34th Annual Precise Time and Time Interval (PTTI) Meeting

SYSTEMATIC EFFECTS IN GPS AND WAAS TIME TRANSFERS

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Abstract

Several systematic effects that can influence SBAS and GPS time transfers are discussed. These include: ionospheric delays, multipath, and signal-to-noise ratio. Estimates for the magnitude of these effects are given.

MOTIVATION

Timing Laboratories should pay more attention to Multipath (MP)

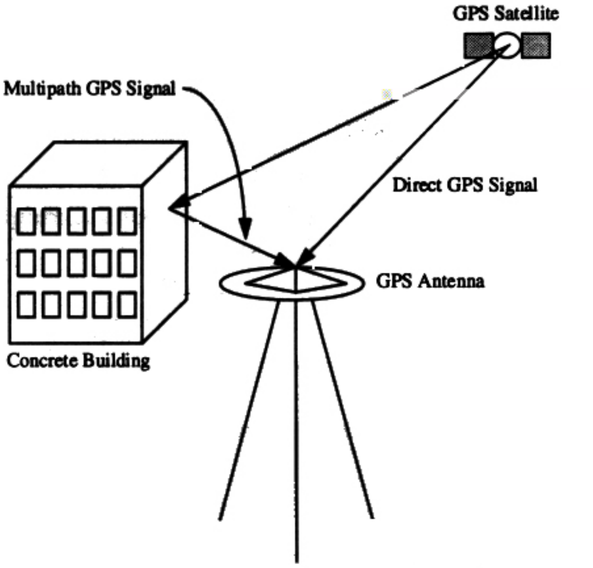
- MP is a systematic effect that can be mitigated
- Calibration of receivers through transportation of a unit does not remove effects of MP
- MP is not constant (can change with time)
- Code-phase MP error is not zero mean, hence, it can not be eliminated through averaging.

INTRODUCTION

- WAAS has taken great steps to reduce effects of MP (timing community can learn from them **[1]**).
- More modern receivers (usually dual-frequency receivers) are mitigating MP. Most timing receivers are single-frequency.
- Several techniques have been proposed for showing the existence of MP and mitigating it.

WHAT IS MULTIPATH ?

- MP is the corruption of the received signal by one or more slightly delayed reflections of the direct GPS signal.
- The effect within the receiver is a distortion of the correlation function and, therefore, of the phase, code, and SNR measurements **[2]**.



RECOGNITION OF MP

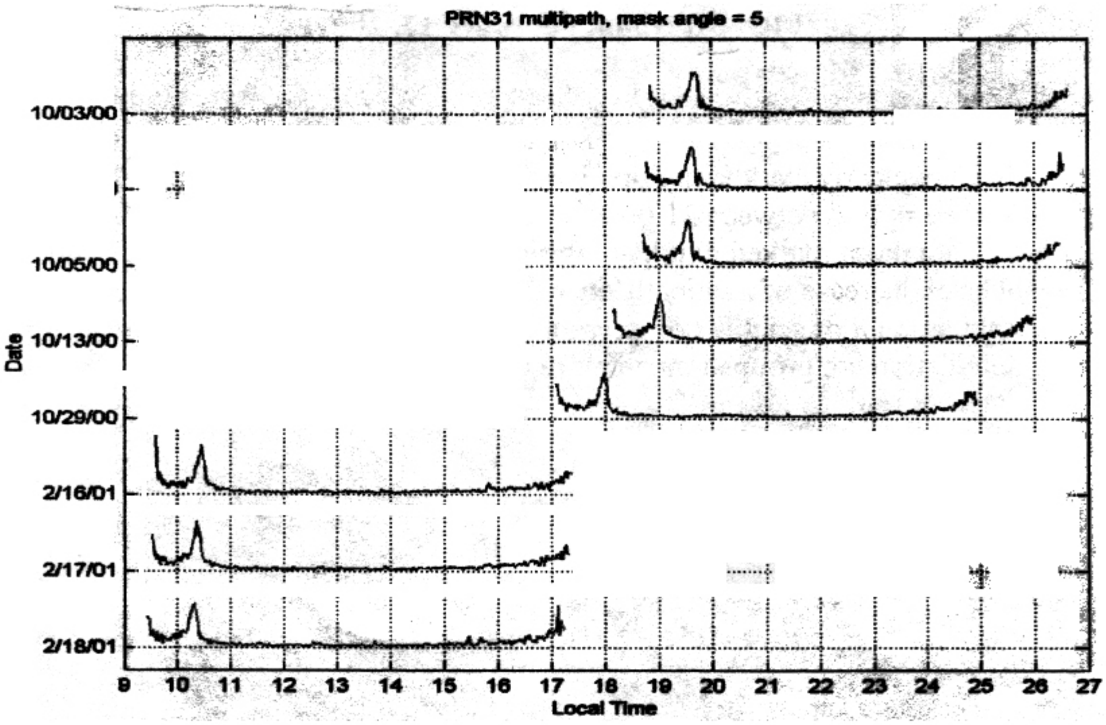


Figure 9. $S_4(L1)$ Signatures as Evidence of Multipath for PRN 31 at Naha ([0 1] $S_4(L1)$ scale between dates)

(Figure is from **[3]**.)

CHARACTERIZATION OF MP

- 1 s pseudorange errors are approximately 1 meter at low elevation
- 1 s pseudorange errors approach 0.2 meters at high elevations
- Consistent with Multipath Estimating Delay Lock Loop (MEDDL) receivers
- For timing accuracy to approach 1 ns, we need to do better.

(Figure is from **[1]**.)

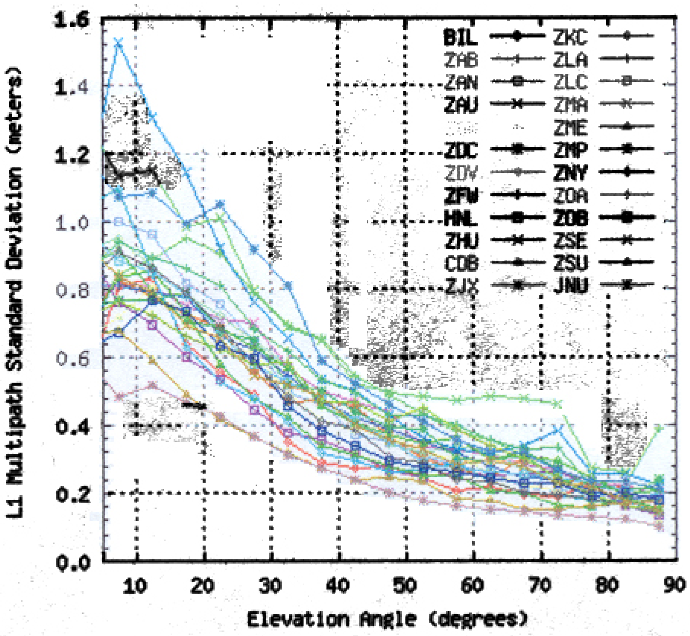


Figure 2. L1 Pseudorange Errors for WAAS Network (5 June 2000, CSMOOTH 100,100)

ANOTHER CHARACTERIZATION OF MP

Then, the total S4, including the effects of ambient noise, is defined as follows:

$$S4_T = \sqrt{\frac{\langle SI^2 \rangle - \langle SI \rangle^2}{\langle SI \rangle^2}} \qquad 3)$$

where $\langle \bullet \rangle$ represents the expected (or average) value over the interval of interest (60 seconds).

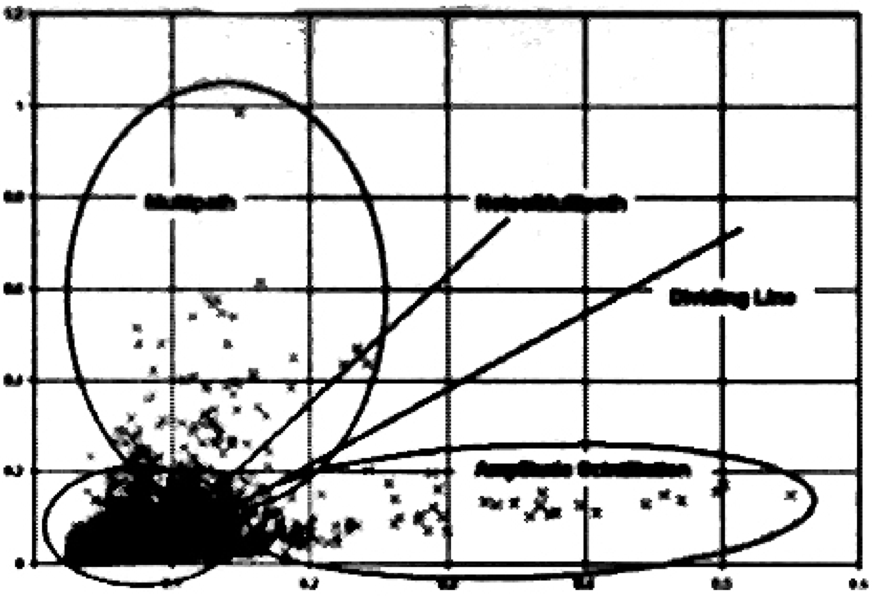


Figure 3. Separating Multipath and Amplitude Scintillation

(Figure is from **[4]**; CCDiv = Code Carrier Divergence.)

TECHNIQUES TO MITIGATE MP

- Siting – most critical
- Antenna – ground plane, choke ring, adaptive antenna array
- Delay Lock Loop (DLL) – improved receivers
- Signaling technique – longer C/A codes (L5)
- Data processing – code carrier smoothing, SNR measurements, repeatability, multiple receivers
- Carrier smoothing techniques
- Spectral decomposition
- CNMP algorithm of WAAS.

HATCH FILTER

- The Hatch filter is one of the most well-known and simplest schemes.
- It estimates the carrier phase bias, λ_c, by averaging the difference of code and carrier measurements:

$$\overline{n\lambda_c(n)} = \frac{1}{n} \sum_{i=1}^{n} [\varphi_c(i) - \tau_c(i)]$$

where n is the length of the data set.

- Using the carrier phase bias as given above, it can be shown **[5]** for the single frequency case that the pseudorange can be estimated recursively by:

$$\rho(n) = \frac{(k-1)}{k} [\rho(n-1) + \Delta\varphi_{L1}(n)] + \frac{1}{k}\tau_{L1}(n)$$

where ρ is the smoothed pseudorange. This smoothing scheme is actually a moving average window of width k.

SPECTRAL ANALYSIS AND MP DECOMPOSITION

- Spectral analysis of MP is the fundamental concept for this technique **[5]**
- Time constants of MP errors can have values from 1 second to hours
- Effective decomposition of multipath error in the frequency domain is critical in MP mitigation techniques:

  - High Frequency (HF) component (1 sec < τ< 1 min); noise and fast fading due to diffuse multipath and receiver tracking errors
  - Medium Frequency (MF) component (1 min < τ < 8 min) due to specular-dominated MP errors
  - Low Frequency (LF) component (τ > 8 min) due to long-term bias-like MP and drift errors.

WAAS CODE NOISE MULTIPATH (CNMP) TECHNIQUE [1]

- Corrects for observed multipath and provides a noise estimate for the residual error in the MP corrected pseudorange measurements
- The CNMP algorithm has three major components:

  - Mean filter
  - Mean error function

- Cycle slip detection

- The MP correction is computed by differencing the mean filter estimate from the current multipath estimate
- The MP corrected pseudorange measurements are carrier-smoothed with a period equivalent to the mean filter time constant.

WAAS CODE NOISE MULTIPATH (CNMP) EQUATIONS

$$M\,P_{L1}[t] \;=\; \rho_{L1}[t] \;-\; \{(1+2k)\,\varphi_{L1}[t] \;-\; 2k\,\varphi_{L2}[t]\}$$

$$M\,P_{L2}[t] \;=\; \rho_{L2}[t] \;-\; \{(2k+2)\,\varphi_{L1}[t] \;-\; (2k+1)\,\varphi_{L2}[t]\}$$

MP correction:

$$\mu_{Lj} \;=\; M\,P_{Lj}[t] \;-\; \overline{M\,P_{Lj}[t]}$$

where:

ρ = pseudorange
φ = carrier range
$k = \dfrac{120^2}{(154^2 - 120^2)}$
j = L1 or L2
t = time of continuous L1 and L2 tracking.

CONCLUSIONS

- Care must be taken by the timekeeping community if you want nanosecond accuracy from GPS time transfers
- Cannot obtain nanosecond accuracy unless one accounts for MP
- There are several ways to mitigate MP
- One must carefully investigate one's locale before choosing a method
- Calibration techniques using a reference receiver should carefully investigate MP at the sites to be visited
- Observations should be made with a dual-frequency receiver.

DISCUSSION

- Can one really expect better than a nanosecond from GPS time transfers?
- For 1 nanosecond, should other techniques be emphasized?

REFERENCES

[1] K. Shallberg, P. Schloss, E. Altshuler, and L. Tahmazyan, 2001, *"WAAS Measurement Processing, Reducing the Effects of Multipath,"* in the Proceedings of the ION GPS-01 Meeting, 11-14 September 2001, Salt Lake City, Utah, USA (Institute of Navigation, Alexandria, Virginia), pp. 2334-2340.

[2] C. Kee and B. W. Parkinson, 1994, *"Calibration of Multipath Errors on GPS Pseudorange Measurements*," in Proceedings of ION GPS-94, 20-23 September 1994, Salt Lake City, Utah, USA (Institute of Navigation, Alexandria, Virginia), pp. 353-362.

[3] R. S. Conker, M. B. El-Arini, K. Matsunaga, and K. Hoshinoo, 2002, *"Preliminary Analysis of the Effects of Ionospheric Scintillation on the MTSAT Satellite-based Augmentation System (MSAS*)," in Proceedings of the 2002 Ionospheric Effects Symposium, 7-9 May 2002, Alexandria, Virginia, USA (JMG Associates, Ltd., Alexandria, Virginia), pp. 167-178.

[4] A. J. Van Dierendonck and Q. Hua, *"Measuring Ionospheric Scintillation Effects from GPS Signals,"* in Proceedings of ION 57th Annual Meeting and CIGTF Biennial Guidance Test Symposium, 11-13 June 2001, Albuquerque, New Mexico, USA (Institute of Navigation, Alexandria, Virginia), pp. 391-396.

[5] D. Dai, T. Walter, C. J. Comp, Y. J. Tsai, P. Y. Ko, P. Enge, and J. D. Powell, 1997, *"High Integrity Multipath Mitigation Techniques for Ground Reference Stations*," in the Proceedings of the ION GPS-97 Meeting, 16-19 September 1997, Albuquerque, New Mexico, USA (Institute of Navigation, Alexandria, Virginia), pp. 593-604.

M. S. Braasch, 1996, *"Multipath Effects*" in **Global Positioning System: Theory and Applications, 1**, chap. 14 (American Institute of Aeronautics and Astronautics, Washington, D.C.).

J. M. Sleewaegen, 1997, *"Multipath Mitigation, Benefits from using the Signal-to-Noise Ratio,"* in Proceedings of ION GPS-97, 16-19 September 1997, Kansas City, Missouri, USA (Institute of Navigation, Alexandria, Virginia), pp. 531-540.

R. van Nee, 1991, *"Multipath Effects on GPS Code Phase Measurements,"* in Proceedings of ION GPS-91, 11-13 September 1991, Albuquerque, New Mexico, USA (Institute of Navigation, Alexandria, Virginia), pp. 915-924.

QUESTIONS AND ANSWERS

TOM CLARK (Syntonics): A couple of comments. One, you mentioned the dual frequency problem. Sometimes dual frequency can actually hurt you more. The normal linear combination is used with two frequency data is to take some number I can never remember, but something like 2.5 times the observable at L1 minus 1.5 times the observable at L2. It is very possible for the phases of the multi-path signals at L1 and L2 not to cancel, but to add, so that you end up with the multi-path effect on the combined observable being as much as 4 times what it was on either of the single frequencies. So I offer that as a caution.

Another thing I would suggest, as I have done many times in the past, that one of the diagnostic tools that you have available in every receiver – unfortunately, it has been poorly supported in RINEX – is to measure the amplitude variability. For every cycle of multi-path you go through, there is also a cycle of amplitude. And in voltage units, the fractional change in amplitude is precisely the same thing as the phase change in radians. So you have, in a sense, an orthogonal measurement that you can use as a diagnostic tool for identifying multi-path in the amplitudes.

BILL KLEPCZYNSKI: Thank you very much. That is a very good comment.

KEN JOHNSTON (U.S. Naval Observatory): I have one comment, Bill. At the Observatory we will soon be getting a beam-forming GPS receiver, a 16-element receiver. What I encourage you to do is take that receiver and compare that to the other data that you can get from the Naval Observatory and hopefully report on that next year at the PTTI meeting.