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Assessment of GPS Signal Multipath Interference

Sung H. Byun
George A. Hajj
Lawrence E. Young

Jet Propulsion Laboratory
California Institute of Technology

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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

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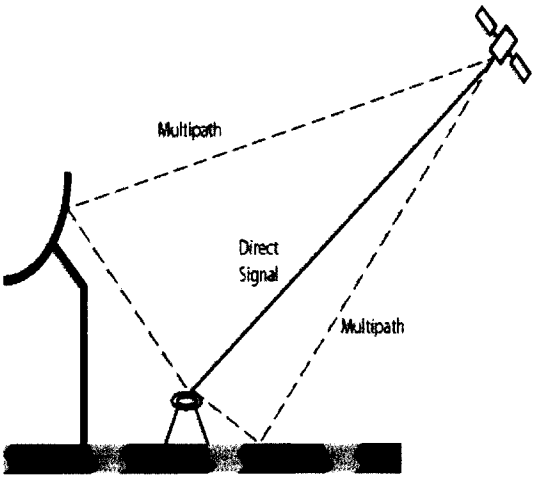
Multipath Problem



- **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**

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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**

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Multipath Simulator

- In the early design phase of an experiment, it would be desirable to predict 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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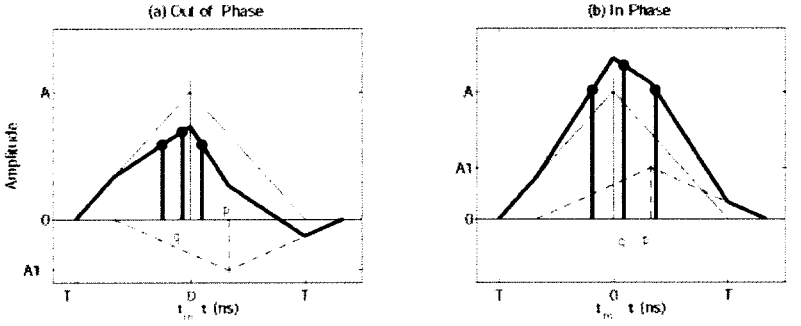
Multipath Effect on GPS Signals

- 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 a 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

Multipath Induced Delay

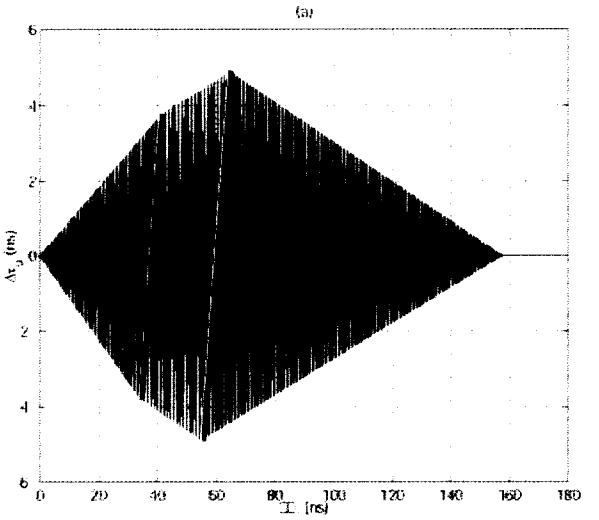


- The code correlation functions corresponding to the direct, multipath, and the combined signal. T is a chip period, p denotes the time delay of multipath, and q denotes the multipath induced range error.

Code Multipath

- **Wide Sampling Interval: S > T/2**
  - **Region 1:** $\Delta\tau_1 < T - S + \Delta\tau^g$
  - **Region 2:** $T - S + \Delta\tau^g < \Delta\tau_1 < S + \Delta\tau^g$
  - **Region 3:** $S + \Delta\tau^g < \Delta\tau_1 < T + S + \Delta\tau^g$
  - **Region 4:** $\Delta\tau_1 > T + S$
- **Narrow Sampling Interval: S < T/2**
  - **Region 1:** $\Delta\tau_1 < S + \Delta\tau^g$
  - **Region 2:** $S + \Delta\tau^g < \Delta\tau_1 < S + \Delta\tau^g$
  - **Region 3:** $T - S + \Delta\tau^g < \Delta\tau_1 < T + S$
  - **Region 4:** $\Delta\tau_1 > T + S$
- **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 A1/A**

P1 Code Tracking Error (Wide)



- *P1 code error due to single multipath source*
- *S > T/2*
- *A1/A = 0.1*
- *T = 98 ns*
- *S = 60 ns*

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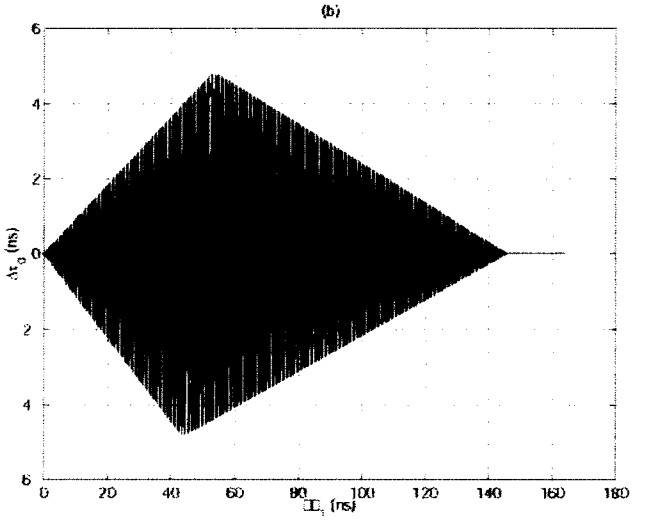
P1 Code Tracking Error (Narrow)



- *P1 code error due to single multipath source*
- *S<T/2*
- *A1/A=0.1*
- *T=98ns*
- *S=48ns*

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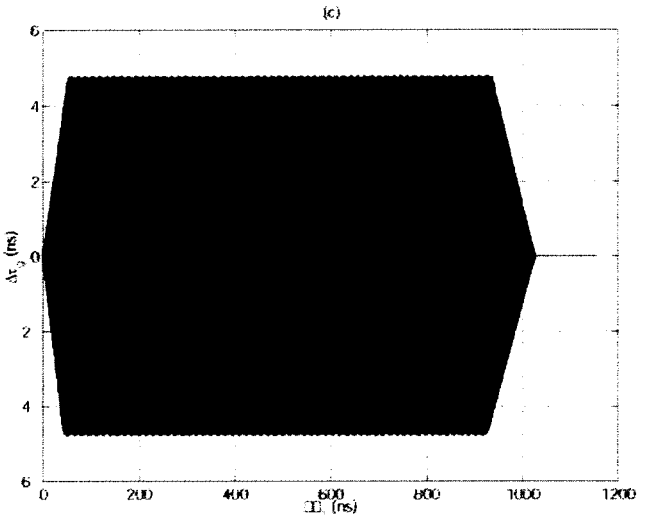
C/A Code Tracking Error (Narrow)



- *C/A code error due to single multipath source*
- *S<T/2*
- *A1/A=0.5*
- *T=980ns*
- *S=48ns*

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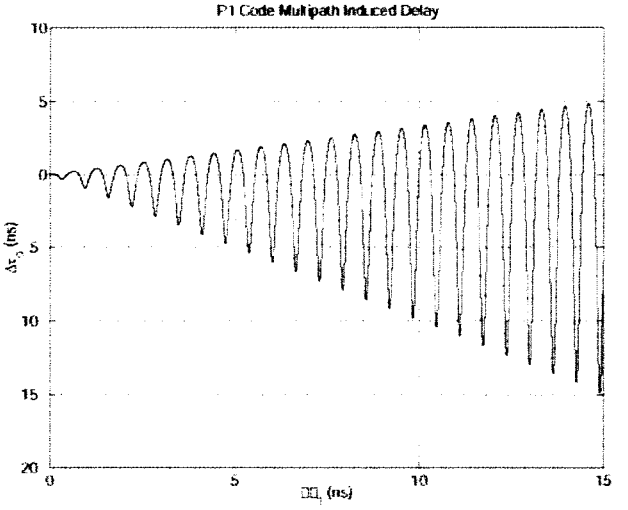
Multipath Induced Bias



- *Region 1 of P1 code tracking error*
- *Asymmetric and biased oscillation due to carrier*
- *A1/A=0.5*
- *T=98ns*
- *S=48ns*

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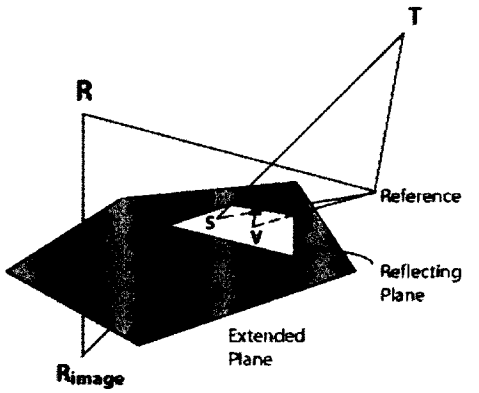
Simulator Description

- **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**

Simulator Description (Cont'd)

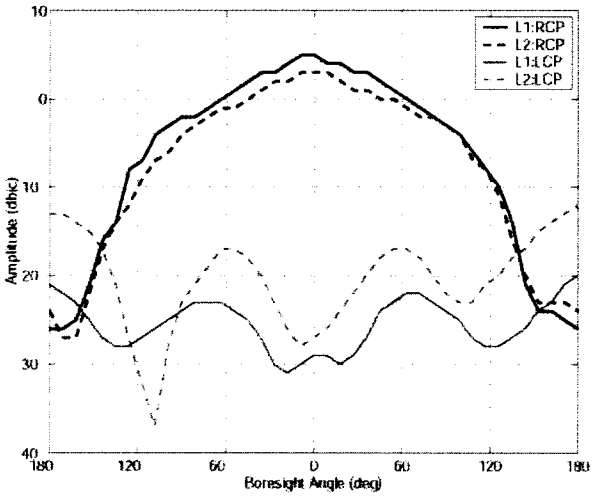
- **Antenna and Receiver:**
  - **Simulates the antenna gain pattern (RCP,LCP for L1,L2)**
  - **Simulates receiver's operations on incoming signals**
- **Surrounding Environment Modeling:**
  - **Simplified model of the real environment is used**
  - **Flat surfaces of arbitrary shape**
  - **Spheres 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

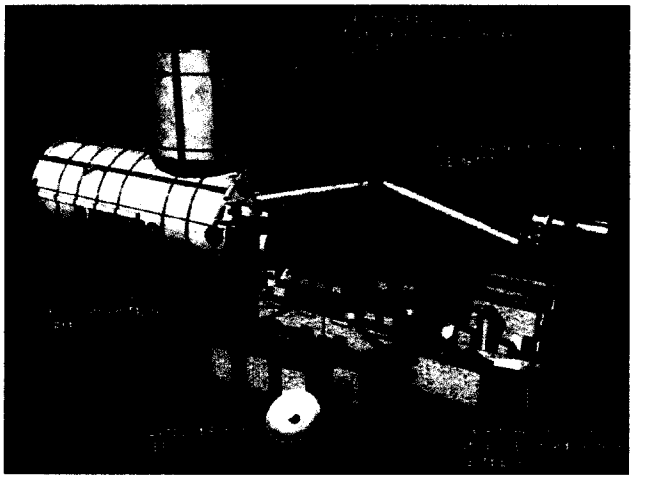


- **Partial multipath rejection**
- **Antenna gain pattern**
- **Polarization**

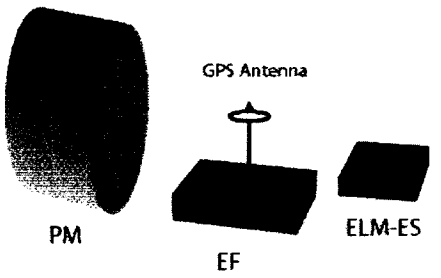
Application of MUSTARD

- 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

Japanese Experiment Module (JEM)



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*

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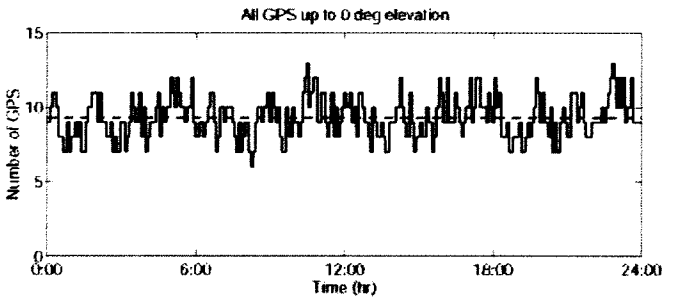
Number of Visible GPS from the ISS Receiver



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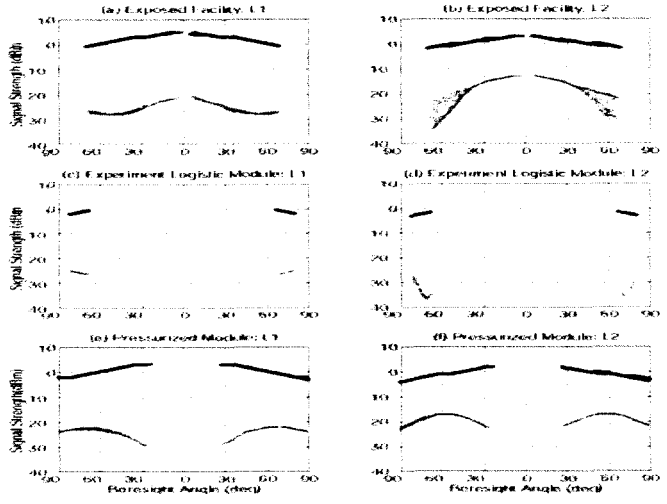
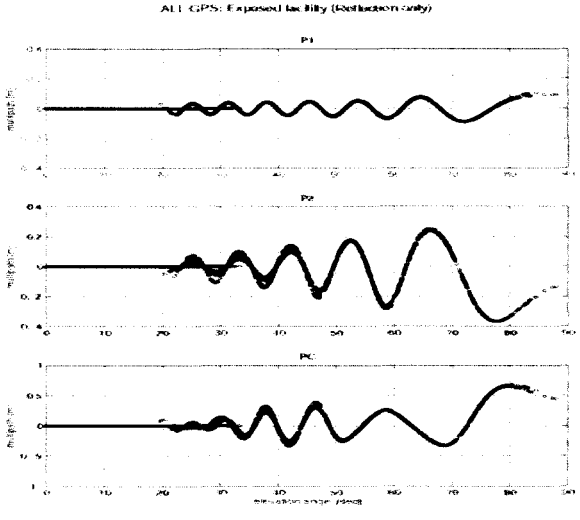
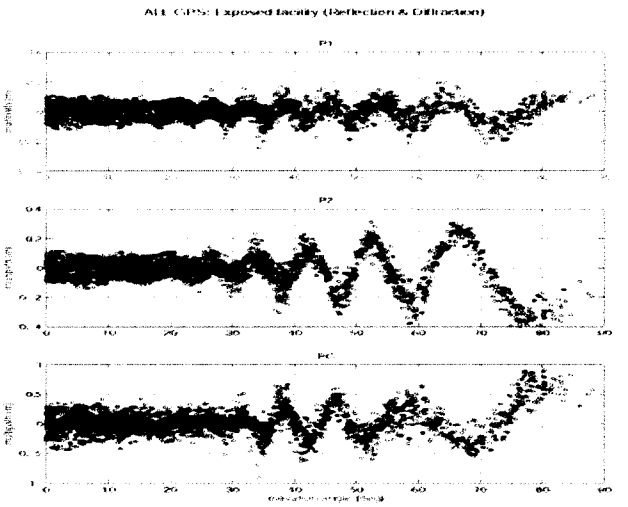
Direct vs. Specular Reflected Signal



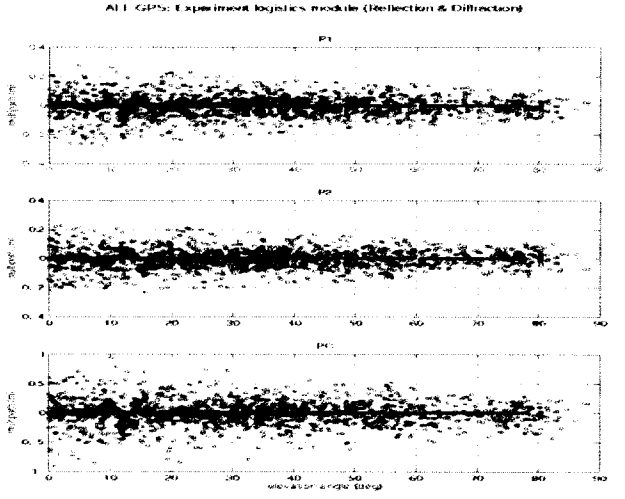
P-Code Multipath Errors from EF



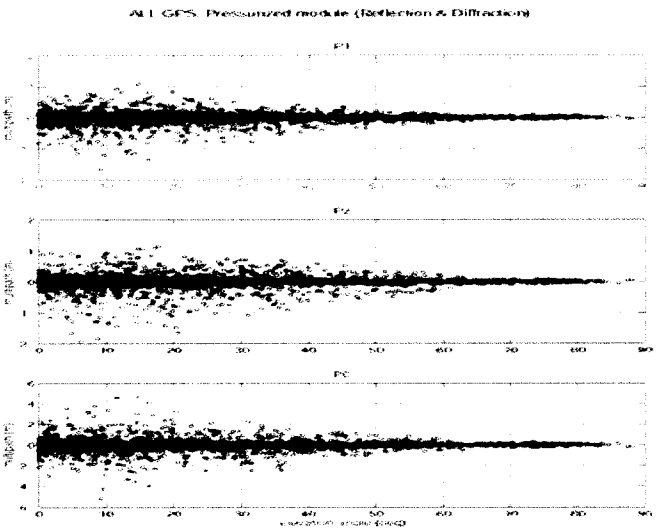
P-Code Multipath Errors from EF (cont'd)



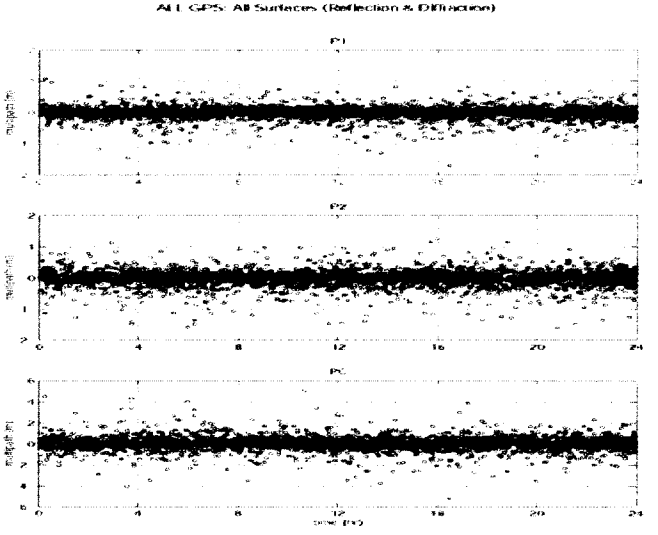
P-Code Multipath Errors from ELM-ES



P-Code Multipath Errors from PM

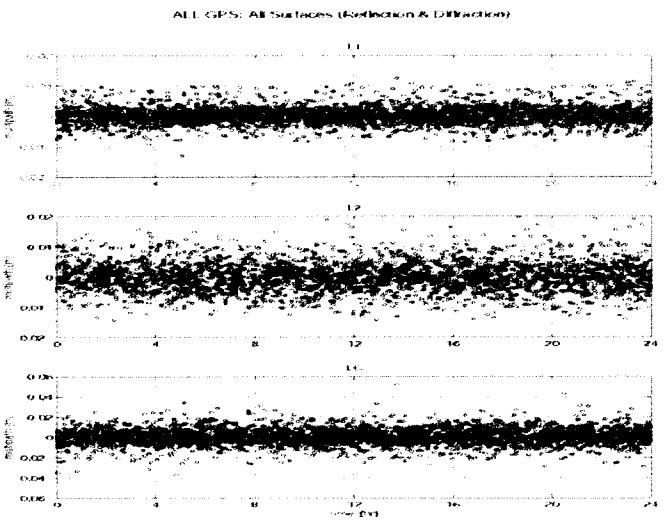


P-Code Multipath Errors from All Surfaces



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

Phase Multipath Errors from All Surfaces



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

Optimal Location of the Antenna

Height	PC (m)	LC (m)
0.2m	0.7970	0.0108
1m	0.7137	0.0087
2m	0.7139	0.0077
3m	0.7066	0.0070
4m	0.6759	0.0067

- 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