GPS TSPI for Ultra High Dynamics

Use of GPS L1/L2/L5 Signals for TSPI

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Batch of 10 off Q20 HD GPS Modules Being Pick and Place Populated During Manufacture
Motivation
GPS Solution
GPS Signals Evolution
Architecture of Receiver
- Signal Conditioning
- Search, Acquisition and Tracking
- Measurements and processing
Performance Simulation
Performance Test Results
Motivation
Motivation

Test and Evaluation Applications for Advanced Weapons

- New class of high energy kinetic weapons
  - Distinguishing characteristics
    - High dynamics envelope: acceleration ~500g; velocity ~5km/s; control range safety zone
- New classes of T&E measurement requirements
  - GPS and coupled (MEMS) IMU
    - Accuracy improvement, Support in ‘difficult’ GPS areas (urban warfare)
- High accuracy TSPI results
  - Moderate to low dynamics
    - End game scoring - ~10cms
- Tactical GPS will be subject to intentional denial in areas of military operation
  - Requirement to test for effects on weapons systems
    - L5 signals provide *independent* navigation grid for T&E
    - Jamming causes unpredictable behaviour – see next slide
Observed Effects of Jamming

Coverage of GPS jamming unit; 25m above ground level, maximum power 1.58W ERP

Ship steering course in blue
- Left track (no jamming)
- Right track – GPS L1 locations reported with jammer switched on
  - Red dots are speeds > 100kts
GPS Solution & Signal Evolution
T&E Solutions using 3 Frequency GPS

GPS Broadcasts on 3 Frequencies

- **L1** 1575.42 MHz (154 x 10.23 MHz) – P(Y) code, C/A code
  - Rapid time to acquisition & fix; high dynamics envelope ~300g+
  - Long code wavelength ($\lambda_{\text{CA}} = 293\text{m}$); short code of 1ms, range ambiguity (293 km)
- **L2** 1227.60 MHz (120 x 10.23 MHz) – P(Y) code + CM, CL code, broadcast from 10 SV’s
  - New civil signals; L2CM, L2CL
  - Longer code wavelength ($\lambda_{\text{L2C}} = 586\text{m}$), potential for dynamics ~500g LOS
  - Codes are 20ms & 1.5 sec, no range ambiguity, greater difficulty in acquisition (esp. CL)
- **L5** 1176.45MHz (115x10.23MHz) – L5I + L5Q, broadcast from 2 SV’s
  - L5 (civil) signals on Block IIF SV’s
  - Operates in aeronautical safety of life band (ITU protected)
  - Short code wavelength ($\lambda_{\text{code}} = 29.3\text{m}$), 10.23Mcps code rate - same as P(Y)
  - Provides independent low dynamic navigation
  - T&E application used for L1/L2 performance assessment during jamming conditions

L1, L2, L5 – offer greater range of T&E performance options
New GPS Signals - ITU Navigation Protected Bands

Navigation Signals in protected bands
- International Telecommunications Union
  - ARNS (aero-nautical band – protected safety of life services)
    - L5 contains DME aircraft transponders
UHD Basic Concepts

Three Frequency GPS Receiver

• Basic civil signal receiver avoiding use of military signals
  – Military code wavelength requires use of IMU to support high dynamics ($\lambda_m=29.3$ m)
  – Military codes are long (1 week) at 10,230 kchips/sec
    – Limited (10dB) benefit against jamming (compared to C/A code)

Processing for fast Time To First Fix (TTFF)

• Direct data download from satellite too slow (30+sec)
  – Typical requirement < 3sec
• Hybrid receiver mode
  – Uses ground Reference Station includes GPS receiver resource
    – Navigation Messages from visible satellites
    – Establishes position estimate and GPS time solution
      – Optionally measure and correct for satellite clock and ephemeris errors (differential mode)
• Solution computed in ground station
  – Options for measurement combinations
UHD Receiver Architecture & Performance Simulation
Main Developments in UHD

Three Frequency GPS Reception
Sustained or Improved TTFF

- Efficient use of hardware architecture to provide >1M acquisition channels
  - Simultaneous frequency and code search algorithm

Multi-channel Tracking for all-in-view Satellites

- Every frequency/signal simultaneously tracked
- Hardware uses high speed multiplex technique
  - Benefits from speed of current FPGA/ASIC switching circuits
    - Reduces circuit area but not power consumption

Tracking Loop Design for Maximum Acceleration Dynamics

- Trades sensitivity for dynamics to limit of GPS capability

Hybrid Receiver Technique to Sustain sub-30 sec TTFF

- Accuracy improvements through DGPS possible
Physical Breadboard

COTS Platform
- 2 FPGA with sufficient capacity
- 2 x Virtex 5 LX220 -2 (Xilinx)
  - Signal conditioning and tracking; signal acquisition
UHD System Architecture

System Architecture

- Separate channels for acquisition and tracking
  - Acquisition requires 100,000’s channels to support short TTFA
  - Tracking requires few physical channels dedicated to visible SV’s (~60 for 5 signals /SV)
    - L1(1); L2(1); L5 (5)
- Signal conditioning
  - Digital transversal filters to set bandwidth (allowing lower sample rates)
  - Received signal samples are stored
    - Acquisition based on analysis of stored data sample (eg 1ms for C/A code; 20ms for L2CM)
      - Acquired signals referenced to common timebase
Dynamic Envelope for Host Vehicle

Stresses the Receiver Measurement Circuits

- Satellite tracking lost if stress too large
- Tracking circuits experience 2 types of stress:
  - Noise - mainly controlled by bandwidth and C/N₀ levels
  - Sources of dynamic stresses:
    - host body - satellite motion resolved along line of sight (LOS) to satellite
- Dynamic stresses arise due to:
  - During signal acquisition
    - transients – imperfect match of estimated code delay and Doppler to actual
  - Un-modeled motion (after acquisition)
    - Tracking architecture holds vehicular motion states (such as position, velocity, etc)
      - Stable states do not contribute to stress
    - Host vehicle states are useful if stable for reasonable intervals
      - Highly dependent on expected host vehicle trajectory
  - Mainly controlled using 3ʳᵈ order tracking loops
    - Model position, velocity, acceleration states
Simulated results for Loop Pull-in Responses

Initial Delay and Velocity Parameters
- Measured during search and acquisition
  - Propagated forward in time to loop closure
  - Delay and velocity errors stimulate transients
    - Example:
      - In linear detector region
      - Non-oscillatory response (direct pull-in)
      - Largest error ~ 0.25 chip (~75m) mainly due to position error
      - Velocity error produces ~0.15 chip response
      - Majority of error is dissipated after 1 sec
  - Loop will pull in from larger errors
    - Loop gain approaches zero at ±0.5 chip
    - Pull-in will not occur for larger errors
  - Noise degrades pull-in limits
Noise Response at Pull-in

Realization of Loop Response

- Results from simulation
  - Combined response of:
    - Noise input
    - 250g acceleration step
    - $\frac{1}{4}$ chip position error
    - 1km/s LOS velocity error
  - Balance between:
    - Noise and dynamic stimuli
  - See approach to critical error (½ sec)
    - $C/N_0 \sim 23$dB (red); 36dB (blue)
      - Identical noise realization in simulation
      - Generated from random number source
Performance Tests and Results
UHD GPS Testing

Verification and Validation Testing Carried Out
- Test cases defined based on User and System requirements
- Performed at QinetiQ and GWEF (Eglin AFB) facilities

Tests with Simulated RF Signals
- Provides repeatability, control, dynamics and truth data - common test scenarios
- QinetiQ: Spirent GSS8800
- GWEF: Spirent GSS7700
- Tested under dynamics
  - acquisition and tracking performance
  - position and velocity accuracy, carrier phase

Tests with Off-air Signals
- L1 (31 satellites), L2C (10 satellites)
  - Combined L1/L2 antenna
- L5 insufficient satellites (2 only so far)
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UHD GPS Headline Achievements

Acquisition and Tracking
• L1 signals, off-Air and simulated
• L2CM/L2CL signals, off-Air and simulated
• L5 signals, simulated – insufficient coverage for off-air testing

All satellites acquired in under 3 seconds in any frequency band

Independent Position solutions generated from L1, L2C, L5 signals
• Uses existing ground segment equipment

Carrier Phase Tracking
• Carrier phase tracking of simulated L1, L2C, L5 signals at >50g Acceleration
  – (Manual) data demodulation and time decoding from L1 carrier tracked off-air signals

Performance detailed on next slides
# UHD GPS Provisional Performance Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Existing JAMI Performance</td>
<td>Current Target</td>
<td>Ultimate Goal</td>
<td>Achieved at End of Program</td>
</tr>
<tr>
<td>Max Acceleration at Satellite Acquisition</td>
<td>50g</td>
<td>600g</td>
<td>1,000g</td>
<td>L1: 800g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L2: 1000g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L5: 100g</td>
</tr>
<tr>
<td>Tracking through Acceleration</td>
<td>50g</td>
<td>600g</td>
<td>1000g</td>
<td>L1: 1000g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L2: 2000g</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L5: 100g</td>
</tr>
<tr>
<td>Maximum (Body) Velocity at Satellite Acquisition</td>
<td>500m/s</td>
<td>3000m/s</td>
<td>5000m/s</td>
<td>L1: 9000m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L2: 11000m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L5: 3000m/s</td>
</tr>
<tr>
<td>Maximum (Body) Velocity Tracking</td>
<td>500m/s</td>
<td>3000m/s</td>
<td>5000m/s</td>
<td>Approx 16000m/s</td>
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<tr>
<td>Position Accuracy</td>
<td>&lt;10m</td>
<td>&lt;10m</td>
<td>&lt;0.3m (with processing)</td>
<td>L1: &lt;5.8m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L2: &lt;6.4m</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>L5: &lt;25m</td>
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<tr>
<td>Velocity Accuracy</td>
<td>1m/s</td>
<td>&lt;1m/s</td>
<td>&lt;0.3/s</td>
<td>L1: &lt;7.9m/s</td>
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<td></td>
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<td></td>
<td></td>
<td>L2: &lt;9.5m/s</td>
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<td></td>
<td></td>
<td></td>
<td>L5: &lt;14.3m/s</td>
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Note: Some performance issues with L5 accuracy to be resolved
## UHD GPS Provisional Performance Results (cont…)

<table>
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<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td></td>
<td>Existing JAMI Performance</td>
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<tr>
<td>Time To First Fix</td>
<td>3.5s</td>
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<tr>
<td>Time to detect last SV (SV32)</td>
<td>7s</td>
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<tr>
<td>Maximum time to acquire all in view</td>
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<tr>
<td>Receiver Type</td>
<td>L1</td>
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<tr>
<td>Receiver Channels</td>
<td>12 channels</td>
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<tr>
<td>Nominal Simultaneous search windows</td>
<td>25,000</td>
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Acknowledgements

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