Sige 4120L	NXP (Glonav) GNR1040	ST5620	ATMEL ATR0601	Maxim MAX2769	Sony CXA3355AER	NemeriX NJ1006A	Units
NF	2.5	N.A	<4.5	6.8	1.4-2.7	≈4	<3	dB
IF frequency	4.092	4.092	4.092	96.764	0-5	1.023/4.092	0	MHz
RX Bandwidth	2.2-4.4	N.A	6	2	Up to 8	2	N.A.	MHz
LO Phase Noise	-80@100kHz	N.A	-80@100kHz	N.A	N.A.	N.A.	-75@100kHz	dBc/Hz
Supported References	16.368	10 to 50	10 to 40	23.104	8 to 44	13/16.368/18.414	13/16.368/19.2	MHz
Max. Gain	N.A.	N.A	105	90	96	100	90	dB
VGA gain range	>40	N.A.	55	70	59	no	60	dB
ADC/AGC	2bit/yes	1 or 2 bit/yes	2bit/yes	1.5bit/yes	1 to 3 bit/yes	1bit/no	2bit/yes	---
Image Rejection (typ)	30	N.A	20	N.A.	25	40	no	dB
Supply Voltage	2.7-3.6	1.8	2.56-3.3	2.7-3.3	2.7-3.3	1.6-2.0	2.2-3.6	V
Power dissipation	10/30	8.3/15	15/40.5	16.7/50	15-18/42.75-51.3	11-13/19.8-23.4	6.9/21	mA/mW
Package	4x4 24pin QFN	4x4 24pin QFN	5x5 32pin QFN	4x4 24pin QFN	5x5 28pin TQFN	5x5 44pin VQFN	5x5 28pin QFN	

RF Front Ends

» Current State-of-the-art (Literature):single frequency

Parameter	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	Units
NF	2.0 (RF+BB)	N.A	5$^+$	3.7	5.3	2	4.8	4	dB
IF frequency	4.092	0	4.092	20.42	9.45	0.150	4.092	1	MHz
RX Bandwidth	<3	<2.5	2	6	2	1	2	<2	MHz
LO Phase Noise	-113dB @1MHz	-130 @1.25MHz	-108 @1MHz	-84 @100kHz	-95 @1MHz	-132 @1MHz	-112@ 1MHz	-108@ 1MHz	dBc/Hz
Voltage Gain	>40	68.2	80	103	81	80	92	110	dB
ADC/AGC	4bit/yes	$\sum\Delta$1bit/no	2bit/yes	1bit/no	2bit/yes	No/no	1bit/no	1bit/no	---
Power dissipation	60/84 (RF+BB)	41/50	11.4/20.5	23/76	20/36	36.7/66	17/30	15/27	mA/mW
Technology	90nm CMOS	130nm CMOS	180nm SiGe	350nm SiGe	180nm CMOS	180nm CMOS	180nm CMOS	180nm CMOS	----
Area	12.8 (RF+BB)	<6.6	3.24	8.4	3.6	N.A	4.1	4.6	mm^2
Architecture	Low-IF	Zero-IF	Low-IF	Low-IF	Low-IF	Low-IF	Low-IF	Double-Conversion	---
Image Rejection	18dB	No	>20dB	No	30	20	30	40	----

RF Front Ends

» Multi-frequency solutions (I)
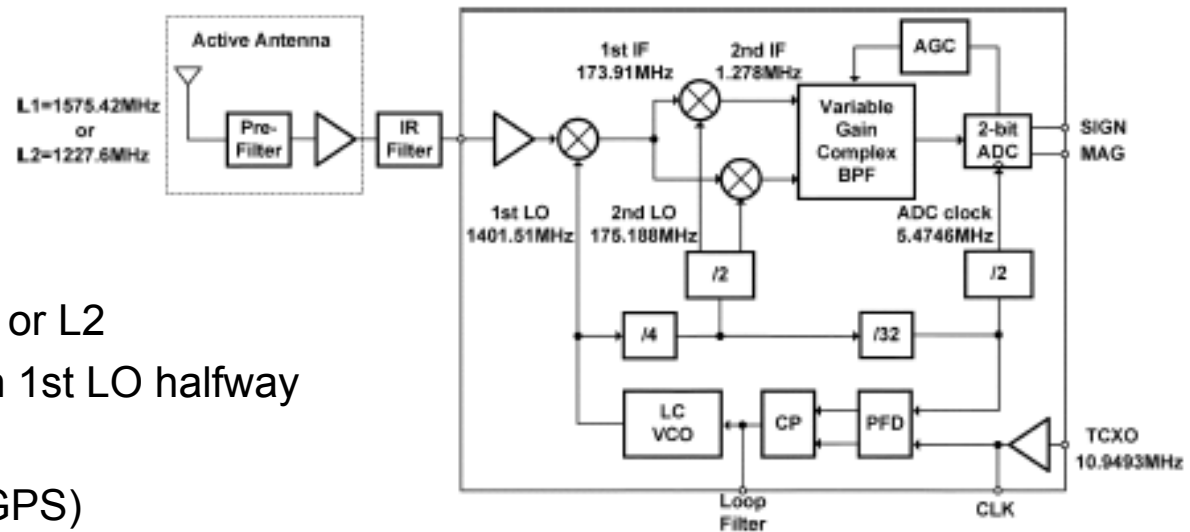
» Chip working at L1 or L2
» Double Conversion 1st LO halfway
» External LNA
» Narrow BW (only GPS)
» 20mW, no commercial product yet →problems?

Jinho Ko, "A 19-mW 2.6-mm2 L1/L2 Dual-Band CMOS GPS Receiver", IEEE JSSC, July 2005

RF Front Ends

» Multi-frequency solutions (II)
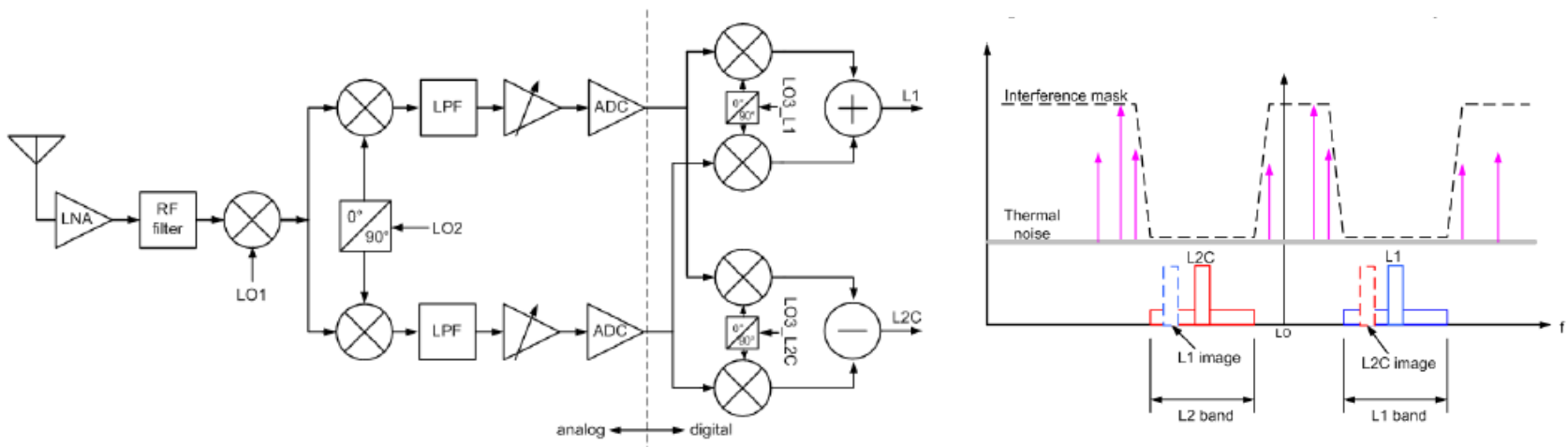
» Shift of LO from midpoint, possible simultaneous reception
» Modified Weaver Architecture, additional digital mixers and ADC
» Narrow BW (only GPS)
» Not clear how PGA can be realized, and no implementation available (power?)

F. Chastellain, "A low Power RF Front End Architecture for an L1/L2CS GPS Receiver", 18th Technical Meeting of the Satellite Division, 2005

RF Front Ends

» Multi-frequency solutions (III)

» Low IF
» Simultaneous/Switching ?
» Narrow BW (only GPS)
» No implementation available,
» High level simulation (unrealistic power consuption figures)
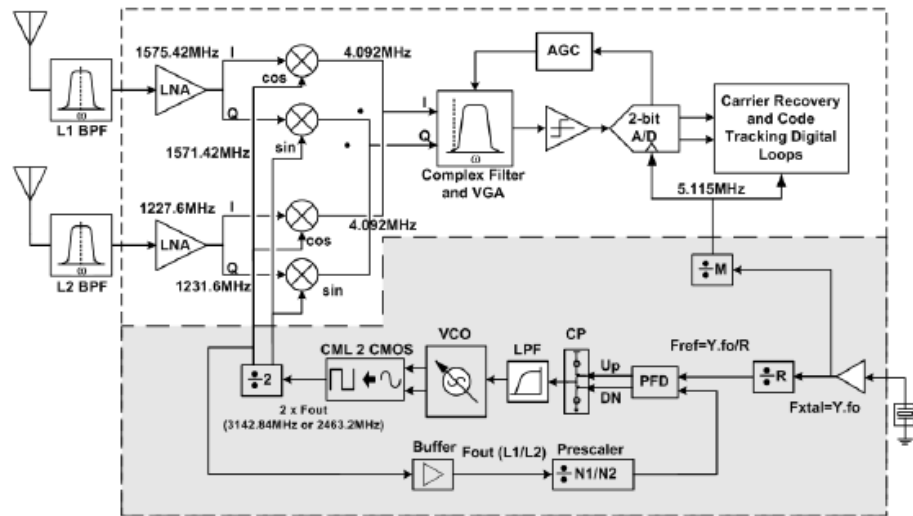
T.A. Abdelrahim," A 12mW fully integrated Low-IF dual-band GPS Receiver on 0.13-um CMOS", IEEE International Symposium on Circuits and Systems, 2007.

T.Esselly, "A Crystal-Tolerant Fully Integrated Frequency Synthesizer For GPS Receivers: System Perspective", IEEE Int. conf. on microelectronics,, 2006.

RF Front Ends

» Multi-frequency solutions (IV)

» Parallel Super-heterodyne L1/L2/L5

» Was Available as IP (Synopsis)

» Only GPS

» BW? Number of Pins?

» Acceptable power but lack of ADC
and only one LNA
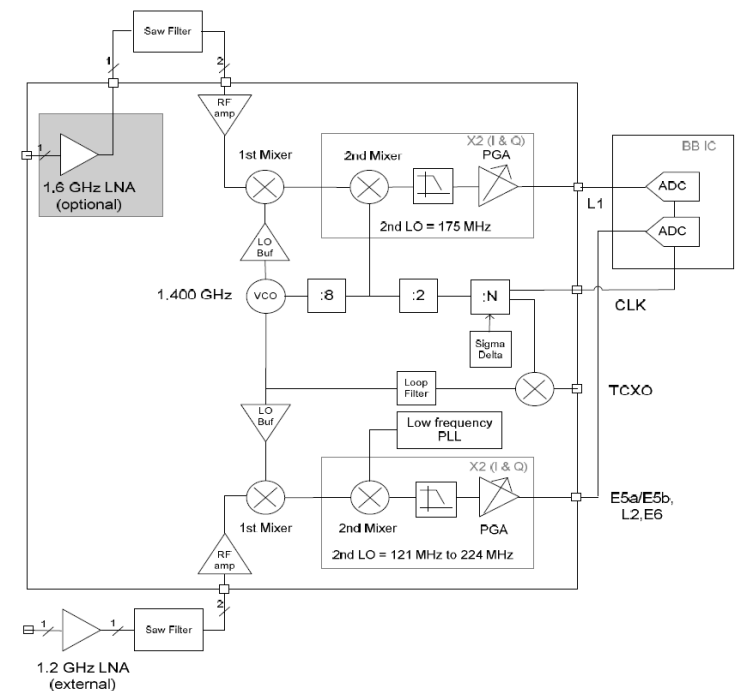
RF Front Ends

» Multi-frequency solutions (V)
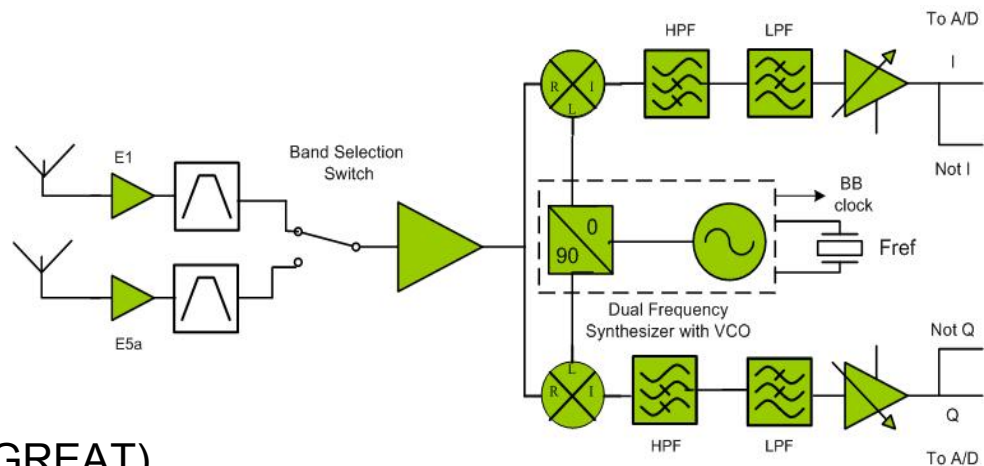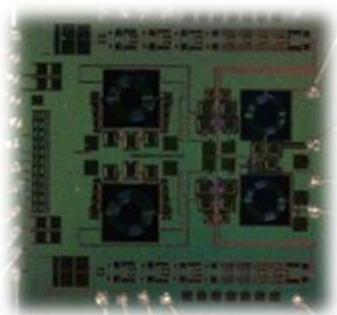
» Switching Architecture (FP6 GREAT)
» Broad BW (<9MHz real)→ GPS L1/L5 and Galileo E1/E5a
» High Linearity (handsets)
» Acceptable power (50mW but lack of ADC)
» Implemented, but switching performance under evaluation (FP7 GRAMMAR)

RF Front Ends

» Multi-frequency in Professional and High precision applications

→ Priorities: Accuracy, Robustness, cost, size, TTFF (in this order…)

» Different power/size constraints

» Replica of COTS or chip (FP6 ARTUS) single frequency FE chains matched to specific needs (BW, ADCs,…)

Javad
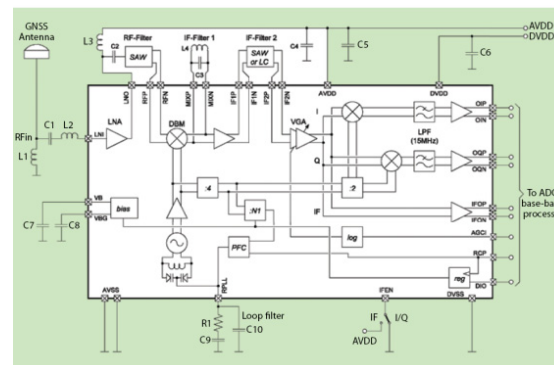
NemeriX ARTUS FE

» High performance GNSS FE could find applications also in professional markets (Scientific, PRS,…) to reduce costs/size/consumption in specific applications

RF Front Ends

» Research and development needed to offer a low cost and compact FE solution for advanced GNSS receivers → GRAMMAR

» First Step: Single chip implementation of switching receiver

    » *Single Chip Dual Band Broadband Receiver*
    » *Embedded LNAs*
    » *Reconfigurable down-conversion and IF sections*
    » *Digital control (SPI)*
    » *No image rejection/Low pass Filtering*
    » *ADCs and AGC*
    » *Low power (60mW) Low cost(CMOS)*
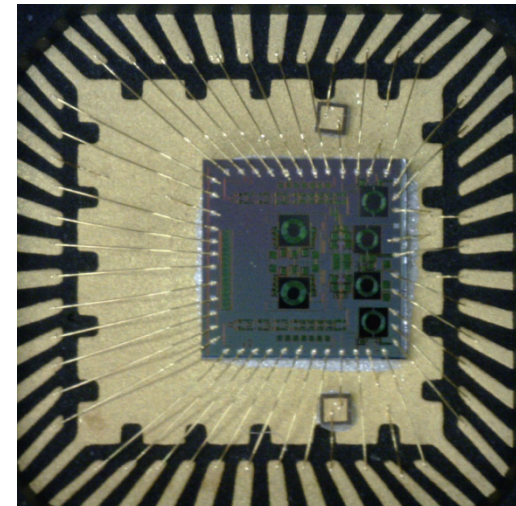
RF Front Ends

» Final Goal: Dual-Parallel Receiver Architecture → optimal choice

» *Dual Channel Receiver*
» *Narrowband and Broadband Optimized Chains*
» *Reconfigurable down-conversion and IF sections*
» *Analog image rejection for enhanced sensitivity and reduction of ADCs*
» *Complex Filtering*
» *Low power (<50mW) Low cost(CMOS)*
» *Power saving modes and reconfigurability (E1, E5a/b, E1+E5a, Switching)*
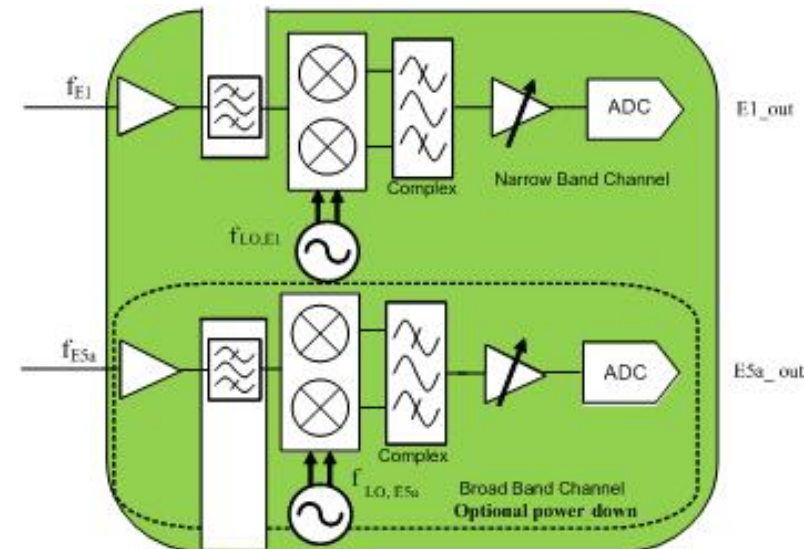
**High Performance Multi frequency receiver FE for a broad market**

Antennas

» Antenna characteristics affect overall receiver features (size, power consumption, cost, performance) and are hence a core critical element to be taken into account (especially in multi frequency environment)

» Antennas required for integration and testing in real conditions

» Analyze the development and evolution antennas at the various GNSS frequencies, as well as possible antenna arrangement for integration in multi-frequency platforms.

  » COTS/Literature Review
  » Low Cost Multi frequency antenna platform

Antennas

» Miniaturized antennas → only L1 COTS

  » Ceramic SMD (monopole)
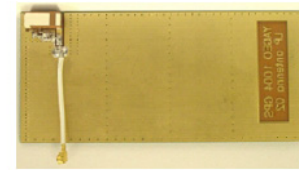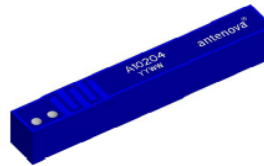
  » Patch Antennas

  » Helix

  » Fractal
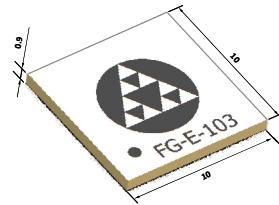
Antennas

» State of the art miniaturized antennas (passive, L1)

Parameter	Brevis A10204	Pulse W3011	Yageo 1044	Ethertronics M420110	Fractus GeoFind™	Maxtena 10mm patch	QFHA SL1300	Units
Dimensions	22x3x3	3.2x1.6x1.1	10x4x4	4x2x1.08	10x10x0.9	10*10*4	7.5 x12	mm
RX Bandwidth*	>40	>20	20	25	>100	>13	>15	MHz
Ground Clerance	no	4x4.25	10x4	<6x2	>10x10	>10*10	no	mm
Peak Gain (linear)	0.7	3.4	1.61	1.1	1.5	N.A.	N.A.	dBi
RHCP Peak Gain	-2.3	0.85	-1.39	-1.9	-1.5	3	-5	dBic
Peak Efficiency	>60	85	>70	59	>70	50	NA	%
Polarization	linear	linear	linear	linear	linear	RHCP	RHCP	---

Antennas

» Other GNSS frequencies: COTS→ only professional solutions available (high weight >0.5Kg and bulky >10cm)

- » Conical Spiral, Archimedean Spiral, Spiral Mode Microstrip
- » Pin Wheel Spiral Antenna, Zephyr Geodetic Antenna
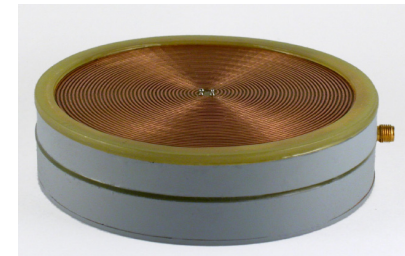- » Multiband Stacked Microstrip, Bow Tie Antennas on Corrugated Ground Plane
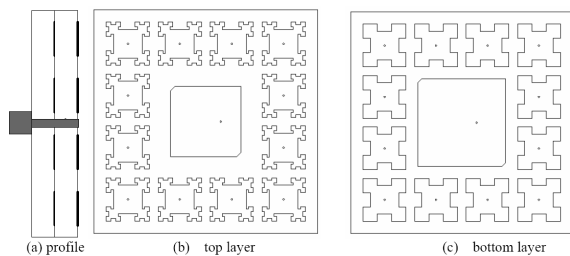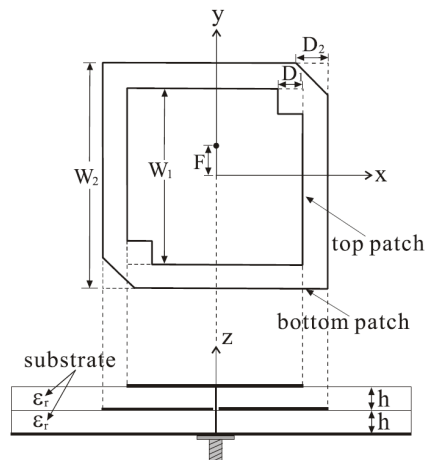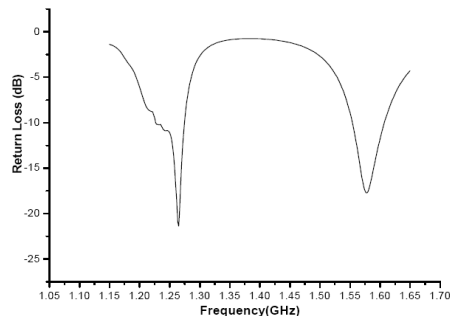
Javad

Novatel

Weo

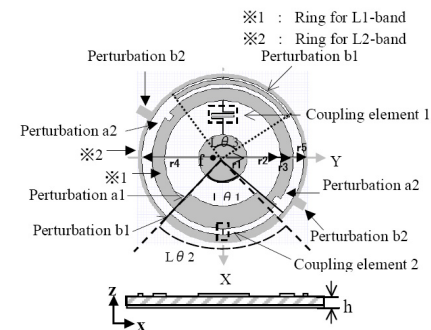» Covering almost all GNSS frequencies (universal antennas)

Antennas

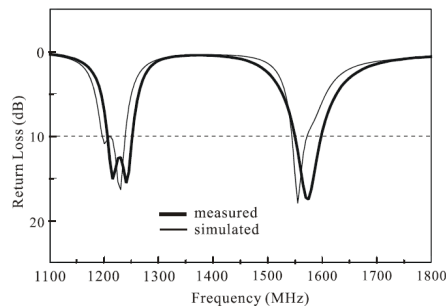» Other GNSS frequencies: literature→ L1-L2 solutions generally based on patch antenna concept
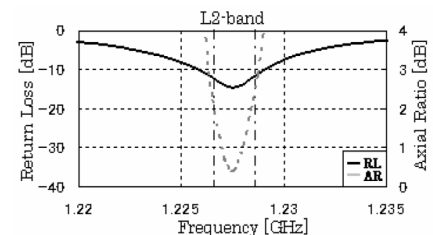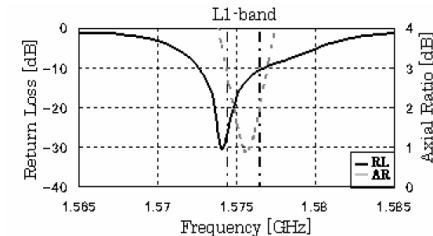

Fractal EBG structure (56mm,[12])

Probe-fed RHCP with stacked patches (52mm,[13])

Single-feed combined patch and ring (30mm,[14])

Antennas

» Dimensions needs still to be opimized for tight integration

» Multi-frequency starts to gain interest for COTS manufacturer: L1-L2 promising solutions presented this year by big industrial mass market antenna provider targeting portable devices.

Maxtena

Sarantel

» → interest in multi frequency solutions for portable high precision devices

...need compact and low cost multi frequency receivers…

Conclusions

» The core technology developments under investigation will pave the way for low-power compact multi-band GNSS receivers, suitable for portable devices requiring high performance and robustness against interference from cellular and legacy services.

» Given the big advances and studies in SW receiver and with the impressive processing speed it could be envisaged the possibility of professional like receiver at very low cost→ consumer market

» If the power constraints are not too stringent (like in cellular handset), the possibility of implementing really broadband solution will not be a problem (full E5, E6)

>→Potential applications to affordable price and comfortable size for professional and high precision products

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3. GRAMMAR D1.2, "Requirements and Receiver Specifications", December 2009 (unpublished)

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12. X. L. Bao and M. J. Ammann "Dual-band GPS Patch Antenna based on Dual-band Fractal EBG Technique", LAPC April 2006

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   http://ec.europa.eu/enterprise/policies/space/galileo/files/galileo_os_sis_icd_revised_3_en.pdf
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6. Compass Status http://scpnt.stanford.edu/pnt/PNT09/presentation_slides/3_Cao_Beidou_Status.pdf
7. Galileo Ready Advance Mass Market Receiver (GRAMMAR) http://www.gsa-grammar.eu

Tutorial Outline

» Introduction: GRAMMAR, Satellite navigation basic principles, existing and emerging GNSS satellite constellations and augmentation systems (30 minutes): Stephan Sand, DLR

» Antennas and RF front-ends for multi-frequency GNSS receivers (30minutes): Marco Detratti, ACORDE

» Advanced receiver algorithms for baseband processing (30 minutes): Simona Lohan, TUT/DCE

» Baseband hardware solutions for multi-system, multi-frequency reception (30 minutes): Heikki Hurskainen, TUT/DCS

» Issues in PVT solution software for GNSS (20 minutes): Francescantonio Della Rosa, TUT/DCS

» Hybridization with other sensor data (30 minutes): Stephan Sand, DLR

» Wrap-up and conclusions (10 minutes): Stephan Sand, DLR

Advanced Galileo receiver algorithms for baseband processing

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13th June 2010

Outline

- » Main baseband characteristics of Galileo
  - » BOC/CBOC modulations briefly
- » Challenges in Galileo:
  - » Multipaths
  - » Ambiguities of the correlation function
- » Solutions
  - » Baseband multipath mitigation algorithms
  - » Unambiguous processing (acquisition/tracking)
- » Conclusions & references

Main baseband characteristics of Galileo

	GPS	Galileo
Multiple access scheme	DS-CDMA	DS-CDMA
Chip rates [MHz]	1.023, 5.115, 10.23	1.023, 2.5, 5.115, 10.23
Modulation types	BPSK, BOC(1,1), BOC(10,5), TMBOC(6,1,4/33)	BPSK, BOCc(10,5), CBOC, AltBOC(15,10)

Abbreviations:

AltBOC = Alternate Binary Offset carrier

BPSK =Binary Phase Shift Keying

BOC= Binary Offset Carrier (sine)
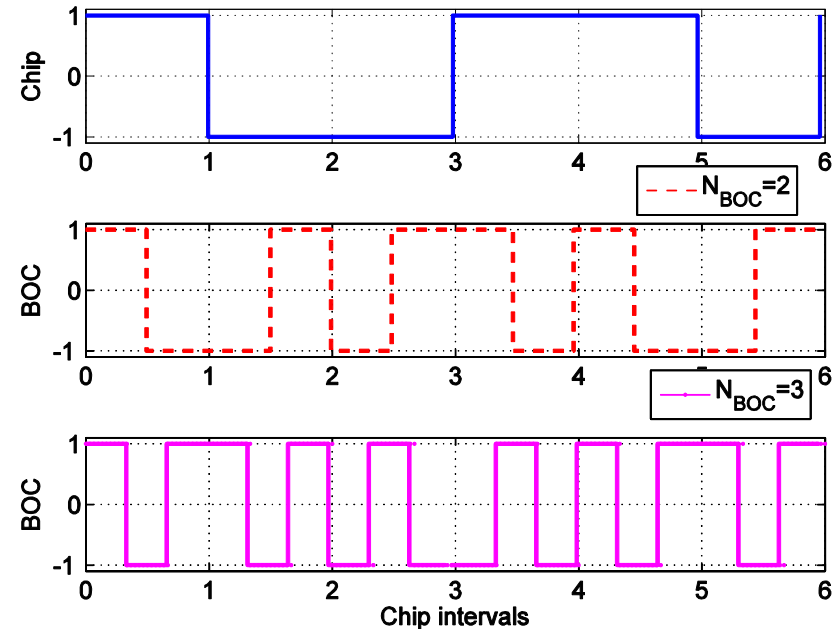
BOCc=cosine BOC

CBOC= Composite BOC

TMBOC = Time Multiplexed BOC

DS-CDMA=Direct Sequence Code Division Multiple Access

Binary Offset Carrier (BOC) modulation

» Square sub-carrier modulation, where the PRN code (of chip rate f_c) is multiplied by a rectangular sub-carrier of frequency f_{sc}

» BOC-modulation order N_{BOC} is defined as:

$$N_{BOC} = 2\frac{f_{sc}}{f_c}$$

» 2 main variants: sine BOC and cosine BOC modulation

Sine and cosine BOC modulation

» **Sine-BOC modulation**

$$s_{BOC}(t) = sign\left(\sin\left(\frac{N_{BOC}\pi t}{T_c}\right)\right) = p_{T_B}(t) \otimes \sum_{i=0}^{N_{BOC}-1} (-1)^i \delta\left(t - i\frac{T_c}{N_{BOC}}\right) \quad \text{(see [1])}$$
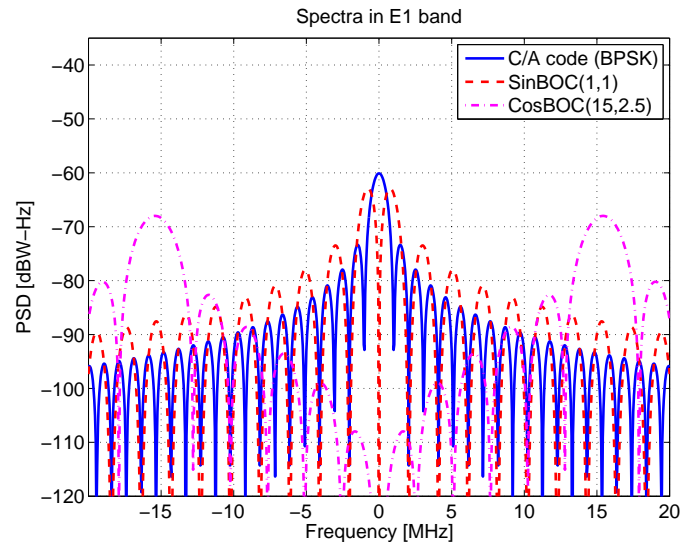
T_c = chip period

$p_{T_B}(t)$ = rectangular pulse of support $\quad T_B = \dfrac{T_c}{N_{BOC}}$

» **Cosine-BOC modulation**

$$s_{CosBOC}(t) = sign\left(\cos\left(\frac{N_{BOC}\pi t}{T_c}\right)\right) = p_{T_B}(t) \otimes \sum_{j=0}^{1} \sum_{i=0}^{N_{BOC}-1} (-1)^{i+j} \delta\left(t - i\frac{T_c}{N_{BOC}} - j\frac{T_c}{2N_{BOC}}\right)$$

Advantages/properties of sine/cosine BOC modulation

» Good spectral separation with BPSK-modulated signals => less interference between Galileo and GPS

» Narrower width of the main auto-correlation lobe => potential of better tracking capability

Spectra in E1 band

C/A code (BPSK)
SinBOC(1,1)
CosBOC(15,2.5)

PSD [dBW–Hz]
Frequency [MHz]

Envelope of the ACF

SinBOC(1,1)
CosBOC(1,1)
BPSK

Abs of ACF
Delay Error [chips]

Composite BOC (CBOC) modulation

» Weighted combination of SinBOC(1,1) and SinBOC(6,1) code symbols
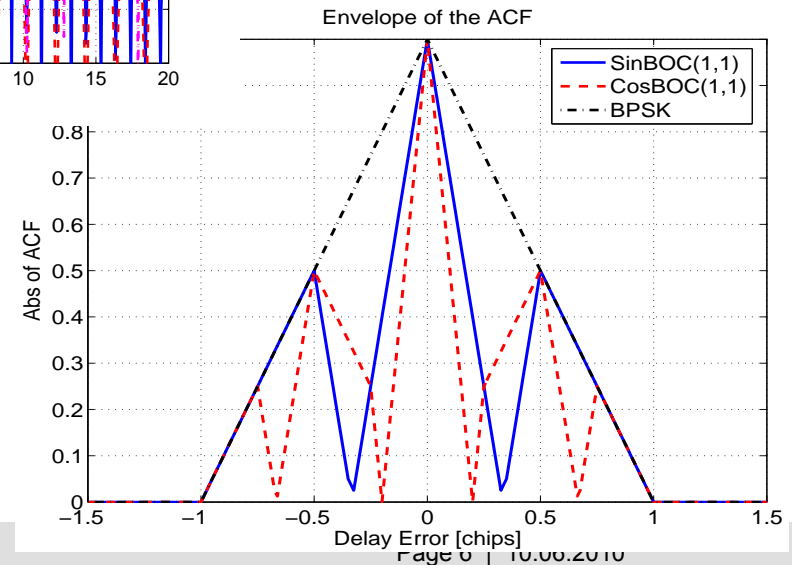
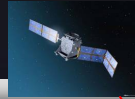$$s_{CBOC}(t) = w_1 s_{BOC(1,1),h}(t) + a w_2 s_{BOC(6,1)}(t)$$

where w_1, w_2 are amplitude weighting factors satisfying $w_1^2 + w_2^2 = 1$. E.g.,

$$w_1 = \sqrt{\frac{10}{11}}, w_2 = \sqrt{\frac{1}{11}}$$

and $a = \pm 1$ is a weighting factor, separating between CBOC(+) and CBOC(-).

» Currently, CBOC(+) is selected for navigation data signals in E1, and CBOC(-) for pilot signals in E1 Galileo.
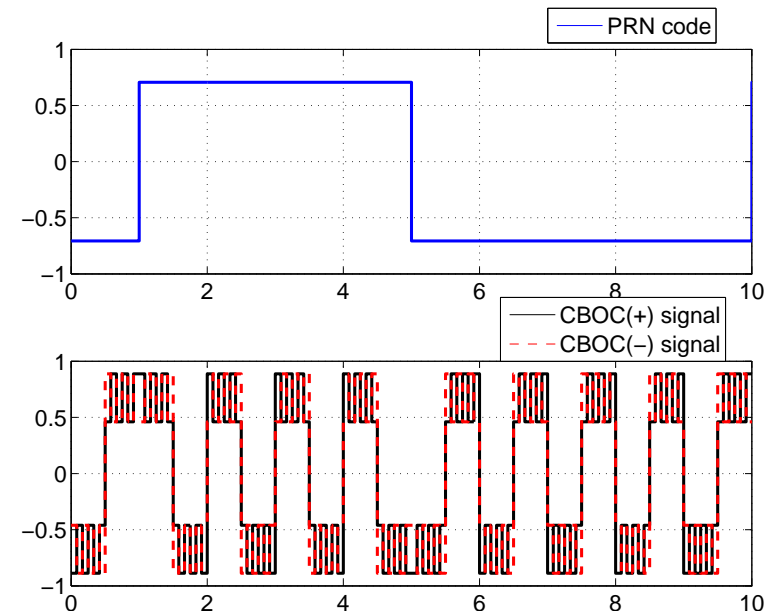
Challenges in Galileo (I)

» Multipaths:

- splitting of signal into 2 or more components due to reflections, scattering, refractions, dispersion, etc.

- replicas of the same transmitted signal arrives at the receiver with different attenuations (amplitudes), phases and delays

How does the multipath affect the position estimate?

» Triangulation principle for PVT computation is based on LOS TOA

» If incorrect LOS estimate or NLOS case only => link-level errors affect the final PVT

» Exact amount depends on how many links are affected and what is the final algorithm for PVT computation
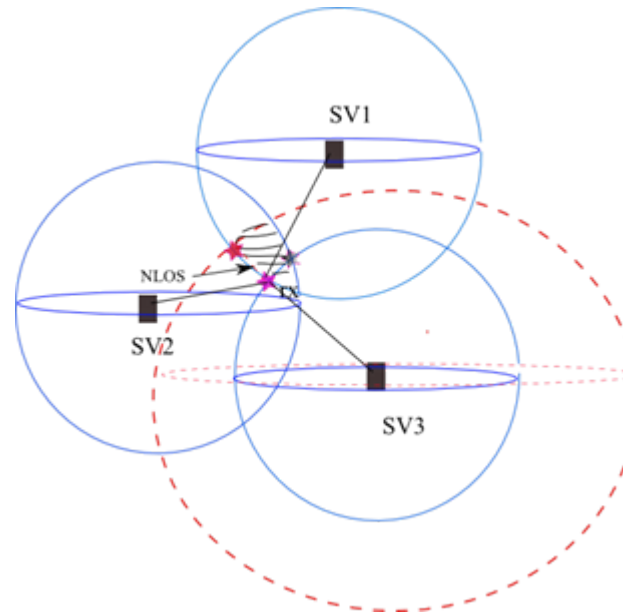
LOS =Line Of Sight
TOA =Time Of Arrival
NLOS= Non Line Of Sight
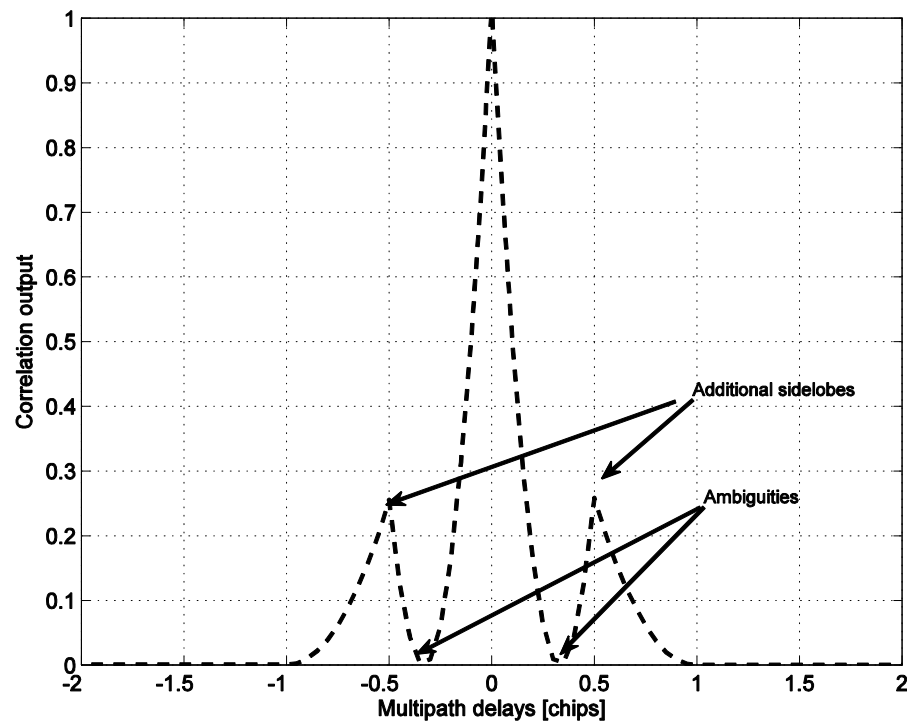PVT= Position, Velocity, Time

A rule of thumb at link-level:

τ_{err} delay error => $c\tau_{err}$

distance error. c=3e8 m/s (speed of light)

Challenges in Galileo (II)

» Due to the split-spectrum modulations (BOC, CBOC) => **ambiguities** (notches) in the envelope of the correlation function and **additional sidelobes**

- *Acquisition stage:*
   -Time-bin step in the searching process needs to be smaller (in chips) than in BPSK modulation => longer time to spend in acquisition stage/ need to remove the ambiguities

-*Tracking stage:*
   -False lock peaks
   -More difficult to cope with multipaths (how to make the distinction between a 'side peak' and a multipath ?)

Example: multipath effect on the correlation function

» Sine BOC(1,1) signal and 3 channel paths
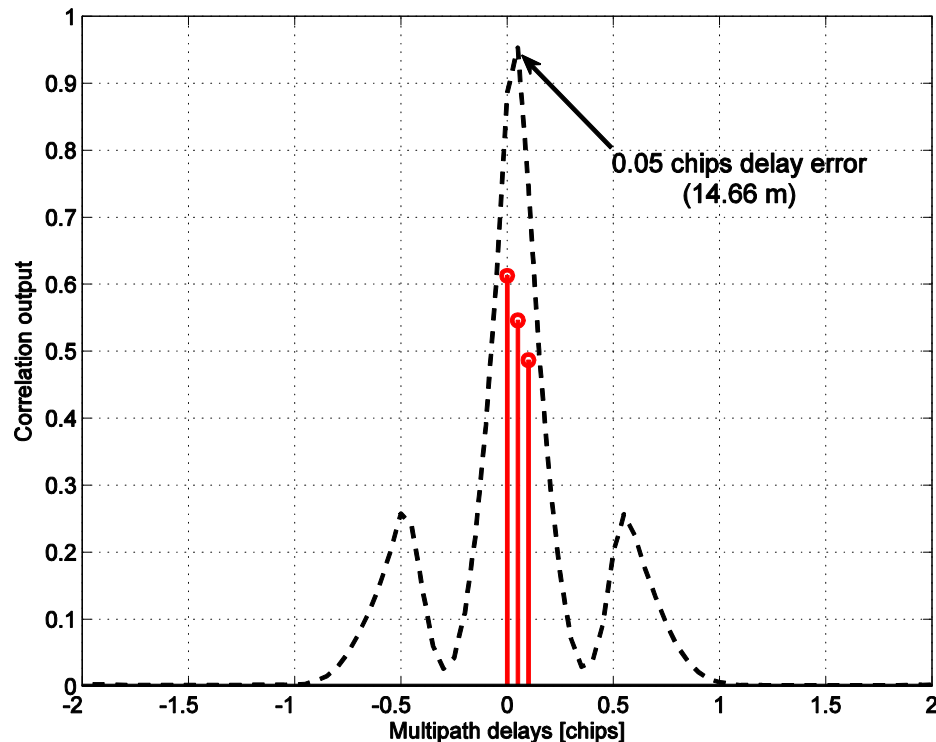
Multipaths introduce errors in the LOS delay estimation => traditional methods (such as looking for the maximum of the correlation envelope) fail in detecting the correct LOS.

The multipath errors are not necessarily increasing with the number of paths

The paths can add together constructively or destructively (according to their phases)

How to cope with multipaths?
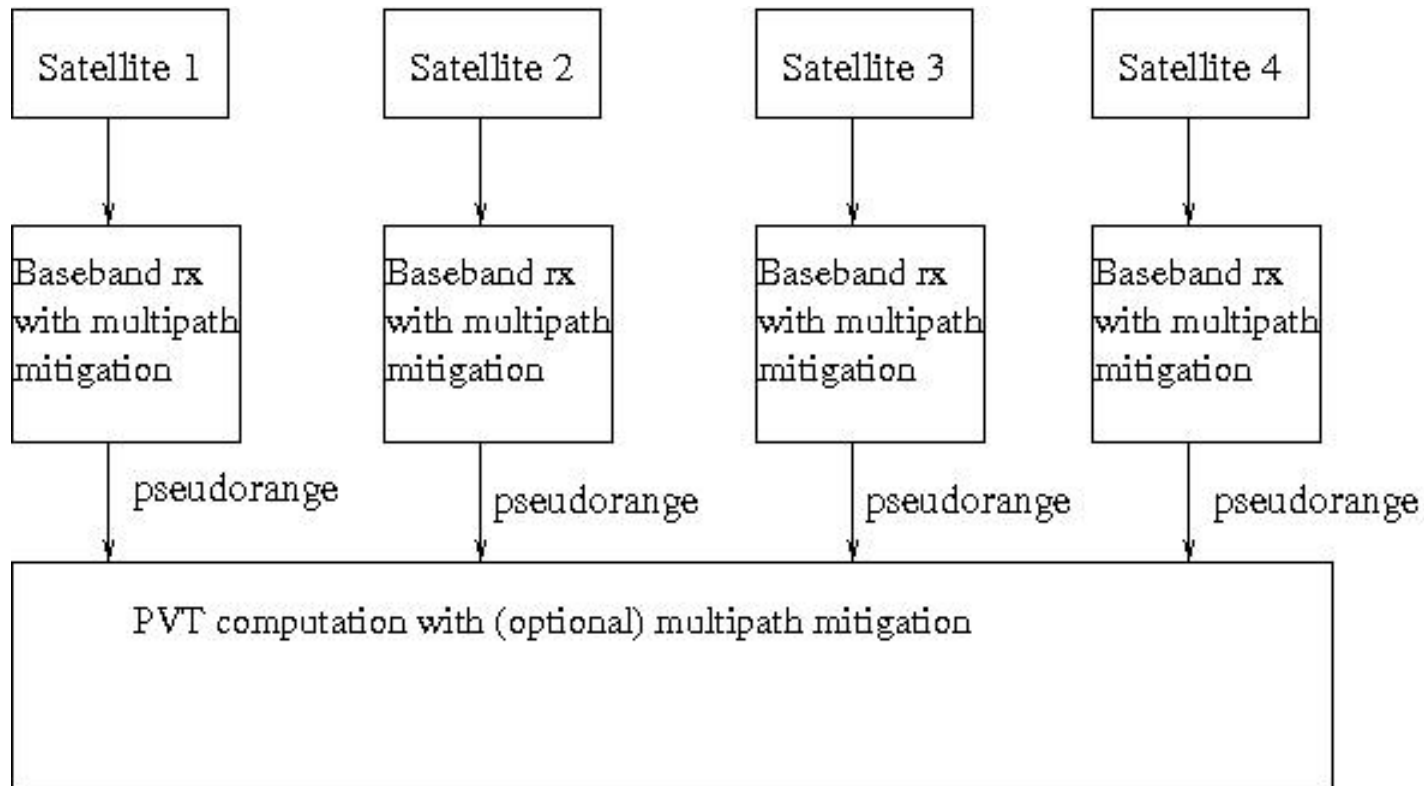
Multipath mitigation algorithms [3,4]

» **Conventional** (low number of correlators, typically up to 5-7 complex correlators):
  » Narrow correlator (NCORR)
  » High Resolution Correlator (HRC); conceptually close to Pulse Aperture Correlator (PAC), strobe correlator and Double –Delta correlators
  » **Multiple Gate Delay structures** (MGD): they cover NCORR and HRC cases
  » **Early-minus Late Slope** (ELS)
  » **A-Posteriori Multipath Estimator** (APME)

» **Advanced** (higher number of correlators, optional additional non-linear processing):
  » Maximum-Likelihood based: **Multipath Estimating Delay Locked Loop** (MEDLL)
  » Other techniques:
    » **Teager-Kaiser** (TK) based
    » Deconvolution algorithms, e.g., **Projection Onto Convex Sets** (POCS)
   » **Peak tracking** algorithm (PT)

Criteria to evaluate the performance of various multipath mitigation algorithms

» Link-level criteria:
  » Most used criterion is the **Multipath Error Envelope** (MEE), see next slide
  » Multipath delay error mean/variance/root mean square error (RMSE)
  » Probability Distribution Functions (PDF) of the delay errors
 » Carrier to Noise Ratios (CNR) needed to achieve a certain performance level

» System-level criterion
  » Ultimately, the error on the estimated PVT (mean, variance, RMSE) would be the most meaningful (also the hardest to evaluate during the algorithm design, since the whole chain including the navigation algorithms should be simulated)

Multipath Error Envelope (MEE)

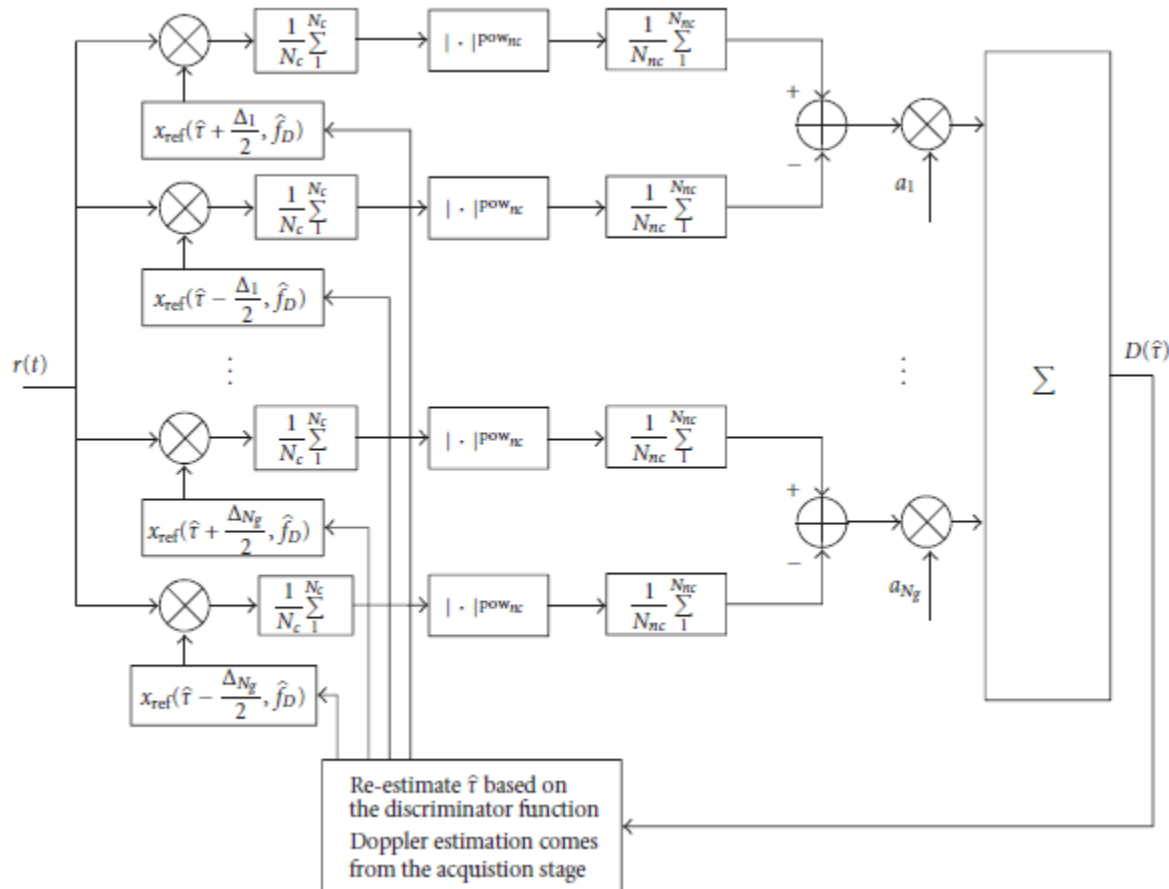» 2 static paths either in-phase (0 degrees phase shift) or out-of-phase (180 degrees phase shift)
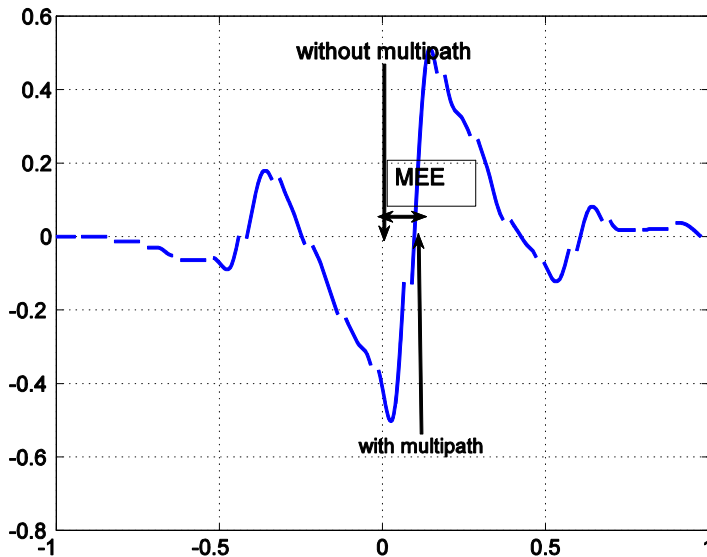
Example about how MEE error is computed from the S curve

MEE; CBOC(-), 24 MHz bandwith, Path Amplitude:[0-6]dB
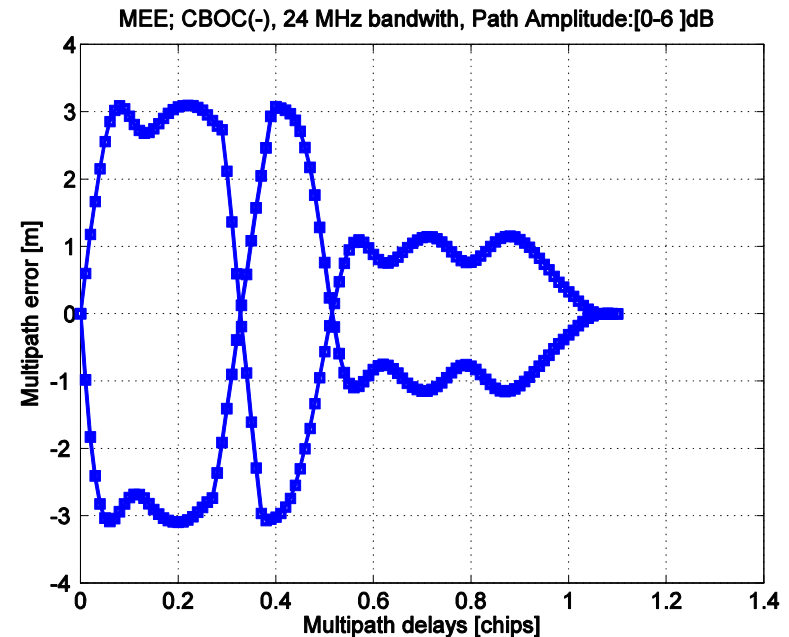
MEE curves - example

Multipath mitigation: Multiple Gate Delays structures [2, 10]

» Cover also NCORR/HRC cases

» Multiple correlator pairs, with variable or fixed spacings

» Discriminator is formed as weighted combination of the various correlators

» Spacings and weights can be optimized

MEE performance of MGD, HRC and NCORR [2]
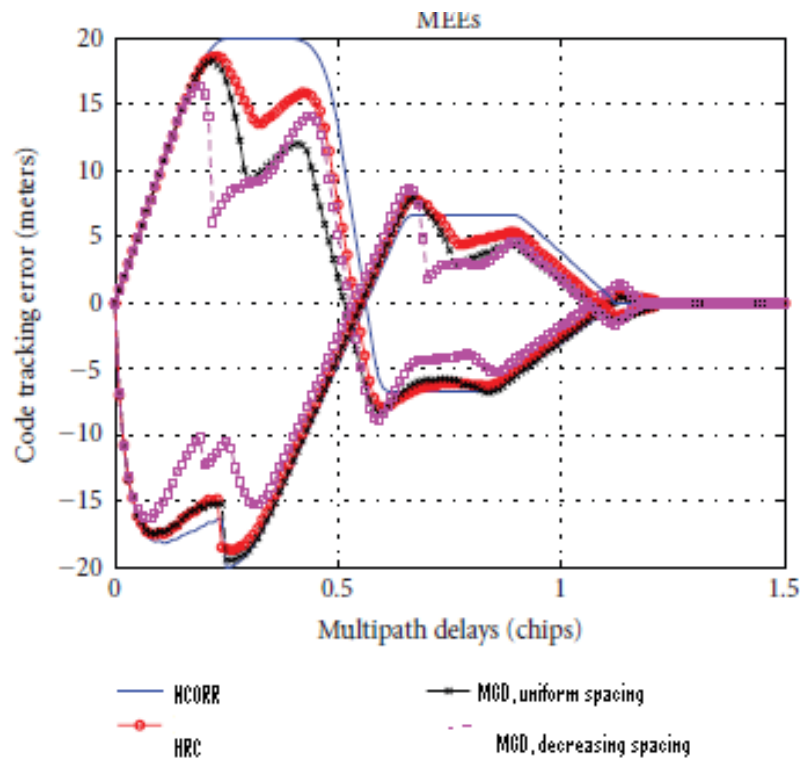
» Slight performance gain if number of correlator pairs is increased (e.g., going from NCORR to MGD with 7 complex correlators)

» Optimization of coefficients according to the target environments allow for un-patented, more flexible solutions

Slope-based multipath mitigation algorithms [9]

» From this family: Early-minus Late Slope (ELS) and A-Posteriori Multipath Estimator (APME)

» Use some 'slope'-related information, carried by additional early (or late) correlators

» *Example (APME):*

A multipath correction based on in-phase correlators I, early-late spacings, and some optimization coefficients is done:

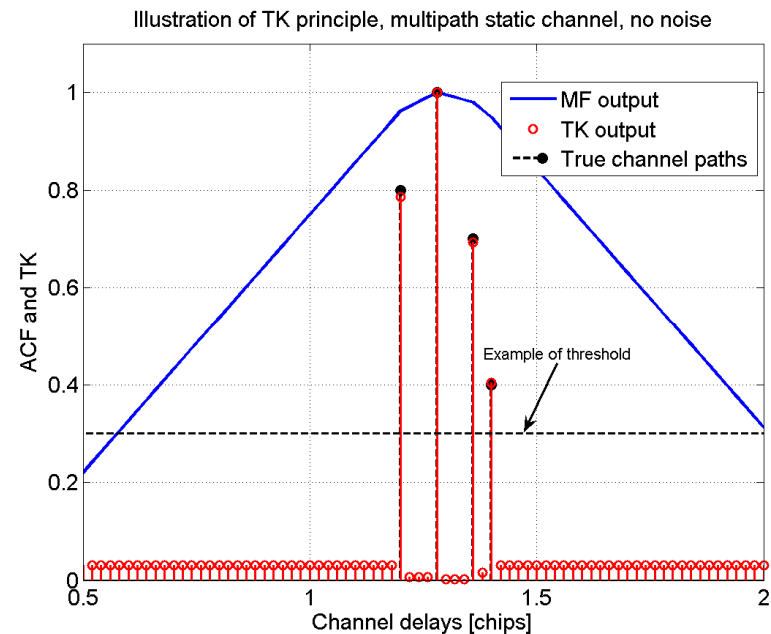$$\sum_{i=-M}^{N} \alpha_i \left(\frac{I_i}{I_P(1-|i|\frac{\Delta_{EL}}{2})} \right)$$
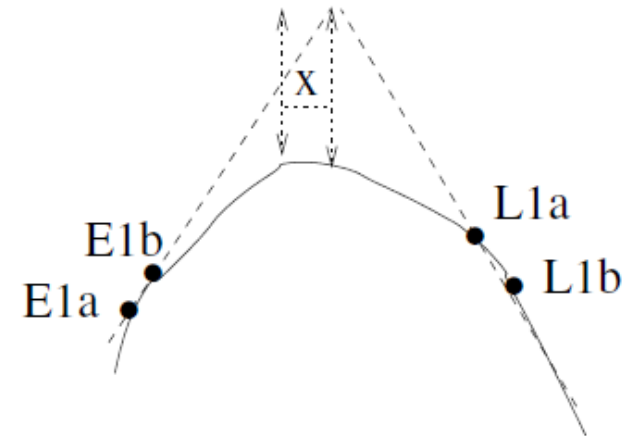
Advanced mitigation: Teager Kaiser [3,8]

» TK introduced for speech signals, in order to extract the signal energy in '90s

» TK applied to a complex signal x(n) is given by:

$$TK(x(n)) = |x(n)|^2 - \frac{1}{2}\left(x^*(n+1)x(n-1) + x(n+1)x^*(n-1)\right)$$

» Sensitive to noise and bandwidth limitations

» Can be very accurate

Illustration of TK principle, multipath static channel, no noise

Legend: MF output, TK output, True channel paths

Example of threshold

ACF and TK

Channel delays [chips]

Advanced mitigation: deconvolution algorithms [3, 11]

» Formulate the delay estimation problem as a linear deconvolution problem

$$y=Ah+n$$

» y are the samples of the correlation function, A is a matrix of the known code auto-correlation function at all possible time delays between 0 and a certain maximum spread, and h is the vector of complex channel coefficients.

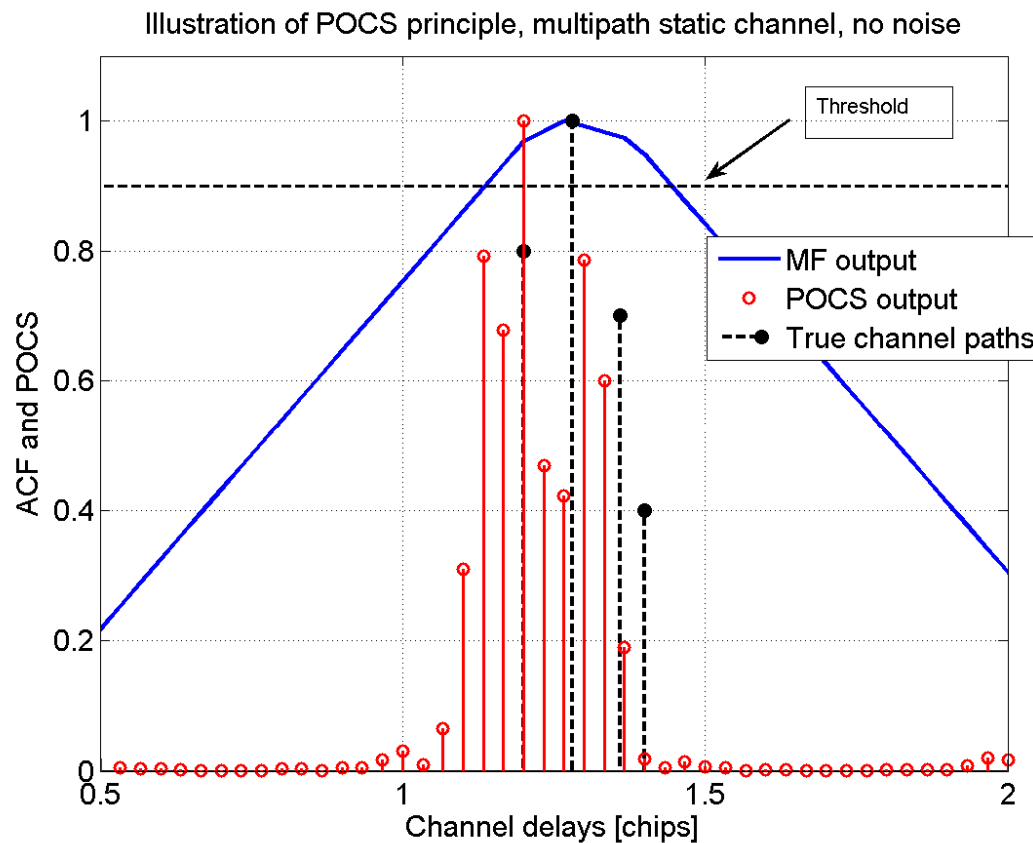» Least Squares (LS)

$$\hat{h}_{LS} = (A^H A)^{-1} A^H y$$

» Minimum Mean Square Error (MMSE)

$$\hat{h}_{MMSE} = (\sigma^2 I + A^H A)^{-1} A^H y$$

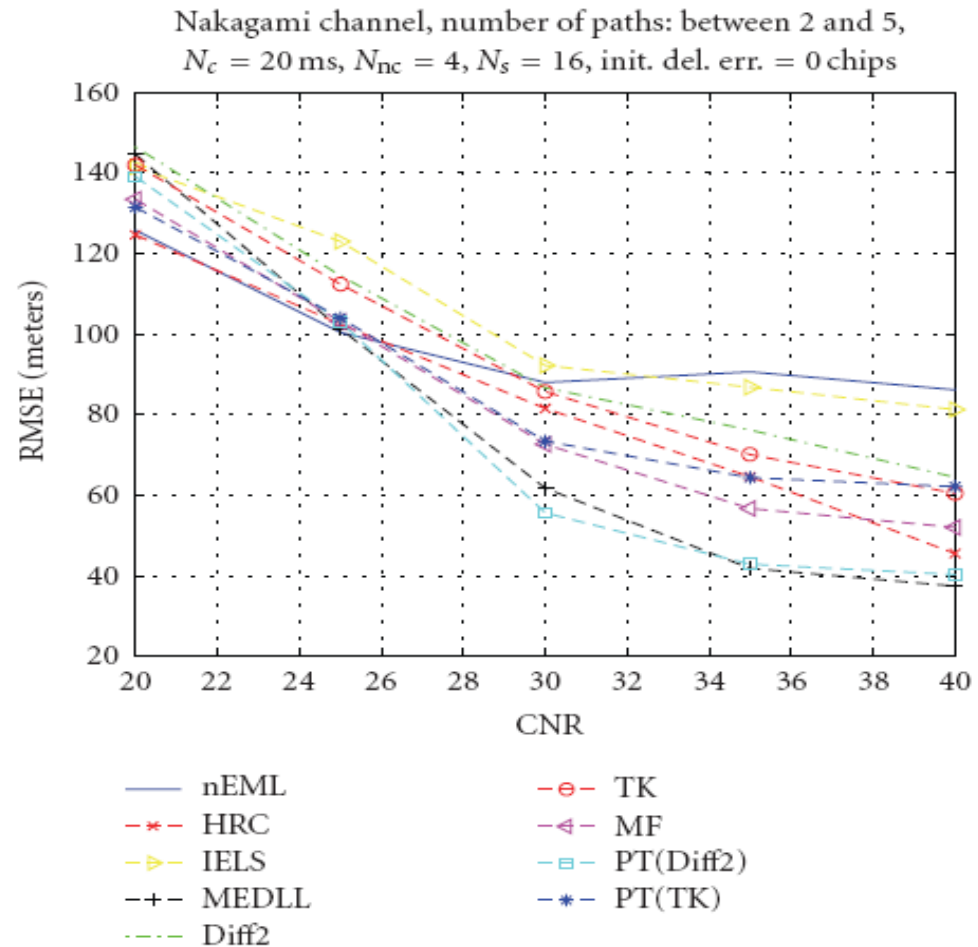» Projection onto Convex Sets (POCS)

$$\hat{h}_{POCS}^{(k+1)} = \hat{h}_{POCS}^{(k)} + (\frac{1}{\lambda} I + A^H A)^{-1} A^H (y - A\hat{h}_{POCS}^{(k)})$$

Example: POCS [11]

Illustration of POCS principle, multipath static channel, no noise

Comparison between various multipath mitigation algorithms [4]

» NCORR (or nEML) is the best estimator at low Carrier to Noise ratios (CNRs)

» Advanced algorithms can offer good performance at moderate-to-high CNRs

» Not many unified studied available [3,4]

Nakagami channel, number of paths: between 2 and 5, $N_c = 20$ ms, $N_{nc} = 4$, $N_s = 16$, init. del. err. = 0 chips

Legend:
- nEML
- HRC
- IELS
- MEDLL
- Diff2
- TK
- MF
- PT(Diff2)
- PT(TK)

Complexity issues in multipath mitigation algorithms

	Number of complex correlators	Complexity
NCORR	3	Low
HRC/PAC	5	Low
MGD	3-9	Low/ moderate
MEDLL	tens	High
APME	>=4	Low
ELS	5	Low
LS/POCS	tens	High
TK	tens	High

What is used on market?

| Company	Multipath mitigation algorithm
Ashtech	Strobe Correlator
Cedar Rapids	HRC
Magellan	Strobe Correlator
Novatel	MEDLL , Vision Correlator, PAC, Early-Late Slope
Septentrio	APME
Sokkia	Vision Correlator and PAC

How to cope with ambiguities? -> Unambiguous processing

» **Unambiguous aquisition methods**: try to recover a 'BPSK-like' correlation shape, such that a higher time-bin step can be used in the acquisition process ->
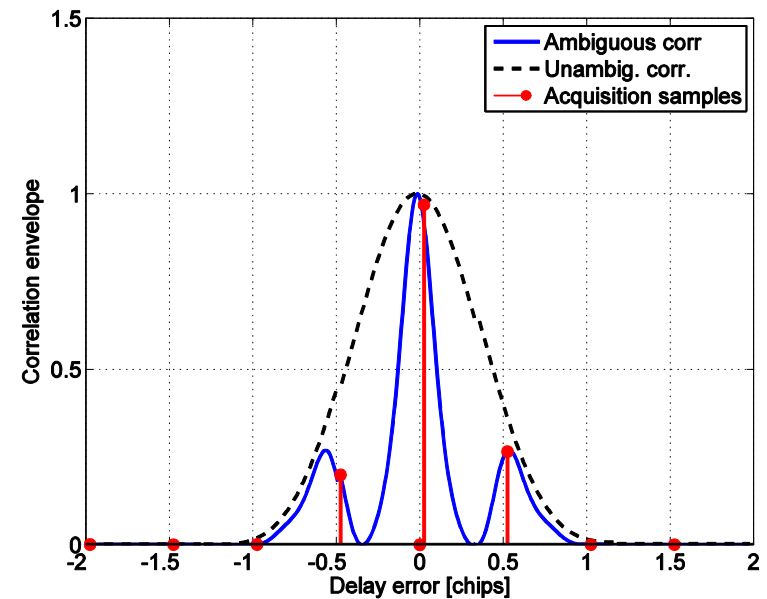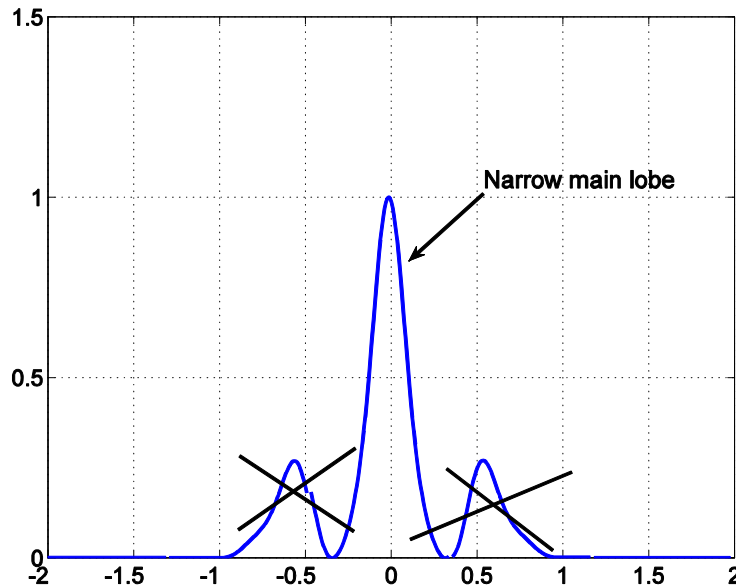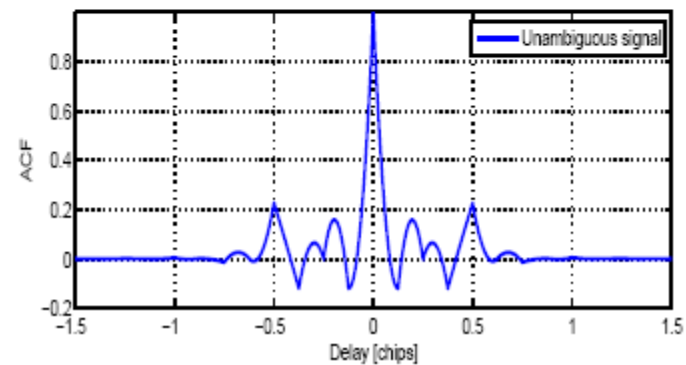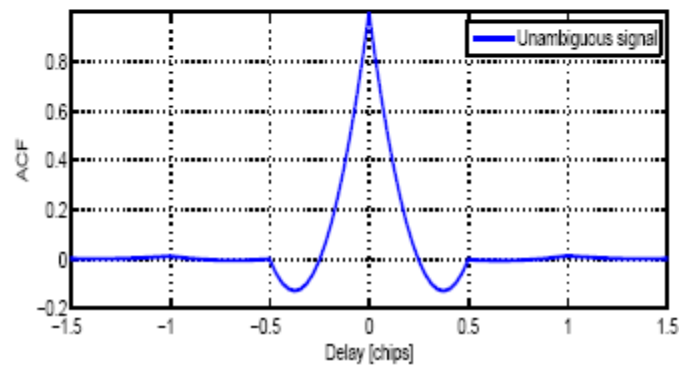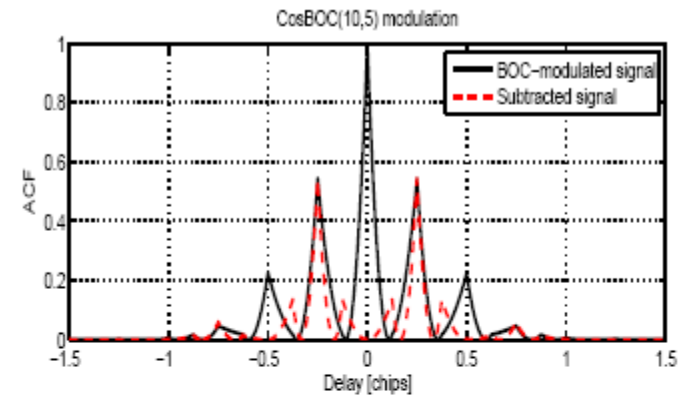
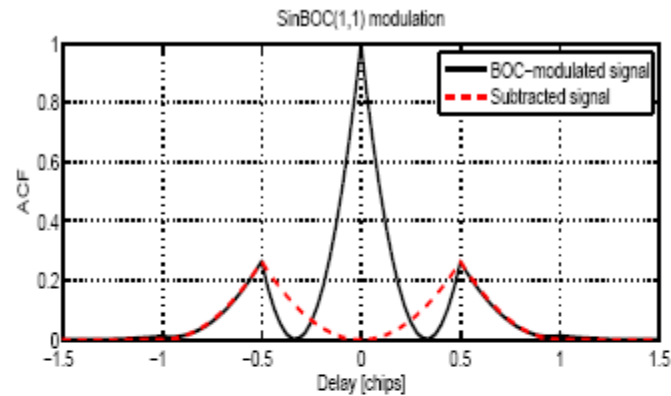

<- **Unambiguous tracking methods**: remove/diminish the additional side lobes (lock to a false peak), while preserving the narrow width of the main correlation lobe

Unambiguous acquisition – example [5]
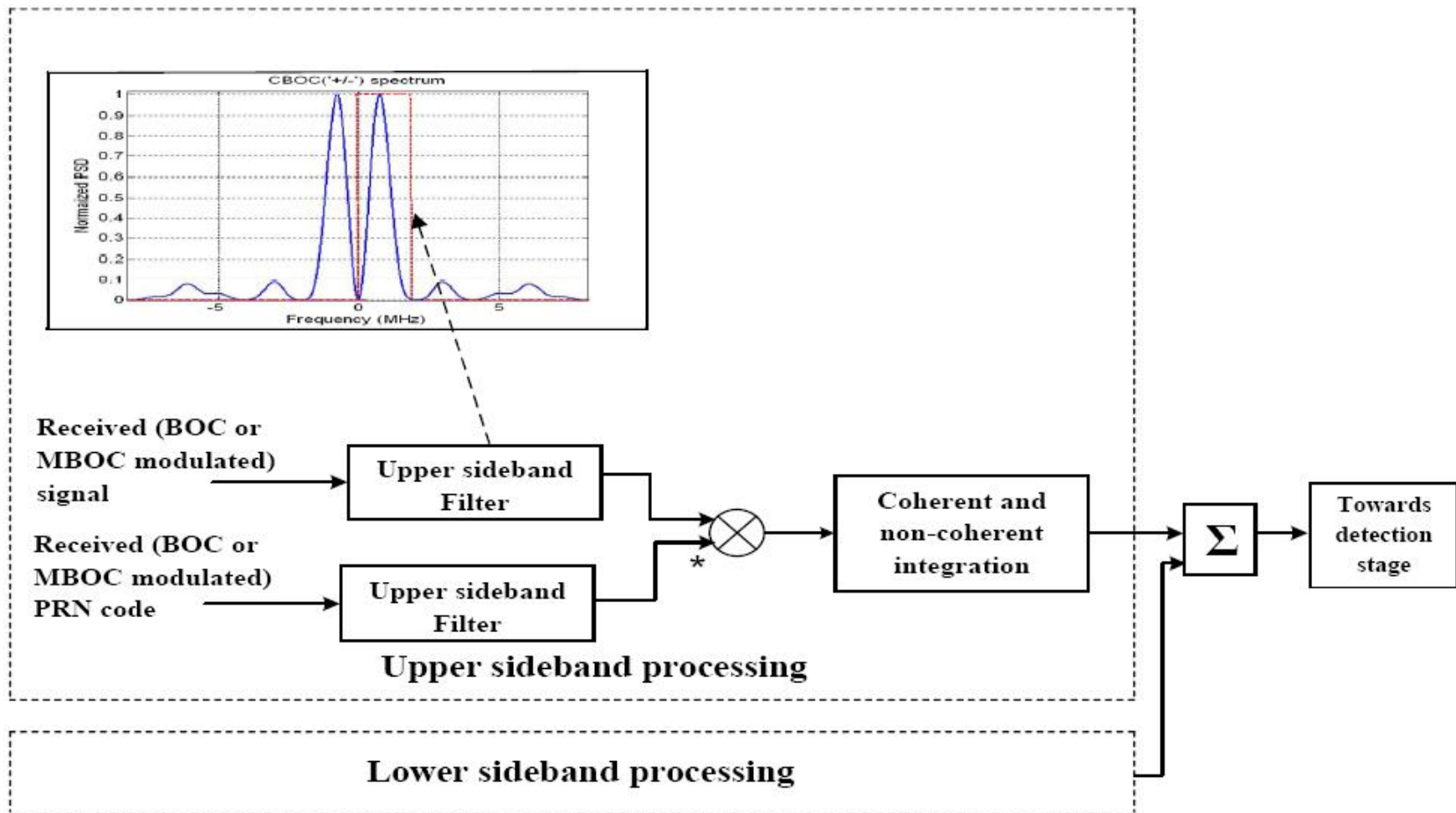
Unambiguous tracking – example [6,7]

» Idea is to cancel/diminish the sidelobes which are closest to the main lobe

Conclusions and open issues

» <u>Lack of unified studies regarding the relative performance and complexity of various algorithms</u>

» Algorithm sensitivity to various modulations and chip rates also not well studied (e.g., most studies made for GPS; newer papers deal also with Galileo)

» New algorithms should not only offer better performance (and/or lower complexity), but also provide patent-free solutions

» A multitude of multipath mitigation algorithms exist nowadays, but there is still a significant place for enhanced algorithms

» Typical structures are those based on multi-correlator type of code tracking. The simplest multi-correlator based multipath reduction techniques (e.g., NCORR, HRC, PAC, ...) are heavily covered by patents.

» Typically, bandwidth limitations and multipath effects on carrier phase and frequency tracking are ignored/poorly documented in the current literature

Links

» Grammar project website: http://www.gsa-grammar.eu/

» Signal processing for wireless positioning group at TUT: http://www.cs.tut.fi/tlt/pos/

» Simulink Galileo E1 baseband transmitter-receiver chain with basic multipath mitigation, **open-source software**: http://www.cs.tut.fi/tlt/pos/Software.htm

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2. H. Hurskainen, E. S. Lohan, X. Hu, J. Raasakka, and J. Nurmi. "Multiple Gate Delay tracking structures for GNSS signals and their evaluation with Simulink, SystemC and VHDL". International Journal of Navigation and Observation, vol. 2008, Article ID 785695, 17 pages, 2008. doi:10.1155/2008/785695

3. E. S. Lohan, A. Lakhzouri, and M. Renfors, "Feedforward delay estimators in adverse multipath propagation for Galileo and modernized GPS signals", EURASIP Journal of Applied Signal Processing, vol 2006, Article ID 50971, 19 pages

4. M. Z. H. Bhuiyan, E. S. Lohan, and M. Renfors. Code tracking algorithms for mitigating multipath effects in fading channels for satellite based positioning. EURASIP Journal on Advances in Signal Processing, DOI: 10.1155/2008/863629, 2008.

5. E.S. Lohan, A. Burian, and M. Renfors ``Low-complexity acquisition methods for split-spectrum CDMA signals'', Wiley International Journal of Satellite Communications, vol. 26, pp. 503-52, 2008

6. Adina Burian, Elena Simona Lohan, and Markku Renfors, Efficient Delay Tracking Methods with Sidelobes Cancellation for BOC-Modulated Signals, Volume 2007 (2007), Article ID 72626, 20 pages

7. JULIEN Olivier ; MACABIAU Christophe ; CANNON M. Elizabeth ; LACHAPELLE Gerard , "ASPeCT : Unambiguous Sine-BOC(n,n) Acquisition/Tracking Technique for Navigation Applications ", IEEE transactions on aerospace and electronic systems, 2007, vol. 43, no1, pp. 150-162

8. R. Hamila, E.S. Lohan, and M. Renfors, ``Subchip multipath delay estimation for downlink WCDMA system based on Teager-Kaiser operator'', IEEE Communications Letters, Volume: 7 Issue: 1, pp. 1-3, Jan. 2003.

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9. M. Z.H. Bhuiyan, E.S. Lohan and M.Renfors, "A Slope-Based Multipath Estimation Technique for Mitigating Short-Delay Multipath in GNSS Receivers," accepted for publication in proceedings of IEEE ISCAS 2010, Paris, France, May/June 2010.

10. J. Zhang, E.S. Lohan and M. Renfors , "Multi-correlator structures for tracking Galileo signals with CBOC and SinBOC reference receiver and limited front-end bandwidth", WPNC, Mar 2010, Dresden, Germany.

11. D. Skournetou, Ali H. Sayed, and E.S Lohan, "A deconvolution algorithm for estimating jointly the Line-Of-Sight code delay and carrier phase of GNSS signals", in Proc. of ENC-GNSS, May 2009, Naples, Italy

Tutorial Outline

» Introduction: GRAMMAR, Satellite navigation basic principles, existing and emerging GNSS satellite constellations and augmentation systems (30 minutes): Stephan Sand, DLR

» Antennas and RF front-ends for multi-frequency GNSS receivers (30minutes): Marco Detratti, ACORDE

» Advanced receiver algorithms for baseband processing (30 minutes): Simona Lohan, TUT/DCE

» Baseband hardware solutions for multi-system, multi-frequency reception (30 minutes): Heikki Hurskainen, TUT/DCS

» Issues in PVT solution software for GNSS (20 minutes): Francescantonio Della Rosa, TUT/DCS

» Hybridization with other sensor data (30 minutes): Stephan Sand, DLR

» Wrap-up and conclusions (10 minutes): Stephan Sand, DLR

grammar
Galileo Ready Advanced Mass Market Receiver

Baseband hardware solutions for multisystem, multi-frequency reception

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13th June 2010

Topics

» Global Navigation Satellite Systems (GNSSs)
  » Galileo and Global Positioning System (GPS)…

» Properties of GPS and Galileo signals
  » CDMA structure…
  » Spreading codes…

» Fundamentals of Baseband hardware
  » Pseudorange estimation…
  » Tracking channel…

» Flexible tracking hardware (the GRAMMAR approach)
 » Implementation details…

GNSS: Multi-system, multi-frequency

» European Galileo and U.S.
Global Positioning System (GPS)
share frequency bands

  » E1/L1 centered at 1.575 GHz

  » E5a/L5 centered at 1.176 GHz

» Currently, only high-end
professional receivers exploit
multiple frequencies.

  » Increased accuracy due to
ionospheric delay error correction

» ESA/GSA. Galileo Open Service Interface Specification (OS SIS ICD). Draft 1. Feb 2008.

» In GRAMMAR we aim at transferring the multiple-frequency technology from high-end receivers to mass market receivers

  » Combination of E1/E5a is seen as the most suitable frequency combination for a dual frequency Galileo mass market receiver
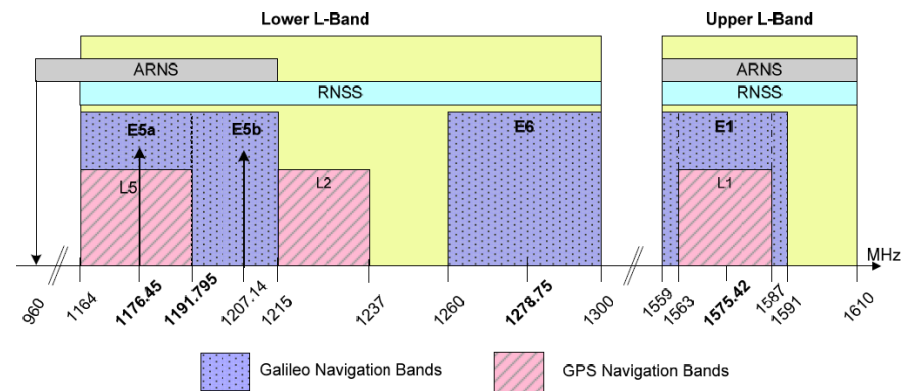
GNSS signal structure

» Both GPS and Galileo are based on Code Division Multiple Access (CDMA) modulation

    » Low rate navigation data (~Hz) is modulated with spreading code (~MHz), possible subcarrier (~MHz) and carrier (~GHz) frequency

    » Satellites are identified due their unique spreading codes
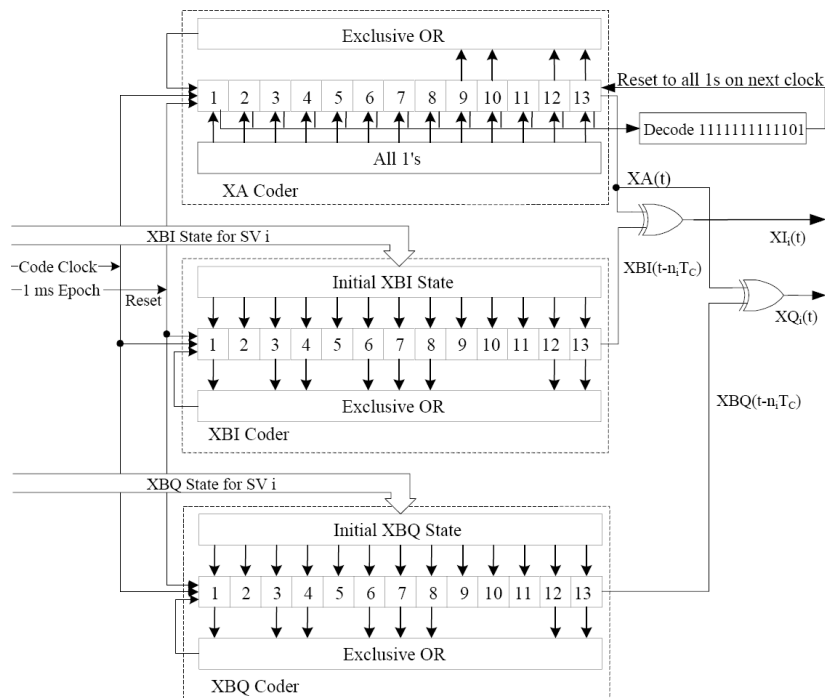
        » Long pseudorandom noise (PRN) codes are used
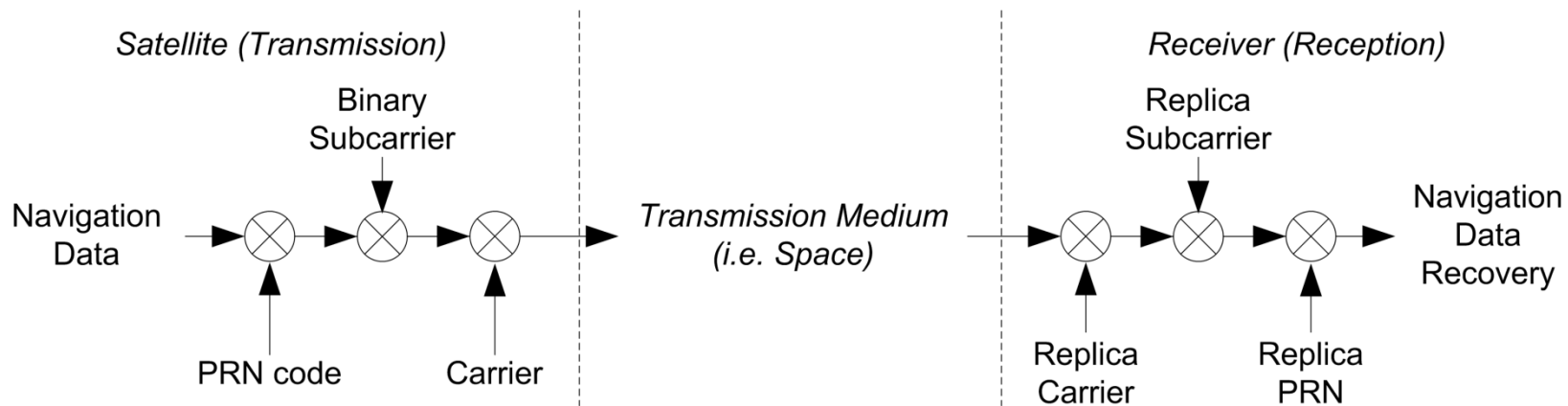
GPS spreading codes – C/A code

» GPS L1 signal PRN codes are based on Gold codes

» Codes are generated by Linear Feedback Shift Registers (LFSR)

» The PRN code is XOR result of two sequences
   » Static sequence - G1 output
   » Changing sequence - 32 Differently delayed versions of G2 output

» After 1023rd chip registers are reset to all '1's
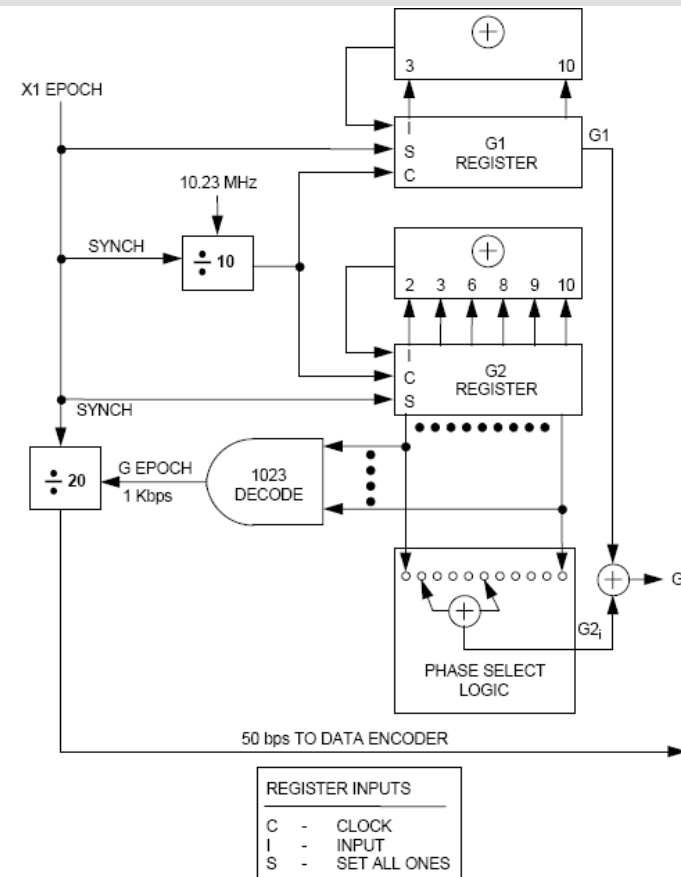
» GPS Interface Control Document (ICD-GPS-200D), IRN-200C-004, U.S. Air Force, Dec, 7. 2004.
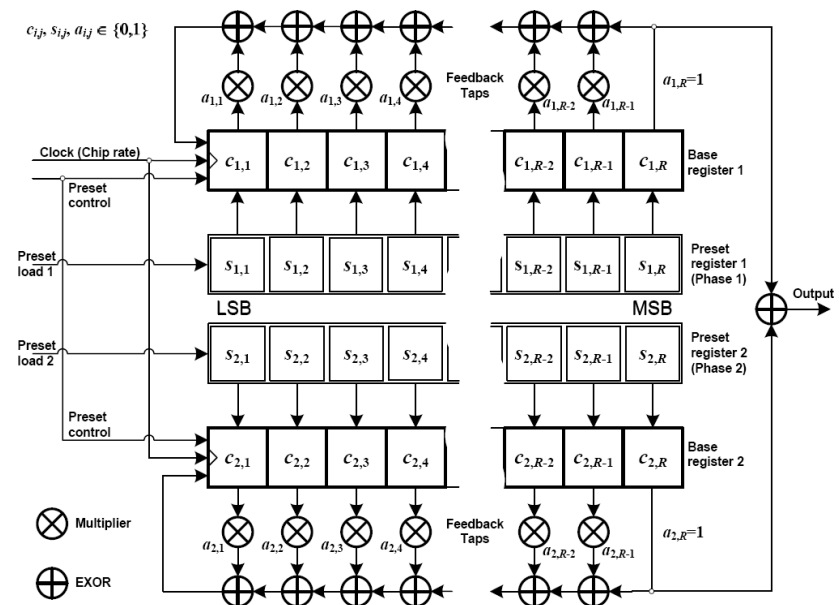
GPS spreading codes – L5 codes

- Exclusive OR
- Reset to all 1s on next clock
- Decode 1111111111101
- All 1's
- XA Coder
- XA(t)
- XBI State for SV i
- Code Clock
- 1 ms Epoch
- Reset
- Initial XBI State
- XBI(t-n$_i$T$_C$)
- Exclusive OR
- XBI Coder
- XBQ(t-n$_i$T$_C$)
- XBQ State for SV i
- Initial XBQ State
- XBQ Coder
- Exclusive OR
- XI$_i$(t)
- XQ$_i$(t)

» GPS L5 contains two PRN codes

 » In-phase (data)

 » Quadrature phase (pilot)

» L5 code generator can create both

» Output(s) are again XOR results from two register

 » Static

 » Changing – different satellites have different register initialization values, listed in ICD

» Navstar GPS Space Segment/User segment L5 Interfaces, IS-GPS-705, U.S. Air Force, Nov. 24, 2003.

Galileo spreading codes – E5 codes

» Galileo E5 code generation follows same fundamentals than GPS L5

» E5a and E5b codes have different register feedback tap specifications

» Together E5a and E5b are using AltBOC modulation, but we are interested only of E5a (BPSK)

» Register initialization values listed in ICD

» ESA/GSA. Galileo Open Service Interface Specification (OS SIS ICD). Draft 1. Feb 2008.

Galileo spreading codes – E1 memory codes

» Galileo E1 signals use dedicated memory codes

  » " *The E1-B and E1-C primary codes are pseudo-random memory code sequences according to the hexadecimal representation provided in Annex C.*"

» Memory codes comparison to generatable ones

  » + Better cross-correlation properties

  » + Improved Autocorrelation Sidelobe Zero property (ASZ)

  » - All memory codes have to be stored on memory for reproduction

    » In Galileo E1 case 32.7kBytes will be used

MBOC/CBOC/BOC(1,1) modulation

» Binary Offset Carrier (BOC) modulation
  » Originally simple BOC(1,1) specified to use with Galileo
» MBOC agreement between U.S. / EU authorities
  » To ensure GPS/Galileo compatibility/interoperatibility
  » Defined modulation only by its Power Spectral Density property (leaves implementation open)
» Galileo MBOC implementation
  » For Galileo it is decided to use Composite BOC (CBOC) to realize the MBOC requirement/agreement
» CBOC is BOC(1,1) compatible
  » BOC(1,1) has easy implementation which is desired in mass market receivers, with only 0.9dB[1] penalty on reception

[1](Hein et al, 2006)

Summary of signals of interest

| Signal	Length [chips]	Rate [MHz]	Modulation	Special
GPS L1 (C/A)	1023	1.023	BPSK	
GPS L5	10230	10.230	BPSK	I/Q
Galileo E5a*	10230	10.230	BPSK	*same for E5b
Galileo E1	4092	1.023	MBOC	Memory code

Baseband - hardware vs. software

» **GNSS Receiver architecture is moving towards software receiver**

  » Following the evolution specified in Moore's law

» **Low cost mobile receivers → accelerating hardware**

  » Ease clock frequency demands by exploiting parallellism by implementing multiple tracking channels in hardware

  » Avoid high power consumption of high performance CPUs
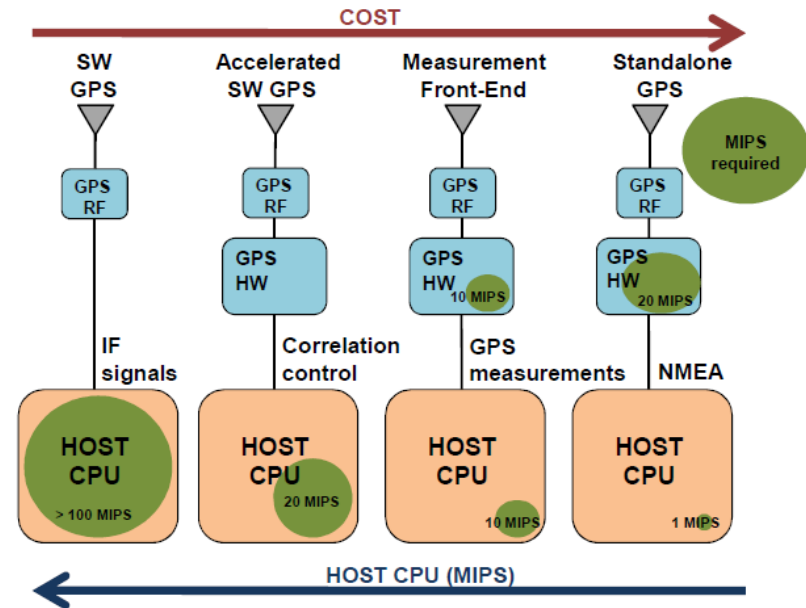
» S. Söderholm, T. Jokitalo, K. Kaisti, H. Kuusniemi, and H. Naukkarinen. Smart Positioning with Fastrax's Software Receiver Solution. In Proc. ION GNSS 2008, Sep. 16 – 19, 2008. Savannah, Georgia, US.

Fundamentals of baseband hardware

» The main two functions of baseband are
  » Acquisition
    » 3-D Search of received signals
      » PRN
      » Code delay
      » Doppler frequency
    » Parallel approach commonly used
      » Matched filter (time domain)
      » FFT (frequency domain)
  » Tracking
    » Measuring the timing of received signal
    » Extracting the navigation data to position calculus

    » Timing and data information are used to estimate the pseudorange

Acquisition Test Statistics

© DLR
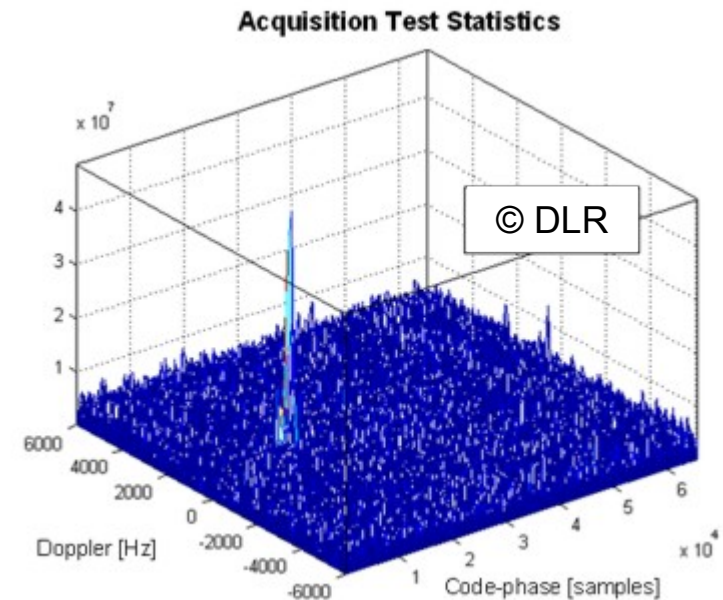
» www.dlr.de

Pseudorange estimation

»Pseudorange can be expressed as:

$$\rho(t) = c\left[t_u(t) - t^{(s)}(t - \tau)\right]$$

Where:

» $t_u(t)$ = arrival time (defined by transition of receiver's clock)

$t^{(s)}(t - \tau)$ = (In case of GPS L1) Z-count [6 s]

»   + number of navigation bits [1/50 Hz = 20 ms]

»   + number of C/A code epochs [1 ms]

»   + number of whole C/A code chips [1/1.023MHz = 0.9775 μs]

»   + fraction of C/A code chip [1/NCO width]

» In dual frequency receiver, two pseudoranges per satellite can be used to cancel the ionospheric delay error
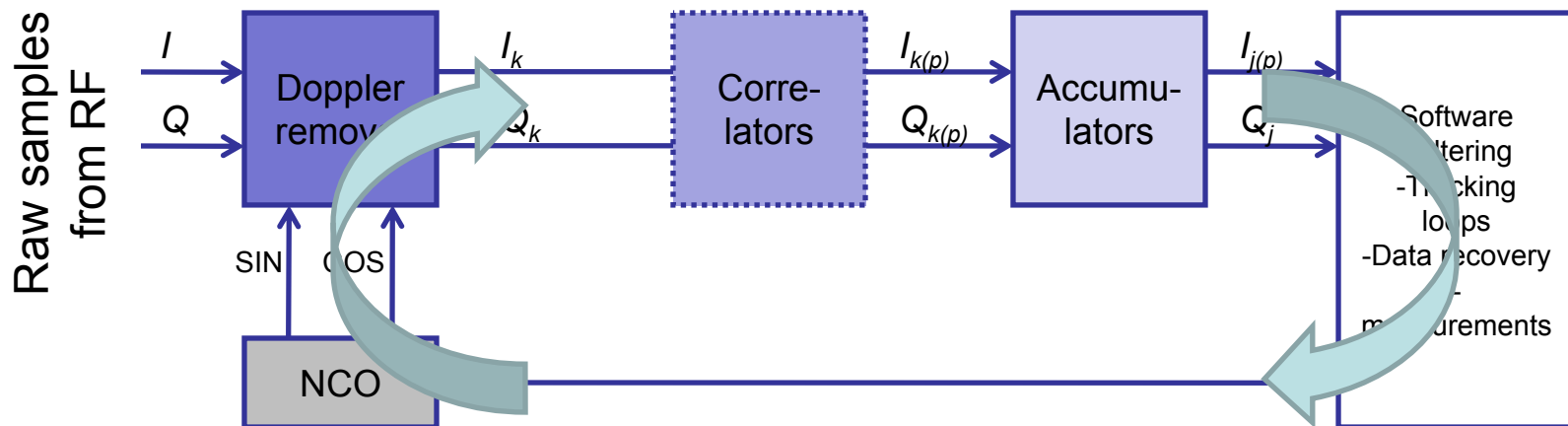
Tracking – carrier tracking components

» Doppler removal (removes also remaining Intermediate Frequency)

   » Incoming samples (I, Q) are multiplied with locally generated sine and cosine waves

   » Doppler removal removes both remaining IF component and Doppler component from incoming signal – resulting signal contains PRN code and data symbol
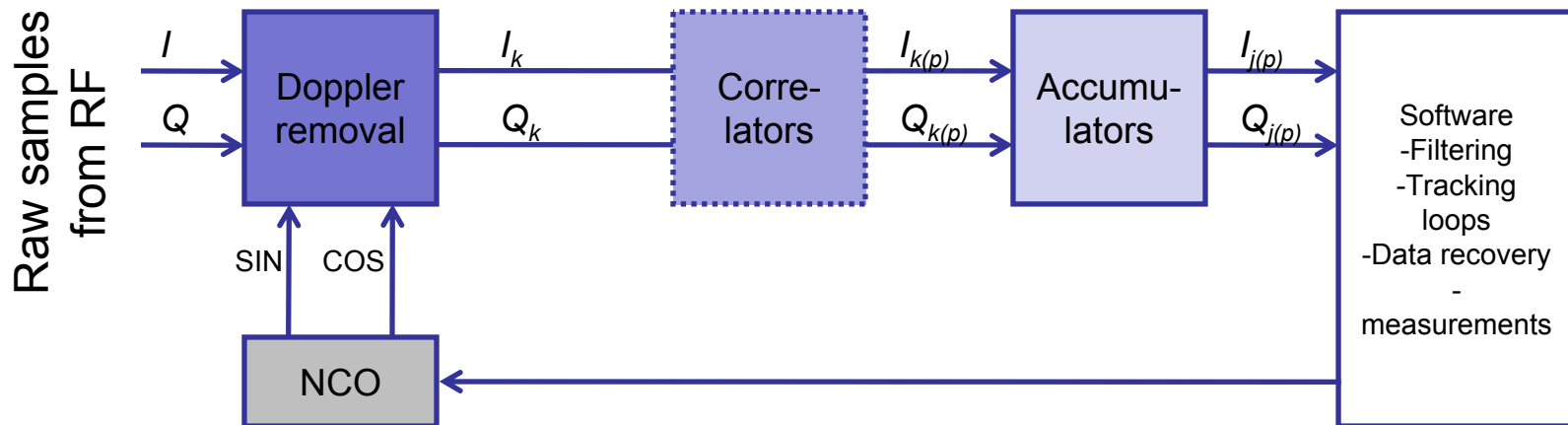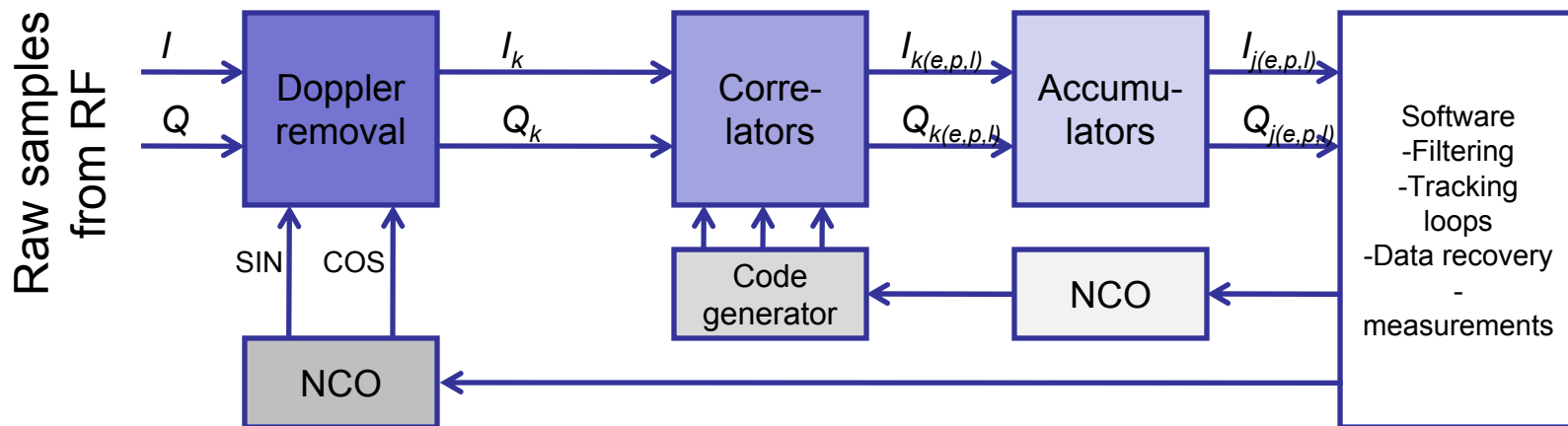
Tracking – carrier tracking loop

» Carrier tracking (Frequency or Phase Locked Loop)

   » Carrier tracking keeps track of the received signal's Doppler frequency

   » Usually FLL is used until Doppler frequency is converged and after that carrier tracking uses PLL

Tracking – code tracking components

» Signals (I_k,Q_k) are correlated with delayed samples of locally generated replica PRN code

  » Traditionally three samples used (early, prompt, late)

  » Nowadays, more correlators used (advanced algorithms, multipath mitigation)

Tracking – code tracking loop

» Code tracking (Delay Locked Loop)

  » Code tracking keeps track with delay of received signal, i.e. keeps prompt correlator aligned with the peak of the autocorrelation function (ACF)

  » PRN code is removed, thus the sign of integration result is data symbol

  » Common DLL discriminators: **EML**   *(E-L)*
   **HRC**   *(E-L)-0.5(VE-VL)*
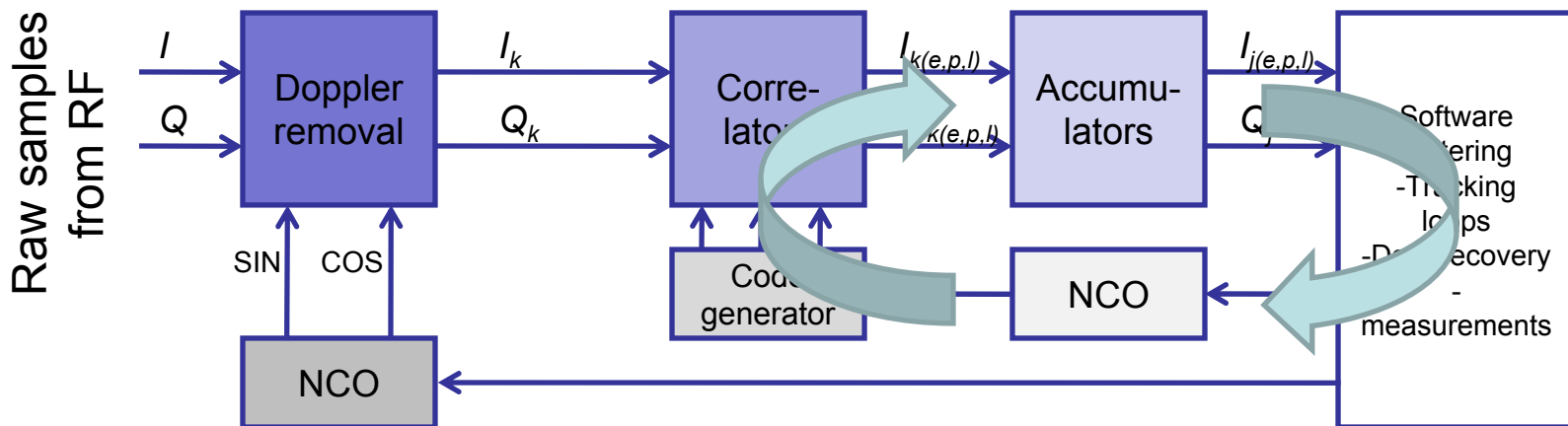
Tracking – tracking channel

» Tracking channel hardware consists of
   » Doppler removal, 2x NCO, correlators, accumulators and code generator unit
» All control is on software
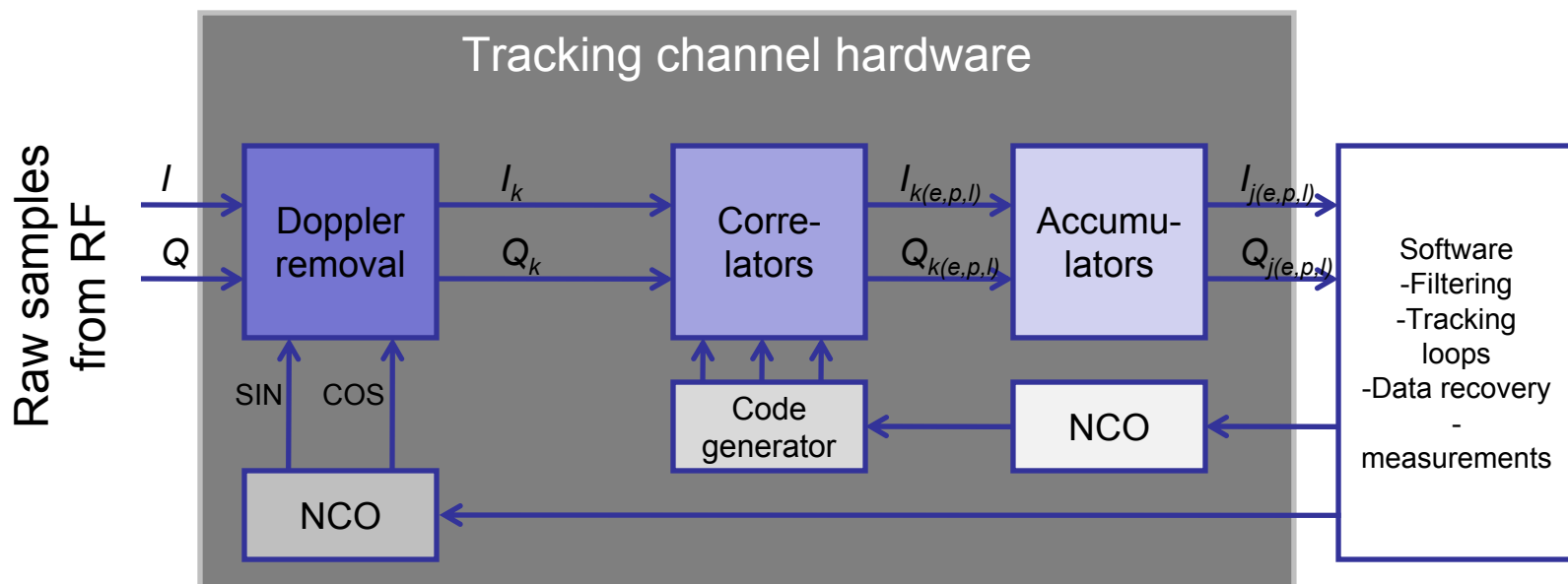
Flexible tracking channel implementation

» Multi system, multi frequency signal reception + mass market requirements (low cost)

» Requires maximal re-use of hardware blocks, approach called flexible tracking channel, where most of the updates are on code generator
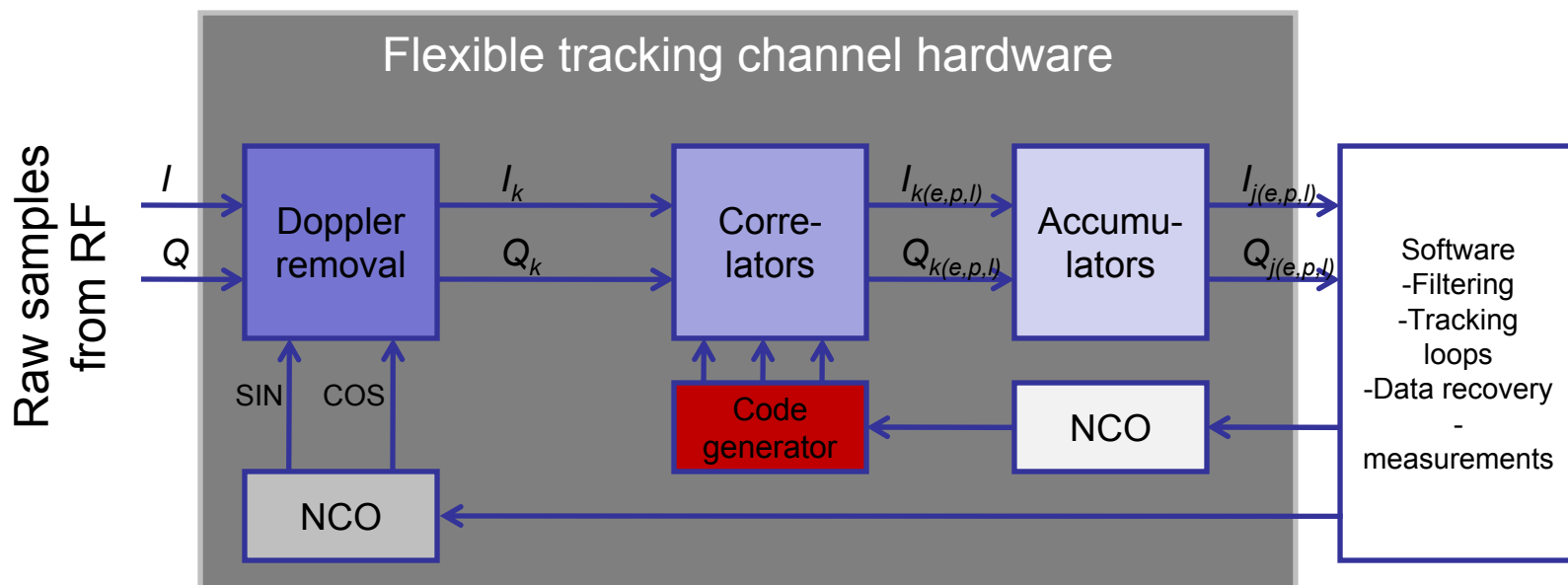
Flexible tracking channel implementation – outside channel

» Receiver has 2 synchronized radio front end outputs
  » E1 signal at intermediate frequency IF_{E1}
  » E5a signal at IF_{E5a}

» Difference between intermediate frequencies is in range of carrier NCO

» Selection of frequency band implemented by a simple multiplexer
  » 1 extra MUX per channel
  » 1 extra bit of control per channel
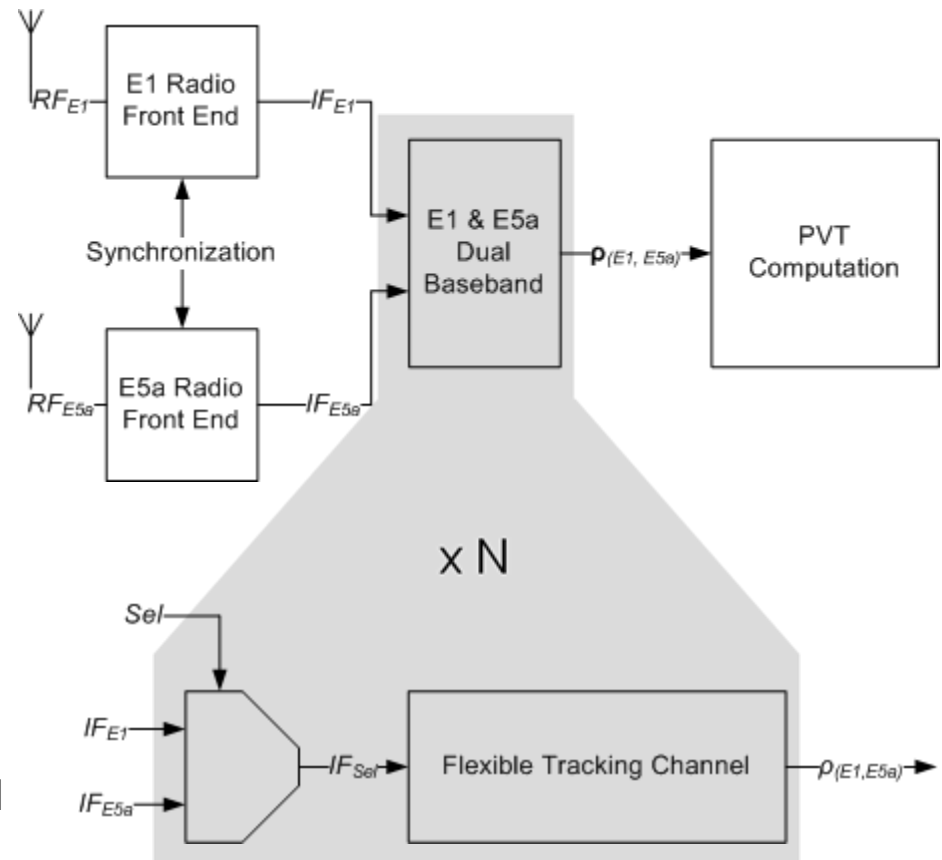
» Hurskainen, et al. 2009

Flexible tracking channel implementation

- » Multi code generator implemented
- » Multiplexing code generators & memory code handler
- » Shared code memory located outside channel
- » Blocks of 32 bits are fetched from memory to channel
- » BOC(1,1) modulation is added in memory handler
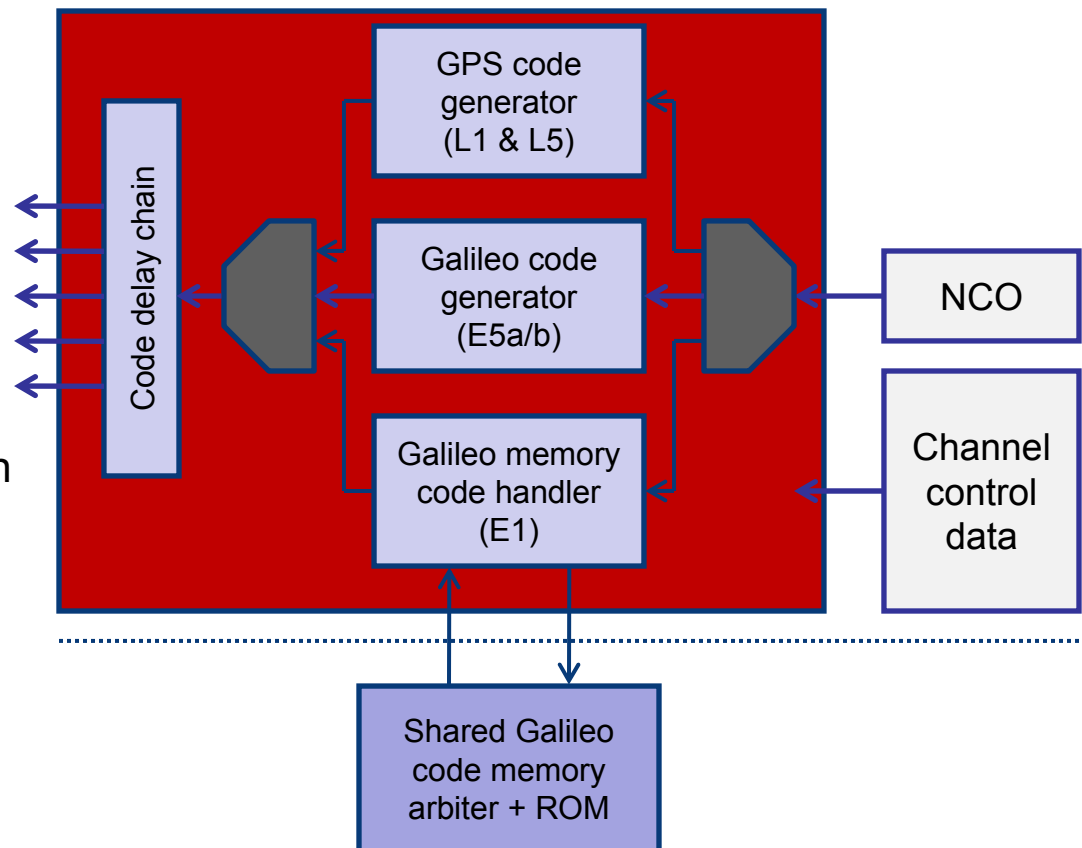
Data / Pilot tracking

» Some signals contain PRN code both on in and quadrature phase

» Combined Data and Pilot component tracking is enabled by allowing channels work in slave mode

  » Tracking parameters – NCO values, phases, synchronization are copied from master channel

  » One bit of prn code selection is switched to create the related pilot component

» All channels are capable of performing in both master and slave modes
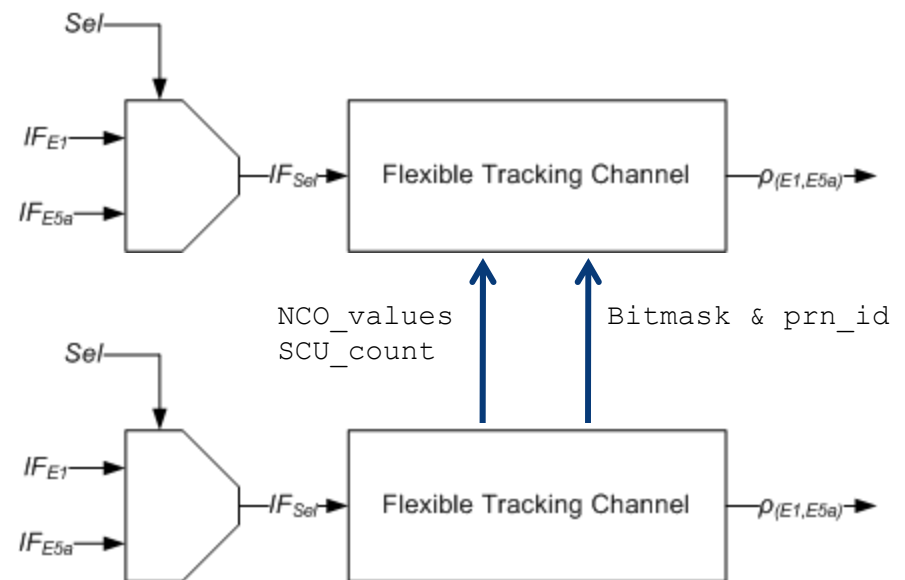
Summary

» E1/E5a is seen as most suitable frequency combination for a dual frequency Galileo mass market receiver

» The main tasks of baseband are acquisition and tracking
  » Tracking provides timing information and data for pseudorange estimation

» Mass market receiver baseband architecture presented
  » A Common dual frequency baseband to be used
  » Possible input selection by using MUXes from dual radio outputs
  » Flexible tracking channel implementation exploiting the similar CDMA property of received signals
  » Multicode generator implemented
  » Data / Pilot tracking enabled by master/slave channel structure

References

» "Galileo Open Service, Signals in space interface control document (OS SIS ICD)", Feb 2008, Draft 1.

» "GPS Interface Control Document (ICD-GPS-200D), IRN-200C-004, U.S. Air Force, Dec. 7, 2004.

» G.W. Hein, J.-A. Avila-Rodriguetz, S.Wallner, et al. "MBOC: the new optimized spreading modulation recommended for Galileo L1 OS and GPS L1C", in Proceedings of the IEEE/ION Position, Location, and Navigation Symposium (PLANS'06), pp.883-892, San Diego, CA, April 2006.

» H. Hurskainen, E-S. Lohan, J. Nurmi, S. Sand, C. Mensing, and M. Detratti. "Optimal Dual Frequency Combination for Galileo Mass Market Receiver Baseband"", *in Proceedings of the IEEE Workshop on Signal Processing Systems Design and Implementation (SIPS)*. Tampere, Finland, October 7-–9, 2009.

» H. Hurskainen, J. Raasakka, T. Ahonen, and J. Nurmi, "Multicore Software-Defined Radio Architecture for GNSS Receiver Signal Processing, " *EURASIP Journal on Embedded Systems*, vol. 2009, Article ID 543720, 10 pages, 2009. doi:10.1155/2009/543720

» "Navstar GPS Space Segment/ User Segment L5 Interfaces, IS-GPS-705, U.S. Air Force, Nov. 24, 2003.

» J. F. Raquet – GNSS Receiver Design. Course slides. Tampere University of Technology. 2010.

» S. Söderholm, T. Jokitalo, K. Kaisti, H. Kuusniemi, and H. Naukkarinen. Smart Positioning with Fastrax's Software Receiver Solution. In Proc. ION GNSS 2008, Sep. 16 – 19, 2008. Savannah, Georgia, US.

» www.dlr.de

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Issues in PVT Solutions Software for GNSS

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13th June 2010

Outline

» **Position, Velocity and Time**

  » Example: Single Point Position

» **Geometry**

» **Navigation Solution Estimation**

» **Navigation Solution for Multi-Systems Receivers**

  » GPS and Galileo

  » Interfaces for Data Flow

» **Decoding Navigation Messages**

» **Least Squares and Kalman Filtering Navigation**

» **Accuracy and Availability**
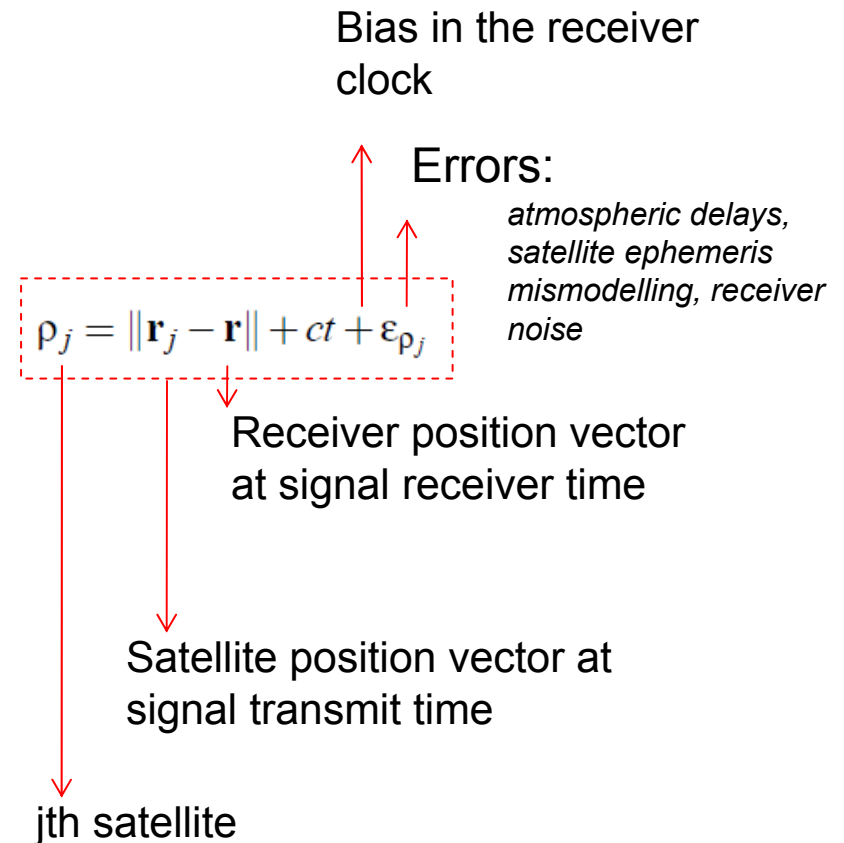
» **Benefits**

User Position, Velocity and Time

» GNSS: Collectivity of different systems, designed to provide position, velocity and timing capabilities to users

» Position: Computation of user's position from biased measurements of the satellite-to-user ranges (pseudoranges)

» Velocity: Biased measurements of satellite-to-user range rates (pseudorange rates)

» Time: Inaccuracy of the receiver clocks; unknown time offset between receiver clock and GNSS time (time bias)

http://www.gmat.unsw.edu.au
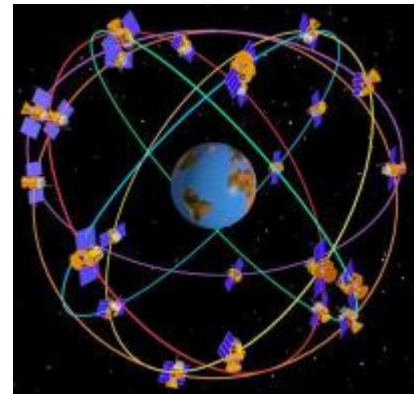
Position estimation

» Four unknowns: Receiver x,y,z and time bias

» User position in three dimensions

» Receiver clock from system time

» Pseudorange measurements from 4 satellites

» Observations can be predicted based on the current estimates

Bias in the receiver clock

Errors: *atmospheric delays, satellite ephemeris mismodelling, receiver noise*

$$\rho_j = \|\mathbf{r}_j - \mathbf{r}\| + ct + \varepsilon_{\rho_j}$$

Receiver position vector at signal receiver time

Satellite position vector at signal transmit time

jth satellite

Position estimation

» Receiver generates j pseudorange measurements from j different satellites

» j pseudorange equations are non-linear $\longrightarrow$ $\rho_j = \|\mathbf{r}_j - \mathbf{r}\| + ct + \varepsilon_{\rho_j}$

  » Iterative techniques (linearization)

    » Simplest

    » Least-Squares estimation

    » Linearize about a nominal point $\longrightarrow$ $\Delta\rho = \mathbf{H}\Delta\mathbf{x}$

    » Solve linear equations $\longrightarrow$ $\Delta\mathbf{x} = \left(\mathbf{H}^T\mathbf{H}\right)^{-1}\mathbf{H}^T\Delta\rho$

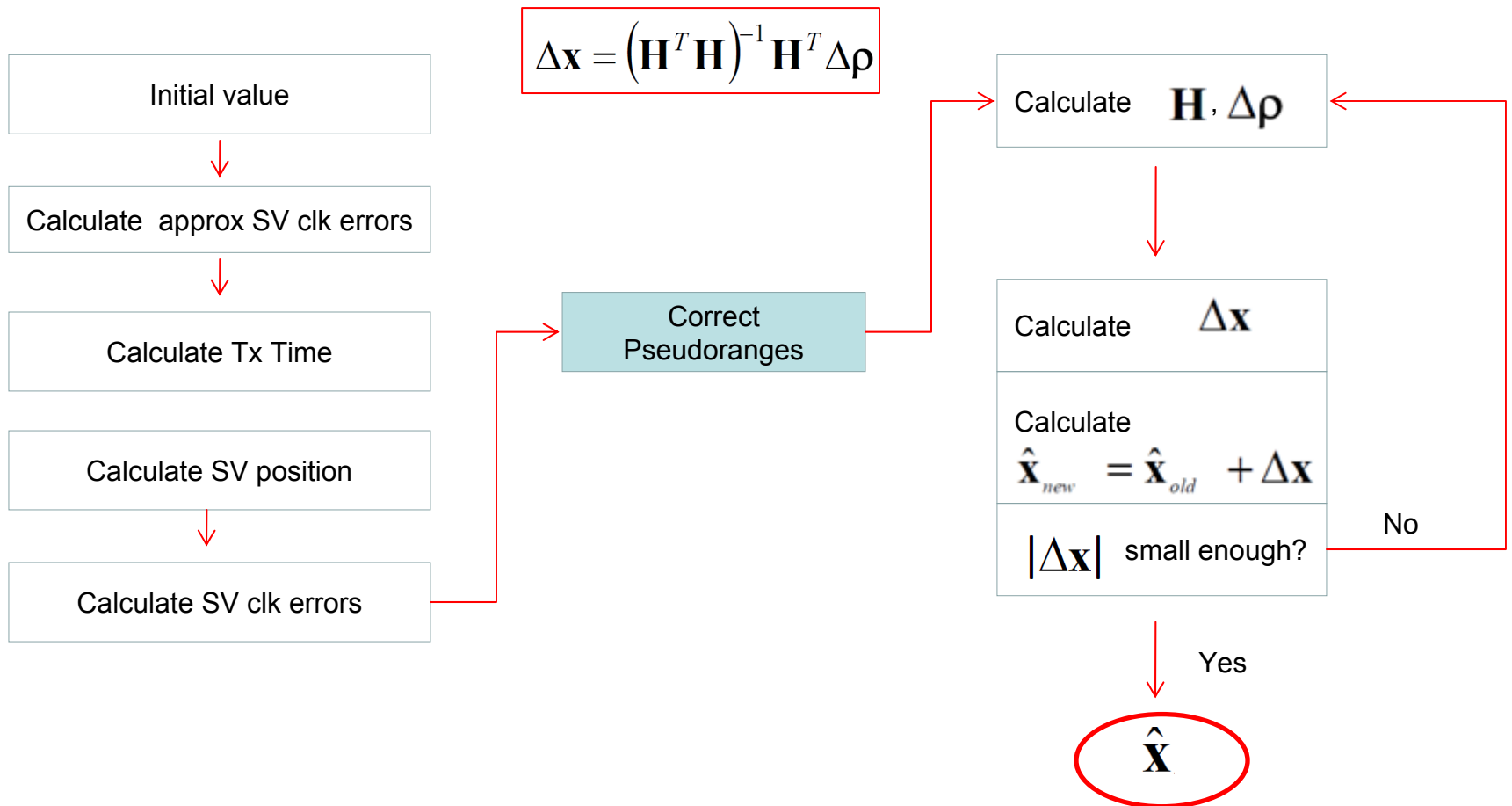   » Goal $\longrightarrow$ $\hat{\mathbf{x}}_{new} = \hat{\mathbf{x}}_{old} + \Delta\mathbf{x}$
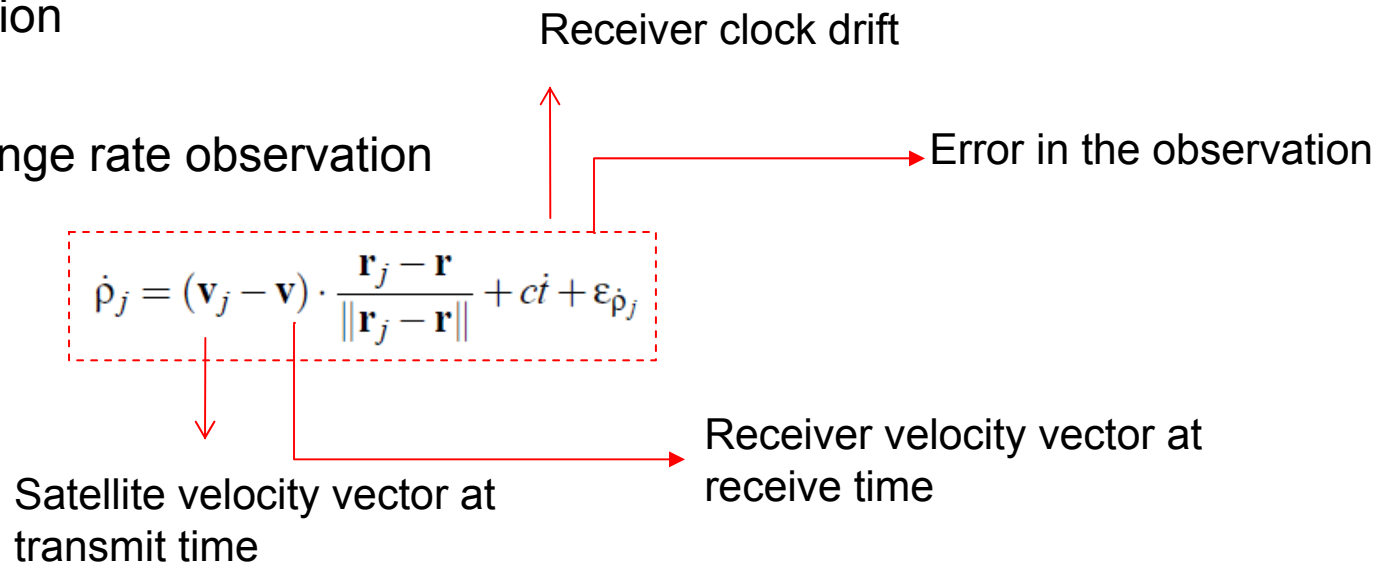
  » Kalman filtering

    » Prediction and Correction

Example: Single Point Position

$$\Delta \mathbf{x} = \left(\mathbf{H}^T \mathbf{H} \right)^{-1} \mathbf{H}^T \Delta \rho$$

Initial value

↓

Calculate approx SV clk errors

↓

Calculate Tx Time

Calculate SV position

↓

Calculate SV clk errors

Correct Pseudoranges

Calculate $\mathbf{H}, \Delta \rho$

↓

Calculate $\Delta \mathbf{x}$

Calculate
$$\hat{\mathbf{x}}_{new} = \hat{\mathbf{x}}_{old} + \Delta \mathbf{x}$$

$|\Delta \mathbf{x}|$ small enough?

No

Yes

$\hat{\mathbf{x}}$

Velocity estimation

» Estimation process similar to user position

» Pseudorange rate observation

Receiver clock drift

Error in the observation

$$\dot{\rho}_j = (\mathbf{v}_j - \mathbf{v}) \cdot \frac{\mathbf{r}_j - \mathbf{r}}{\|\mathbf{r}_j - \mathbf{r}\|} + c\dot{t} + \varepsilon_{\dot{\rho}_j}$$

Satellite velocity vector at transmit time

Receiver velocity vector at receive time

» Observations can be predicted based on the current estimates

Time

» Time intervals (time bias)

  » construction of pseudoranges on the accuracy of time difference between satellite transmit time and receiving time

» Uncorrected time biases

  » 1 ms -> 300 km

» Biased pseudoranges

 » increased area of uncertainty in the navigation solution

$$p_3 = c \cdot (T_3 - T_{clock})$$

$$p_1 = c \cdot (T_1 - T_{clock})$$

$$p_2 = c \cdot (T_2 - T_{clock})$$

SV$_1$, SV$_2$, SV$_3$, MT
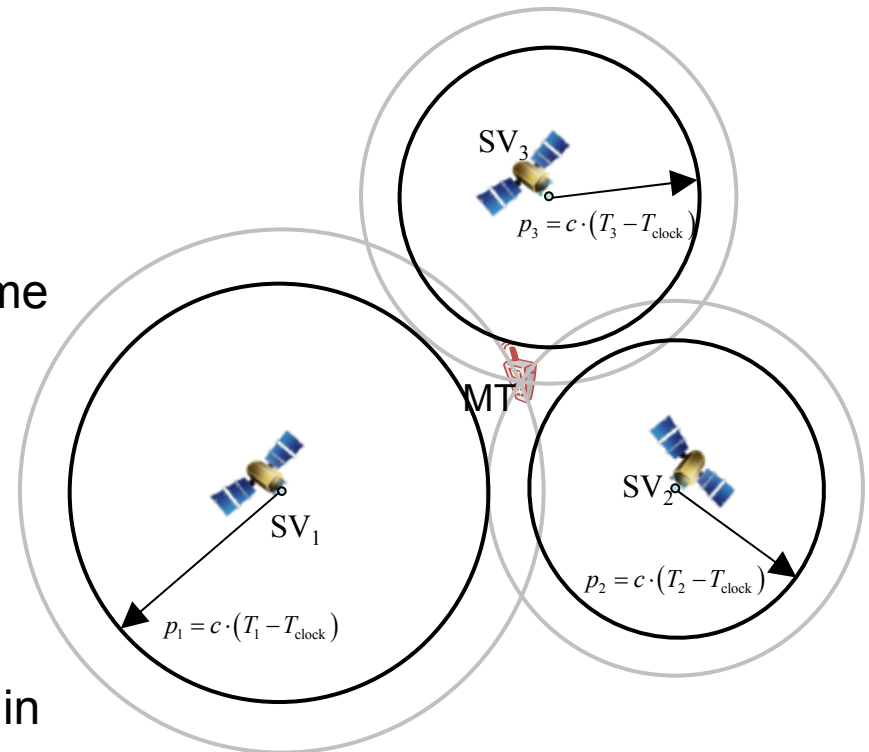
Time

» GNSS time system

» Multiple different time domains:

  » GPS System Time

  » Onboard Satellite (SV) Time

  » User Time

» The Galileo system has its own time reference

» Hybrid receivers have to deal with a fifth unknown parameter, (time offset between receiver clock and Galileo system time)

» The effect is mitigated by a GPS to Galileo Offset (GGTO)
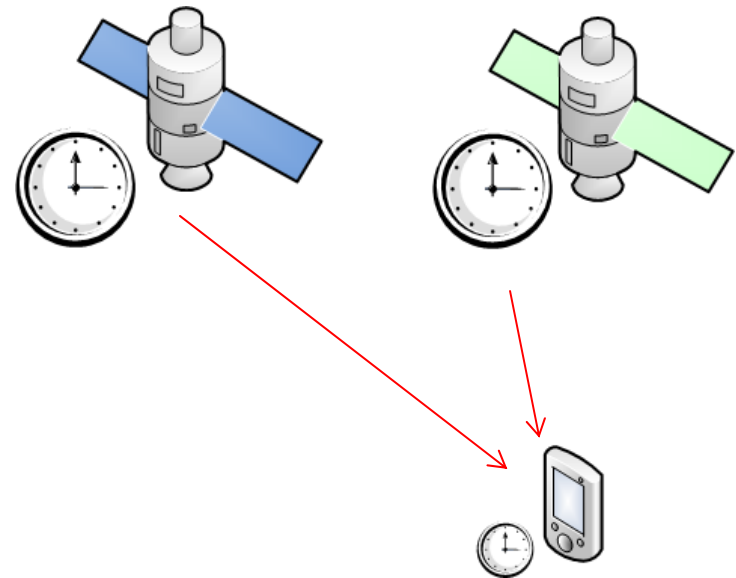
Geometry: DOP
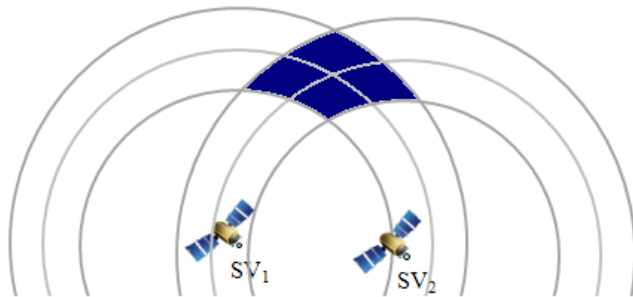
» Quality of user's position depends on the quality of the range measurements but also on user/satellite observation geometry

» Issue when dealing with multiple constellations
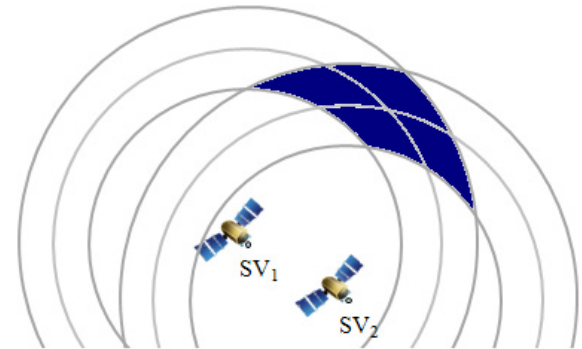
» Dilution of precision (DOP): Overview of the geometrical strength of the user/satellite configuration

» Same quality of range but different quality of position (area of uncertanty due to biased measurements)

Navigation Solution Estimation

» Navigation Solution is needed to produce the position (P), velocity (V) and receiver time (T) information

» It operates independently (from baseband)
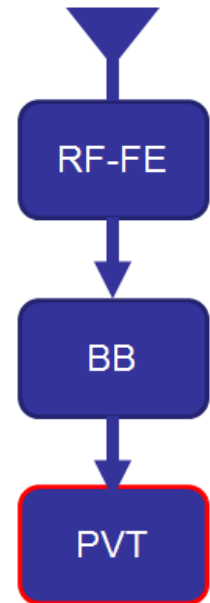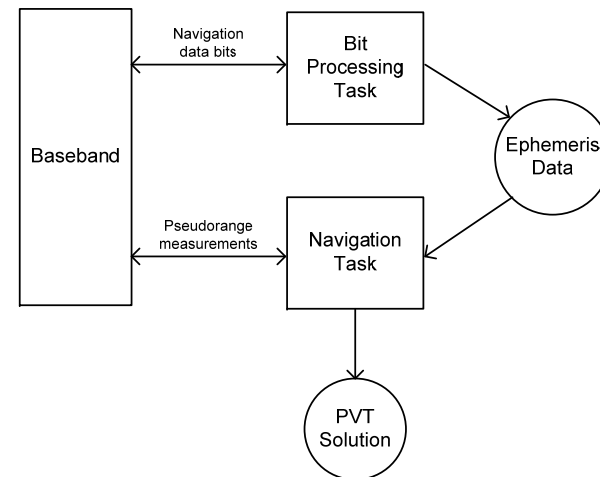
Navigation Solution for Multi-Systems receivers

» The receiver is designed to compute the Position (P), Velocity (V), and Time (T) using measurements from the Baseband

» Output from the baseband:
  » GNSS navigation message (to be decoded)
  » Doppler frequency (corrections)
 » Carrier- and Code phase (corrections)
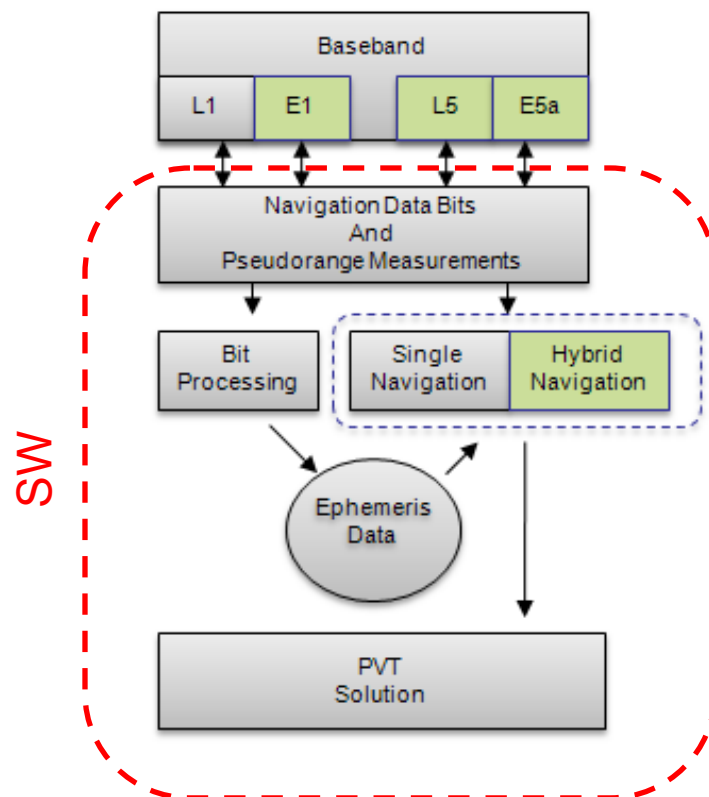
GPS and Galileo

» Navigation solution has GNSS navigation data bits as input from the baseband channels

» Navigation bits are necessary to construct full *frames* from the separate incoming navigation bits

» When the complete frame structure has been detected, the meaning of each data bit stream is interpreted
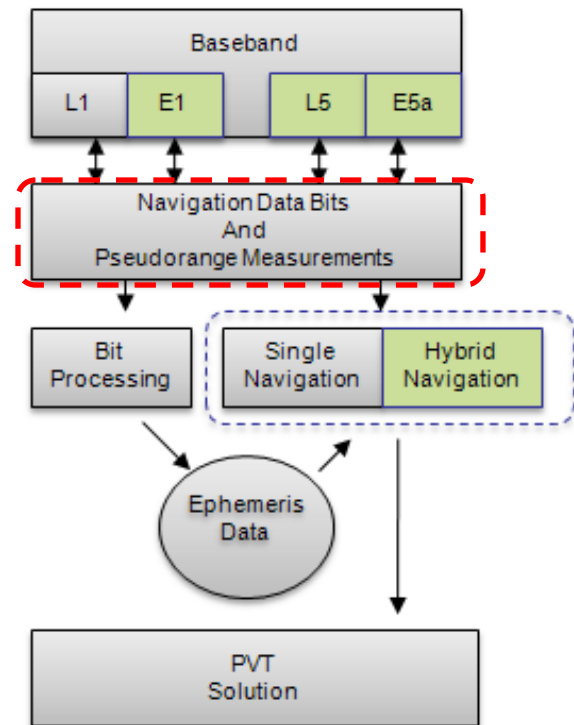
Interfaces for Data Flow

» Interfaces with the baseband must be taken into consideration

» When raw data are processed *ephemeris* data can be found

» The pseudorange construction is also performed from the incoming raw data
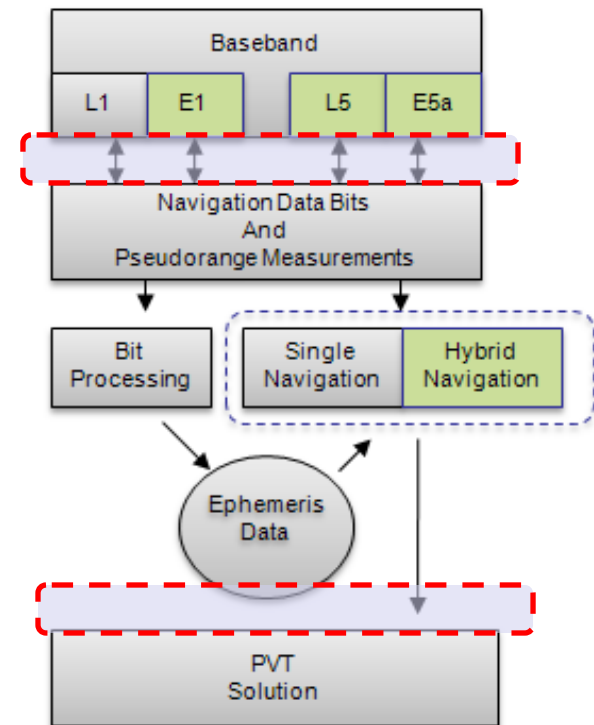
Decoding Navigation Messages (GPS and Galileo)

» GPS: check the received navigation data in case of bit errors

» GPS navigation data has been encoded with parity check algorithm

» Galileo data uses more advanced Forward Error Coding (FEC) – schemes

» GPS algorithm is unable to correct (data bit) errors, unlike the algorithms present in Galileo
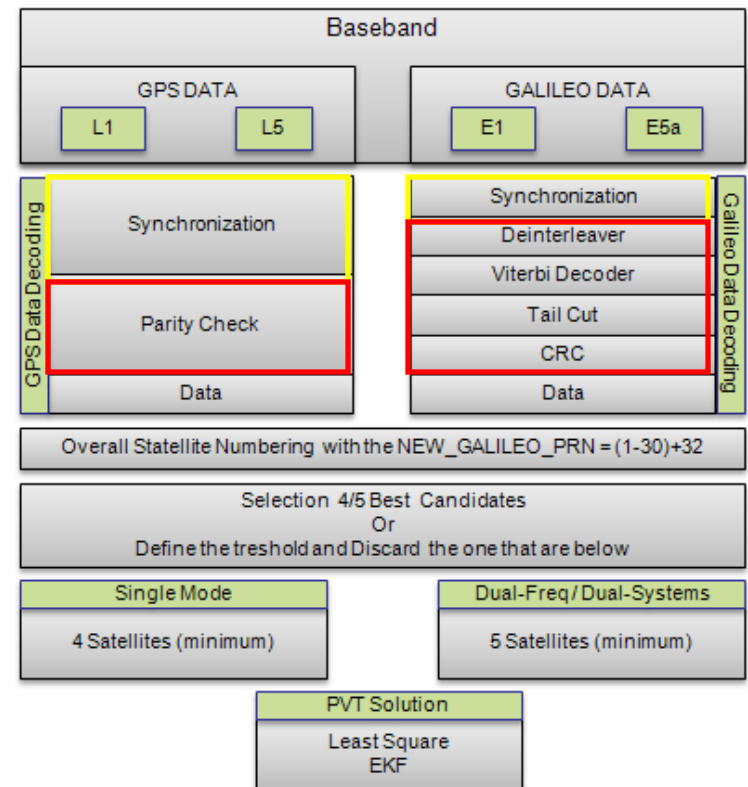
Ephemeris parameters

» Ephemeris data is the basic set of data that is needed for calculating satellite position

» A complete set of 16 ephemeris parameters, also known as quasi-Keplerian parameters must be acquired

» 6 basic Keplerian elements,
» 9 correction terms of time perturbations and
» 1 time epoch parameter

Parameter	Name
t_{0e}	Ephemeris reference time
$\sqrt{a}$	Square root of the semi-major axis
e	Eccentricity
i_0	Inclination angle at the reference time
Ω_0	Longitude of the ascending node at the beginning of GPS week
ω	Argument of perigee
M_0	Mean anomaly at the reference time
Δn	Correction to the computed mean motion
i	Rate of inclination
$\dot{\Omega}$	Rate of right ascension
C_{uc}, C_{us}	Amplitudes of harmonic correction terms for the computed argument of latitude
C_{rc}, C_{rs}	Amplitudes of harmonic correction terms for the computed orbit radius
C_{ic}, C_{is}	Amplitudes of harmonic correction terms for the computed inclination angle

Least Squares and Kalman Filtering Navigation

» The navigation solution contains error components due to effects like multipath and atmospheric effects

» The ephemeris data inaccuracies also contribute to the total error in navigation solution

» *LS* and *Kalman filtering* for the navigation results

» The navigation solution is finally converted into a suitable format for displaying the results for the user
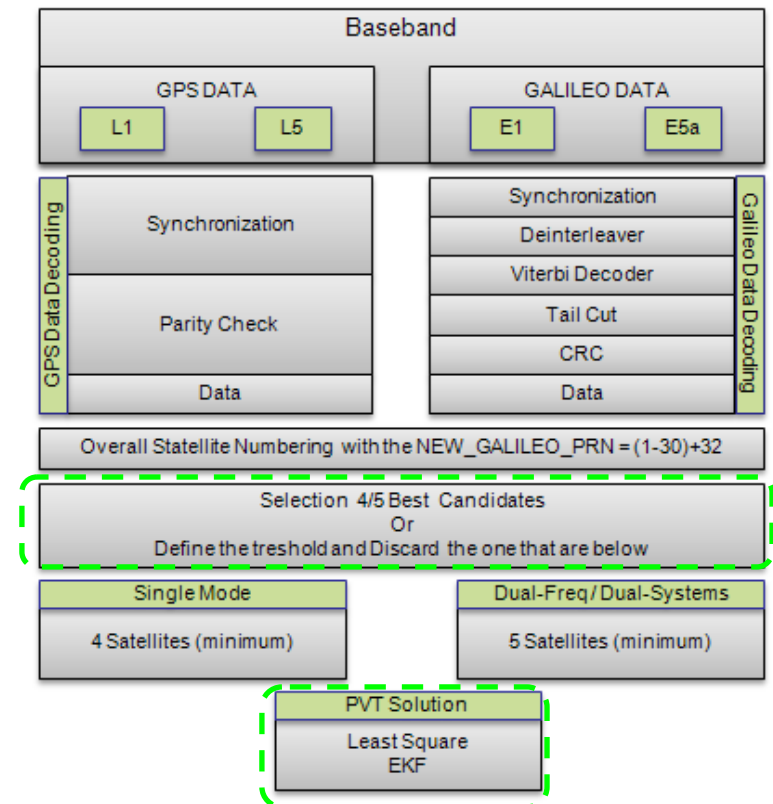
Least Squares and Kalman Filtering Navigation
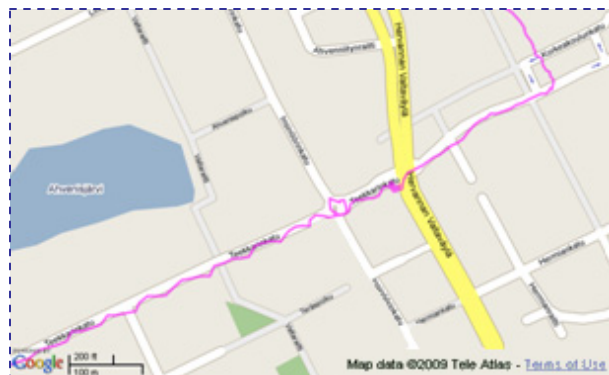
» LS can be applied to the navigation problem for the position estimation and velocity estimation problem taking into account only the current measurements when estimating the unknowns

» Using more measurements from more than 4 satellites means to solve an overdetermined system of equations
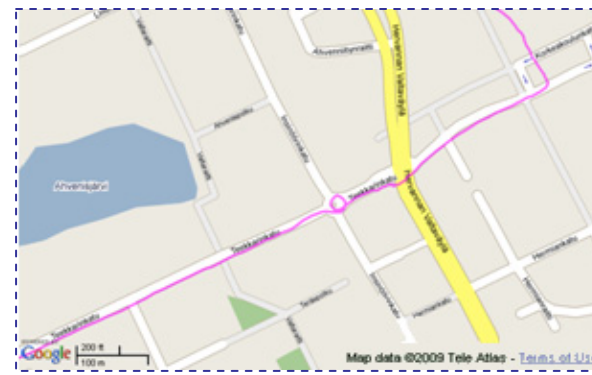
» KF is preferred in navigation applications

» It combines information on the statistical nature of system errors with system dynamics data (state space model) to estimate the state of the navigation system

Accuracy and Availability

- » *Accuracy:*
  - » The interoperability of signals allows for improved accuracy in the Position, Velocity and Time (PVT) solution

- » *Greater Availability:*
  - » The receiver can seamlessly use a GPS signal to a Galileo signal depending on coverage provided by the constellation that is visible
  - » This allows for uninterrupted service for the user
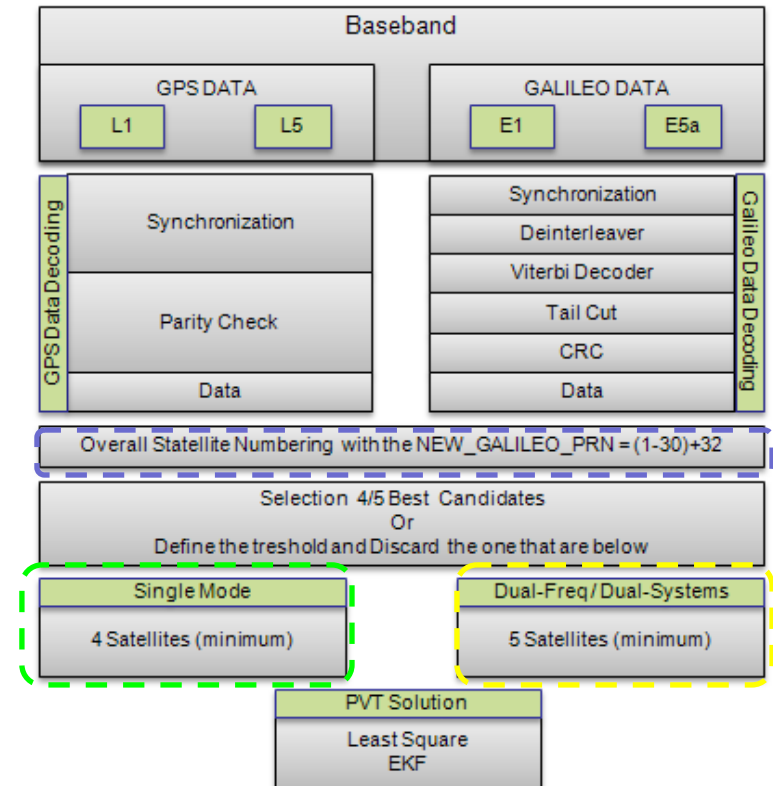
Benefits

» Mitigation of Ionosphere source of errors by estimating group delay and phase advance (ionosphere-free pseudorange model)

» Ionosphere error corrections from 5 up to 1 meter

» Multiple satellite constellations available

» Performances (position accuracy) are competitive if compared to existing GNSS

Error sources for single frequency receivers

Ionospheric effects	± 5 m
Shifts in the satellite orbits	± 2.5 m
Clock errors of the satellites' clocks	± 2 m
Multipath effect	± 1 m

Accuracy with Dual-Frequency

	Single-Frequency	Dual-Frequency
Horizontal	15m	4m
Vertical	35m	8m

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2. "GPS Interface Control Document (ICD-GPS-200D), IRN-200C-004, U.S. Air Force, Dec. 7, 2004.
3. H. Hurskainen, T. Paakki, L. Zhongqi, J. Raasakka, J. Nurmi, "GNSS Receiver Reference Design".
4. T. Paakki, "Implementation of Robust GNSS Navigation Algorithm", M.Sc. Thesis , Tampere University of Technology, Finland.
5. H. Kuusniemi, "User-Level Reliability and Quality Monitoring in Satellite-Based Personal Navigation", PhD Thesis, Publication 544, Tampere University of Technology, Finland.
6. K. Borre, D. M. Akos, N. Bertelsen, P. Rinder, "A Software-Defined GPS and Galileo Receiver: A Single-Frequency Approach (Applied and Numerical Harmonic Analysis).
7. E. Kaplan, C. Hegarty, " Understanding GPS: Principles and Applications, Second Edition".
8. J. F. Raquet – GNSS Receiver Design. Course slides. Tampere University of Technology. 2010.
9. http://www.gmat.unsw.edu.au/currentstudents/ug/projects/Meyers/Current.htm

Tutorial Outline

» Introduction: GRAMMAR, Satellite navigation basic principles, existing and emerging GNSS satellite constellations and augmentation systems (30 minutes): Stephan Sand, DLR

» Antennas and RF front-ends for multi-frequency GNSS receivers (30minutes): Marco Detratti, ACORDE

» Advanced receiver algorithms for baseband processing (30 minutes): Simona Lohan, TUT/DCE

» Baseband hardware solutions for multi-system, multi-frequency reception (30 minutes): Heikki Hurskainen, TUT/DCS

» Issues in PVT solution software for GNSS (20 minutes): Francescantonio Della Rosa, TUT/DCS

» Hybridization with other sensor data (30 minutes): Stephan Sand, DLR

» Wrap-up and conclusions (10 minutes): Stephan Sand, DLR

Challenges in Multi-System Multi-Frequency GNSS Receiver Design — Hybridization with Other Sensor Data

Stephan Sand (DLR)

stephan.sand@dlr.de
http://www.gsa-grammar.eu/
http://www.dlr.de/kn
http://www.kn-s.dlr.de/Groups/Mobile/Welcome/group_mobile_us.html

13th June 2010

Hybridization with Other Sensor Data — Outline

- » Introduction
- » Sensors
  - » Inertial navigation
  - » Wireless mobile communication
- » Hybrid data fusion (HDF)
- » Conclusions

- » Acknowledgements
  - » Helena Leppäkoski (TUT)
  - » Christian Mensing (DLR)
  - » Wireless Hybrid Enhanced Mobile Radio Estimators (WHERE) project
  - » GALILEO Receivers for Mass Market (GREAT) project

Introduction

» Visibility of global navigation satellite systems (GNSSs) in urban canyon scenarios

Chicago, IL, USA

Venice, Italy
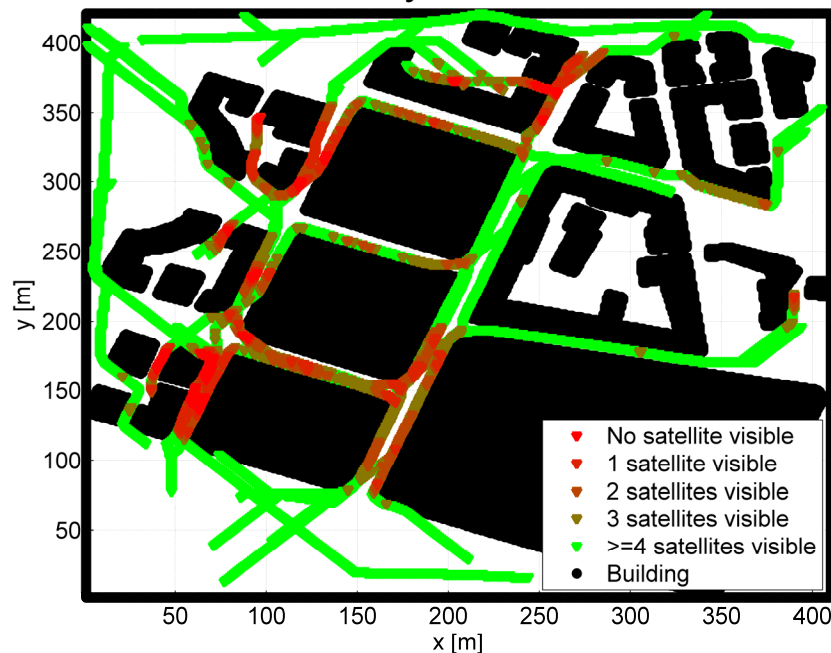

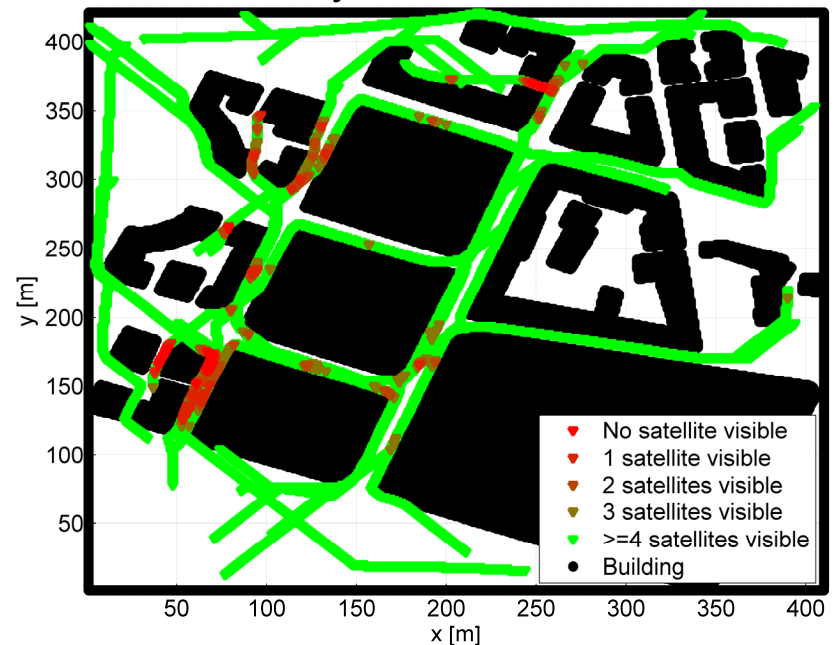Critical scenario for GNSS ???

Critical scenario for GNSS !!!

Introduction

» Motivation: Visibility of global navigation satellite systems (GNSSs) in urban canyon scenarios


Visibility of GPS

Visibility of GPS+Galileo

» Often less than four satellites visible
⇒ Critical situation for GNSS positioning, support from other sensors required

Sensors — Inertial Navigation: Dead Reckoning

» Collins English Dictionary 1.0a:

  » Dead reckoning: a method of establishing one's position using the distance and direction travelled rather than astronomical observations.

» Examples

  INS: Inertial navigation system

  » Accelerometer triad + gyro triad

  PDR: Pedestrian dead reckoning

  » Pedometer + compass or gyro

  VDR: Vehicular dead reckoning

  » Car odometer + gyro

  Barometric altimeter can be used to aid each of these methods

Dead reckoning in 2 dimensions

$$x_k = x_{k-1} + \Delta L_k \cdot \sin\psi_k$$
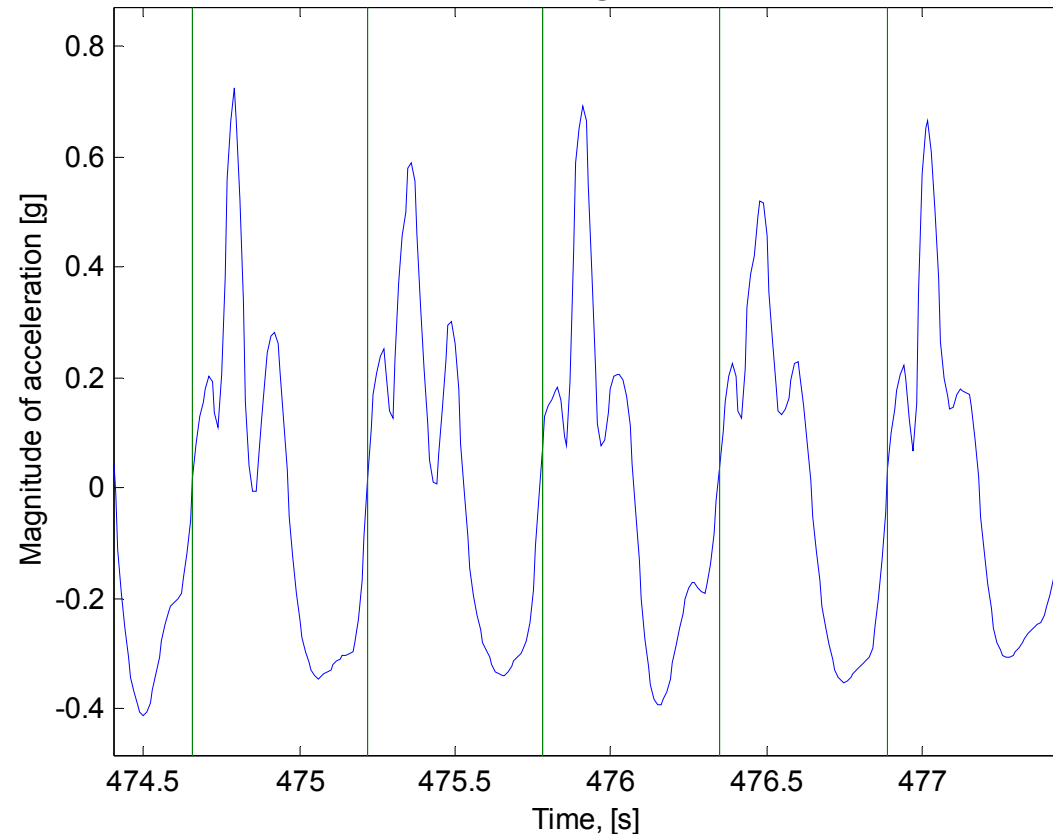$$y_k = y_{k-1} + \Delta L_k \cdot \cos\psi_k$$
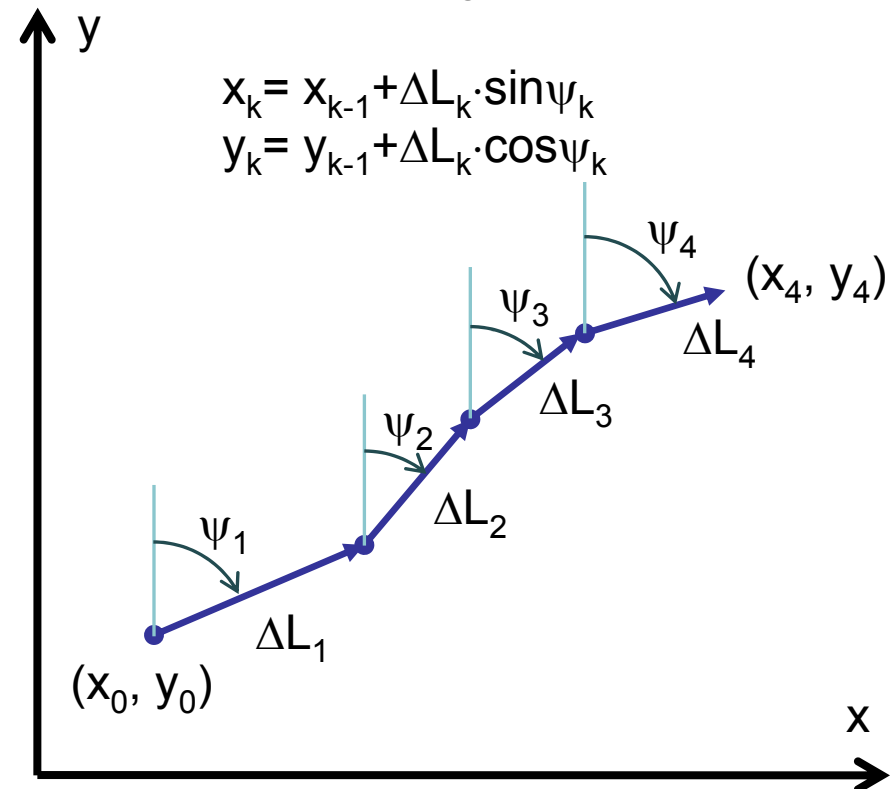
Sensors — Inertial Navigation:
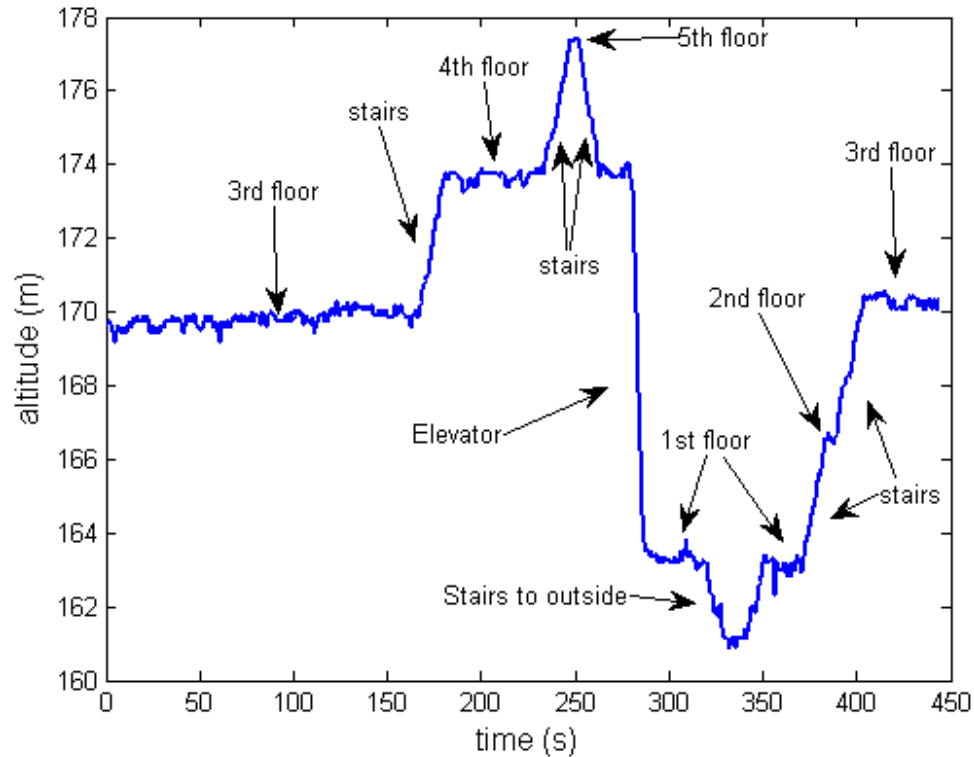# Step Detection using Accelerometer Triad

» Accelerations measured using three orthogonal accelerometers a_1, a_2, a_3:

$$y = \sqrt{a_1^2 + a_2^2 + a_3^2} - b$$

» Result independent on triad orientation

» Significant error reduction: From cubic to linear in time

DLR real-time **NavShoe** prototype

Footfall recognition

Sensors — Inertial Navigation:
Differential Barometry, Walk inside Building

Sensors — Wireless Mobile Communication: Measurements

- **Received Signal Strength (RSS)**
  - Corrupted by propagation effects

$$p = \alpha - 10\beta \log(d)$$

- **Time of Arrival (TOA)**
  - Requires synchronization between transmitter and receiver

$$t_a = t_d + \frac{d}{c}$$

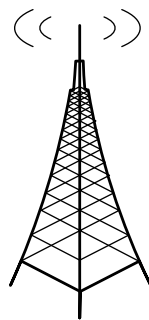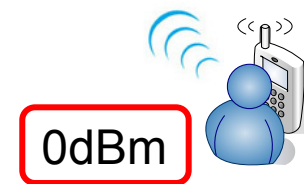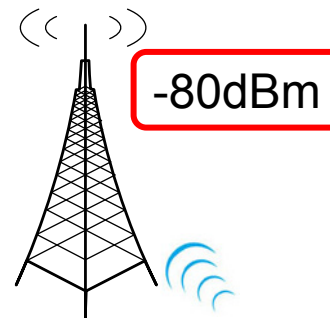- **Time Difference of Arrival (TDOA)**
  - Requires synchronization in the network

$$T_a = t_d + \frac{d_1}{c} - \left(t_d + \frac{d_2}{c}\right) = \frac{d_1 - d_2}{c}$$

- **Angle of Arrival (AOA)**
  - Strongly influenced by shadowing effect
  - Requires directional antennas

$$\theta_a = \operatorname{atan}\left(\frac{y_d - y_a}{x_d - x_a}\right)$$

-80dBm

0dBm

Sensors — Wireless Mobile Communication: Measurements

- **Received Signal Strength (RSS)**
  - Corrupted by propagation effects

$$p = \alpha - 10\beta \log(d)$$

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$$T_a = t_d + \frac{d_1}{c} - \left(t_d + \frac{d_2}{c}\right) = \frac{d_1 - d_2}{c}$$

$t_a = 3.4\mu s$

- **Angle of Arrival (AOA)**
  - Strongly influenced by shadowing effect
  - Requires directional antennas

$$\theta_a = \operatorname{atan}\left(\frac{y_d - y_a}{x_d - x_a}\right)$$

$t_d = 1\mu s$

Sensors — Wireless Mobile Communication: Measurements

- **Received Signal Strength (RSS)**
  - Corrupted by propagation effects

$$p = \alpha - 10\beta \log(d)$$

- **Time of Arrival (TOA)**
  - Requires synchronization between transmitter and receiver

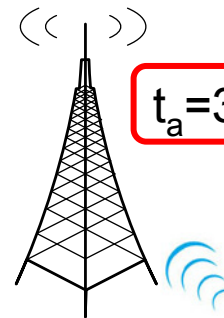$$t_a = t_d + \frac{d}{c}$$

- **Time Difference of Arrival (TDOA)**
  - Requires synchronization in the network

$$T_a = t_d + \frac{d_1}{c} - \left(t_d + \frac{d_2}{c}\right) = \frac{d_1 - d_2}{c}$$

- **Angle of Arrival (AOA)**
  - Strongly influenced by shadowing effect
  - Requires directional antennas

$$\theta_a = \operatorname{atan}\left(\frac{y_d - y_a}{x_d - x_a}\right)$$

$t_a=3.4\mu s$

$t_a=4.1\mu s$

$T_a=0.7\mu s$

$t_d=1\mu s$

Sensors — Wireless Mobile Communication: Measurements

- **Received Signal Strength (RSS)**
  – Corrupted by propagation effects

$$p = \alpha - 10\beta \log(d)$$

- **Time of Arrival (TOA)**
  – Requires synchronization between transmitter and receiver

$$t_a = t_d + \frac{d}{c}$$

- **Time Difference of Arrival (TDOA)**
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- **Angle of Arrival (AOA)**
  – Strongly influenced by shadowing effect
  – Requires directional antennas
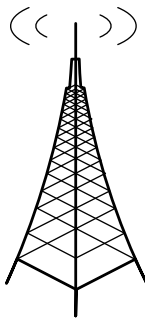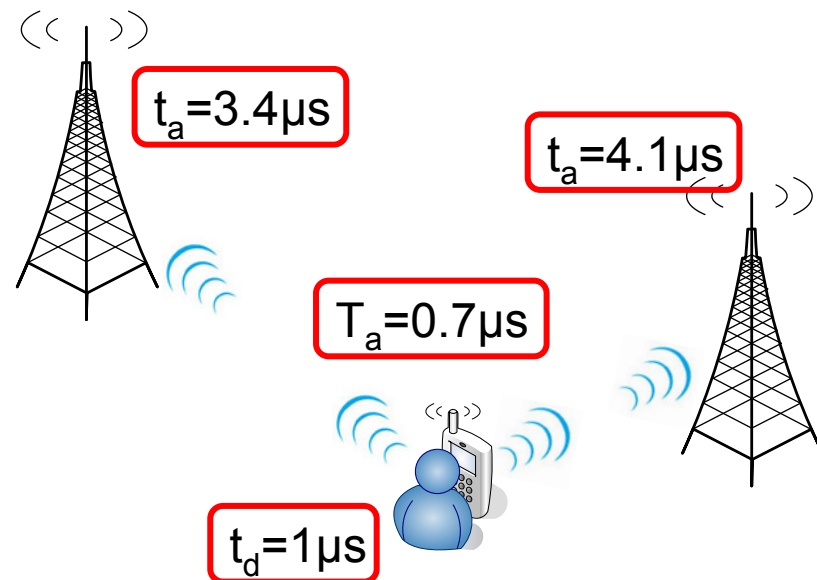
$$\theta_a = \operatorname{atan}\left(\frac{y_d - y_a}{x_d - x_a}\right)$$

$\theta_a = -10°$

Sensors — Wireless Mobile Communication: Cellular System

Cellular network, $N_{BS} = 4$

Legend:
- ▼ Involved BS
- ○ Not involved BS
- ▫ MS
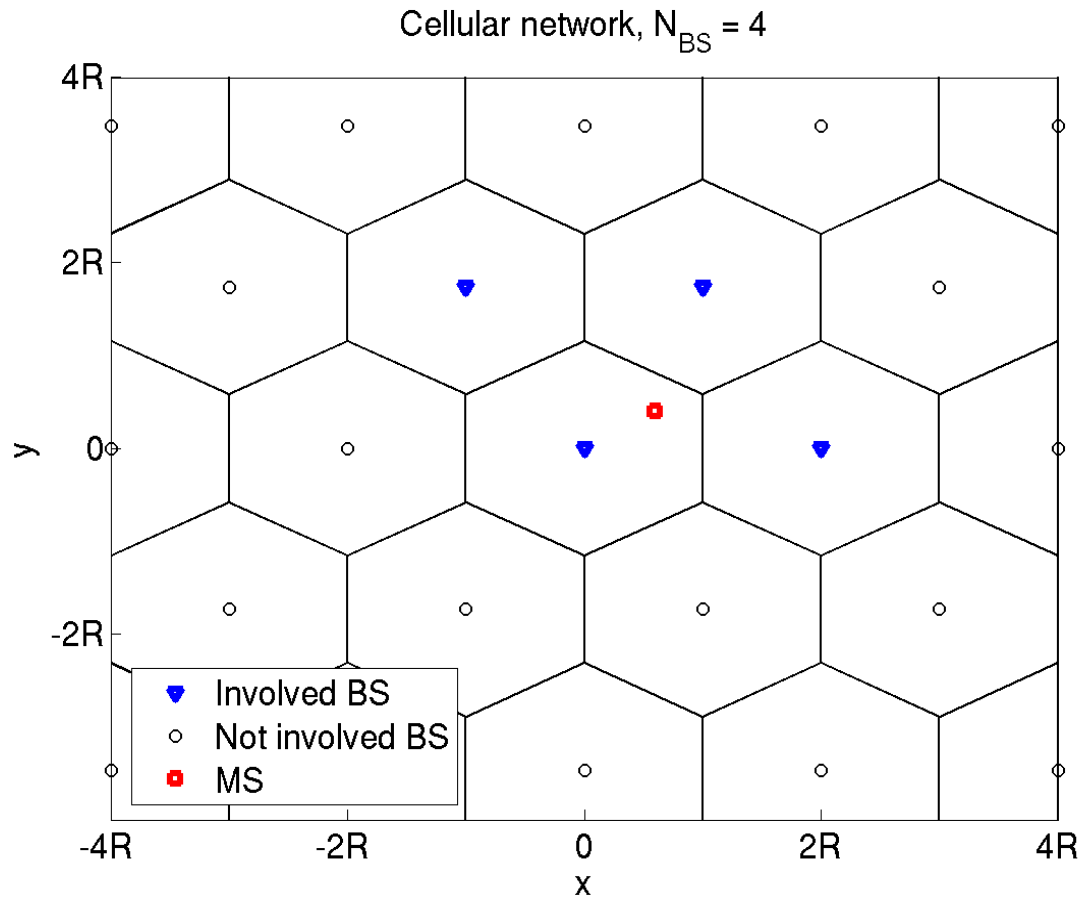
Sensors — Wireless Mobile Communication: Received Signal Strength (RSS) Based Positioning

RSS measurements

Measure RSS from multiple base stations

Apply pathloss model

Estimated distances

Determine receiver position
Apply trilateration / multilateration
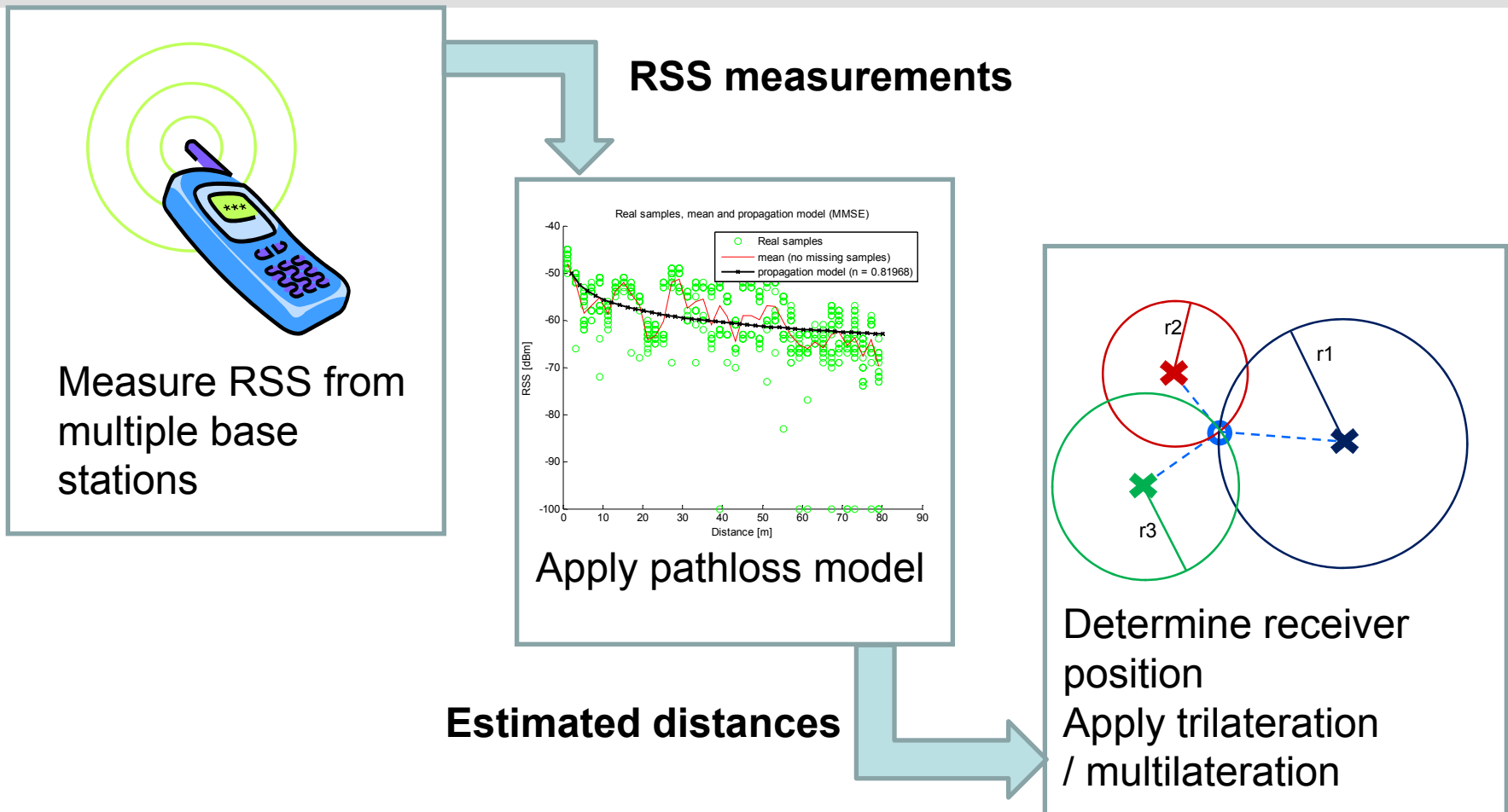
Sensors — Wireless Mobile Communication: Time of Arrival (TOA) Based Positioning
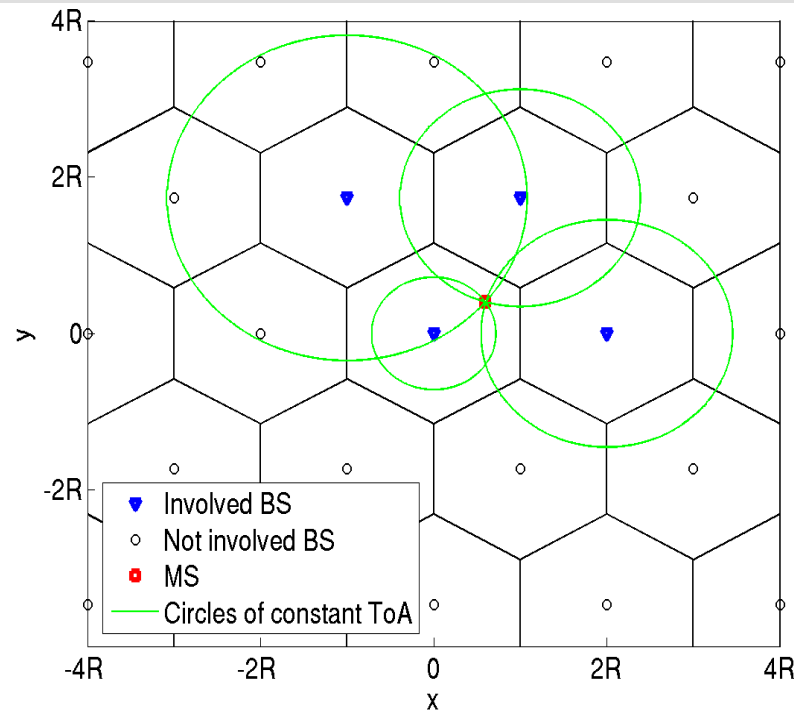
» Propagation time proportional to distance

» Measures propagation time from base station (BS) to mobile station (MS)

» Exact time knowledge is necessary at the MS (synchronization)

» At least three BSs have to be visible for triangulation

Sensors — Wireless Mobile Communication:
Time Difference of Arrival (TDOA) Based Positioning
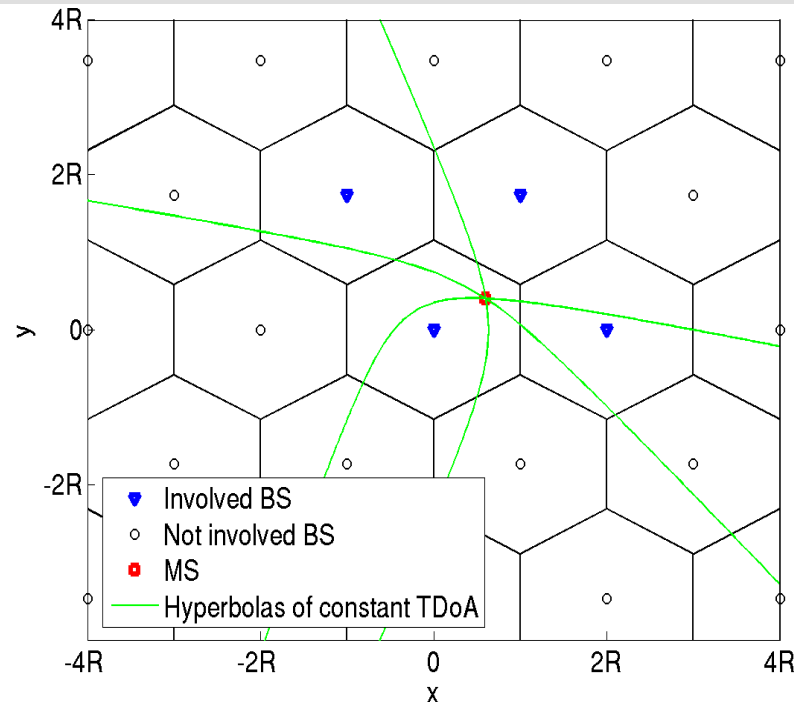
» Measures time difference of received signals from various BSs

» No full synchronization between MS and BS network necessary

» MS lies on hyperbolas with foci at the two related BSs

→ Results in link-level synchronization problem for several BSs

Sensors — Wireless Mobile Communication: Fingerprinting Based Positioning — WLAN

Generation of radio map

Two approaches:
- PDF approximations for probabilistic methods
- RSS averages for pattern recognition
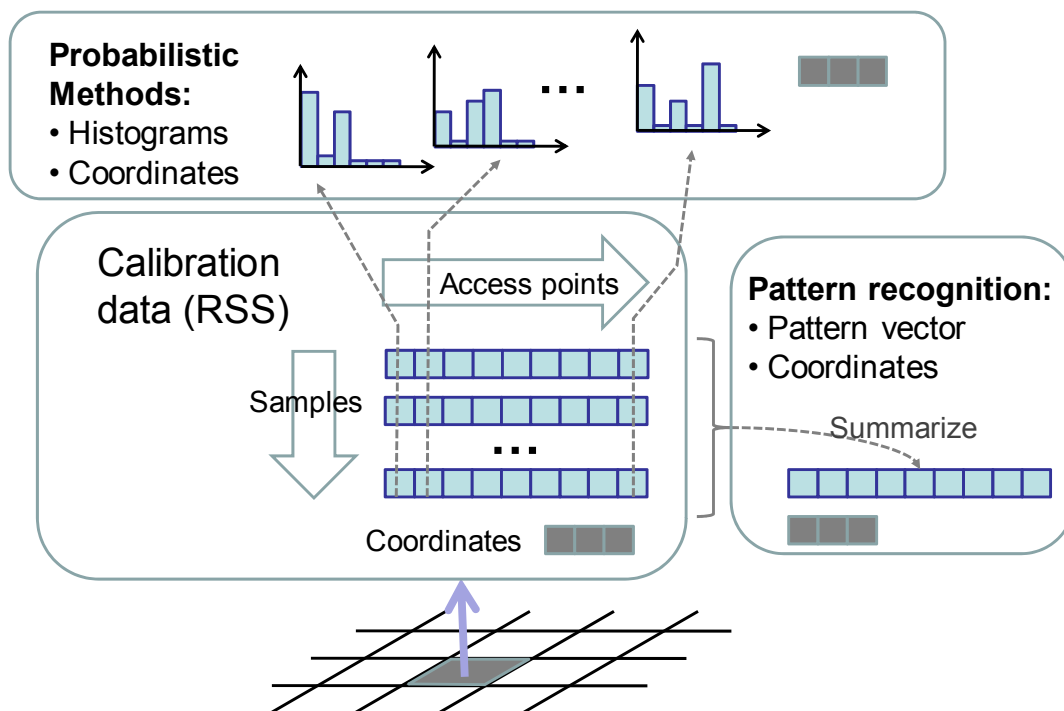
Probabilistic Methods:
- Histograms
- Coordinates

Calibration data (RSS)

Access points

Samples

Coordinates

Pattern recognition:
- Pattern vector
- Coordinates

Summarize

Sensors — Wireless Mobile Communication: Fingerprinting Based Positioning — WLAN

Radio map
 (= fingerprint database)
• Received signal strengths
• As a function of location
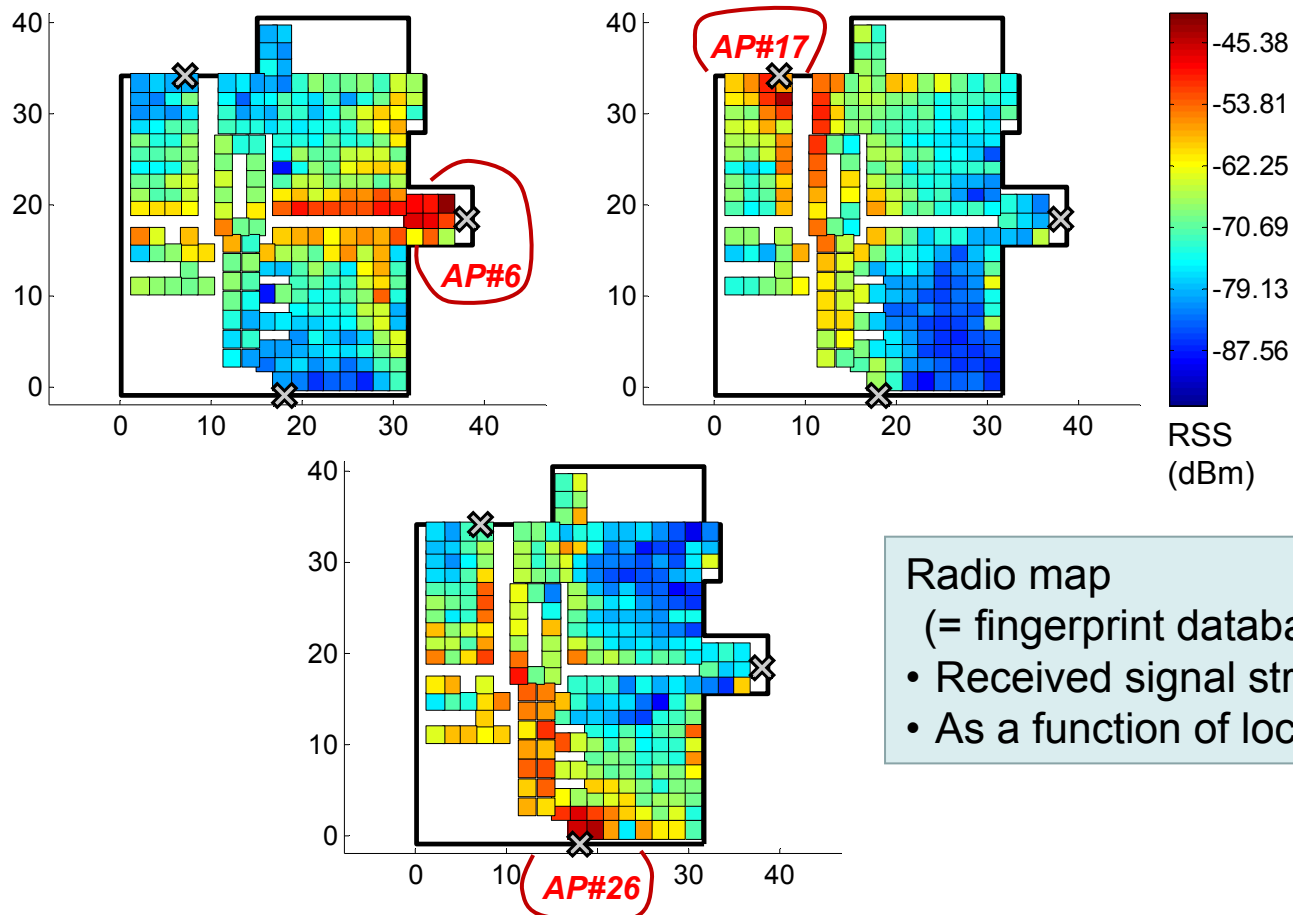
Sensors — Wireless Mobile Communication: Fingerprinting Based Positioning — WLAN

Offline phase:
Generation of radio map
 (= fingerprint database)
• Received signal strengths
• As a function of location

Online phase:
Position estimation using
• Radio map
• Current RSS measurements
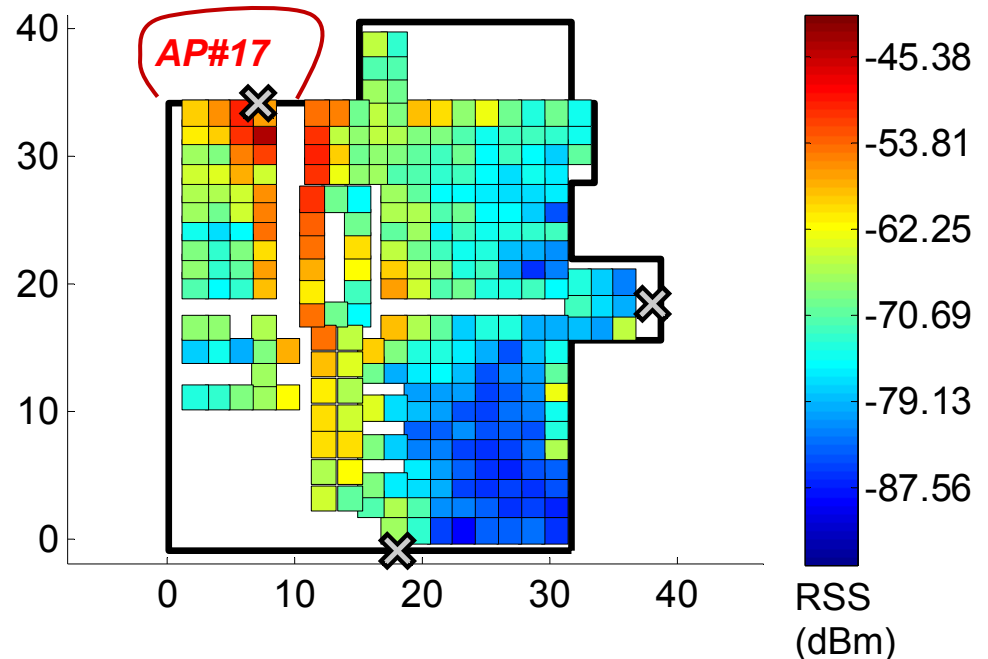
Sensors — Wireless Mobile Communication: Fingerprinting Based Positioning — WLAN

Performance of positioning

Average error distance
•A function of location

Average error (m)
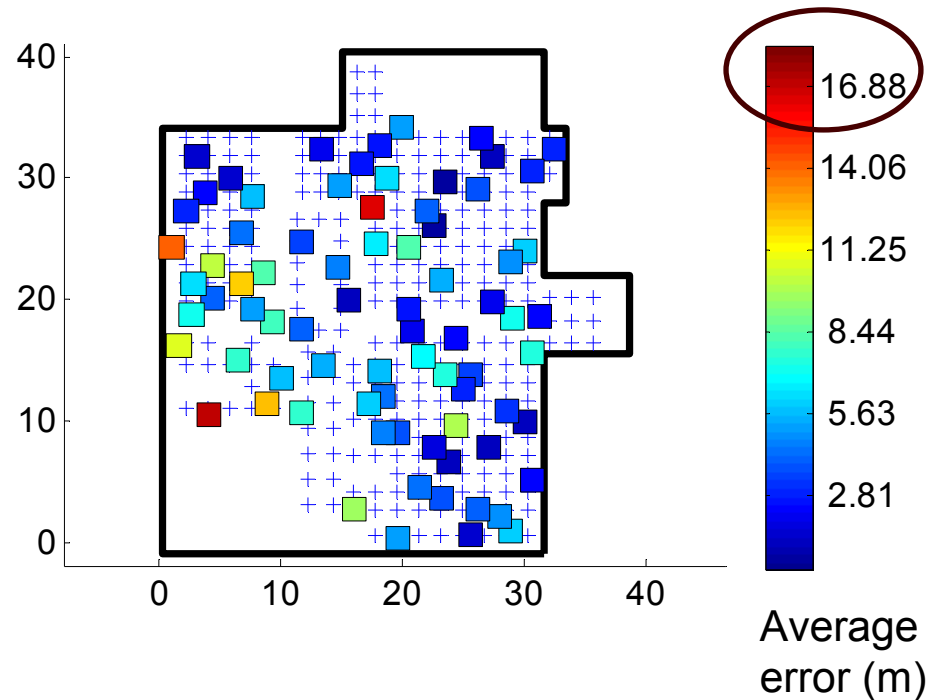
Sensors — Wireless Mobile Communication: More Methods

» Angle of arrival (AOA)
  » Measures the angle of arrival for the incident wave
  » Multiple antennas necessary
  » Only two BSs for positioning

» Cell identity (ID) or media access control (MAC) address of access point
  » Always possible
  » Sector ID for sectorized cells
  » Accuracy strongly depend on
    » Cell size
    » Location uncertainty of access point

Sensors — Wireless Mobile Communication: Standards

Positioning in cellular communications standards

- » 3GPP
    - » GSM: cell ID, uplink TOA, enhanced observed time difference (E-OTD), A-GPS
    - » UMTS: cell ID, observed time difference of arrival (O-TDOA), A-GPS
- » 3GPP2
    - » cdmaOne/cdma2000: cell ID, advanced forward link trilateration (A-FLT), A-GPS

Positioning in future cellular communications systems

- » 3GPP-LTE, WiMAX, 4G
- » OFDM based, using high bandwidths (up to 100 MHz)
- » Heterogeneous structure (wide area, metropolitan area, hot spots)
- » Challenges: frequency re-use of one, interference, overlay systems

Sensors — Wireless Mobile Communication:
Mobile Communication System versus GNSS

Mobile communication system	GNSS
Comparatively strong received signals	Very weak received signals
One strong signal from the serving BS	Long averaging necessary and possible, depends on the user dynamic
Much weaker signals from out-of-cell BSs ⇒ strong interference	Long spreading codes and small resource load ⇒ weak interference
Complete signal not a-priori known to support high data rates, only certain pilots	Signal a-priori known due to low data rates
Synchronization of the BSs not a-priori guaranteed	Very accurate synchronization of the satellites by atomic clocks
Non line of sight (NLOS) access as normal case	Line of sight (LOS) access as normal case
2-dimensional positioning	3-dimensional positioning

Hybrid Data Fusion (HDF):
How to position a mobile?

» Combine and weight all measurements in optimum way

» Dependence between measurements and position non-linear

» Static, iterative solution navigation equation

» Bayesian filter approaches for HDF and tracking

  » Input of position dependent measurements

  » A-priori knowledge of user mobility: mobility models

  » Linear Kalman filter

  » Extended Kalman filter

  » Unscented Kalman filter

  » Particle filter

Hybrid Data Fusion (HDF): Position Computation and Tracking

» Static solution: Iterative solution of navigation equation

  » Gauss-Newton (GN) method

  » For initialization of the position tracking algorithms

  » Low complexity

» Positioning Kalman filter (PKF)

  » Smoothing of the static solutions according to mobility models

  » Linear Kalman filter approach

  » Low complexity

» Extended Kalman filter (EKF)

  » Deterministic Kalman filter approach for non-linear models

  » Processing of the measurements directly

  » Can compensate situations with less than four measurements over a certain time

  » Medium complexity

Hybrid Data Fusion (HDF):
Position Computation and Tracking

» Unscented Kalman filter (UKF)

  » Kalman filter approach approximates the PDFs by a set of deterministic chosen sigma points

  » More efficient and robust implementation compared to EKF

  » Outperforms EKF for non-Gaussian measurements and situations with rapidly changing directions

  » Medium complexity

» Particle filter (PF)

  » PDFs are approximated by randomly chosen particles

  » Resampling of particles in each time-step

  » Is optimum if number of particles goes to infinity

  » For the current implementation around 1000 particles are needed

  » Very high complexity

» Simple random-walk mobility model for filter design

Hybrid Data Fusion (HDF): Flowchart
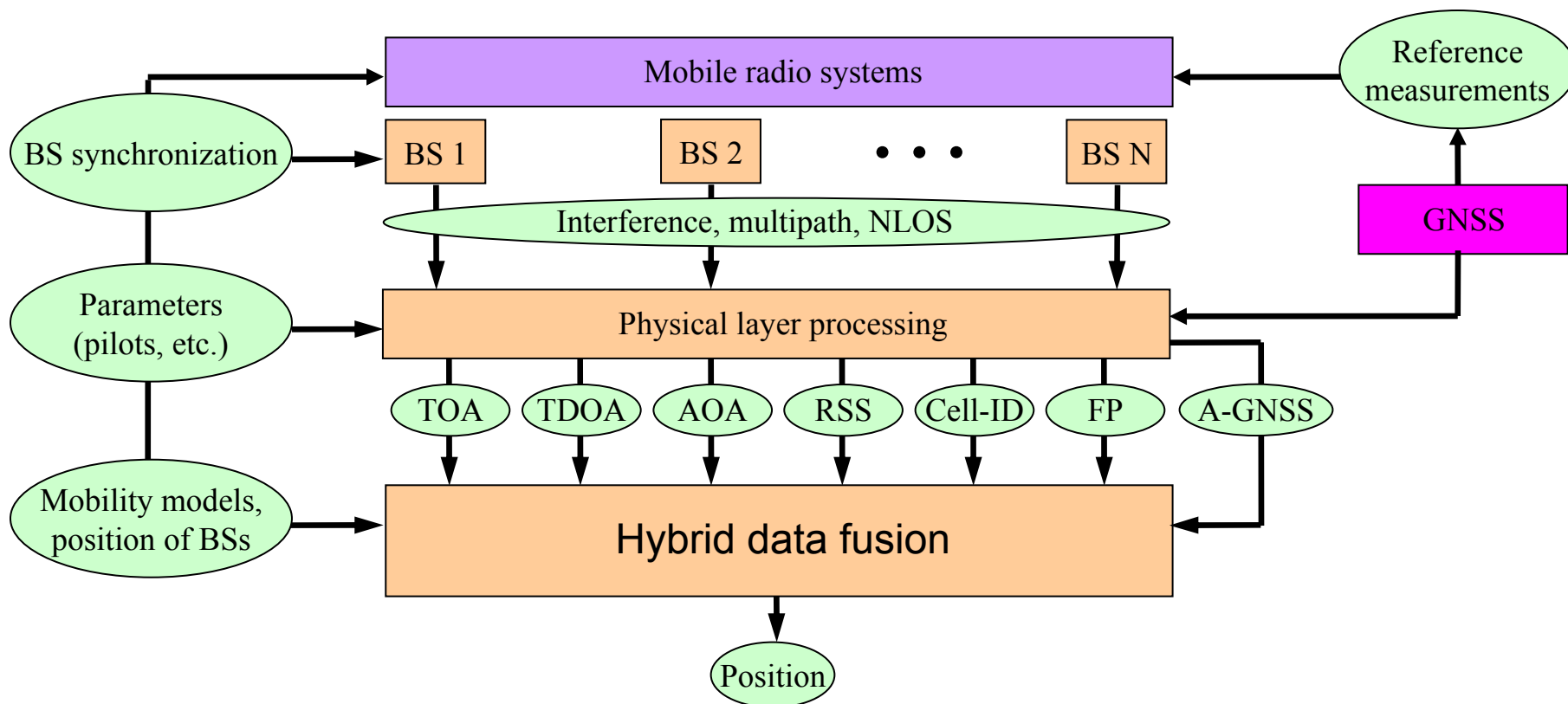
Hybrid Data Fusion (HDF):
Urban Canyon Scenario

» Urban canyon scenario in Munich, average building size of 26m

» Fixed GNSS constellation

» Intersite distance between BSs of 1500m

» Close to BS and cell edge scenario

» Pedestrian user, path track generation with gas diffusion model

» Channel impulse responses (CIRs) by raytracing

Different track realizations
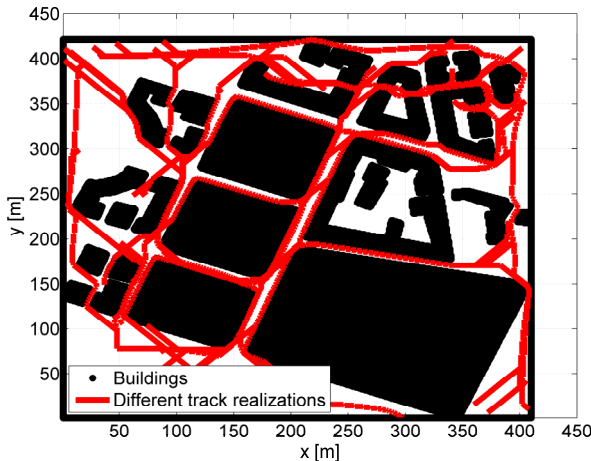
Cell layout, simulated scenarios
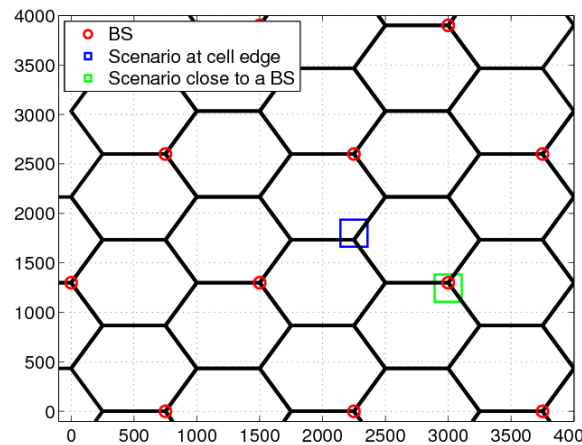
CIR for GPS satellite
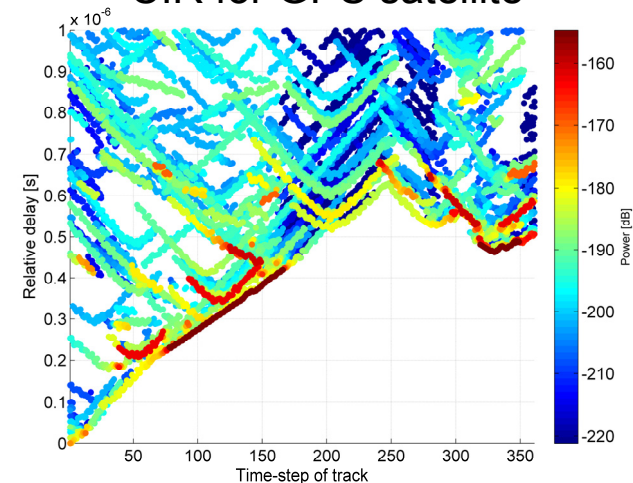
Hybrid Data Fusion (HDF): Urban Canyon Scenario

» GNSS positioning

  » Multipath bias, narrow-early-minus-late correlator (0.1 chip spacing)

  » Combined with standard user-equivalent range error models
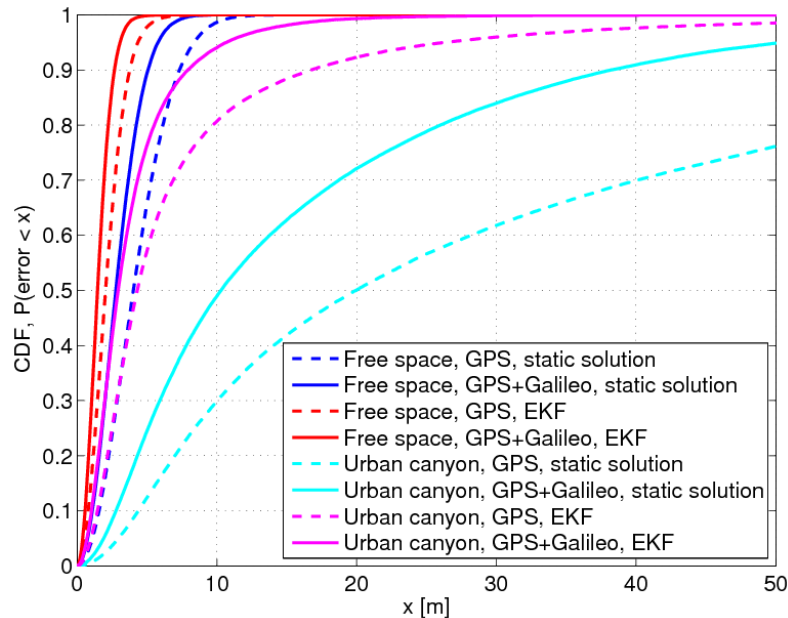
» TDOA positioning

  » 3GPP-LTE parameters

  » SINR threshold of -17dB
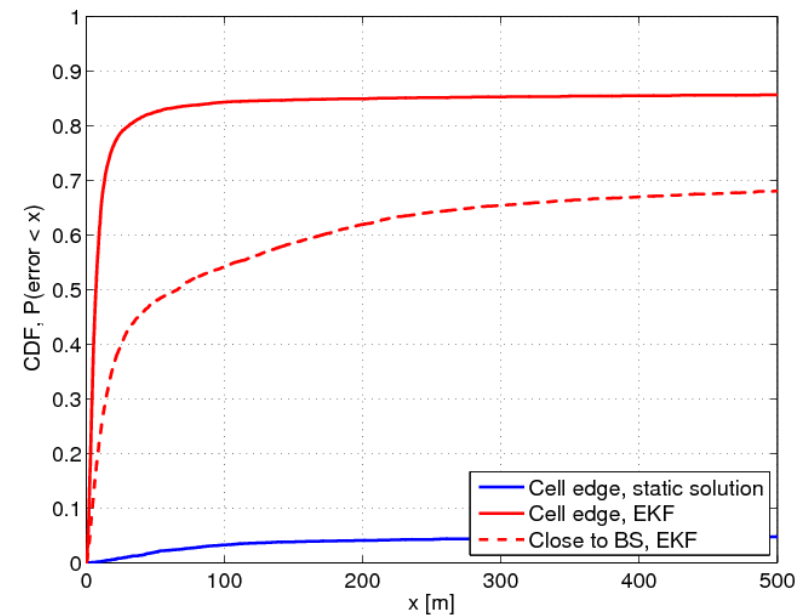
Hybrid Data Fusion (HDF): Urban Canyon Scenario

» GNSS+TDOA positioning in urban canyon scenario

» GNSS threshold of 4, SINR threshold of -17dB

» Positioning with EKF
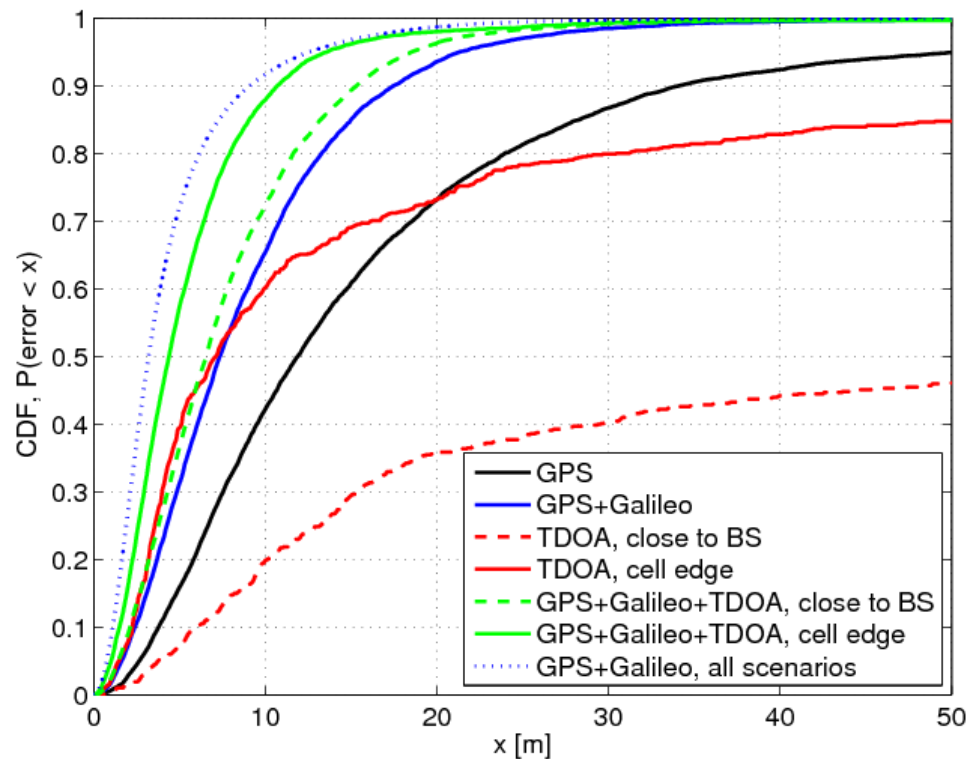
Hybrid Data Fusion (HDF): Urban Canyon Scenario

» GNSS+TDOA positioning in urban canyon scenario

» GNSS threshold of 4, SINR threshold of -17dB

» Positioning with EKF

GNSS visibility vs. time for one track
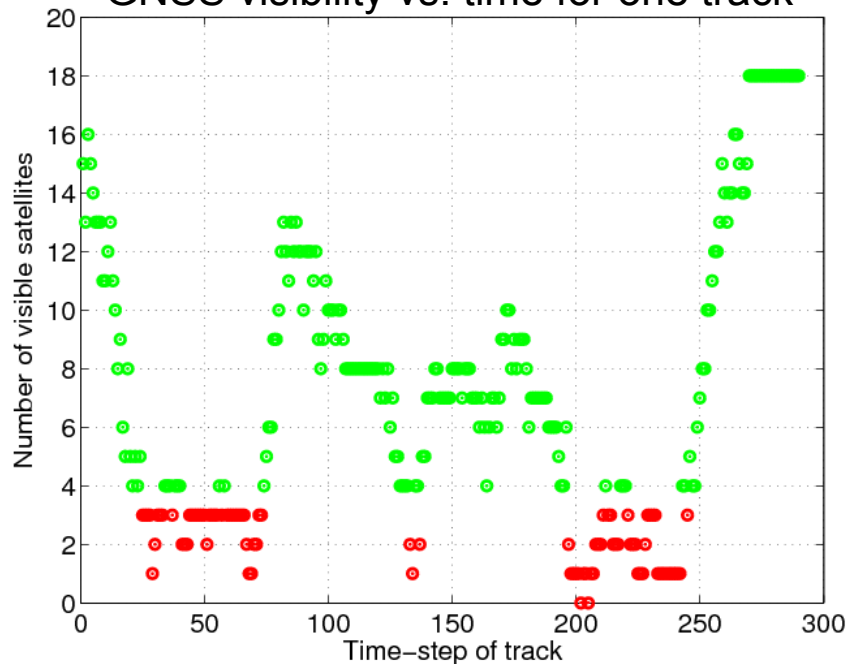
RMSE vs. time for one track
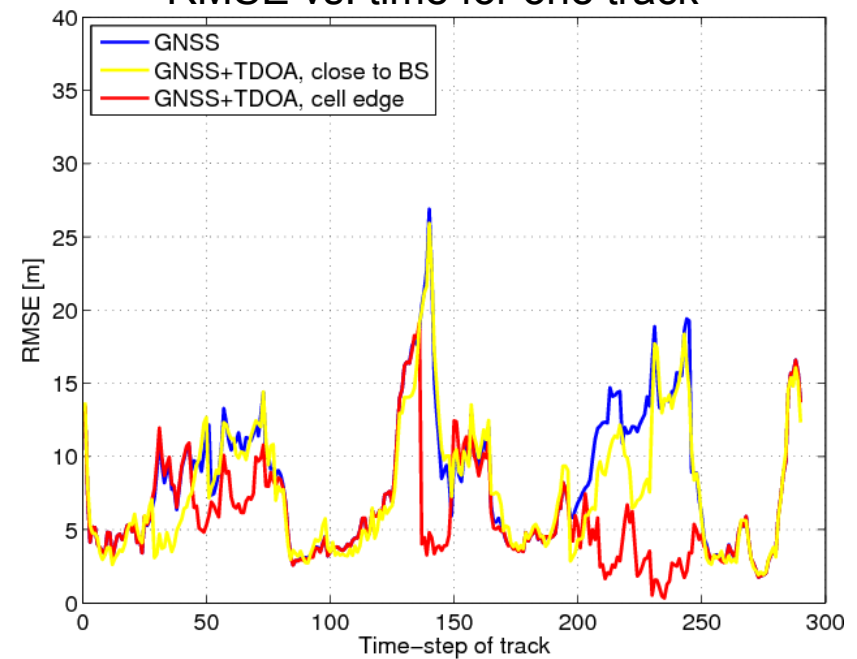
Conclusions

» Sensors

  » Inertial navigation:

    » Dead reckoning: Relative positioning

    » Accelerometer triad, gyro triad, pedometer + compass , car odometer

  » Wireless mobile communication:

    » Received signal strength, time of arrival, time-difference of arrival, angle of arrival, fingerprinting, cell-ID

    » Mobile Communication System versus GNSS

      » Comparatively strong received signals, but strong interference

      » Non line of sight propagation

      » 2-dimensional positioning

Conclusions

» Hybrid data fusion algorithms

  » Static solutions: Iterative solution of navigation equation (Gauss-Newton)

  » Positioning Kalman filter: Smoothing static solutions, linear filter, low complexity

  » Extended Kalman filter (EKF): Direct input of measurements, non-linear filter, medium complexity

  » Particle filter: Direct input of measurements, approximates PDFs with random particles, optimum for infinite particles, high complexity

» Hybrid data fusion results

  » Combination of measurements from GNSS and communications systems for performance enhancement in critical scenarios

  » Joint hybrid data fusion and tracking by EKF

  » Quality depends strongly on location of MS in cellular network

  » TDOA measurements can compensate lack of satellites in GNSS-critical situations (e.g., urban canyons)

Hybrid Data Fusion (HDF): System Model

» System model for communications system

  » MS located at $x = [x, y, z]^\top$

  » N_{BS} involved BSs at $x_\mu = [x_\mu, y_\mu, z_\mu]^\top, \quad \mu \in \{1, 2, \ldots, N_{BS}\}$

  » → Distances between MS and BSs

$$r_\mu(x) = \sqrt{(x_\mu - x)^2 + (y_\mu - y)^2 + (z_\mu - z)^2}$$

  » Corresponding TDOAs

$$d_{\nu,1}(x) = r_\nu(x) - r_1(x), \quad \nu \in \{2, 3, \ldots, N_{BS}\}$$

  » Noisy TDOAs

$$\mathsf{d}_{\nu,1} = d_{\nu,1}(x) + \mathsf{n}_{\nu,1}$$
$$= \varepsilon_\nu - \varepsilon_1 + \mathsf{n}_\nu - \mathsf{n}_1, \quad \nu \in \{2, 3, \ldots, N_{BS}\},$$

  » Noise from each link is assumed to be AWGN

  » ε_μ calculated by using pilot sequences

Hybrid Data Fusion (HDF):
System Model

» System model for GNSS

  » General principle: propagation time measurements between MS and fully synchronized satellites

  » Both GPS and Galileo systems are considered

  » Totally $N_{\mathsf{Sat}} = N_{\mathsf{GPS}} + N_{\mathsf{Galileo}}$ satellites are visible line of sight

  » Resulting pseudo-ranges

  $$\mathsf{r}_\mu = r_\mu\left(\boldsymbol{x}\right) + b_{\mathsf{clock}} + b_{\mathsf{multipath},\mu} + \mathsf{n}_\mu, \quad \mu \in \{1, 2, \ldots, N_{\mathsf{Sat}}\}$$

  » Bias introduced by receiver time offset b_{clock}

  » Multipath contribution for each satellite link $b_{\mathsf{multipath},\mu}$

  » Elevation depending residual error n_μ distributed according to user-equivalent range error (UERE) models

Hybrid Data Fusion (HDF):
Static Solution of the Navigation Equation

» Input: pseudo-ranges and TDOAs with corresponding covariances

$$\left[r_1, \ldots, r_{N_{\text{Sat}}}, d_{2,1}, \ldots, d_{N_{\text{BS}}-1,1} \right]^{\mathsf{T}} \in \mathbb{R}^{N_{\text{Sat}}+N_{\text{BS}}-1}$$

» Non-linear least squares minimization problem

» Usually based on Gauss-Newton (GN) method

» Also other methods can be applied

   » Steepest descent

   » Levenberg-Marquardt

   » Factor graphs

   » ML

   » etc.

» Output: Estimated position (and receiver time offset)

$$\left[\hat{x}_{\text{static}}\left[n \right], \hat{y}_{\text{static}}\left[n \right], \hat{z}_{\text{static}}\left[n \right], \hat{b}_{\text{clock}}\left[n \right] \right]^{\mathsf{T}} \in \mathbb{R}^4$$

» Will also be used for initialization of the tracking algorithms

Hybrid Data Fusion (HDF):
Linear / Position Kalman Filter (PKF)

» Smoothing of the static solutions according to mobility models

» Linear vector Kalman filter approach

» State-space and observation equation

$$s\,[n] = A s\,[n-1] + u\,[n]$$

$$x\,[n] = H s\,[n] + w\,[n]$$

» State-space vector $s\,[n] = \left[x\,[n]\,, y\,[n]\,, z\,[n]\,, v_x\,[n]\,, v_y\,[n]\,, v_z\,[n]\,, b_{\mathsf{clock}} \right]^{\mathsf{T}} \in \mathbb{R}^7$

» → Parameters to be estimated in each time-step

» Observation vector $x\,[n] = \left[\widehat{x}_{\mathsf{static}}\,[n]\,, \widehat{y}_{\mathsf{static}}\,[n]\,, \widehat{z}_{\mathsf{static}}\,[n]\,, \widehat{b}_{\mathsf{clock}}\,[n] \right]^{\mathsf{T}} \in \mathbb{R}^4$

» → Given by static solution of navigation equation in each time-step

» Dependency between observation and state-space vector

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{4 \times 7}$$

Hybrid Data Fusion (HDF):
Linear / Position Kalman Filter (PKF)

» Linear Kalman filter equations

  » Prediction step

  $$\hat{s}[n|n-1] = A\hat{s}[n-1|n-1] \in \mathbb{R}^7$$

  » MMSE matrix after prediction step

  $$M[n|n-1] = AM[n-1|n-1]A^\top + Q \in \mathbb{R}^{7\times 7}$$

  » Kalman gain matrix

  $$K[n] = M[n|n-1]H^\top$$

  $$\cdot \left(C[n] + HM[n|n-1]^\top H^\top \right)^{-1} \in \mathbb{R}^{7\times 4}$$

  » Final estimate of state-space vector

  $$\hat{s}[n|n] = \hat{s}[n|n-1] + K[n]\left(x[n] - H\hat{s}[n|n-1] \right) \in \mathbb{R}^7$$

  » Corresponding MMSE matrix

  $$M[n|n] = \left(\mathbf{I}_7 - K[n]H \right) M[n|n-1] \in \mathbb{R}^{7\times 7}$$

Hybrid Data Fusion (HDF):
Extended Kalman Filter (EKF)

» Deterministic Kalman filter approach for non-linear models

» Processing of TDOAs and pseudo-ranges directly

» Can handle situations with too less sources over a certain time

» Flexible design: number of sources can change in each time-step

» State-space and observation equation

$$s\left[n\right] = As\left[n-1\right] + u\left[n\right]$$

$$x\left[n\right] = h\left(s\left[n\right]\right) + w\left[n\right]$$

» Observation vector $x\left[n\right] = \left[r_1, \dots, r_{N_{\text{Sat}}}, d_{2,1}, \dots, d_{N_{\text{BS}}-1,1}\right]^{\top} \in \mathbb{R}^{N_{\text{Sat}}+N_{\text{BS}}-1}$

» → No intermediate step of static solution required

» Based on linearization

$$h\left(s\left[n\right]\right) \approx h\left(\hat{s}\left[n|n-1\right]\right) + H\left[n\right]\left(s\left[n\right] - \hat{s}\left[n|n-1\right]\right)$$

» with Jacobian matrix

$$H\left[n\right] = \left.\frac{\partial h\left(s\left[n\right]\right)}{\partial s\left[n\right]}\right|_{s[n]=\hat{s}[n|n-1]}$$

Hybrid Data Fusion (HDF):
Extended Kalman Filter (EKF)

» EKF equations

  » Prediction step

  $$\hat{s}\left[n|n-1\right] = A\hat{s}\left[n-1|n-1\right] \in \mathbb{R}^7$$

  » MMSE matrix after prediction step

  $$M\left[n|n-1\right] = AM\left[n-1|n-1\right]A^\top + Q \in \mathbb{R}^{7\times 7}$$

  » Kalman gain matrix

  $$K\left[n\right] = M\left[n|n-1\right]H^\top\left[n\right]$$
  $$\cdot\left(C\left[n\right] + H\left[n\right]M\left[n|n-1\right]H^\top\left[n\right]\right)^{-1} \in \mathbb{R}^{7\times(N_{\mathrm{Sat}}+N_{\mathrm{BS}}-1)}$$

  » Final estimate of state-space vector

  $$\hat{s}\left[n|n\right] = \hat{s}\left[n|n-1\right] + K\left[n\right]\left(x\left[n\right] - h\left(\hat{s}\left[n|n-1\right]\right)\right) \in \mathbb{R}^7$$

  » Corresponding MMSE matrix

  $$M\left[n|n\right] = \left(\mathbf{I}_7 - K\left[n\right]H\left[n\right]\right)M\left[n|n-1\right] \in \mathbb{R}^{7\times 7}$$

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Tutorial Outline

» Introduction: GRAMMAR, Satellite navigation basic principles, existing and emerging GNSS satellite constellations and augmentation systems (30 minutes): Stephan Sand, DLR

» Antennas and RF front-ends for multi-frequency GNSS receivers (30minutes): Marco Detratti, ACORDE

» Advanced receiver algorithms for baseband processing (30 minutes): Simona Lohan, TUT/DCE

» Baseband hardware solutions for multi-system, multi-frequency reception (30 minutes): Heikki Hurskainen, TUT/DCS

» Issues in PVT solution software for GNSS (20 minutes): Francescantonio Della Rosa, TUT/DCS

» Hybridization with other sensor data (30 minutes): Stephan Sand, DLR

» Wrap-up and conclusions (10 minutes): Stephan Sand, DLR

Challenges in Multi-System Multi-Frequency GNSS Receiver Design — Wrap-Up and Conclusions

Stephan Sand (DLR)

13th June 2010

Wrap-Up and Conclusions

» Introduction

  » Satellite navigation principles

    » Measure signal propagation time from transmitter to receiver
➔ Distance between transmitter and receiver

    » GNSS measures pseudoranges
➔ At least 4 pseudoranges for x,y,z and receiver clock bias b

  » Global navigation satellite systems (GNSS)

    » GPS, Galileo, Compass: Code division multiplex, multi-frequency

» Antennas and RF front-ends for multi-frequency GNSS receivers

  » Low-power compact multi-band GNSS receivers:
Suitable for portable devices requiring high performance and robustness against interference from cellular and legacy services.

  » Big advances in SW receivers with impressive processing speed:
Professional like receiver at very low cost ➔ consumer market

  » Not too stringent power constraints, e.g., cellular handset:
Really broadband solutions (full E5, E6) possible

➔ Potential applications at affordable price and comfortable size for professional and high precision products

Wrap-Up and Conclusions

» Advanced Galileo receiver algorithms for baseband processing
  » Lack of unified studies regarding
    » Relative performance and complexity of various algorithms
    » Algorithm sensitivity to various modulations and chip rates
    » Bandwidth limitations and multipath effects on carrier phase and frequency tracking
  » Multitude of multipath mitigation algorithms:
    » Typically multi-correlator based code tracking
    » Simplest multipath reduction techniques covered by patents
    » Significant place for enhanced algorithms
» Baseband hardware solutions for multisystem, multi-frequency reception
  » E1/E5a: Most suitable frequency combination for dual frequency Galileo mass market receiver
  » Main tasks of baseband: Acquisition and tracking (timing information and data for pseudorange estimation)
  » GRAMMAR: Flexible tracking channel implementation exploiting similar CDMA property of received signals introduced and implemented

Wrap-Up and Conclusions

» Issues in PVT solutions software for GNSS

  » Dual-frequency GNSS receiver (E1/E5a)

    » Increased accuracy

      » Reduced ionospheric errors: Dual-frequency corrections

      » Reduced dilution of precision: More satellites

    » Increased availability: More satellites

» Hybridization with other sensor data

  » Joint hybrid data fusion and tracking by extended Kalman filter of measurements from GNSS and communications systems in critical scenarios

  » Quality depends strongly on location of MS in cellular network

  » TDOA measurements can compensate lack of satellites in GNSS-critical situations (e.g., urban canyons)

Wrap-Up and Conclusions

» Galileo Ready Advanced Mass Market Receiver (GRAMMAR)

  » Dual-frequency low power single chip GNSS RF-FE and FPGA BB prototype GNSS receiver targeted at mass market for rapid prototyping of advanced algorithms and techniques

  » Identification, evaluation and simulation of enhanced algorithm concepts for next generation mass market receivers

http://www.gsa-grammar.eu