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AN AUTOMATIC EDITING ALGORITHM FOR GPS DATA

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Abstract. An algorithm has been developed to edit automatically Global Positioning System data such that outlier deletion, cycle slip identification and correction are independent of clock instability, selective availability, receiver–satellite kinematics, and tropospheric conditions. This algorithm, called TurboEdit, operates on undifferenced, dual frequency carrier phase data, and requires (1) the use of P code pseudorange data and (2) a smoothly varying ionospheric electron content. The latter requirement can be relaxed if the analysis software incorporates ambiguity resolution techniques to estimate unresolved cycle slip parameters. TurboEdit was tested on the large data set from the CASA Uno experiment, which contained over 2500 cycle slips. Analyst intervention was required on 1% of the station–satellite passes, almost all of these problems being due to difficulties in extrapolating variations in the ionospheric delay. The algorithm is presently being adapted for real time data editing in the Rogue receiver for continuous monitoring applications.

Introduction

Carrier phase data from the Global Positioning System (GPS) have been used in recent years to measure regional scale geodetic networks with sub-centimeter precision [e.g., *Dong and Bock*, 1989]. Results using the GIPSY (GPS-Inferred Positioning System) software show sub-centimeter agreement in the horizontal baseline components with solutions inferred by very long baseline interferometry in California [*Blewitt*, 1989]. Three dimensional baseline accuracies of 1.5 parts in 10^8 have been demonstrated over distances of 2000 km [*Lichten and Bertiger*, 1989]. A prerequisite to such high precision GPS-based geodesy is the reliable detection of and, where possible, correction of integer discontinuities (cycle slips) in the carrier phase data, caused by receivers losing lock on GPS signals. Without an adequate data editing capability, further processing of GPS data to extract geophysical results would be futile.

GPS data editing has generally involved a variety of heuristic methods, most of which operate on differences of data between pairs of stations and pairs of satellites in order to reduce instrumental biases. Visual inspection of the data using interactive graphics or printouts have been routinely used by analysts to find and correct problems where algorithms have failed. Such labor-intensive data preprocessing has been the major obstacle to improving baseline production efficiency, uniformity, and reproducibility. The > 2500 cycle slips in the data set from the CASA Uno experiment made it clear that manual intervention in the data analysis had to be minimized since the task would have required many analysts, with a variety of non-reproducible editing styles.

This paper presents a reliable, automatic algorithm for editing dual-frequency GPS carrier phase data from receivers with P code pseudorange capability. The technique is especially attractive because, unlike most algorithms, it does not require any differencing of data between receivers or satellites. The algorithm could, therefore, be implemented in real time by receivers in the field. In addition, a model of the geometrical delay is not necessary, thus the algorithm is applicable to kinematic GPS (however, as will be explained, certain antenna effects must be accounted for).

The algorithm has been incorporated into the GIPSY software as a module called TurboEdit. The principles of the algorithm are described here in some detail, followed by a discussion of its performance, and possible adaptation to codeless receivers and ionospheric conditions which cause severe variations in phase delay.

Observable Model and Definitions

Many of the concepts outlined here were developed in *Blewitt* [1989] for purposes of carrier phase ambiguity resolution, which is the task of determining the integer number of wavelengths associated with the first phase measurement of a pass. Subsequent phase measurements will have the same associated integer, provided the receiver maintains lock on the GPS signal. Losses of lock cause integer discontinuities in the phase measurements, which in this paper are called "cycle slips." (As a cautionary remark, some engineers do not use this term if the discontinuity is caused by a low signal to noise ratio. For convenience, this paper makes no such distinctions). A time series of phase data which has no cycle slips is called a "phase connected arc." The objective of GPS data editing is to (1) delete data outliers, (2) identify cycle slips, (3) correct cycle slips wherever possible, and (4) introduce a carrier phase ambiguity parameter for each phase connected arc for further estimation using already established techniques [*Blewitt*, 1989; *Dong and Bock*, 1989].

Consider the following model for the GPS carrier phase and pseudorange observables specific to a receiver–satellite pair (i.e., for undifferenced data)

$$\begin{aligned} L_1 &\equiv -c\,\Phi_1/f_1 \\ &= \rho - I\,f_2^2/(f_1^2 - f_2^2) + \lambda_1 b_1 \qquad (1a) \\ L_2 &\equiv -c\,\Phi_2/f_2 \\ &= \rho - I\,f_1^2/(f_1^2 - f_2^2) + \lambda_2 b_2 \qquad (1b) \\ P_1 &= \rho + I\,f_2^2/(f_1^2 - f_2^2) \qquad (1c) \\ P_2 &= \rho + I\,f_1^2/(f_1^2 - f_2^2) \qquad (1d) \end{aligned}$$

where Φ_1 and Φ_2 are the recorded carrier phases, L_1 and L_2 are the carrier phases expressed as ranges, P_1

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and P_2 are the P code pseudoranges, c is the speed of light, the carrier frequencies $f_1 = 154 \times 10.23\,\mathrm{MHz}$ and $f_2 = 120 \times 10.23\,\mathrm{MHz}$, and the wavelengths $\lambda_1 \simeq 19.0\,\mathrm{cm}$ and $\lambda_2 \simeq 24.4\,\mathrm{cm}$. The term ρ refers to the non-dispersive delay, lumping together the effects of geometric delay, tropospheric delay, clock signatures, selective availability (rapid variations of the 10.23 MHz GPS reference frequency) and any other delay which affects all data types identically. The term I in equations (1) is an ionospheric delay parameter; b_1 and b_2 are phase biases which can change spontaneously by integer values (cycle slips).

Terms ignored by equations (1) include data noise, multipath, phase center effects, and higher order ionospheric effects. The differential delay between the L_1 and L_2 antenna phase centers could be easily accounted for [e.g., *Blewitt*, 1989]. Provided the L_1 and L_2 phase centers are less than about 2 cm apart, this term can be safely ignored for editing data from stationary antennas (but may be required for moving antennas).

Another term missing for kinematic GPS applications is due to antenna rotation causing a phase advance in the circularly polarized wavefront. This effect must be removed either by (1) external calibration, (2) differencing the data between two satellites, or (3) using only the wide-lane phase combination $(\Phi_1 - \Phi_2)$, which is rotationally invariant, but by itself is not suitable for regional geodesy since it is uncalibrated for ionospheric delay.

A cycle slip in L_1, denoted Δn_1, is defined as an integer discontinuity in the value of b_1, and similarly for Δn_2. Thus a cycle slip in dual frequency data can be described by the expression

$$(\Delta n_1, \Delta n_2) = (b_1' - b_1, b_2' - b_2) \tag{2}$$

where b_1' and b_2' are the new values of the phase biases after the cycle slip. Most often, cycle slips occur concurrently and differently on the L_1 and L_2 channels, so that non-zero values of Δn_1 and Δn_2 must be independently detectable.

Linear Combinations of Data

For purposes of estimating cycle slip parameters (Δn_1, Δn_2) we are free to choose 2 linear combinations of the 4 observables, expressed in equations (1), which are independent of the term ρ. This will guarantee that the data editing algorithm will be insensitive to clock instability, selective availability, and receiver–satellite kinematics.

The Wide-lane Combination

As was shown for the problem of ambiguity resolution [*Blewitt*, 1989], the wide-lane phase combination $\Phi_\delta \equiv (\Phi_1 - \Phi_2)$ can be adequately fit using pseudorange data of the quality produced by TI-4100 receivers. From equations (1), the wide-lane phase delay can be written

$$\begin{aligned} L_\delta &\equiv -\Phi_\delta \lambda_\delta \\ &= (f_1 L_1 - f_2 L_2)/(f_1 - f_2) \\ &= \rho + I\, f_1 f_2/(f_1^2 - f_2^2) + \lambda_\delta b_\delta \end{aligned} \tag{3}$$

where the wide-lane wavelength $\lambda_\delta \equiv c/(f_1 - f_2) \simeq 86.2\,\mathrm{cm}$, and the wide-lane bias, $b_\delta \equiv (b_1 - b_2)$.

To solve for wide-lane cycle slips the following pseudorange combination is subtracted from L_δ:

$$\begin{aligned} P_\delta &\equiv (f_1 P_1 + f_2 P_2)/(f_1 + f_2) \\ &= \rho + I\, f_1 f_2/(f_1^2 - f_2^2) \end{aligned} \tag{4}$$

From equations (3) and (4) we can write

$$b_\delta = \frac{1}{\lambda_\delta}\,(L_\delta - P_\delta) \tag{5}$$

The TurboEdit algorithm calculates time-averages of b_δ in equation (5) both before and after a cycle slip, and the difference is required to be close to an integer $\Delta n_\delta \equiv (b_\delta' - b_\delta) = \Delta n_1 - \Delta n_2$. The actual decision as to what constitutes a cycle slip, and whether phase connection is successful, will be described later.

The Ionospheric Combination

The ionospheric phase combination is defined as follows:

$$\begin{aligned} L_I &\equiv L_1 - L_2 \\ &= I + \lambda_1 b_1 - \lambda_2 b_2 \\ &= I + \lambda_1 (b_1 - b_2) + (\lambda_1 - \lambda_2) b_2 \\ &= I + \lambda_1 b_\delta - \lambda_I b_2 \end{aligned} \tag{6}$$

where the ionospheric wavelength $\lambda_I \equiv (\lambda_2 - \lambda_1) \simeq 5.4$ cm. The corresponding pseudorange combination is

$$P_I \equiv P_2 - P_1 = I \tag{7}$$

Unlike the wide-lane combination, the ionospheric carrier phase cannot be successfully calibrated by the pseudorange, since it would require that multipath be controlled at the centimeter level. The approach that will be described assumes that the ionospheric parameter I behaves as a reasonably smooth function.

Cycle slip Detection and Correction

Cycle Slip Detection in the Wide-Lane Combination

The wide-lane bias, equation (5), is estimated independently at every data epoch. An a priori RMS scatter of 0.5 wide-lane cycles is assumed (a good assumption in almost all cases), and the algorithm sequentially updates $\langle b_\delta \rangle$, the mean value of b_δ, and σ, the RMS scatter, using the following recursive formulae:

$$\langle b_\delta \rangle_i = \langle b_\delta \rangle_{i-1} + \frac{1}{i}\left(b_{\delta\, i} - \langle b_\delta \rangle_{i-1}\right) \tag{8a}$$

$$\sigma_i^2 = \sigma_{i-1}^2 + \frac{1}{i}\left\{\left(b_{\delta\, i} - \langle b_\delta \rangle_{i-1}\right)^2 - \sigma_{i-1}^2\right\} \tag{8b}$$

The calculation of the mean is exact; the calculation of the RMS is a good approximation to simplify the code, and has the diminishing error term of $O(1/i^2)$, where i is the current number of points in the data arc. Subsequent epoch estimates $b_{\delta\, i+1}$ are required to lie within $4\sigma_i$ of the running mean $\langle b_\delta \rangle_i$. Isolated outliers are deleted, and any two consecutive outliers lying within 1 cycle are considered to indicate the possibility that a cycle slip has occurred. Starting with these two points, a new average is started, and continues until a potential cycle slip is again encountered. The values $\langle b_\delta \rangle$ and σ for each phase connected arc are computed using equations (8), and are stored for further analysis.

Wide-lane Phase Connection

The stored values of $\langle b_\delta \rangle$ for each phase connected arc are differenced with the value which has smallest standard error in the mean $\sigma_N/\sqrt{(N-1)}$, where N is the number of data in the arc. The integer offset between the two arcs is determined by rounding off this difference if the standard error in the difference is less than 0.15 ($\sim 1/6$) cycles, and the fractional part of the difference is less than 0.30 cycles (2 standard deviations).

As data arcs are phase connected, the time-average $\langle b_\delta \rangle$ of the aggregate arc is computed at each step to statistically enhance subsequent phase connection. For multiple losses of lock which cause a sequence of cycle slips to occur in a short period of time, the approach taken is to delete all the data between the first and last cycle slip, and to subsequently connect phase across this gap, which is typically a few minutes.

Usually, for the TI-4100 receiver, 15 minutes of continuous phase data before and after a cycle slip is adequate to satisfy the criteria for wide-lane phase connection. For the Rogue receiver [*Thomas*, 1988] with a choke-ring backplane, 1 minute of data is sufficient. The critical factor determining the required length of time is the accuracy of the pseudorange measurements, which is both a function of receiver precision and the effectiveness of antenna backplanes in controlling multipath. Sample rate is not an important factor (assuming receivers internally average the pseudorange signal), neither is the carrier phase measurement accuracy.

Cycle Slip Detection in the Ionospheric Combination

First, the hypothesis is made that there are cycle slips in the ionospheric combination (L_I of equation (6)) whenever there are wide-lane cycle slips. We should, however, be prepared for the extremely unlikely event that a cycle slip occurs such that the widelane discontinuity $\Delta n_\delta = 0$, i.e., $\Delta n_1 = \Delta n_2$. To guard against this, a polynomial fit Q to P_I of equation (7) is subtracted from L_I, and then we search for discontinuities in the residual, $(L_I - Q)$. (This fit to the pseudorange spans all the data, since the pseudorange does not have integer cycle discontinuities).

Standard statistical techniques for optimizing the order of the polynomial fit are not applicable in this case because the pseudorange multipath errors can be very correlated with high order polynomials. We have empirically found it more effective to use the following integer arithmetic to compute the polynomial order: $m = \min[(N/100 + 1), 6]$. Undoubtedly, better algorithms could be developed for fitting the ionosphere, but only a crude fit is necessary to search for discontinuities and this fit is not used to infer the value of the cycle slip.

If we denote the value of the polynomial Q at epoch j as Q_j, then we identify i as the first good data point after the occurrence of a cycle slip if both of the following two conditions are met:

$$(L_{I\,i} - Q_i) - (L_{I\,i-1} - Q_{i-1}) > k \text{ cycles} \tag{9a}$$

$$(L_{I\,i+1} - Q_{i+1}) - (L_{I\,i} - Q_i) < 1 \text{ cycles} \tag{9b}$$

Equation (9a) is also used to identify outliers. The value of k defaults to 6 cycles, but can be set to a more appropriate value should ionospheric conditions be unusual. The reasons for having such a high tolerance (6×5.4 cm) for ionospheric discontinuities are that (1) there are quite often large phase variations for receivers at high latitudes due to ionospheric activity which are not to be confused with cycle slips and (2) the chances of having identical slips, $\Delta n_1 = \Delta n_2$, of less than 6 cycles are very slim, based on to our experience with the TI-4100 receiver. Note that equation (9b) is much more stringent than (9a), because the initial point in a data arc is often spurious due to the receiver having not completely recovered from losing lock.

Ionospheric Phase Connection

If wide-lane phase connection is successful, a polynomial fit is made to L_I of equation (6) before the cycle slip, then extrapolated to data just after a cycle slip. Using our knowledge of Δn_δ, it is then straightforward to resolve $\Delta n_2 = (b_2' - b_2)$ by subtracting the extrapolated fit from the first few data points after the cycle slip. The order of the polynomial is chosen by increasing the order until the subsequent reduction in post-fit residual scatter is consistent with that due to random noise. This procedure most often selects a quadratic fit.

Before attempting ionospheric phase connection, however, the validity of polynomial extrapolation is tested on a set of at least 20 data which are free of cycle slips, immediately before the cycle slip in question. The procedure is considered valid if the backward extrapolation gives an estimate of the imaginary cycle slip of less than 0.25. If valid, then extrapolation across a bias break is attempted. If the cycle slip has an estimated value of $\Delta n_2 < 0.5$, then the cycle slip hypothesis is discarded. If $\Delta n_2 > 0.5$, then a cycle slip is assumed, and the nearest integer value is taken if the deviation of the estimate from this integer is < 0.25. If the fit fails to connect phase, a second attempt is made using twice as many points in the fit.

Integer-Cycle Adjustment of Data

Each carrier phase data point is corrected by an integer number of cycles, and the "phase connected ranges" are formed:

$$R_1 = L_1 + \lambda_1 m_1 \tag{10a}$$

$$R_2 = L_2 + \lambda_2 m_2 \tag{10b}$$

The integer values of m_1 and m_2 for the first data epoch are arbitrary, but for reasons of convenience are chosen such that R_1 and R_2 agree as closely as possible with the pseudoranges, P_1 and P_2. Subsequent changes in the bias values are calculated using the above algorithms:

$$(\Delta m_1, \Delta m_2) = (-\Delta n_\delta - \Delta n_2, -\Delta n_2) \tag{11}$$

In the event of an unresolved cycle slip, the best available values for $(\Delta m_1, \Delta m_2)$ are used and, as described by *Blewitt* [1989], they are eventually resolved using ambiguity resolution techniques after Kalman filtering all available data (assuming a sufficiently well-designed network).

Discussion of the Algorithm

Properties

The algorithm is completely insensitive to variations in non-dispersive delay, whether they be due to clock behavior, frequency variations of selective availability, receiver–satellite relative motion, tropospheric delay, etc. However, the algorithm can be sensitive to ionospheric activity and multipath environments. In addition, since the algorithm relies on time-averaging, it may not work too well if the receiver never maintains lock for more than about 10 minutes. Ionospheric problems may be alleviated using a higher data sampling rate. We suggest that bad multipath conditions and high cycle slip rates are better addressed by an appropriate selection of field equipment and sites rather than by data processing techniques.

Performance

Studies with this algorithm applied to the vast CASA Uno data set indicate that the need for additional manual editing has been virtually eliminated. Over 99% of the station–satellite passes required no further analyst intervention. Almost all of the remaining 1% had incorrectly determined integer discontinuities due to rapid variations in the ionospheric phase delay.

Subjectively, the algorithm sometimes appears to be overly conservative in deciding whether to correct for cycle slips; however, experience has shown that the analyst can be easily misled by anomalous clock and ionospheric behavior. Therefore, the general philosophy recommended here is for the algorithm to insert extra bias parameters when in doubt, leaving them to be resolved later by ambiguity resolution techniques.

Efficiency

On a Digital MicroVAX II computer, the cpu time used by this algorithm was approximately 20 sec per station–satellite arc (each approximately of 3 hours duration, with a 30 sec data sampling rate), which turns out to be about 1 day for the entire, 3 week CASA Uno data set. This number includes cpu time for various plotting computations to give a record of decisions made by the algorithm.

Adaptations

The algorithm above can be adapted for (1) non-P code receivers and (2) bad ionospheric conditions. In the case of codeless receivers, an alternative to using the pseudorange to calibrate the wide-lane phase as in equation (5) is to fit the wide-lane phase using polynomials. The disadvantage to this is would be the algorithm's sensitivity to to clocks, satellite motion, etc. Should receiver clocks be insufficiently stable, the algorithm can still be applied to differenced data from a pair of satellites to a common receiver. This still allows the algorithm to be implemented in real time on the receiver, but may fail under certain conditions of selective availability. Note that the difficulty in editing wide-lane data for codeless receivers is compounded by half integer cycle slips.

Under conditions of high ionospheric activity, an alternative approach to using the ionospheric combination is to use the well-known ionosphere-free combination $L_C \equiv (f_1{}^2 L_1 - f_2{}^2 L_2)/(f_1{}^2 - f_1{}^2)$. Assuming that wide-lane phase connection has been successful, cycle slips in the L_C linear combination are integer multiples of 10.7 cm wavelengths [c.f. *Blewitt*, 1989]. Unfortunately, this approach is very sensitive to clock variations. A possible solution to this is to use high quality receiver clocks. Differencing L_C data between pairs of satellites may also be effective; however, this increases the variability in the data due to satellite clocks and measurement noise.

Conclusions

An algorithm has been developed for rapid GPS data editing which can ultimately be implemented in real time field software for dual-frequency P code pseudorange receivers. Most importantly, the algorithm is insensitive to clock variations, satellite motion, and conditions of selective availability. Tests on the CASA Uno data sample with TI-4100 receivers show that 99% of station–satellite arcs require no further analyst intervention. The algorithm is adaptable to non P code receivers, or situations with high ionospheric activity, provided a stable receiver clock is used. Developments are currently underway to implement code based on this algorithm in the Rogue receiver for continuously operating arrays.

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