An Automatic Cycle-Slip Processing Method and Its Precision Analysis

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ABSTRACT  On the basis of analyzing and researching the current algorithms of cycle-slip detection and correction, a new method of cycle-slip detection and correction is put forward in this paper, that is, a reasonable cycle-slip detection condition and algorithm with corresponding program COMPRE (COMpass PRE-processing) to detect and correct cycle-slip automatically, compared with GIPSY and GAMIT software, for example, it is proved that this method is effective and credible to cycle-slip detection and correction in GPS data pre-processing.

KEYWORDS  GPS; cycle-slip; detection; correction; ambiguity

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Introduction

In the applications of GPS positioning, orbit determination or navigation, carrier phase and pseudo-range are two main measurements. Among others, pseudo-range is free to ambiguity and cycle-slip, and simply computing, but with low measurement precision; carrier phase wavelength is far shorter than code ranging and of higher precision, the precision of carrier phase measurements can be about 2 mm\(^3\), the precision of point positioning can be cm-level and of relative positioning can be mm-level. So for the mm-level precise positioning and scientific study one must use carrier phase measurements, but should be aware of the problem of cycle-slip and ambiguity resolution. Therefore it is the main aim to detect and correct cycle-slip and resolve ambiguity in GPS pre-processing.

Presently, many methods of cycle-slip detection and correction have been developed, such as differential\(^2\), wide-lane combination and pseudo-range combination\(^3\), ionospheric combination, multi-normal fitting\(^4\), linear fitting, dynamic model, differential between satellites and differential between stations, Autch\(^5\) in GAMIT and Turboedit in GIPSY, and so on. Jia Peizhang analyzed the effective of Turboedit in GIPSY\(^6\) and put forward the Kalman filtering algorithm and wavelet analysis method of single frequency GPS data\(^7\). A new method of cycle-slip detection and correction is put forward in this paper.

1 Measurement equations and their linear combinations

1.1 Measurement equation

In equations of carrier phase and pseudo-range, we neglected some effects of systematic error and random error, usually, the basic measurement equations of carrier phase and pseudo-range in consideration of these effects are shown as follows.

\[
L_1 = \lambda_1 \phi_1 = \rho - \frac{f_2}{f_1} d_{\text{ion}} + \lambda_1 b_1 + \sum M_{t_1}
\]

\[
L_2 = \lambda_2 \phi_2 = \rho - \frac{f_1}{f_2} d_{\text{ion}} + \lambda_2 b_2 + \sum M_{t_2}
\]

(1)
\[
P_1 = \rho + \frac{f_1^2}{f_1^2 - f_2^2} d_{\text{ion}} + \sum M_{1_1}
\]
\[
P_2 = \rho + \frac{f_1^2}{f_1^2 - f_2^2} d_{\text{ion}} + \sum M_{1_2}
\]
where
\[
\sum M_{1_1} = C_1 + C_2 + d_{\text{ion}} + d_{M_1} + R + \epsilon = M_1 + \epsilon
\]
\[
\sum M_{1_2} = C_1 + C_2 + d_{\text{ion}} + d_{M_2} + R + \epsilon = M_1 + \epsilon
\]
\[
\sum M_{1_1} = C_3 + C_4 + d_{\text{ion}} + d_{M_1} + R + \epsilon = M_2 + \epsilon
\]
\[
\sum M_{1_2} = C_3 + C_4 + d_{\text{ion}} + d_{M_2} + R + \epsilon = M_2 + \epsilon
\]
\[
M' = C_1 + C_2 + d_{\text{ion}} + R \text{ is the item free from frequency; } c \text{ is light velocity; } \lambda_1, \lambda_2 = \frac{c}{f_1}, \frac{c}{f_2} \text{ are phase, frequency, wavelength and ambiguity of } L_1, L_2 \text{ respectively; } P_1, P_2 \text{ are pseudo-ranges of } L_1, L_2 \text{ respectively; } d_{\text{ion}} \text{ is ionospheric effect; } \rho \text{ is geometry distance from satellite to station; } C_1 \text{ is satellite clock offset; } C_2 \text{ is receiver clock offset; } d_{\text{ion}} \text{ is tropospheric delay; } d_M \text{ is the multi-path effect; } R \text{ is relative effect; } \epsilon, e \text{ are noise respectively; } \sum M_{1_1}, \sum M_{1_2} \text{ are the total carrier measurements error of } L_1, L_2 \text{ respectively; } \sum M_{1_1}, \sum M_{1_2} \text{ are the total code measurements error of } P_1, P_2 \text{ respectively.}
\]

1.2 Wide-lane combination

According to the basic equations, let
\[
L_2 = \lambda_2 (\phi_2 - \phi_2) = \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2} = \rho + d_{\text{ion}} - \frac{f_1 f_2}{f_1^2 - f_2^2} + \lambda_2 b_2 + \epsilon
\]
where \( \lambda_2 = \frac{c}{f_1 - f_2} \approx 86.2 \text{ cm is wide wavelength; } b_2 = b_2 - b_1 \text{, we define } b_2 \text{ is the ambiguity residual between two frequencies.}
\]
What is more, let
\[
P_z = \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2} = \rho + d_{\text{ion}} - \frac{f_1 f_2}{f_1^2 - f_2^2} + e
\]
Then, combining the Eq. (3) and Eq. (4), we can get
\[
b_{1_1} = b_1 - b_2 = \frac{1}{\lambda_2} (L_3 - P_4) = \phi_1 - \phi_2 - k(\bar{P}_1 + \bar{P}_2) + \bar{e}
\]
where
\[
k = \frac{f_1 - f_2}{f_1 + f_2} = \frac{17}{137}, \bar{P}_1 = \frac{P_1}{\lambda_1}, \bar{P}_2 = \frac{P_2}{\lambda_2}.
\]
In Eq. (5), wide-lane combination deletes geometry distance \( \rho \), ionospheric effect and systematic error, and just leaves ambiguity item, it is close to a constant if no cycle-slip.

From Eq. (2), geometry distance can be shown:
\[
\rho = \frac{f_1 f_2}{f_1^2 - f_2^2} \cdot P_1 - \frac{f_1 f_2}{f_1^2 - f_2^2} \cdot P_2 + e
\]
Differential between adjacent epochs of \( b_2 \):
\[
\Delta b_2 (t_n, t_{n-1}) = \Delta b_1 - \Delta b_2 = \frac{1}{\lambda_2} (\Delta L_4 - \Delta P_4) = \Delta \phi_1 - \Delta \phi_2 - k (\Delta \bar{P}_1 + \Delta \bar{P}_2)
\]
Ionospheric effect:
\[
d_{\text{ion}} = P_2 - P_1
\]

1.3 Single epoch ambiguity

According to Eq. (1), we can get the formulas of single epoch ambiguity as follows:
\[
b_1 = \phi_1 + \frac{1}{\lambda_1} (\frac{f_1 f_2}{f_1^2 - f_2^2} d_{\text{ion}} - \rho)
\]
\[
b_2 = \phi_2 + \frac{1}{\lambda_2} (\frac{f_1 f_2}{f_1^2 - f_2^2} d_{\text{ion}} - \rho)
\]
It is well known that there is no systematic error in single epoch ambiguity according to the Eq. (9). We can calculate single epoch ambiguity on \( L_1 \) and \( L_2 \) with Eq. (9), if there is no cycle-slip, the ambiguity of adjacent epoch is similar. So we can detect cycle-slip by adjacent epoch ambiguity.

2 Cycle-slip detection and correction

2.1 Detection condition

The regressive computation formula of \( b_2 \) is
\[
\langle b_2 \rangle_i = \langle b_2 \rangle_{i-1} + \frac{1}{i} (b_2 - \langle b_2 \rangle_{i-1})
\]
where \( \langle \rangle \) means the mean value computed by regression method.

Besides, the regressive computation formula of ambiguity is