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Global Navigation Satellite Systems (GNSS)

- Provide **autonomous geo-spatial positioning with global coverage**
- Active systems
  - US Global Positioning System (GPS)
  - European System Galileo
  - The Russian GLONASS
  - The Chinese Compass system
  - The Indian Regional Navigational Satellite System (IRNSS)
  - The Japanese Quasi-Zenith Satellite System (QZSS)
- All these systems will operate independently and without interfering with each other
System overview: Galileo

- Constellation: 30 satellites (27 operational + 3 active spares), positioned in three circular Medium Earth Orbit (MEO) planes at 23,222 km altitude above the Earth.
- High system reliability is of primary importance
  - Especially for operation in critical environments, like for air navigation and SoL services.
- Important dates:
  - 21 October 2011: Launch of satellite 1&2
  - Summer 2012: Launch of satellites 3&4
  - 2014 Initial Operational Capability (IOC)
  - 2018 Full Operational Capability (FOC)
GNSS Positioning

• Estimate the user position
  • Triangulation based on the knowledge of the distance between user and known points (satellites)
• Distances are computed as the time needed for the signal transmitted by the satellites to reach the user
  • Additional time uncertainty due to non ideal synchronization between clocks
  • Not ranges but pseudoranges
  • At least 4 satellites are needed
Receiver Operations

Code Synchronization Phase:
• Acquisition
  • *Coarse timing* and frequency estimation
• Tracking
  • *Fine timing* and frequency estimation

Position computation:
• Ephemeris extraction
• Pseudorange calculation
• Navigation system solution
Types of Aiding

- **Physical Level**
  - Assist Acquisition
    - Visible satellites
    - Doppler frequency
      - AIM: Reduce TTFF
    - Keep tracking circuits locked
      - AIM: help reacquisition

- **Position Level**
  - Provide missing information during signal outages
    - AIM: enhance positioning availability
    - P2P
    - INS
CODE ACQUISITION AIDING TECHNIQUES
Code Acquisition in CDMA Systems

- **Goal:** Identify the Code Epoch ($\tau$) and the Frequency Offsets ($f_e$) of a specific satellite signal
- **Uncertainty Region (UR) is discretized into time slots $\Delta \tau$, and the frequency domain is discretized into frequency bins $\Delta f$:**
  - Two-dimensional matrix must be scanned to find Correct Hypothesis ($H_1$)
  - A large number of Incorrect Hypotheses ($H_0$)

![Diagram showing code acquisition process](image)

- Zero Value: Code Acquisition block collects only noise
- Secondary Peak: the tracking block can lock onto this outlier peak
Two different Search Strategies can be defined:

- **Serial search** (i.e. schemes based on one or more correlators)
  - Consecutive time/frequency tests
- **Parallel acquisition** strategies (i.e. FFT/IFFT schemes)
  - Simultaneously tests all the possible code phases (frequency tests are required)

**Serial Scheme**

**Parallel Scheme**

Selection of the correct hypothesis through different **Decision Criteria**

**MAX**
- Decides in favor of the cell with the largest correlation value
- Requires to scan the entire UR

**Threshold Crossing (TC)**
- Compares each decision variable in turn with an optimized threshold

**MAX/TC**
- Hybrid solution
Aiding techniques

• **Motivation:**
  • Speed-up initial synchronization

• **Issues:**
  • Very low SNR values and large uncertainty region causes operations to be performed several times

• **Techniques:**
  • A-GNSS
  • P2P
  • Cross-Band Aiding
Cross-Band Aiding (CBA) Idea

- **Context**
  - Dual-band (E1/E5) receivers

- **Motivation**
  - **Fast Acquisition for Dual-Band GNSS Receivers**

- **Idea**
  - Signals in the two bands are transmitted using a common time reference
  - Information can be exchanged in order to mutually reduce uncertainty regions

- **Issues**
  - Different propagation delays
  - Different chip rates
  - Different code lengths

<table>
<thead>
<tr>
<th>Primary Code</th>
<th>E1</th>
<th>E5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code Lenght</td>
<td>4092</td>
<td>10230</td>
</tr>
<tr>
<td>Chip rate</td>
<td>1.023Mcps</td>
<td>10.23Mcps</td>
</tr>
<tr>
<td>Code Period</td>
<td>4 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Chip Duration</td>
<td>977.5 ns</td>
<td>97.75 ns</td>
</tr>
</tbody>
</table>
E1-E5 CBA strategy

- Acquisition in E1 over the complete uncertainty region (E1-CUR) Master Signal
- Acquisition in E5 with a reduced uncertainty region (E5-RUR) Slave Signal

First Step - Master Signal E1

Second Step - Slave Signal E5
E5-E1 CBA strategy

- Acquisition in E5 over the complete uncertainty region (E5-CUR) Master Signal
- Acquisition in E1 with a reduced uncertainty region (E1-RUR) Slave Signal
Timing Structures

- **E1-E5 CBA**
  - Code epoch of the slave signal E5 can be searched inside a RUR of length:
  \[
  E5_{RUR} = \frac{Rc_{E5}}{Rc_{E1}} = 10 \text{ chips} E5
  \]

- **E5-E1 CBA**
  - The Synchronization in E1 slave signal need distinguish the start of the primary code between four macro-hypotheses.
  \[
  E1_{RUR} = \frac{T_{code-E1}}{T_{code-E5}} = 4 \text{ chips} E1
  \]
Analytical Overall Mean Acquisition Time: Unidirectional Information Flow (UD)

\[ P_{EM} \cdot Z^{P_f \cdot T_{URM}} = (1 - P_{DM}) Z^{P_f \cdot T_{URM}} \]

\[ P_{DM} \cdot Z^{P_f \cdot T_{URM}} \]

\[ P_{ES} \cdot Z^{P_f \cdot T_{URS}} = (1 - P_{DS}) Z^{P_f \cdot T_{URS}} \]

\[ P_{DS} \cdot Z^{P_f \cdot T_{URS}} \]

- The acquisition procedure can be modeled as a Markov Chain:
  - Represented by the associated Flow Graph
  - MAX criterion: the entire uncertainty region is scanned by choosing the largest detection variable

\[ P_{DM} = \text{Master Band Probability of Detection} \]
\[ P_{DS} = \text{Slave Band Probability of Detection} \]
\[ P_f = \text{Processing Factor} \]
\[ T_{URM} = \text{Master Signal Uncertainty Region} \]
\[ T_{PM} = \text{Master Penalty Time} \]
\[ T_{URS} = \text{Slave Band Uncertainty Region} \]
\[ T_{PS} = \text{Slave Penalty Time} \]

\[ P_A(z) = \frac{P_{DM} P_{DS} \cdot Z^{P_f (T_{URM} + T_{URS}) + T_{CB}}}{(1 - P_{EM} \cdot Z^{P_f T_{URM} + T_{PM}})(1 - P_{ES} \cdot Z^{P_f T_{URS} + T_{PS}})} \]

\[ OMAT_{UD} = \left. \frac{dP_A(z)}{dz} \right|_{z=1} = T_{CB} + \frac{P_{DM} (P_f T_{URS} + T_{PS}) + P_{DS} (P_f T_{URM} + T_{PM} - P_{DM} (T_{PM} + T_{PS}))}{P_{DM} P_{DS}} \]
Results: UD performance timing

![Graph showing Mean Acquisition Time vs E1 and E5 C/No](image)

- CBA E5-E1, Timing Errors (UD)
- CBA E5-E1, no Timing Errors (UD)
- CBA E1-E5, Timing Errors (UD)
- CBA E1-E5, no Timing Errors (UD)
- E1&E5 Timing Errors
- E1&E5 no Timing Errors

Mean Acquisition Time [msec] vs E1 C/No [dBHz]

- 4.000978 ms
Analytical Mean Acquisition Time:
Bi-directional Information Flow (BD)

Master Search

Slave Error
Slave Search “Empty”
Slave Search “Full”
Slave Error

\[ T_{P(E1-acq)} = 10 \cdot T_{code-E1} \]
\[ T_{P(E5-acq)} = 10 \cdot T_{code-E5} \]

OMAT_{BD} = \left. \frac{dP_A(z)}{dz} \right|_{z=1} = \frac{T_{CB} + P_f (T_{URM} + T_{URS}) + T_{PS} (1 - P_{DM} P_{DS})}{P_{DM} P_{DS}}

- \( P_{DM} \) = Master Band Probability of Detection
- \( P_{DS} \) = Slave Band Probability of Detection
- \( P_f \) = Processing Factor
- \( T_{URM} \) = Master Signal Uncertainty Region
- \( T_{PM} \) = Master Penalty Time
- \( T_{URS} \) = Slave Band Uncertainty Region
- \( T_{PS} \) = Slave Penalty Time

\[ z^{T_{PS}} \]
\[ z^{T_{PS}} \]
\[ P_{DS} \cdot z^{P_f T_{URS}} \]
\[ P_{DM} \cdot z^{P_f T_{URM} + T_{CB}} \]
\[ (1 - P_{DM}) \cdot z^{P_f T_{URM} + T_{CB}} \]
\[ (1 - P_{DS} - P_m) \cdot z^{P_f T_{URS}} \]
Results: BD performance timing

![Graph showing Mean Acquisition Time vs E1 C/No (dBHz) for different scenarios]

- **E1&E5 no Timing Errors (BD)**
- **E1&E5 Timing Errors (BD)**
- **CBA E1-E5 no Timing Errors (BD)**
- **CBA E1-E5 Timing Errors (BD)**
- **CBA E5-E1 no Timing Errors (BD)**
- **CBA E5-E1 Timing Errors (BD)**

4.000978 ms
Performance Comparison: UD Vs BD

![Graph showing performance comparison between UD and BD](image-url)
CODE TRACKING AIDING TECHNIQUES
Code Tracking

- Refine the coarse values of code phase and frequency
- Keep track of the signal properties over time
- Necessary for pseudorange estimation
- Code tracking
  - usually based on a feedback scheme identified as Delay Lock Loop (DLL)
- Carrier tracking
  - either tracking the phase or the frequency
Tracking Aiding Techniques

• **Motivation:**
  - Improve tracking loops ability to stay locked in the presence of
    - Multipath
    - Ionospheric scintillation
    - Noise
    - High receiver dynamics
  - Improve timing estimation precision

• **Goal:** **Robust Code Tracking for GNSS signals**

• **Solutions:** **Vector Tracking**
  **Ultratight Integration**
Vector Tracking Functioning

- User position and velocity are used to predict code phase and carrier frequency
  - Combines tracking and navigation processing
  - All received signals are processed together
- Feedback provided by the navigation processor
- Characteristics:
  - Noise reduction
  - Robustness to temporary blockages
  - Better optimization
  - Performance improvement with respect to scalar loops
  - Errors in one channel can affect other channels
• Additional states in the estimation filter require additional measurements
• Atmospheric error and satellite clock errors predictions can be extracted from the broadcasted navigation data
Ultra-tight Code Tracking

• **Motivation:**
  • improve tracking loops ability to stay locked
  • improve timing estimation precision

• **Inertial Sensors:**
  • Autonomous Navigation Systems $\rightarrow$ Robustness against signal outages and jamming
  • High update rate
  • Precision that degrades with time

• **Goal:** **Robust Code Tracking for GNSS signals**

• **Solution:** **Ultra-tight Integration**
GAUSS Ultra-tight integration

- The Gaussian AUtocorrelation Scaled Sum (GAUSS) scheme:
  - An artificial autocorrelation peak is generated from INS information

\[
G(t) = \frac{1}{\sqrt{2\pi\sigma^2_{INS}}} e^{-\frac{(t-\mu_{INS})^2}{2\sigma^2_{INS}}}
\]

delay estimated by the INS

\[
D_{GAUSS} = \frac{MSE_{INS} D_{GNSS} + MSE_{GNSS} D_{INS}}{MSE_{GNSS} + MSE_{INS}}
\]

The two sets of autocorrelation are summed non-coherently each scaled by its Mean Square Error (MSE)
GAUSS concept

![Graph showing GNSS Correlation, INS Gaussian, and INS-Gaussian Autocorrelation Scaled Sum (GAUSS) with code phases and magnitude of correlation.]

GAUSS results

-0.025
-0.02
-0.015
-0.01
-0.005
0
0.005
0 20 40 60 80 100 120 140 160 180 200
Iterations
Chips
Tracking Estimation GNSS stand alone
GAUSS Ultra-Tight Tracking Estimation Te=20 s
GAUSS Ultra-Tight Tracking Estimation Te=200 s
International Projects

- **ESA-TT&C-I** (Spread Spectrum Codes suitable for Mono-mode TT&C Transponders)
- **ESA-P2P** (Distributed and cooperative positioning innovative GNSS applications)
- **EU-GAMMA-A** (Galileo Receiver for Mass Market Applications in the Automotive Area)
- **TAS-I** (*Study of GNSS Software Radio Receivers*)
Publications


Short Courses

- NEWCOM++ Winter School, 2-6 Febbraio 2009, Aachen, Germania
- Short-Range Positioning Systems: Fundamentals and Advanced Research Results with Case Studies, 5-6 March 2009, Bologna
- GPS/INS Multisensor Kalman Filter Navigation, 10-14 Maggio 2009, Parigi, Francia
- SatNEx Summer School, 27-31 Luglio 2009, Salisburgo, Austria
- Heterogeneous wireless networks: architectures, Qos performance and applications, 9 e 11 Settembre 2009, Bologna
- Aster DOC, 5-10 Luglio 2010, Bologna

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Position Level Aiding

• **Motivation:**
  • improve positioning solution availability
  • improve accuracy

• **Inertial Sensors:**
  • Autonomous Navigation Systems $\rightarrow$ Robustness against signal outages and jamming
  • High update rate
  • Precision that degrades with time

• **P2P cooperation:**
  • Peers in a network have positions correlated to each other

• **Goal:** **Availability and Accuracy improvements in positioning**
  • **Solution:** **Loose/Tight Integration**
    P2P positioning
Motivation

• The P2P paradigm:
  • Peers belonging to the same network have positions and velocities that are correlated to each other
  • Exploitation of direct communication links among nodes in a network used to exchange aiding information
  • Increased positioning capabilities especially in those scenarios where triangulation would be impossible for a single user
P2P Positioning

- Different solutions
  - GNSS-data only Algorithm (exchange of pseudorange measurements)
  - Hybrid Algorithm (exchange of terrestrial ranging information)

- Method:
  - Extended Kalman Filter

- Goal:
  - GNSS-data only → Improve service availability
  - Hybrid → Improve accuracy