Characterization of GPS Carrier Phase Multipath and Mitigation through the use of Multiple Antennas

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WHY IS CARRIER PHASE MULTIPATH IMPORTANT?

- It is not reduced through differential processing (highly localized)
- It can reach magnitudes of 0.25 of a wavelength
- It generally causes a systematic error in the measurements
- It can affect the accuracy of positioning and attitude determination
- It can significantly affect the ability to resolve integer ambiguities

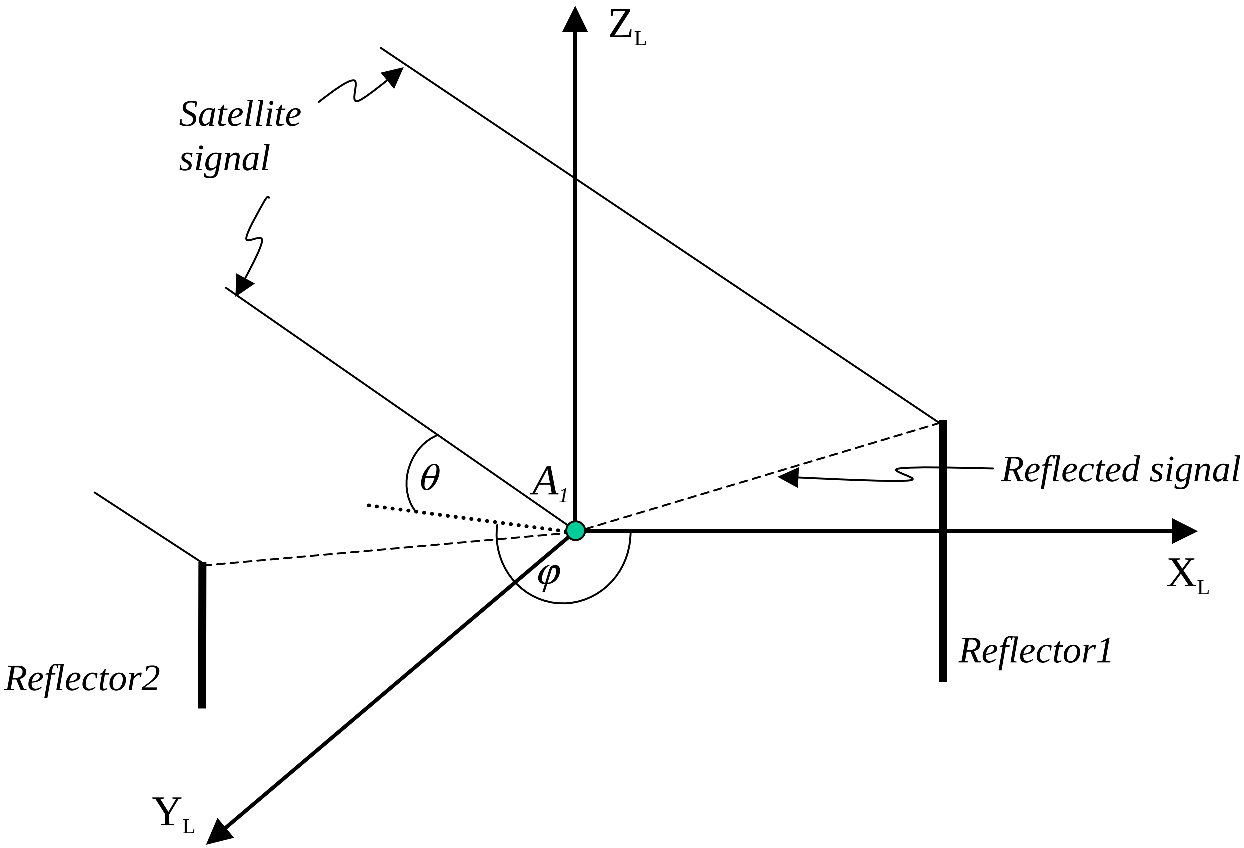
OUTLINE

- Objective
- Multipath parameters
- Multipath from antenna-reflector geometry
- Simulation description
- Simulation results
- Multipath mitigation through multi-antennas

OBJECTIVES OF CARRIER PHASE MULTIPATH CHARACTERIZATION

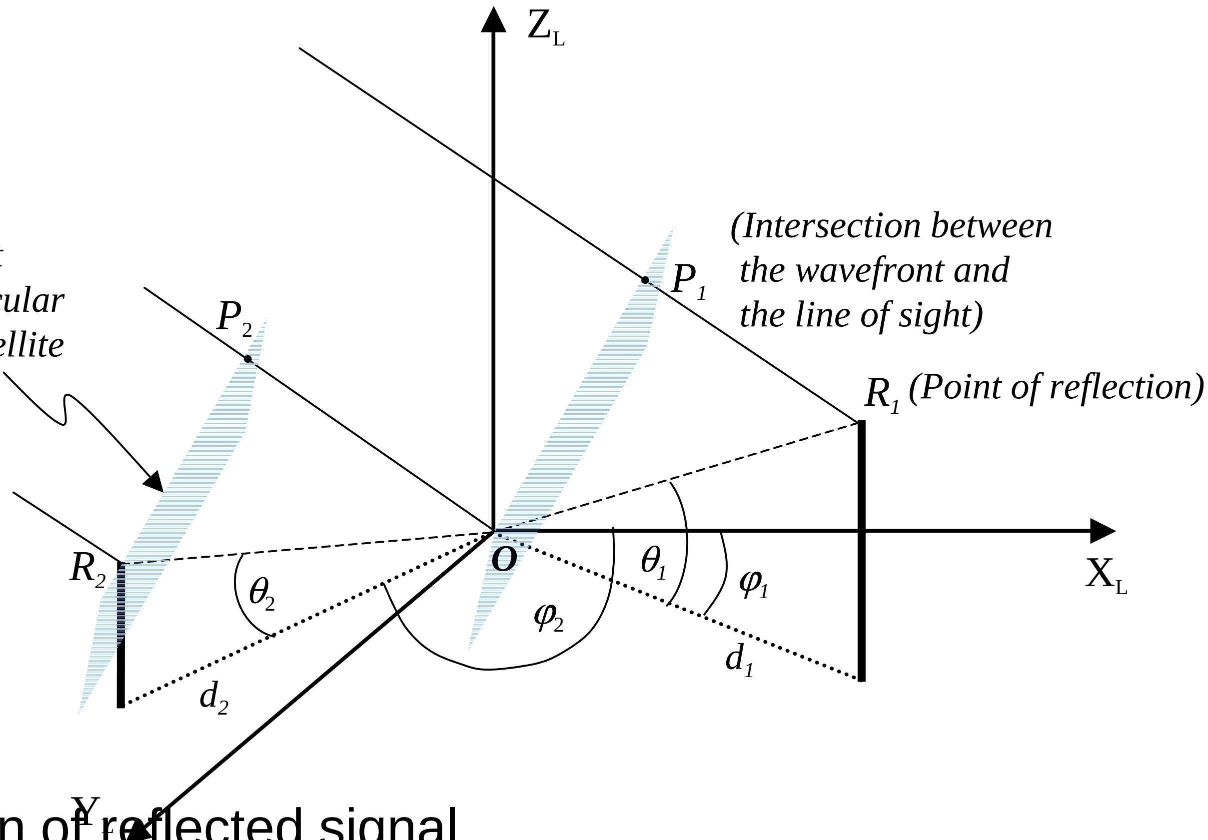
- Relate carrier phase multipath
  - amplitude, phase, phase rate
- With
  - antenna-reflector geometry
  - satellite dynamics
  - signal frequency
  - SNR
- In a
  - multi-antenna system
  - multi-reflector environment
- Using
  - mathematical models
  - simulation models
- Mitigate
  - Using multiple antennas

MULTIPATH FROM GEOMETRY (1/3)



- θ : elevation of direct signal
- φ : azimuth of direct signal

MULTIPATH FROM GEOMETRY (2/3)



- θ_k : elevation of reflected signal
- φ_k : azimuth of reflected signal
- d_k : distance between antenna and reflector in the horizontal plane
- path delay : $P_1R_1+R_1O$ (case 1) and R_2O-P_2O (case 2)

MULTIPATH FROM GEOMETRY (3/3)

- Differential path delay

$$a_k = c * \tau_k = d_k \left(\frac{1}{\cos\theta_k} - \tan\theta_k \sin\theta - \cos\theta \cos(\varphi - \varphi_k) \right)$$

  - c is the velocity of light

- Reflected signal relative phase

$$\gamma_k = \frac{2\pi a_k}{\lambda_L}$$

- Path delay, phase and phase rate depend upon
  - antenna-reflector distance
  - antenna-reflector geometry
  - satellite line-of-sight
  - signal wavelength

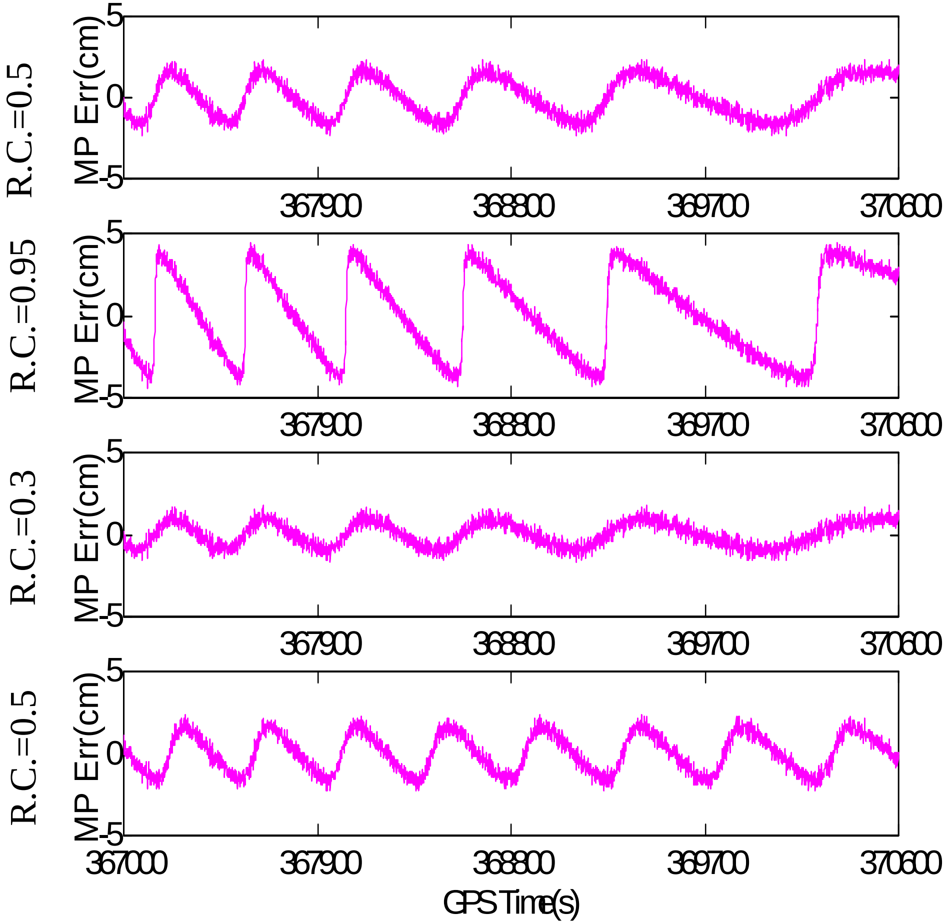
MULTIPATH SIMULATION SOFTWARE

- Carrier phase multipath simulation and mitigation
- Inputs
  - reflector parameters
  - antenna parameters
- Outputs
  - true carrier phase
  - measured carrier phase
  - estimated carrier phase

- Multi-antenna configuration
- Multi-reflector environment
- Satellite trajectory from stored ephemeris

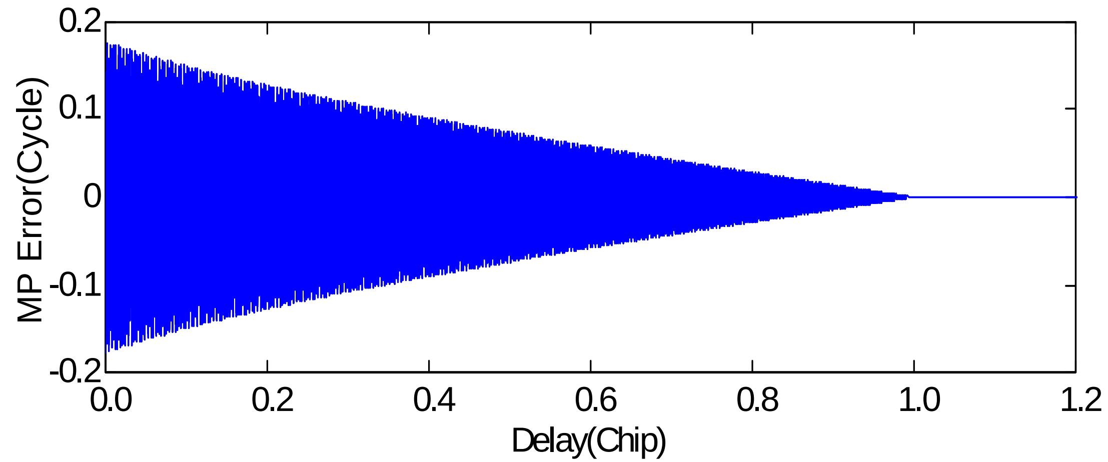
MULTIPATH VS. REFLECTION COEFFICIENT

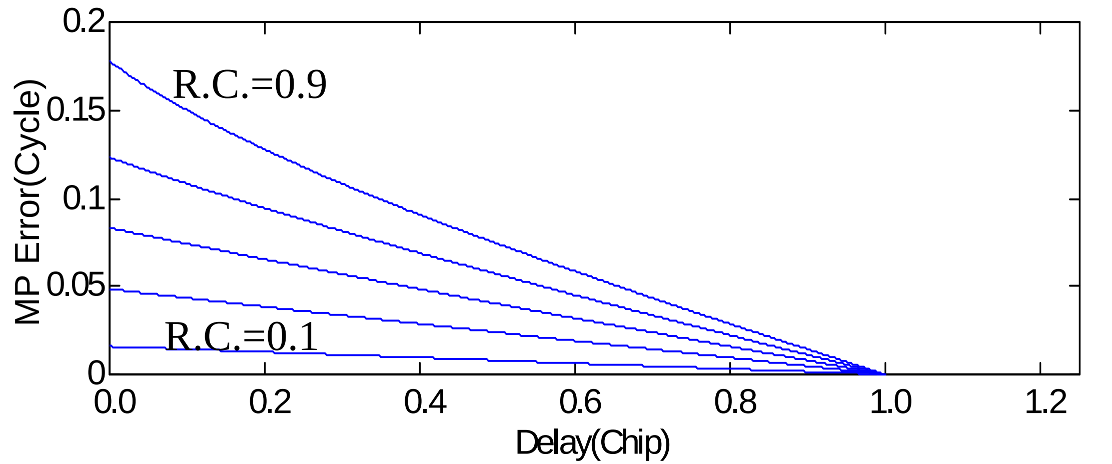
- Reflection Coefficient (R.C.): 0.5, 0.95, 0.3 and 0.5
- Antenna-reflector distance = 5m
- In the last case reflector location altered
- Error sinusoidal for low R.C.
- Error inverted sawtooth for high R.C.
- Highly dependent on antenna-reflector geometry



MULTIPATH VS. DISTANCE

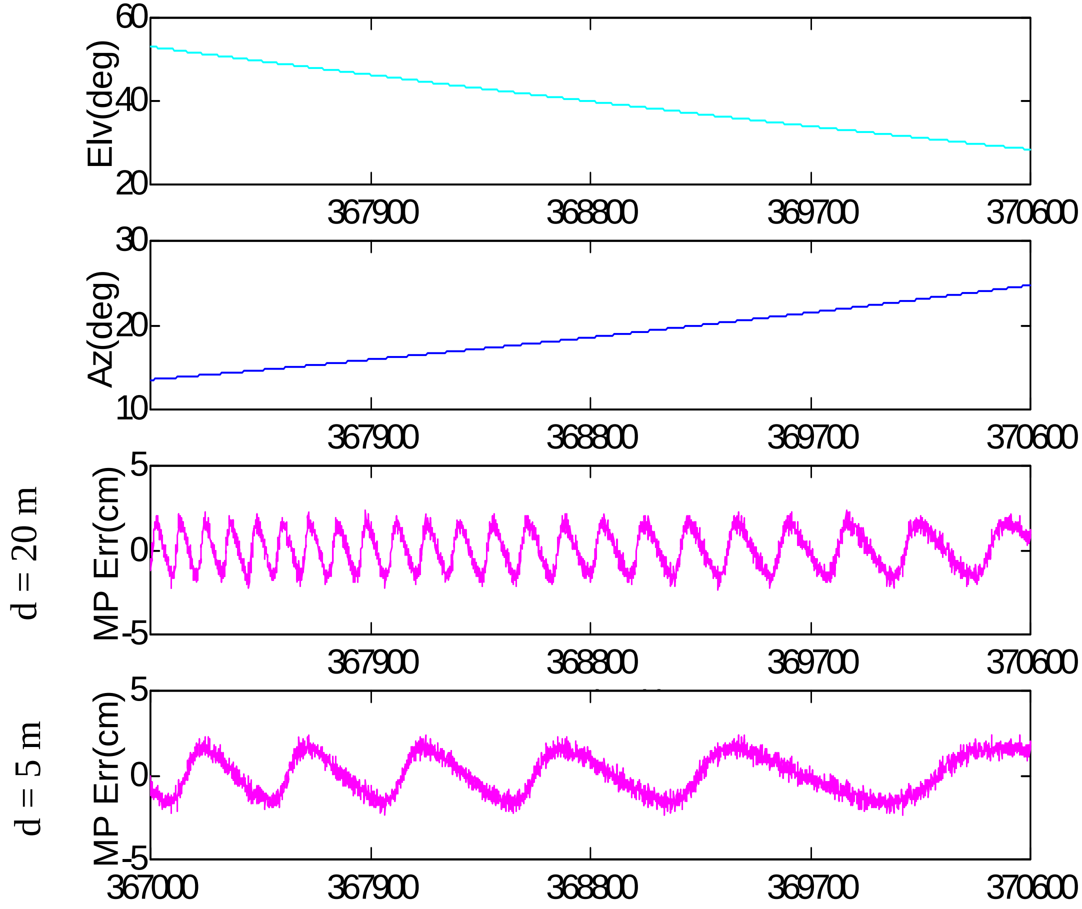
- Amplitude inversely proportional to distance
- Zero mean
- Envelope size proportional to R.C.
- Affected by path delay up to one chip





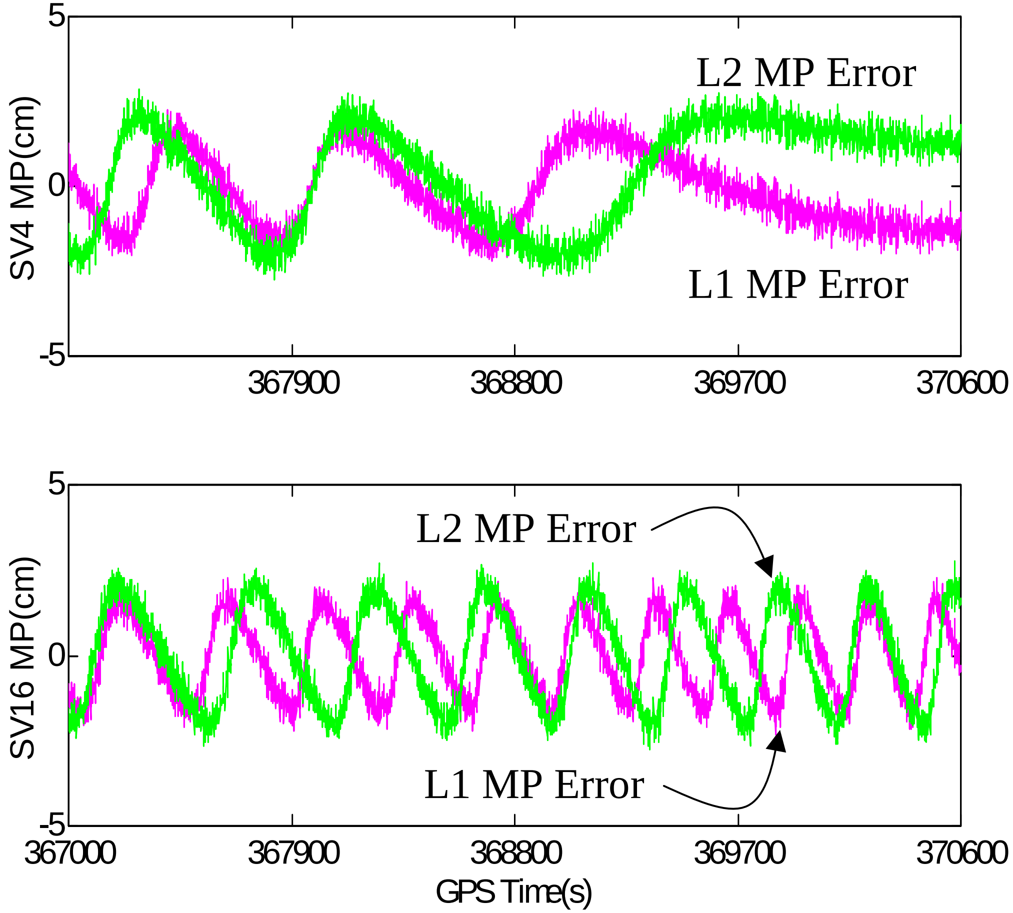
MULTIPATH VS. SATELLITE DYNAMICS

- Reflector at 20 m and 5 m from the antenna
- Change in multipath due to satellite dynamics only
- Typical for stationary user



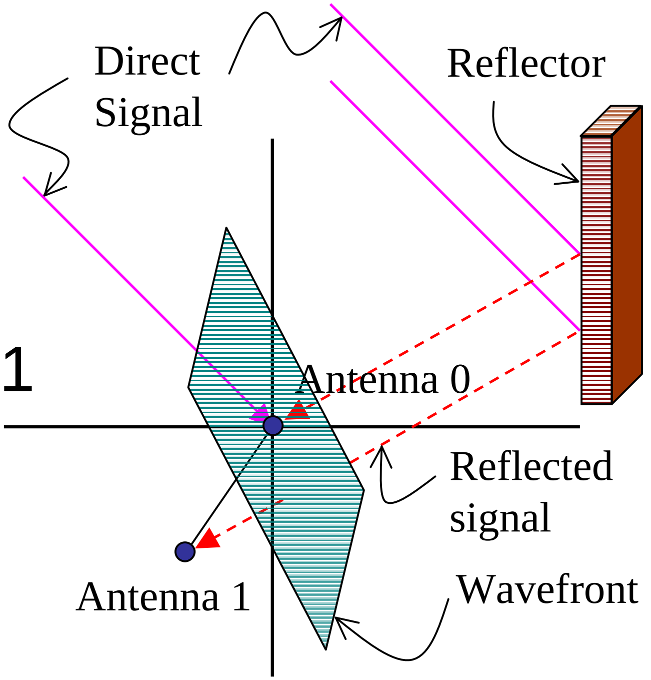
MULTIPATH VS. SIGNAL FREQUENCY

- Errors in L1 and L2 carrier due to multiple reflectors for satellites 4 and 16
- L1 multipath has higher frequency
- L1 and L2 have the same phase error amplitude
- Highly dependent on antenna-reflector and line-of-sight vectors



MULTIPATH SPATIAL CORRELATION (1/2)

- Multipath phase at an antenna is related to the phase in a close-by antenna by
  - their relative geometry
  - direction of the multipath signal



- For example, phase at Antenna 1

$$\gamma_1 = \gamma_0 + \frac{2\pi}{\lambda} \frac{a_{01}\cos(\varphi_1 - \phi_{01})}{\cos\theta_1}$$

where

γ_0 is multipath phase at Antenna 0

a_{01} is distance between 0 and 1

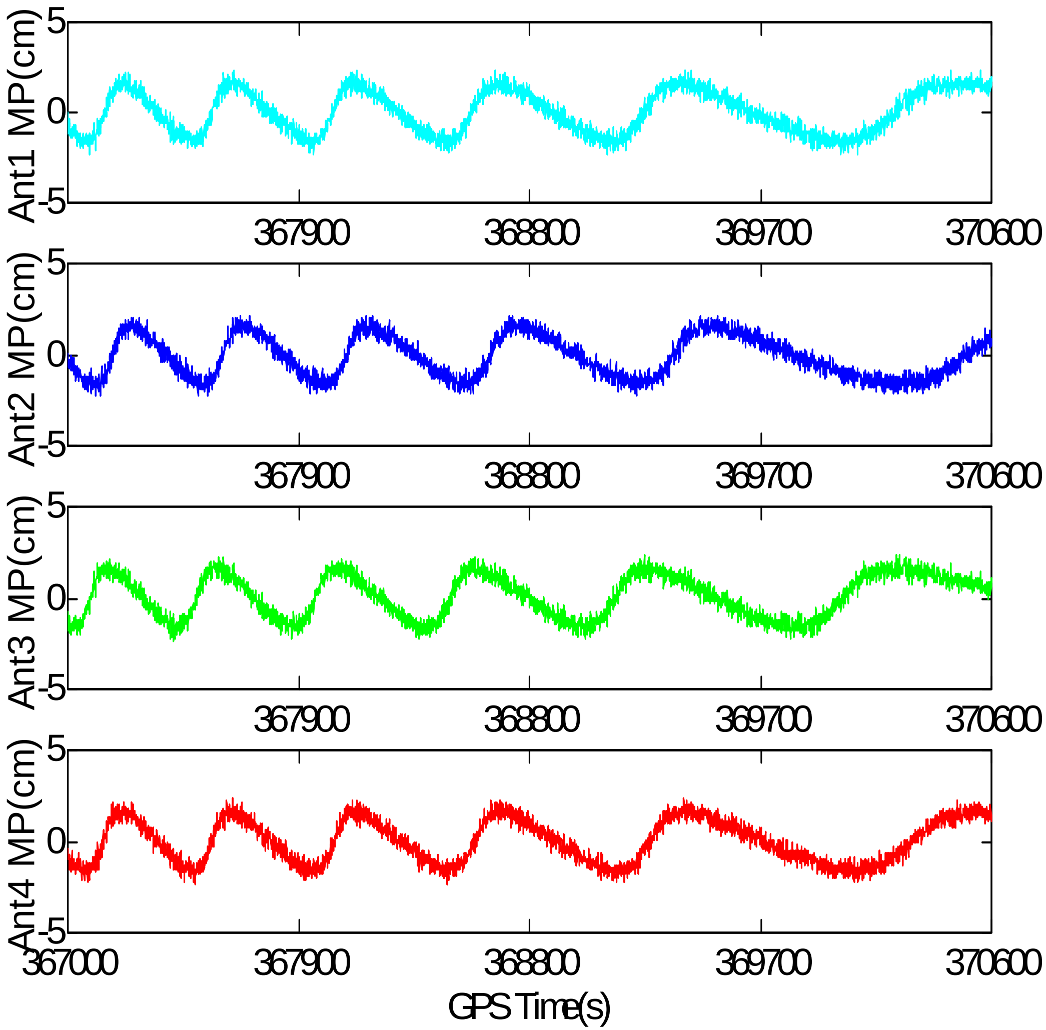
φ_1 is azimuth of multipath signal

ϕ_{01} is azimuth of vector 0-1 and

θ_1 is elevation of multipath signal

MULTIPATH SPATIAL CORRELATION (2/2)

- Antennas 5 to 10 cm away from each other
- Reflector distance approximately 5 m
- Spatially correlated
- Spatial correlation may be used for mitigation
- Larger size reflector causes higher correlation



MULTIPATH PHASE RATE (1/2)

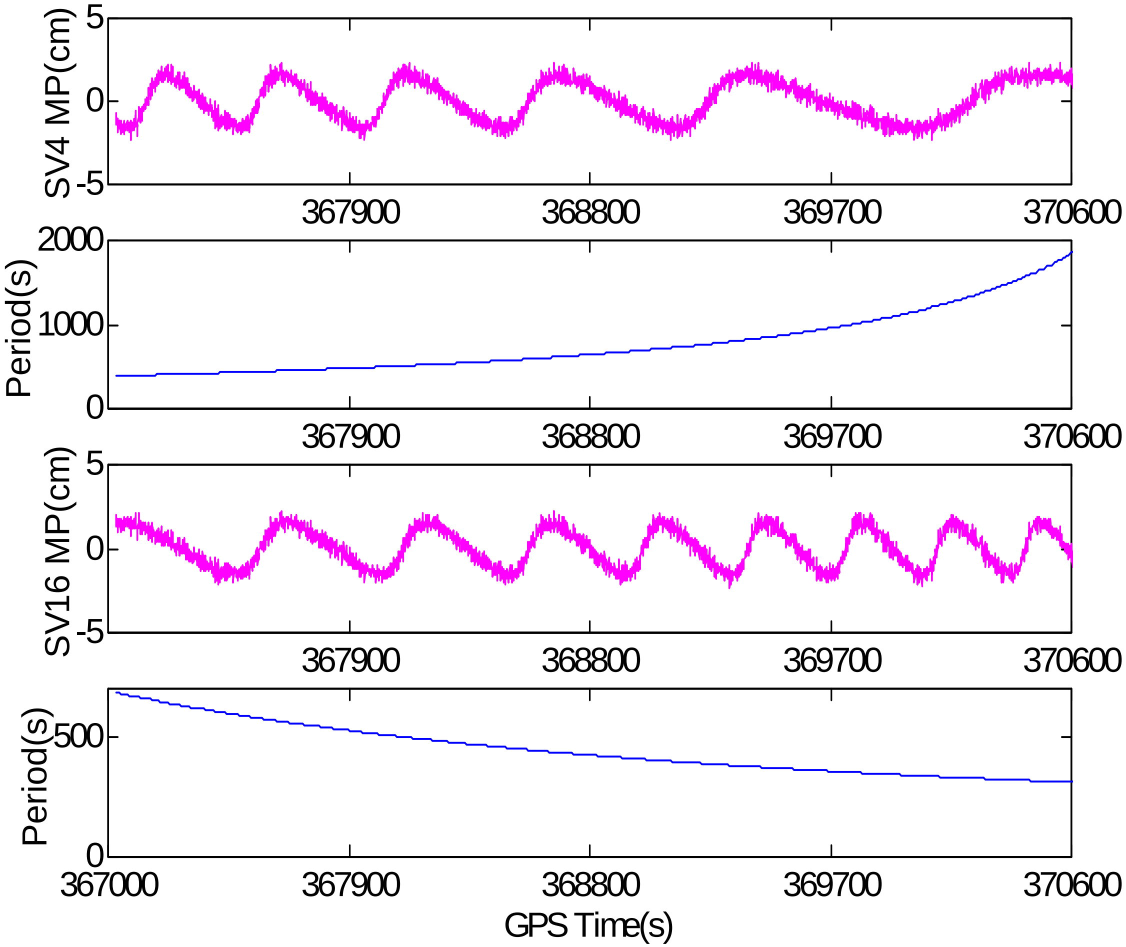
- Multipath phase rate:

$$\frac{\delta\gamma}{\delta t} = \frac{2\pi d_1}{\lambda_L}\left(\begin{array}{l} \{\sin(\theta)\cos(\varphi-\varphi_1) - \cos(\theta)\tan(\theta_1)\}\frac{\delta\theta}{\delta t} \\ + \{\cos(\theta)\sin(\varphi-\varphi_1)\}\frac{\delta\varphi}{\delta t} \end{array} \right)$$

  - directly proportional to the antenna-reflector distance
  - inversely proportional to the carrier wavelength
  - directly proportional to the satellite elevation rate
  - directly proportional to the satellite azimuth rate
  - dependent upon antenna-reflector vector
  - dependent upon line-of-sight vector

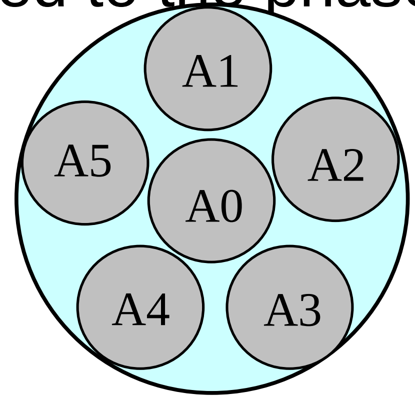
MULTIPATH PHASE RATE (2/2)

- Multipath error for satellites 4 and 16 and their estimated periods
- Phase rate estimated from antenna-reflector geometry



MULTIPATH MITIGATION TECHNIQUE (1/4)

- A virtual reflector with time varying parameters is equivalent to all the reflectors in the system
- If normalized reflection coefficient and multipath phase of the virtual reflector are estimated, total multipath error can be computed
- Normalized reflection coefficient is almost the same for all antennas in a closely-spaced antenna assembly
- Multipath phase at an antenna is related to the phase at another antenna by
  - their relative geometry
  - direction of the multipath signal



MULTIPATH MITIGATION TECHNIQUE (2/4)

- For example, phase at Antenna 1

$$\gamma_1 = \gamma_0 + \frac{2\pi}{\lambda} \frac{a_{01}\cos(\varphi_0 - \phi_{01})}{\cos\theta_0}$$

where

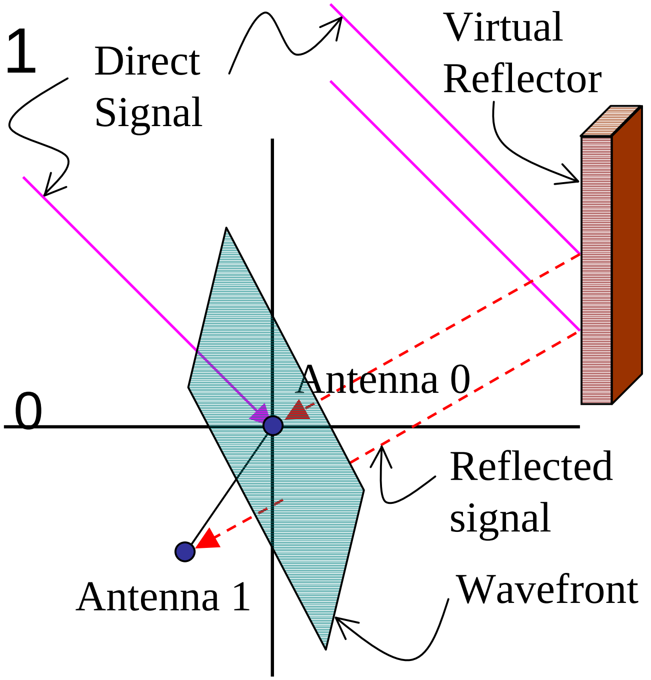
γ_0 is multipath phase at Antenna 0

a_{01} is distance between 0 and 1

φ_0 is azimuth of multipath signal

ϕ_{01} is azimuth of vector 0-1 and

θ_0 is elevation of multipath signal



MULTIPATH MITIGATION TECHNIQUE (3/4)

- A Kalman filter can be developed to estimate the multipath signal parameters at the reference antenna (generally the center antenna in the assembly)
- State vector:

$$\begin{bmatrix} \alpha \\ \gamma_0 \\ \theta_0 \\ \varphi_0 \end{bmatrix} = \begin{bmatrix} \text{Reflection coefficient} \\ \text{Multipath signal phase} \\ \text{Multipath signal elevation} \\ \text{Multipath signal azimuth} \end{bmatrix}$$

- Though the parameters are for a single multipath signal, the filter estimates the composite multipath due to all reflectors in the environment

MULTIPATH MITIGATION TECHNIQUE (4/4)

- Single difference carrier phase between closely-spaced antennas (6-7cm apart):

$$\Delta\Psi_{0,i} = \Delta\rho_{0,i} + \Delta N_{0,i}\lambda + c\Delta t_{0,i} + \varepsilon_{\varphi 0,i} + \varepsilon_{MP0,i}$$

- In this,
  - range difference due to spatial separation ($\Delta\rho$) can be removed
  - phase due to carrier cycle ambiguity ($\Delta N\lambda$) can be removed
  - clock bias error ($c\Delta t$) negligible if driven by a common clock

- The resultant residual contains difference of multipath (ε_{MP}) and carrier phase noise (ε_{φ})
- Measurement vector consists of single difference carrier phase residual $\left[\Delta\Psi_{0,1},\ldots\ldots\Delta\Psi_{0,m-1}\right]^T$

FIELD TEST DESCRIPTION

- A special antenna array was assembled with six antennas mounted close together (aprox. 6 cm apart) on an aluminum plate
- Three NovAtel BeeLine™ receivers were used for data collection. The BeeLine™ is an 8+8 channel (L1-L1) receiver
- All receivers were driven by a common clock
- Data was collected for several sessions on the roof of the Engineering building at the University of Calgary

ANTENNA ASSEMBLY

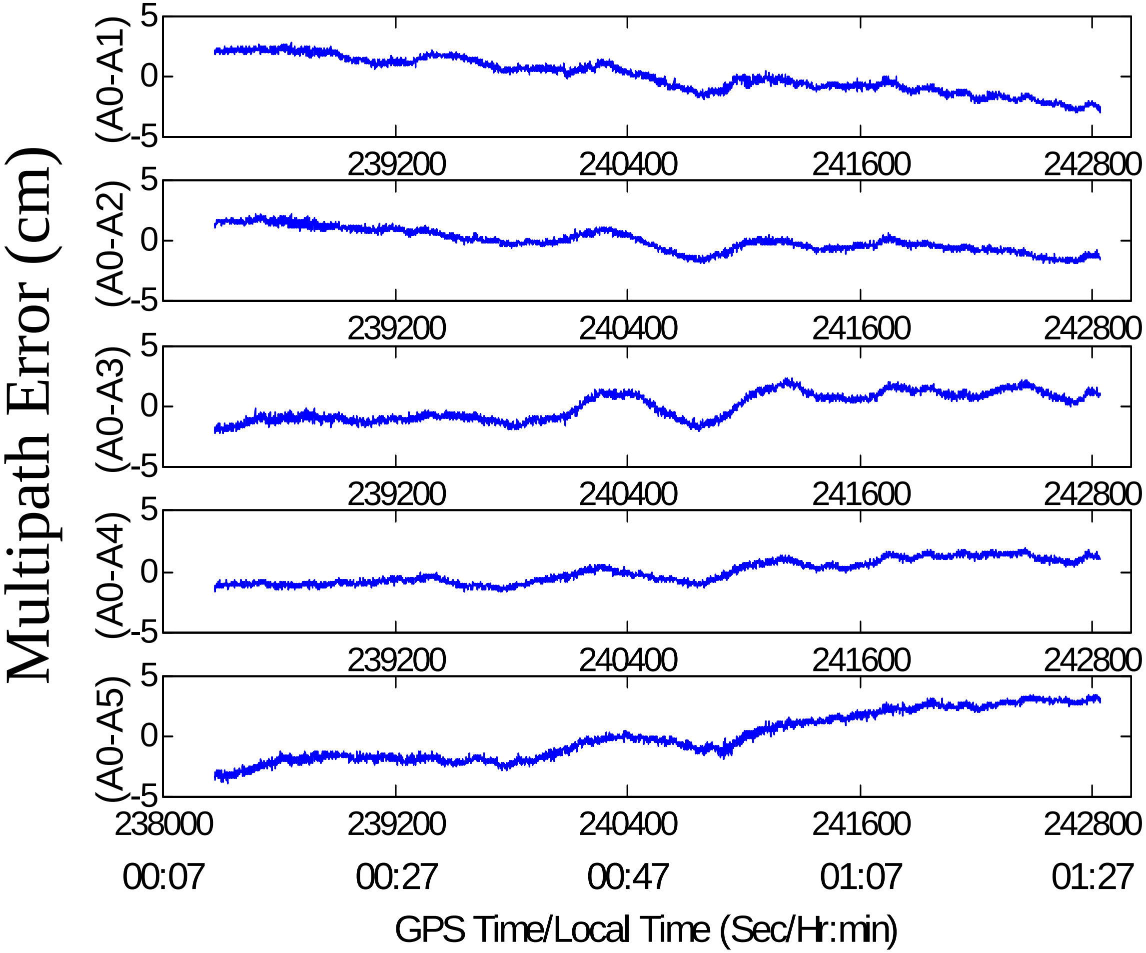
TEST SET-UP: PART 1

TEST PROCEDURE

- Establish the relative geometry of the antennas in the array
- Form single difference carrier phase residuals and input to the filter
- Estimate parameters of the virtual reflector by the filter
- Compute multipath error at each antenna due to virtual reflector and remove it from measurement
- Form single difference carrier phase residuals with corrected measurements
- Compute RMS values of single difference carrier phase residuals before and after multipath correction

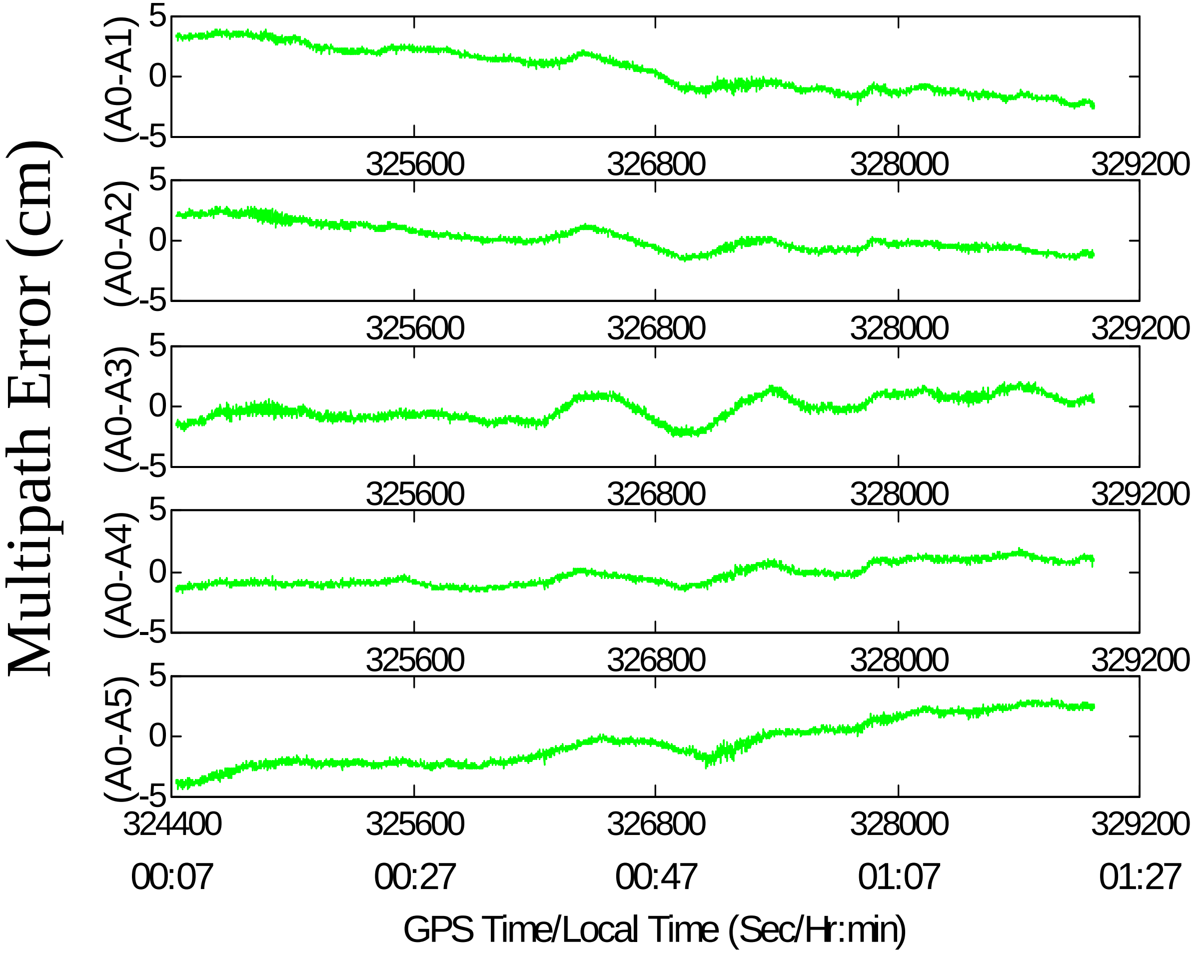
SINGLE DIFFERENCE FOR SV 21
No Multipath Correction

- Data from August 25, 1998 (RMS = 1.3 cm)



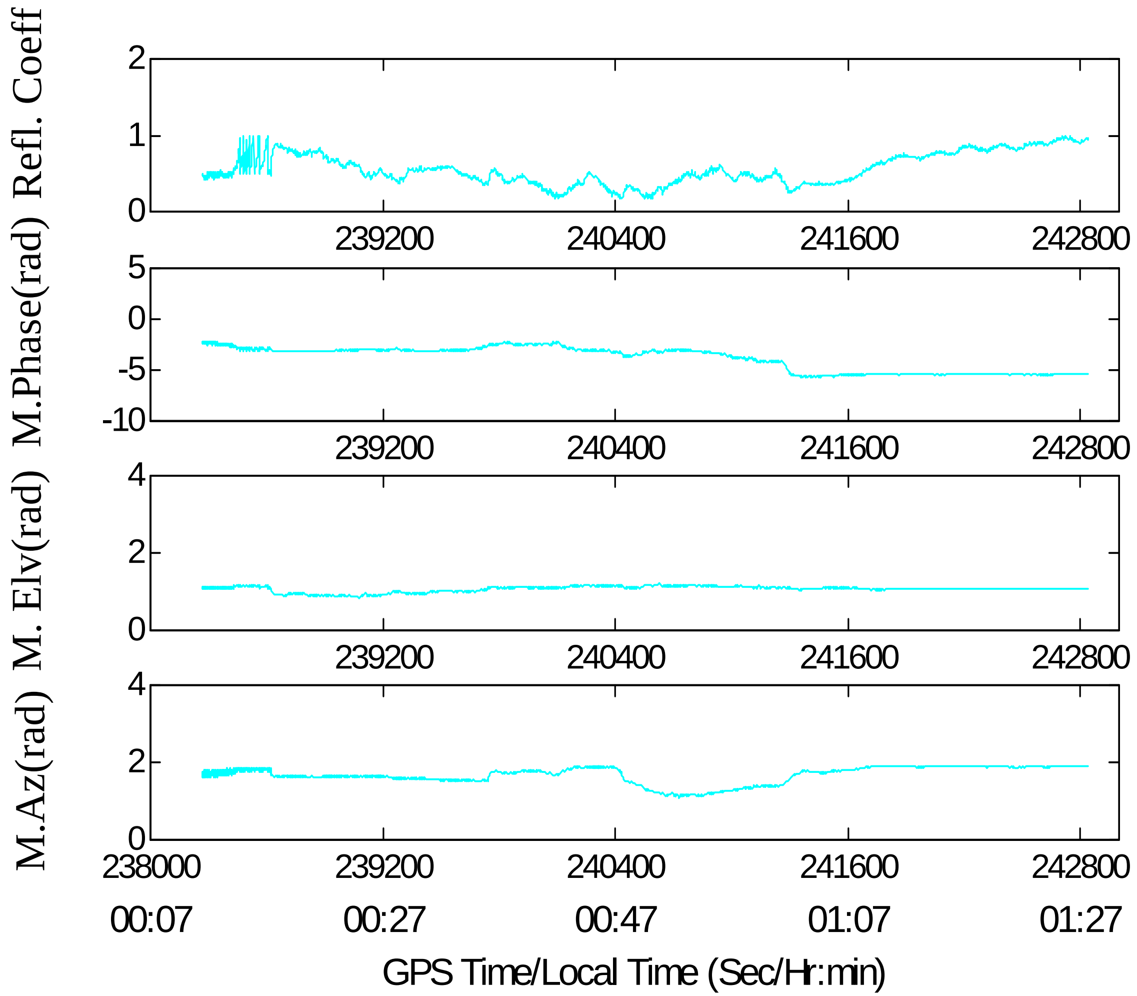
SINGLE DIFFERENCE FOR SV 21
No Multipath Correction

- Data from August 26 (RMS = 1.3 cm, correlation = 84%)



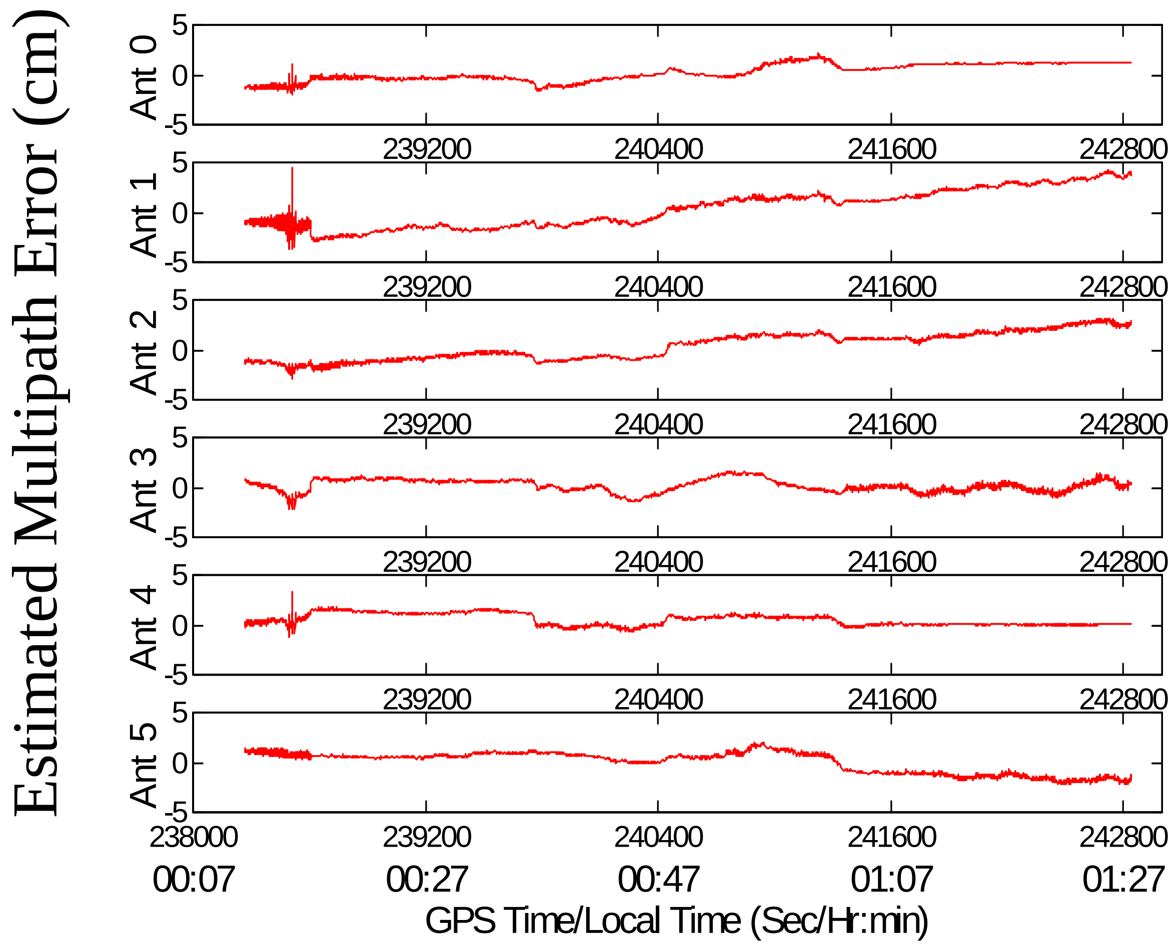
ESTIMATED PARAMETERS OF THE VIRTUAL RELFLECTOR FOR SV 21

- Data from August 25



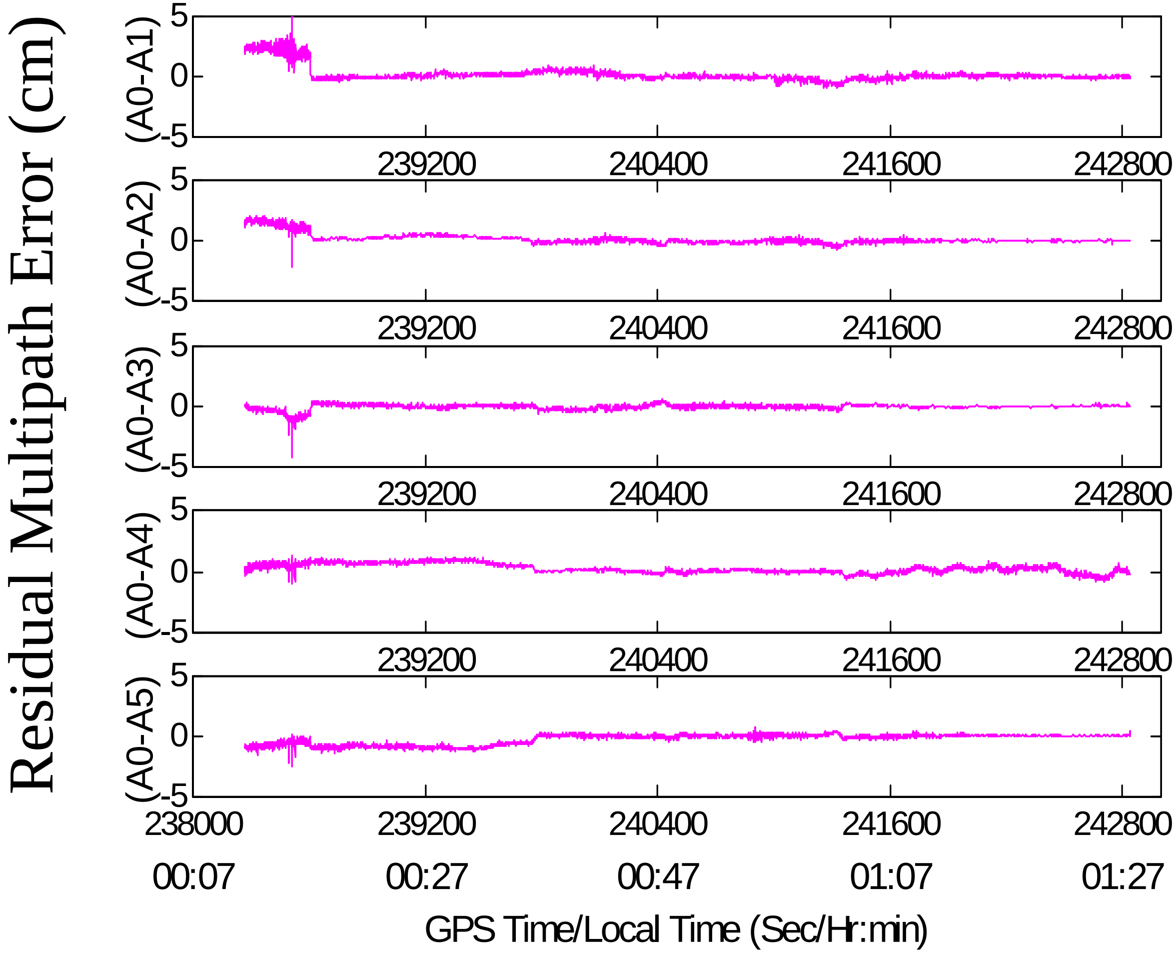
ESTIMATED MULTIPATH ERROR FOR SV 21

- Confirms that this technique estimates composite multipath



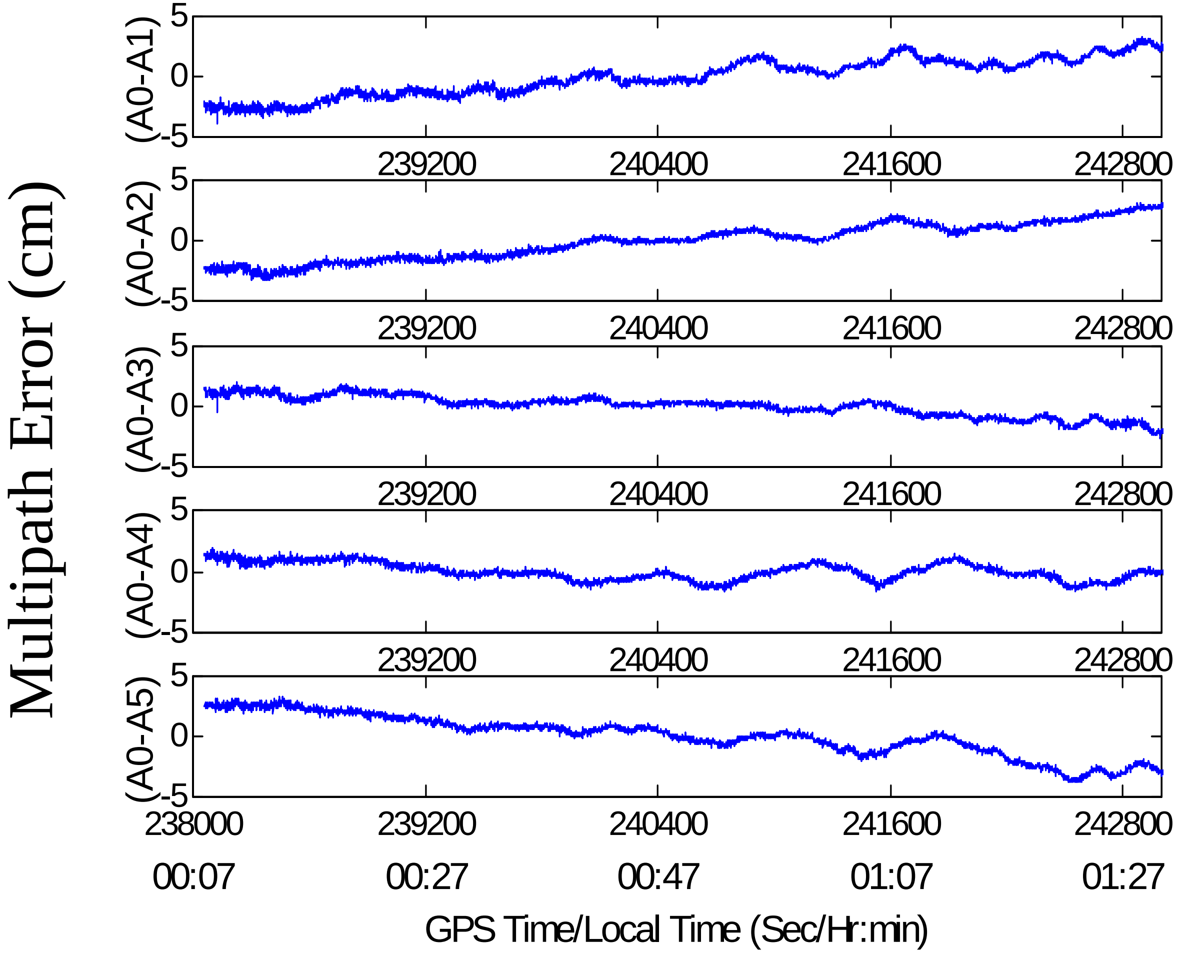
SINGLE DIFFERENCE FOR SV 21
After Multipath Correction

- RMS = 0.3 cm and improvement = 76.2%



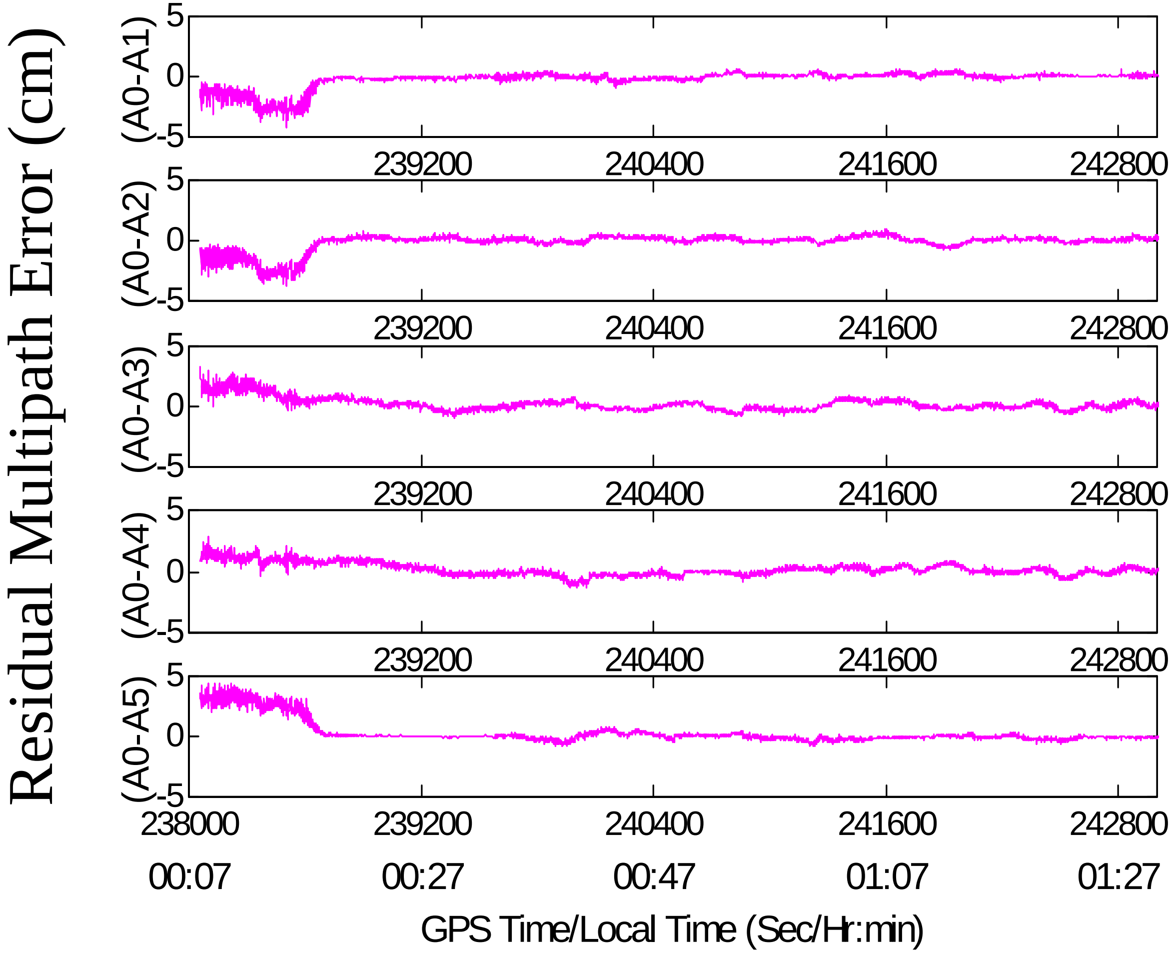
SINGLE DIFFERENCE FOR SV 31
No Multipath Correction

- Data from August 25, 1998 (RMS = 1.3 cm)



SINGLE DIFFERENCE FOR SV 31
After Multipath Correction

- RMS = 0.3 cm and improvement = 78.5%

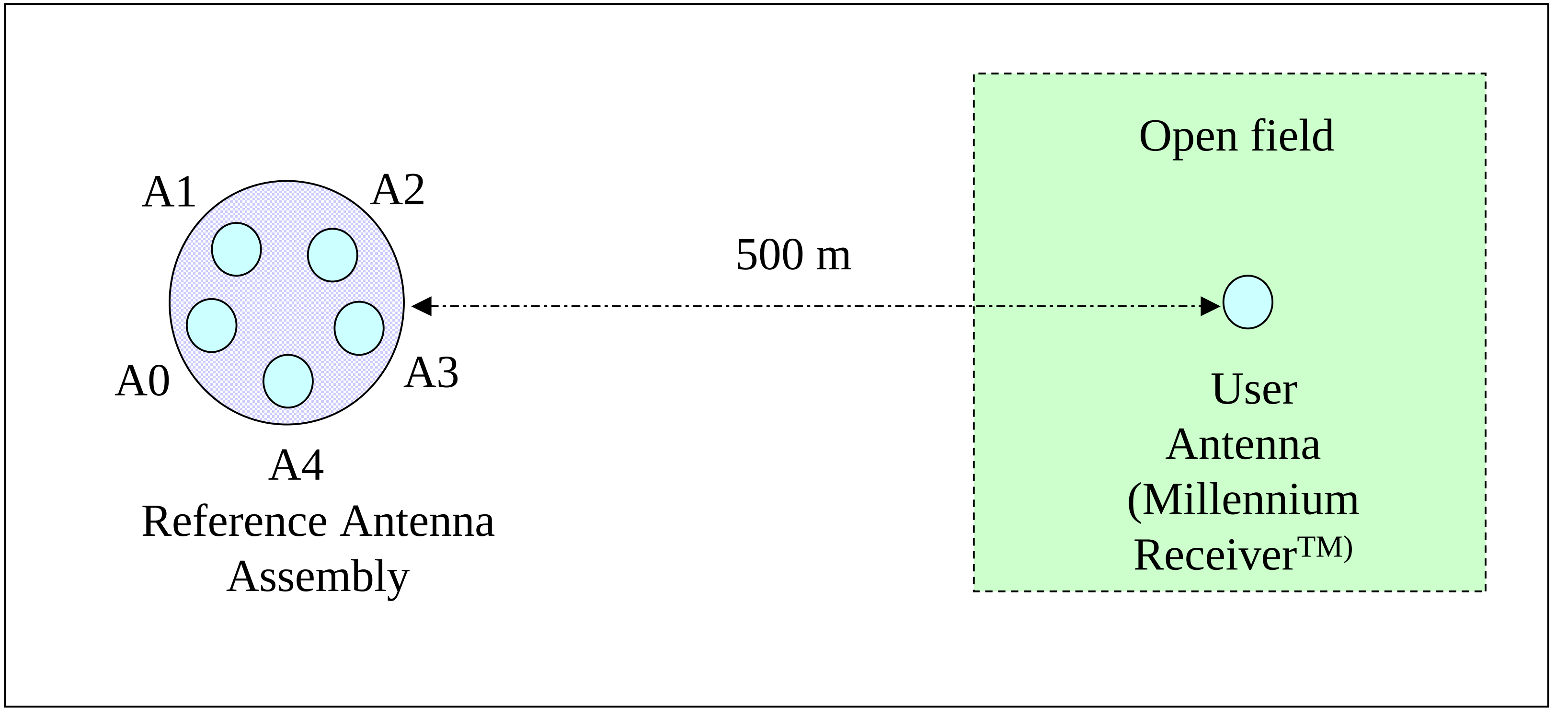


MEASUREMENT DOMAIN TEST RESULTS

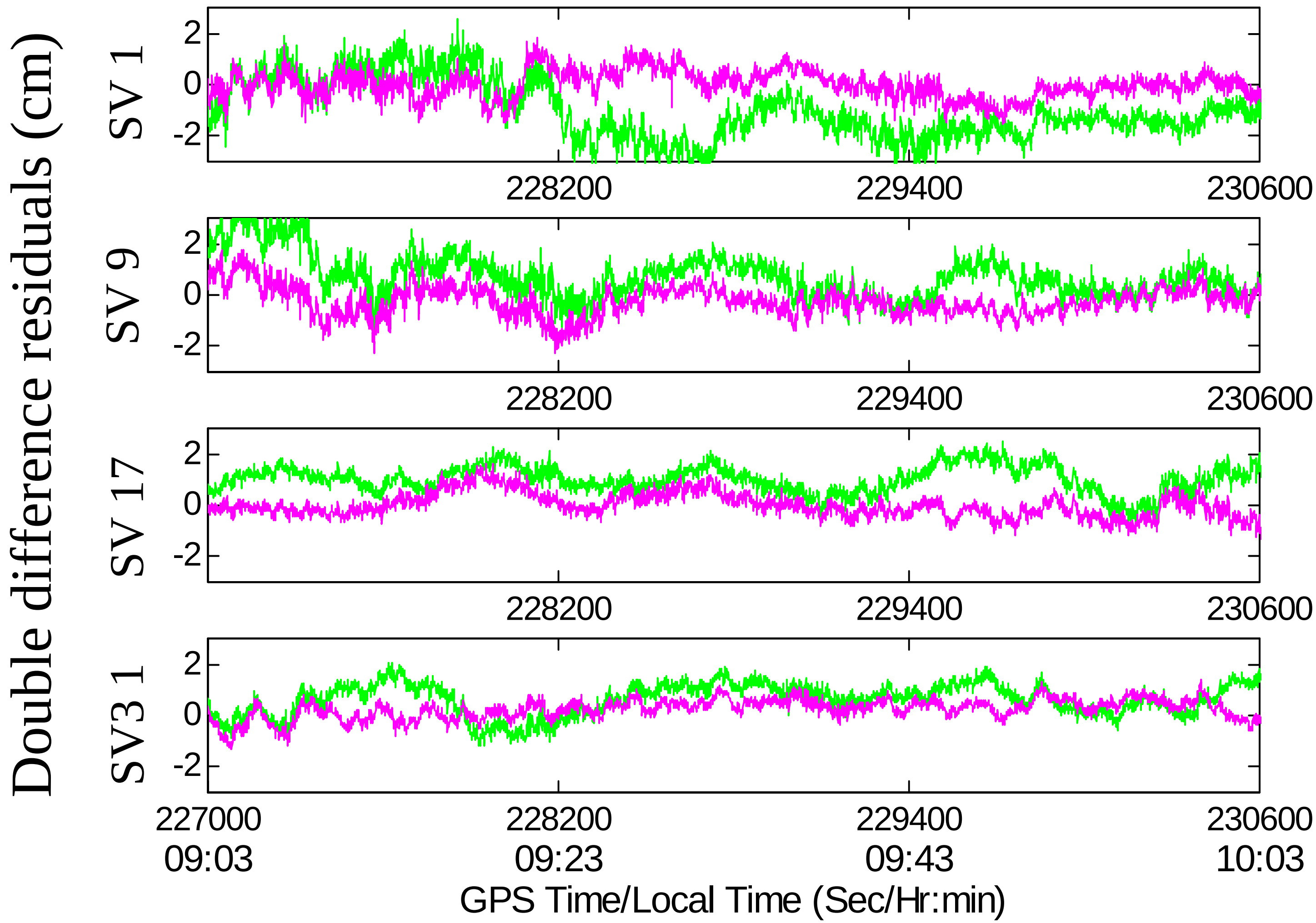
- RMS value of single difference carrier phase residual before and after multipath correction
- Average improvement = 73%

SV ID	August 25					August 26				
	Before correction		After Correction		Improve-ment	Before correction		After correction		Improve-ment
	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	%	Mean (cm)	RMS (cm)	Mean (cm)	RMS (cm)	%
17	0.1	1.8	0.0	0.4	77.4	0.1	1.7	0.0	0.4	78.0
21	0.0	1.3	0.0	0.3	76.2	-0.1	1.3	-0.0	0.2	82.0
23	-0.2	1.7	0.3	0.6	65.3	-0.2	1.7	0.3	0.8	60.0
31	0.0	1.3	0.0	0.3	78.5	0.0	1.3	0.0	0.5	63.5

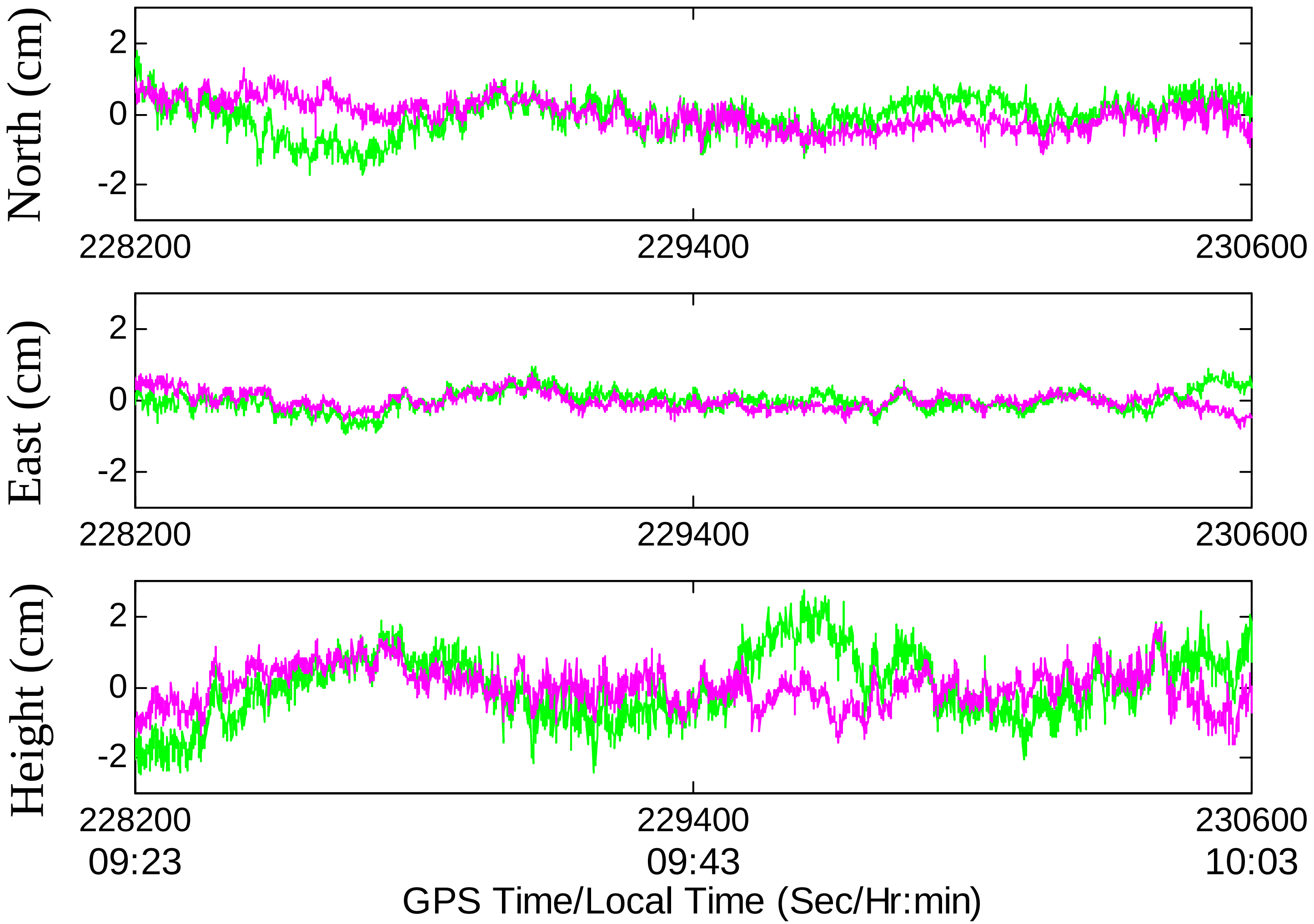
DIFFERENTIAL TEST SET-UP: PART 2



DD CARRIER PHASE RESIDUALS BETWEEN ANTENNA 1 AND THE USER



USER POSITION ERROR



TEST STATISTICS
DD MEASUREMENT DOMAIN

SV No.	Elevation Angle	Antenna No.	Multipath σ *before correction* (cm) [3]	Multipath σ *after correction* (cm) [4]	Multipath Reduction ([3]-[4])/[3] (%)
9	13° - 27°	A0	0.80	0.49	38.91
		A1	0.88	0.64	27.40
		A2	0.45	0.48	-5.12
		A3	0.53	0.57	-7.16
		A4	0.75	0.45	40.11
31	23° - 35°	A0	0.55	0.26	52.54
		A1	0.58	0.57	1.20
		A2	0.84	0.55	34.75
		A3	0.84	0.32	61.90
		A4	0.58	0.48	17.02

TEST STATISTICS POSITION DOMAIN

Antenna No.	3D position error due to multipath + noise σ (cm) [4]		3D position error due to multipath only σ (cm) [5]		Improvement in 3D position accuracy (5[a]-5[b])/ 5[a] (%)
	Before [a]	*After* [b]	*Before* [a]	*After* [b]	
A0	1.20	0.77	0.97	0.30	69.34
A1	1.29	0.84	1.08	0.46	57.79
A2	1.01	1.08	0.72	0.87	-6.93
A3	1.19	1.04	0.96	0.76	20.47
A4	1.40	0.88	1.21	0.52	57.22

Nominal position error due to phase noise = PDOP*standard deviation of phase noise

SUMMARY

- Carrier phase multipath was characterized in terms of reflector, distance, frequency
- A method to mitigate the total effect of carrier phase multipath due to all sources was developed using multiple, closely-spaced antennas
- The technique was shown to be highly effective reducing the multipath error residuals up to 60% and the position error up to 70%
- This has applications to reference stations and for attitude determination (being investigated)

REFERENCES AND WEB PAGE

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http://www.geomatics.ucalgary.ca/GPSRes/GPSResIndex.html