Assessment of GPS Signal Multipath Interference

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Jan 30, 2002

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GPS Solution Accuracy

- **Baseline Solution**: 1-2 parts in $10^9$
- **Orbit Solution**: a few parts in $10^9$
- **GPS Data Accuracy Limitation**
  - *Instrumental thermal noise*
    - RMS of 10 cm for P-code
    - RMS of 0.1 mm for phase after one second average
  - *Tropospheric effects*
    - cm level
  - *Higher order ionospheric effect*
    - sub cm level under normal condition
  - *"Multipath"*
    - Highly localized phenomenon
    - Can not be removed by differential approach
Multipath Problem

- A signal arrives at an antenna via several paths: reflection and diffraction
- Multipath error is scaled according to wavelength
  - P-code: up to few meters
  - Phase: few centimeters
- Multipath can be a dominant source of error

Previous Work

- Signal Processing Within the GPS Receiver
  - GPS receiver technology
- Multipath Mitigation Performed Outside the Receiver
  - Special Antennas
    - Antenna gain pattern: Low gain near horizontal direction
    - Antenna polarization: RCP and LCP
    - Choke-ring antenna
  - Antenna Arrays
  - Long-term Signal Observation
  - Using Signal-To-Noise Ratio
In the early design phase of an experiment, it would be desirable to predict the environment that can cause severe multipath:

- Modify the structural configuration if possible
- Recommend the best antenna type, location, and orientation within the given configuration

**MUSTARD** has been developed at JPL:

- The simulator traces the signal accounting for all possible paths the signal can take
- Geometrical Theory of Diffraction (GTD) is used to account for reflection and diffraction
- The multipath signals are added to the direct signal
- The receiver's tracking loop is simulated
- Range and phase multipath error are estimated

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The receiver's response to multipath can be parameterized by:

- Signal amplitude, Time delay, Phase, and Phase rate

**Carrier Phase Multipath**

**Code Multipath**

- The received signal is correlated with a locally generated replica of the code
- Receiver computes the correlation function at three different modeled delays: prompt, early, and late
- The early and late delays are different from the prompt delay by a receiver sampling interval $+S$ and $-S$
- The receiver fits an equilateral triangle with base length of two chop period, $2T$, on these three points and declares the location of the peak to be the true delay
The code correlation functions corresponding to the direct, multipath, and the combined signal. $T$ is a chip period, $p$ denotes the time delay of multipath, and $q$ denotes the multipath induced range error.

**Code Multipath**

- **Wide Sampling Interval: $S > T/2$**
  - Region 1: $\Delta \tau_1 < T - S + \Delta \tau$  
  - Region 2: $T - S + \Delta \tau < \Delta \tau_2 < S + \Delta \tau$  
  - Region 3: $S + \Delta \tau < \Delta \tau_3 < T + S + \Delta \tau$  
  - Region 4: $\Delta \tau > T + S$
- **Narrow Sampling Interval: $S < T/2$**
  - Region 1: $\Delta \tau_1 < S + \Delta \tau$  
  - Region 2: $S + \Delta \tau < \Delta \tau_2 < S + \Delta \tau$  
  - Region 3: $T - S + \Delta \tau < \Delta \tau_3 < T + S$  
  - Region 4: $\Delta \tau > T + S$
- Upper Envelope: multipath error is in phase  
- Lower Envelope: multipath error is out of phase  
- The asymmetry of the envelope is amplified for higher values of $A/A$.
**P1 Code Tracking Error (Wide)**

- P1 code error due to single multipath source
  - $S > T/2$
  - $A1/A = 0.1$
  - $T = 98\, \text{ns}$
  - $S = 60\, \text{ns}$

**P1 Code Tracking Error (Narrow)**

- P1 code error due to single multipath source
  - $S < T/2$
  - $A1/A = 0.1$
  - $T = 98\, \text{ns}$
  - $S = 48\, \text{ns}$
C/A Code Tracking Error (Narrow)

- C/A code error due to single multipath source
  - $S < T/2$
  - $A1/A = 0.5$
  - $T = 980\text{ns}$
  - $S = 48\text{ns}$

Multipath Induced Bias

- Region 1 of P1 code tracking error
- Asymmetric and biased oscillation due to carrier
  - $A1/A = 0.5$
  - $T = 98\text{ns}$
  - $S = 48\text{ns}$
**Simulator Description**

- **Multipath Simulator, MUSTARD (MUltipath Simulator Taking into Account of Reflection and Diffraction)**, had been developed at JPL
- **GPS Signals:**
  - RCP and LCP signals at L1 and L2 frequencies
  - Pseudorange and phase
- **Reflection Modeling:**
  - Geometrical Theory of Diffraction (GTD)
  - Signal reflection and diffraction from surfaces, edges, and corners

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**Simulator Description (Cont’d)**

- **Antenna and Receiver:**
  - Simulates the antenna gain pattern (RCP,LCP for L1,L2)
  - Simulates receiver's operations on incoming signals
- **Surrounding Environment Modeling:**
  - Simplified model of the real environment is used
  - Flat surfaces of arbitrary shape
  - Spheres or sections of spheres
  - Cylinders or sections of cylinders
  - Conducting or dielectric surfaces
- **Geometry:**
  - Models the motion of the GPS transmitter and receivers and their attitudes (generates time series of the multipath error)
Reflection from a Flat Surface

- T: transmitter
- R: receiver
- V: defined point on the surface
- n: unit vector normal to the surface
- S: point of reflection
- Once S is determined, check whether it lies inside or outside of the finite surface

Gain Pattern of a D-M Antenna

- Partial multipath rejection
- Antenna gain pattern
- Polarization
Application of MUSTARD

- PARCS (Primary Atomic Reference Clock in Space)
- Demonstrating atomic clock performance in space
- The micro-gravity environment of space allows significant improvements in clock performance
- Carried out on the International Space Station (ISS)
- GPS measurement is used for the ISS orbit determination
- GPS antenna will be located at the Japanese Experiment Module (JEM) where the multipath interference is severe
Environmental Modeling of JEM

- Three major multipath sources
- D-M antenna gain pattern
- Azimuth symmetry
- Antenna location
  - At the center of EF
  - One meter above the surface
- Assume the receiver tracks all visible GPS satellites

Number of Visible GPS from the ISS Receiver

All GPS up to 0 deg elevation

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P-Code Multipath Errors from EF (cont'd)

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P-Code Multipath Errors from ELM-ES

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P-Code Multipath Errors from PM

All L. CES. Propagating modes (Reflection & Diffraction)

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P-Code Multipath Errors from All Surfaces

All CES. All Surfaces (Reflection & Diffraction)

- Unit (m)
- P1: 0.22
- P2: 0.30
- PC: 0.71

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Phase Multipath Errors from All Surfaces

- Unit (cm)
  - L1: 0.31
  - L2: 0.50
  - LC: 0.87

Optimal Location of the Antenna

<table>
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<th>Height (m)</th>
<th>PC (m)</th>
<th>LC (m)</th>
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<tr>
<td>0.2</td>
<td>0.7970</td>
<td>0.0108</td>
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<tr>
<td>1</td>
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<td>0.0087</td>
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<tr>
<td>2</td>
<td>0.7139</td>
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<td>4</td>
<td>0.6759</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

- When changing the surrounding environment is not an option, find the best antenna location
- For demonstration purpose, no extensive search for the best antenna location was performed
- The antenna location was fixed at the center of EF, but its height was adjusted
- It is possible that better results could be obtained with a more easily accommodated flushing mounted antenna using a more favorably shaped antenna gain pattern
Conclusion

- It is possible to investigate the multipath effect on the GPS signal by using a multipath simulator: MUSTARD has been developed at JPL.

- The multipath simulator is useful in the initial design phase of an experiment:
  - Identify environmental configurations that can cause severe multipath
  - Assess the upper limits on the antenna backlobe gains
  - Determine the ideal antenna location, height, and orientation within a given environment

Conclusion (cont’d)

- Once the optimal geometric configuration is determined, MUSTARD can provide a realistic and quantitative estimate of multipath errors on GPS data.

- This can provide a means of testing different ways of analyzing the data to reduce the solution errors from multipath.