Observations of Signal-to-Noise Ratios (SNR) at Geodetic GPS Site CASA: Implications for Phase Multipath

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Abstract. Specular multipath remains an unmodeled and significant error source for GPS positioning. While it has been demonstrated that, in principle, it should be possible to use signal-to-noise ratios (SNR) to construct corrections for the carrier phase multipath error, the complexity of SNR behavior and multipath environments make it challenging to implement such a technique. This paper presents observations of SNR data from a continuously operating GPS receiver (CASA), which show strong evidence of ground and monument multipath. The SNR data at CASA demonstrate daily repeatability and seasonal trends that indicate a strong dependence of multipath error on changes in the antenna environment. When the SNR data show variability due to multipath, SNR observations are consistent with positioning postfit phase residuals. This indicates that SNR-based corrections for geodetic applications may be feasible.

1 Introduction

Range error introduced by specular multipath has been explored by many researchers (Cohen and Parkinson, 1991; Elosegui *et al.*, 1995; Ray, 2000; Van Nee, 1995), but a rigorous method for removing multipath errors has not yet been developed for routine usage by the geodetic community. Specular multipath is a similar phenomenon to a reflection off of a mirror, where no significant energy is directed out of the main beam path in the process of reflection. Unlike diffuse multipath, specular multipath is systematic and cannot be easily removed via filtering within the GPS receiver; a different technique for mitigating specular multipath is desirable.

The signal-to-noise ratio (SNR) recorded by a GPS receiver can be used as a proxy for understanding and possibly correcting multipath errors. SNR is a quantity routinely measured by the receiver and is used in a limited capacity for data quality checking, in the sense that low SNR values indicate a large tracking error. Like the carrier phase measurement, SNR is impacted directly by multipath signals and can therefore be used to assess carrier phase multipath conditions.

Previous studies have incorporated SNR measurements in correcting carrier phase multipath in aerospace environments (Comp and Axelrad, 1997; Reichert, 1999; Reichert and Axelrad, 1999) and geodetic GPS installations (Scappuzzo, 1997), but with limited success. Before applying these SNR-based multipath mitigation techniques to data acquired at geodetic GPS installations, it is important to first understand any short and long-term trends in those SNR measurements and what they tell us about the multipath environment.

2 SNR Data Analysis

SNR is a measure of the ratio of the amplitude of the recovered GPS carrier signal to the noise. In a geodetic receiver the environment noise level is constant, so SNR corresponds directly to the GPS received signal strength. This SNR is dependent on factors external to the receiver such as GPS satellite transmit power, space loss and atmospheric attenuation, and local factors like the receiving antenna gain, tracking loop design and multipath. To isolate multipath effects, we must eliminate or reduce the external and other local contributors to measured SNR.

Unlike GPS code and phase observables, a standard practice for computing and reporting SNR has not been established. Thus, the recovered signal amplitude value and the units used for reporting it differ among manufacturers. To use SNR effectively as a basis for analyzing multipath, one must first understand the representation used in the particular GPS receiver model and then apply appropriate adjustments for the receiving antenna pattern and incident signal strength. The effects of transmit power,

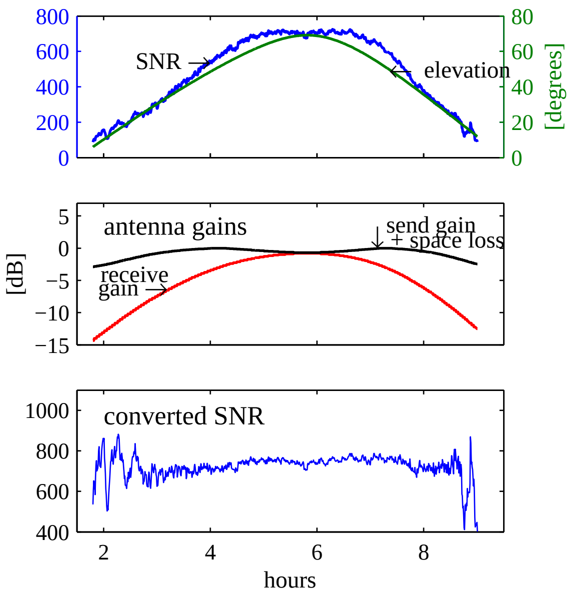

Figure 1: SNR conversion for GPS27 at CASA, 02jun21. The SNR reported by a GPS receiver (top) is dominated by the effects of the receiving and transmitting antenna gain patterns (center). Removing the gain patterns and converting to common SNR units (bottom) reveals SNR variablity due to multipath.

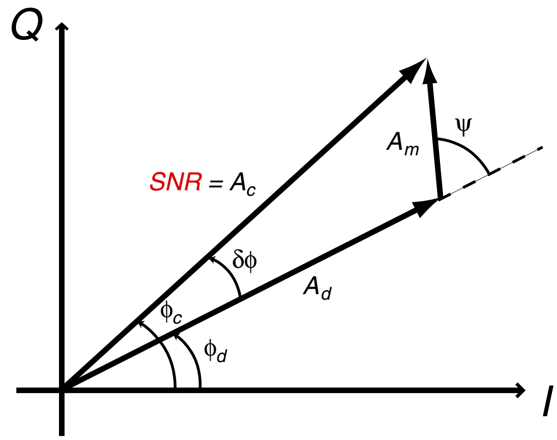

Figure 2: This generalized GPS signal phasor diagram depicts operation of a phase lock loop, where the GPS receiver records in-phase (I) and quadrature (Q) components of the GPS signal to determine a best estimate of the carrier phase ϕ_d. Here, an indirect or multipathed signal (amplitude A_m) combines with the direct signal (A_d), creating the composite signal (A_c) recorded by the receiver. The phases shown on the diagram are the direct ϕ_d, composite ϕ_c, multipath relative phase ψ, and the phase error due to multipath, $\delta\phi$.

space loss and antenna gain patterns can be removed to the first order using published antenna gain patterns (Schupler *et al.*, 1994; SRI International, 2002). Figure 1 shows an example of the measured SNR in the receiver's natural units, adjustments for the antenna patterns and space loss in dB, and finally, the remaining variable component of SNR, which should be indicative of multipath.

As described by *Comp* [1996] and others, a phasor diagram (Figure 2) can be used to describe the relationship between the phase error $\delta\phi$ and the recorded SNR or composite signal amplitude A_c. From Figure 2, SNR and phase error for a single reflector can be represented as a function of direct and multipath signal amplitudes and the multipath relative phase ψ:

$$SNR \equiv {A_c}^2 = {A_d}^2 + {A_m}^2 + 2A_dA_m\cos\psi \quad (1)$$

$$\tan(\delta\phi) = \frac{A_m\sin\psi}{A_d + A_m\cos\psi} \quad (2)$$

From Equation 1, changes in the multipathed or direct signal amplitudes or the multipath relative phase will result in increased or decreased SNR magnitude. The direct signal amplitude A_d is a function of the gain patterns of the receiving and transmitting GPS antennas (discussed above) and the output power of the transmitting satellite. In addition to these factors, the indirect or multipathed component amplitude A_m is also highly dependent upon the reflectivity of the reflecting surface. In most environments the reflected amplitude is much smaller than the direct signal amplitude, i.e. $A_m \ll A_d$. For small $\frac{A_m}{A_d}$, variations in SNR and $\delta\phi$ are proportional to $\cos\psi$ and $\sin\psi$, respectively, yielding oscillations in SNR and $\delta\phi$ which will be 90° out-of-phase with each other.

The foundation for SNR-derived phase corrections is to use the SNR observable and the relationship in Equation 1 to find A_d, A_m, and ψ for each multipath reflection and then apply these estimates in Equation 2 to construct a phase correction. In fact, for typical geodetic applications utilizing the ionosphere-free carrier phase combination $L3$, a separate correction profile would be constructed for $L1$ and $L2$ and then combined in the same proportions as the phase observations.

In order to find the three parameters (A_d, A_m, and ψ) for each reflection, a series of SNR observations must be used with some assumptions about the time dependence of the parameters. In this work we have assumed that after removing the known dependence on satellite elevation shown in Figure 1, the direct signal component (A_d) is constant, and the multipath amplitude (A_m) varies as a function of satellite elevation angle. The time dependence of ψ is governed by the satellite motion (causing the multipath phasor in Figure 2 to spin around the end of the direct signal phasor) and the location and orientation of the reflecting surface. For a horizontal reflecting surface at distance h from the antenna phase center, we find that the multipath relative phase is given by

$$\psi = 2\pi \frac{2h}{\lambda} \sin\theta + \phi_0 \tag{3}$$

where ϕ_0 is a constant phase shift that occurs at the reflecting surface (180° for a perfect conductor) (Reichert, 1999) and θ is the satellite elevation angle. We observe that the multipath relative phase for a horizontal reflector is linearly dependent on the sine of the satellite elevation angle with a spatial frequency

$$\omega_{SNR} = 2h/\lambda \tag{4}$$

The linear dependence noted above allows a significant simplification in the process of identifying multipath parameters. By resampling the SNR measurements in regular increments of $\sin\theta$ (Figure 3b), a periodogram can be used to identify the spatial frequencies present in the data. Each dominant frequency (ω_{SNR}) in the periodogram corresponds to a separate reflecting surface, and contributions from multiple reflectors can be summed together. Once frequency values are known, a least squares solution for each A_d, A_m, and ϕ_0 can be computed from the SNR time series and a phase correction profile may be constructed. The height of the antenna phase center above each surface is found using Equation 4.

For geodetic receiver installations, the most likely multipath reflectors are the ground and the antenna monument (Elosegui *et al.*, 1995); thus, the assumption of horizontal reflecting surfaces is quite reasonable. For antennas mounted on sloped or nonuniform surfaces, some degredation due to this assumption should be expected.

Multipath degrades GPS positioning by introducing a range error; for the carrier phase observable, the true phase is misreported as either too large or too small and this error evolves through time. To assess the impact of multipathed signals on GPS positioning, carrier phase data were analyzed using the GIPSY/OASIS II software developed at the Jet Propulsion Laboratory (Lichten and Border, 1987). Precise orbits from the IGS (Beutler *et al.*, 1994) were held fixed. The estimated parameters for each receiver are Cartesian position, satellite and receiver clocks, carrier phase ambiguities, and a zenith troposphere delay. The $L1$ and $L2$ phase data are linearly combined to form the ionosphere-free $L3$ observable. Most geodetic receivers record observations at a 30-second rate; this sampling rate was retained for the GIPSY analysis. No model of multipath is used in GIPSY; therefore any multipath signals present should be found in the carrier phase postfit residuals.

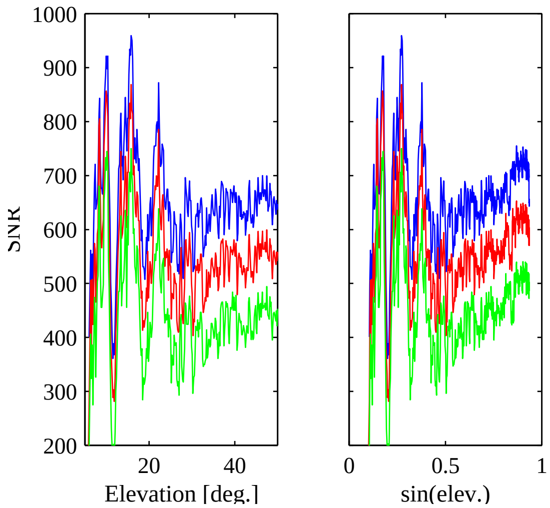

Figure 3: a) L1 SNR data from ascending pass of GPS27 as observed June 21-23 (blue, red, green), 2002 at CASA. SNR data are offset by 100 units for display purposes. b) SNR data plotted as a function of sine(elevation angle).

3 Multipath at CASA

The permanent GPS installation CASA, operating near Mammoth Lakes, California, provides an example of SNR observations and their relationship to multipath. The CASA monument is a concrete pillar ~0.5 meters tall, situated in a grassy field. The antenna is mounted ~0.1 m above the pillar top. No structures are located near the antenna. CASA is in the Sierra

Nevada (at a height of 2390 meters), and subject to significant snowfall during the winter months. The remainder of the year has relatively stable weather conditions, with little rainfall. The station itself has been operating the same equipment (Rogue SNR-8000 receiver, Dorne-Margolin chokering antenna) since 1994 and the same firmware since 1999, providing a long time series of available, consistent SNR data.

SNR data from CASA spanning June 2002 to June 2003 were analyzed; data analysis involves first removing antenna gain and space loss effects from SNR data for a single satellite pass. SNR data were interpolated to even spacing in sine of elevation angle as required by Equation 3; the data were first divided into ascending and descending segments to avoid aliasing any signal present in the data when interpolating. Periodograms were used to determine SNR oscillation frequencies (cycles per arc), which were then mapped to the effective reflector height. These antenna-reflector distances were then used to calculate reconstructed SNR and phase correction profiles. Each satellite in view over the course of a 24-hour period was analyzed individually as described above. In this study we rely on the L1 SNR data only. The lack of civilian access to the L2 frequency P-code casts doubt upon the reliablity of the L2 SNR measurement; however, SNR on the L1 frequency are considered sound due to the unencrypted C/A code. Thus, L2 SNR data were not used in this study.

Over the space of several days, SNR data show very consistent values. Figure 3 shows day-to-day repeatability of SNR data for a single satellite in the month of June. Over the course of a year (Figure 5), however, the SNR data are found to be inconsistent in both frequency and amplitude of oscillations. In the months of June-November, the SNR data consistently show evidence of horizontal reflectors at heights of ∼0.65 and ∼0.20 meters, which roughly correspond to distances between the antenna phase center and the ground or monument pillar top, respectively. The amplitude of these reflectors do vary, which could correspond to changes in the environment (rainfall, vegetation growth, or obstructions on the antenna mount). The winter months are much more variable. In December, no significant reflectors can be estimated from the SNR data. One month later, a reflector at ∼0.21 meters is visible, but the ground (peak at 0.64 m) is now much less reflective. In February and and March there are significant reflectors, although the ground reflectors are closer to the antenna, ∼0.5 meters, which may correspond to significant snowfall on the ground.

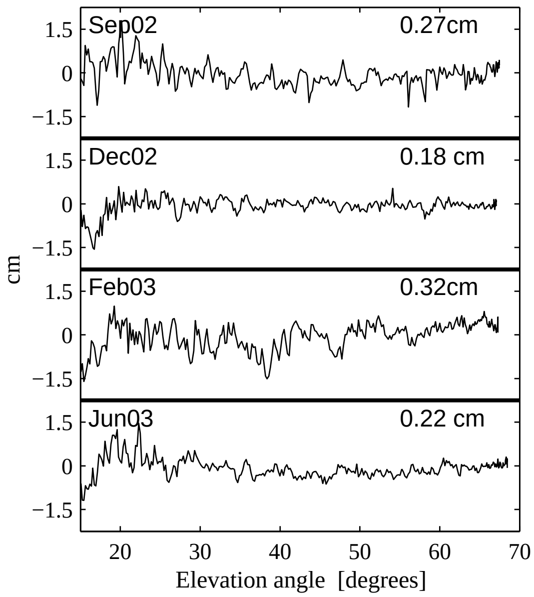

Figure 4: $L3$ GIPSY residuals for GPS30 on 02sep01, 02dec01, 03feb01, and 03jun01.

CASA position solutions were computed for September, December, and February. If the SNR analysis is valid, the CASA postfit residuals should be smallest for December, and significantly larger for September and February. Figure 4 demonstrates that quantitatively this relationship is valid, with postfit residual RMS of 1.8 cm in December, 2.7 cm in September, and 3.2 cm in February.

The horizontal reflectors estimated in the bottom half of Figure 5 can be used to compute carrier phase multipath corrections. As an example, the L1 SNR for September find strong horizontal reflectors at 0.12 and 0.67 m. For each of these reflector heights, carrier phase corrections (Equation 2) for the $L1$ and $L2$ carrier frequencies will differ due to their different wavelengths (∼ 19.0 and 24.4 cm, respectively); the inverse relationship between frequency and wavelength dictates that close-in reflectors such as the monument top will create slower SNR oscillations than far-off reflectors like the ground (Figure 6). The full multipath correction is computed using the $L3$ ionosphere-free data combination.

An example of SNR analysis and carrier phase

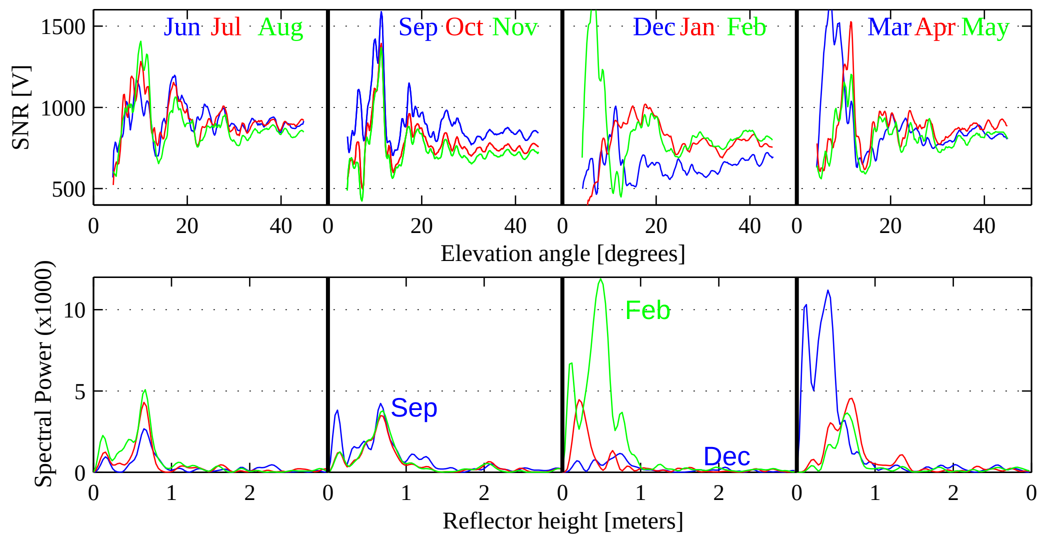

Figure 5: One year of SNR observations as seen on the first of each month (June 2002 to May 2003) for the ascending pass of GPS30. The top panel displays SNR data as a function of elevation angle, and the bottom panel gives periodograms for these data, where frequencies have been converted to the vertical antenna-reflector distance for a representative horizontal reflector.

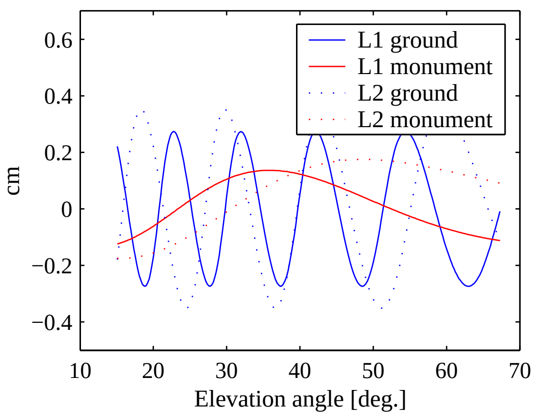

Figure 6: Predicted $L1$ and $L2$ multipath errors for horizontal reflectors at 0.67 m (ground - blue curves) and 0.12 m (monument - red curves) below the average phase center, as a function of elevation angle.

multipath corrections is shown in Figure 7. This day was chosen based upon daily repeatability of both SNR and postfit residuals for several consecutive days. From the periodogram of the ascending pass of GPS 30, several peak frequencies are contained in the SNR data. Since the peaks near 0.23 and 0.62 m are physically significant (corresponding to monument and ground reflections), we chose to model carrier phase corrections based upon only the first two ω_{SNR} maxima. A SNR profile estimated using only these two reflectors corresponds well to the recorded SNR (Figure 7b). Likewise, GIPSY postfit residuals for the same satellite show strong agreement with L3 corrections (Figure 7c). Corrections were computed for the full span of the SNR data (down to 5° elevation) whereas the GPS data analysis and thus postfit residuals only use data above 10° elevation.

4 Conclusions

The technique presented here of SNR-based corrections to GPS carrier phase multipath shows promise. Since mulitipath is unmodeled in GPS positioning, one would expect this error to remain in the postfit residuals. Our example (Figure 7) demonstrates close agreement between postfit residuals and the SNR-based correction profile given very simple antenna environment assumptions of ground and monument reflections. Although the results presented here are encouraging, this technique needs to be applied to multiple stations of varying multipath complexity and for all seasons and weather conditions for a complete evaluation of the technique.

The sensitivity of SNR to changes in the multipath environment, as shown by the winter months of Figure 5, can be both a strength and

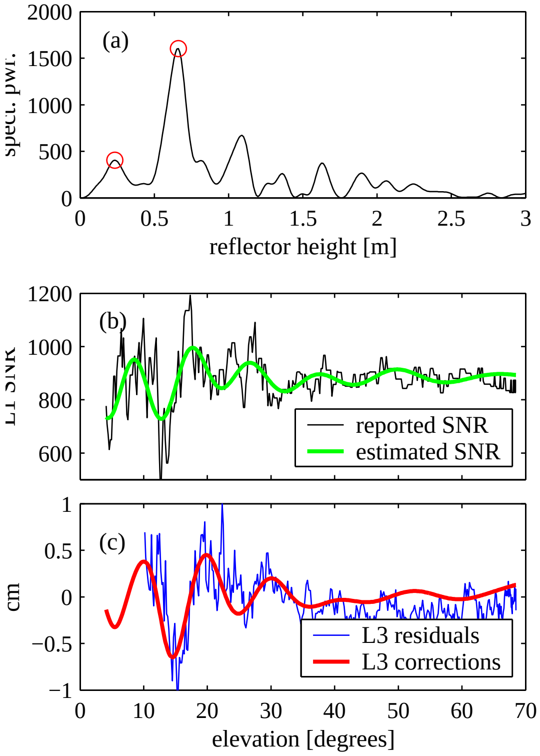

Figure 7: Results of reflector estimation and carrier phase corrections for the ascending pass of GPS30 on June 1, 2003. a) Periodogram with reflectors at 0.23 and 0.62 m marked by circles. b) SNR recorded by the receiver with the reconstructed SNR (bold line). c) Comparison of $L3$ postfit residuals and phase corrections generated from the SNR analysis.

a liability. Changes in SNR amplitude and frequency of oscillation can indicate changes in surface reflectivity or reflector height, respectively, and consequently changes in the carrier phase multipath errors. In this case, SNR provides a dynamic measure of multipath errors which a static physical antenna environment model could not accomplish. However, the results from February 2003 provide a cautionary example where SNR variability may not follow multipath assumptions. Early February SNR data are highly repeatable and oscillatory, but SNR-based phase corrections do not properly mirror postfit residuals. It is likely that snow resting on the antenna dome could create phase delays and therefore phase errors which show up in the residuals, yet these errors cannot be modeled by multipath assumptions of horizontal reflectors.

Other difficulties may present obstacles to automated application of SNR-based phase corrections. First, there are no standard units for reporting SNR so that SNR measurements can vary significantly between GPS receiver models. Knowledge of SNR units is crutial to proper gain pattern removal and scaling in order to yield meaningful phase corrections. Also, doubtful L2 SNR measurements due to lack of direct P-code access eliminates another possible data source for multipath identification and correction. The Department of Defense plans to add a civilian code to the L2 frequency (L2C) on the next generation of GPS satellites (Fontana *et al.*, 2001). An unencrypted code on a second frequency would make L2 SNR-based corrections more feasible.

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