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ORIGINAL ARTICLE

Multipath detection based on single orthogonal dual linear polarized GNSS antenna

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Abstract Based on the polarization difference between the multipath and the line-of-sight (LOS) signal, a method for multipath detection using a single antenna is proposed. The antenna has two channels to receive two orthogonal linear polarized components of the multipath and LOS signal, respectively. A hypothetical model of the antenna is employed such that the antenna patterns of the channels are assumed identical regarding amplitude and phase and are independent of azimuth. The antenna gain in the direction below the local horizon is assumed to be larger than in the direction toward LOS signals. Parallel cross-cancellation is used to remove the LOS signal from the received signals based on the magnitude and phase difference between the two orthogonal components. Then the residual signals are processed by a conventional digital processor of global navigation satellite system. The multipath can be detected by parallel cross-cancellation in the receiver in real time. The proposed method makes use of the polarization and spatial information of the multipath and LOS signal, and can detect short-delay multipath.

Keywords Multipath detection · Dual-polarized antenna · Parallel cross-cancellation · GNSS

Introduction

The estimated position using GNSS is affected by several sources of errors including atmospheric, orbital, and receiver clock errors, and jamming. Although differential processing techniques eliminate many errors, the multipath still compromises the performance of GNSS. Multipath propagation is caused by reflections and diffractions of the GNSS signals from objects such as ground, wall, and tree. The spread spectrum signal of GNSS is resistant to the multipath phenomenon. Signal processing techniques such as narrow correlation (Dierendonck et al. 1992) and double-delta multiple correlators (McGraw and Braash 2009) can also be used to mitigate multipath. However, these techniques have inherent drawbacks and are not effective for short-delay multipath.

A single antenna with choke ring or large ground plane can improve the down-to-up ratio and weaken the received multipath. However, the choke ring antenna performs badly when the multipath arrives from low elevation near the horizon. Helix antennas with cutoff patterns (Tatarnikov et al. 2016) could provide 20-dB suppression of the multipath, starting from low elevations. Determinate beamforming has been proposed to design the multipath limiting antenna for Local Area Augmentation System (LAAS) (Sharawi and Aloi 2006). These kinds of antennas are too large and heavy to be considered for a compact receiver.

In multiple-antenna receivers, spatial diversity has been shown to be an effective tool to mitigate multipath. There are adaptive multipath mitigation algorithms based on unusual arrays, such as a moving array (Daneshmand and Broumandan 2013), switch array (LaMance and Small 2011), and L-shape array (Sun et al. 2015). These algorithms can effectively mitigate the effect of multipath but require either previous knowledge of the LOS signal or high signal-to-noise ratio (SNR). Moreover, a maximum likelihood (ML) algorithm is also proposed to mitigate multipath (Rougerie et al. 2011; Rougerie and Carrie 2012; Seco-Granados et al. 2005). These algorithms perform well

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and achieve coherent multipath mitigation when multipath is present, at the cost of an increased computational burden when compared to the regular delay lock loop (DLL).

Multipath detection is considered an effective tool to mitigate the influence of multipath for local survey GNSS receivers. The detected characteristics of multipath can be used to assist the DLL to mitigate the influence of multipath. Otherwise, in GNSS monitoring stations, multipath detection can help the system to determine the quality of observations.

Existing multipath detectors with single antenna usually operate at the observable level, e.g., day-to-day correlation can be used to identify and remove multipath errors. These strategies are typically based on the pseudorange, the SNR (Comp and Axelrad 1998), and the instantaneous difference between the pseudorange and the carrier phase (Braasch 1994). However, these techniques are still unable to cope with short-delay multipath.

The multiple-antenna receiver can distinguish different sources. For instance, the relation between the arithmetic and the geometric means of the eigenvalues of the covariance matrix has been used to detect multipath (Closas and Fernández-Prades 2011). Nevertheless, the method needs a prior knowledge of the number of multipaths present. With a multiple-antenna receiver in tracking mode, the statistical values of the correlates of multiple channels can be exploited to define a multipath detector using an analysis of variance algorithm (Brenneman et al. 2010). However, the method cannot be applied directly to the input signal because the GNSS signal is a weak spread spectrum signal that is not statistically detectable. Beamforming can be applied to remove the LOS signal from the received signals, then the normal DLL can detect the multipath from residual signals (Li et al. 2015), but the direction of arrival (DOA) of the LOS signal must be known prior, and the multipath may also be removed by beamforming.

Polarization estimation is an effective tool to detect multipath. Orthogonal multi-polarized antenna known as vector sensor has been proposed by Nehorai and Paldi (1994). The DOA and the polarization can be estimated using three orthogonal electric fields and three orthogonal magnetic fields measured by the three dipoles and three loops (Wong et al. 2004). Further, physical airborne vector sensors are tested by Mir and Sahr (2007), and distributed vector sensor with the same performance has been proposed by Monte et al. (2007). However, the vector sensor is difficult to be miniaturized, and the requirements on the production process are very high. Multipath detection can also be achieved based on polarized diversity (Manandhar and Shibasaki 2004; Brenneman et al. 2007; Jiang and Groves 2014). Right-hand circular polarized (RHCP)/left-hand circular polarized (LHCP) signals are received by dual-polarized antennas individually. The difference in the SNR of the RHCP and LHCP signal is observed to detect the presence of multipath. However, the method can only be applied on software-defined receiver.

We propose a multipath detector based on a single dual-polarized antenna, without any previous knowledge of their characteristics and an increased computational burden. The antenna is assumed to have two pure LP channels on the direction of x-axis and y-axis individually. The patterns of the two channels are assumed to be the same both in gain and in phase and to be azimuth-independent. The polarized diversity between the horizontal polarized and the vertical polarized component of RHCP is used to remove the LOS signal by parallel cross-cancellation when the DOA of the LOS signal is known prior. Then the multipath can be detected by parallel cross-cancellation in the receiver in real time.

Ground reflection characteristics

The specular reflections model is widely used for estimating the characteristics of reflection. The basic geometry for ground reflection is shown in Fig. 1. The polarization of the ground reflected signal experiences a transformation upon reflection.

Any polarized incoming wave can be resolved in two orthogonal components, such as the vertical polarized and horizontal polarized component. As shown in Fig. 1, the propagating direction of the incoming wave is orthogonal to the instantaneous electric field. The two orthogonal components of incoming wave E_i and reflected wave E_r can be expressed as

$$E_i = \begin{bmatrix} E_{i\theta} \\ E_{i\phi} \end{bmatrix} = E_i \begin{bmatrix} \sin\gamma e^{j\eta} \\ \cos\gamma \end{bmatrix} \qquad (1)$$

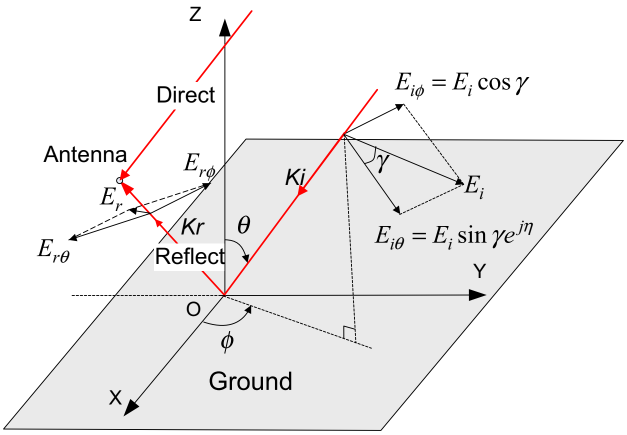

Fig. 1 Basic geometry of incoming wave and reflected wave

$$E_r = \begin{bmatrix} E_{r\theta} \\ E_{r\phi} \end{bmatrix} = E_i e^{j2\pi f \Delta\tau} \begin{bmatrix} \Gamma_{\mathrm{HP}} \sin\gamma e^{j\eta} \\ \Gamma_{\mathrm{VP}} \cos\gamma \end{bmatrix} \tag{2}$$

where $E_{i\theta}$, $E_{i\phi}$, $E_{r\theta}$, and $E_{r\phi}$ denote the horizontal polarized and vertical polarized component of the incoming and reflected wave, respectively. Additionally, γ denotes the angle between the electric field E_i and the horizontal polarized component $E_{i\theta}$, while η denotes the advance phase of $E_{i\theta}$ versus $E_{i\phi}$. The γ and η represent the polarization of the incoming wave, with $\gamma = 45°$ and $\eta = -90°$ for RHCP signal. In (2), the symbol $\Delta\tau$ denotes the extra delay of multipath compared to the LOS signal. The extra transmission loss is ignored, and f represents the frequency of the incoming wave.

The reflection factor for vertical polarization Γ_{VP} and horizontal polarization Γ_{HP} is given by Sharawi and Aloi (2006),

$$\begin{aligned} \Gamma_{\mathrm{VP}}(\theta) &= \frac{\left(\varepsilon_r - j\frac{\sigma}{f\varepsilon_0}\right)\cos\theta - \sqrt{\left(\varepsilon_r - j\frac{\sigma}{f\varepsilon_0}\right) - \sin^2\theta}}{\left(\varepsilon_r - j\frac{\sigma}{f\varepsilon_0}\right)\cos\theta + \sqrt{\left(\varepsilon_r - j\frac{\sigma}{f\varepsilon_0}\right) - \sin^2\theta}} \\ \Gamma_{\mathrm{HP}}(\theta) &= \frac{\cos\theta - \sqrt{\left(\varepsilon_r - j\frac{\sigma}{f\varepsilon_0}\right) - \sin^2\theta}}{\cos\theta + \sqrt{\left(\varepsilon_r - j\frac{\sigma}{f\varepsilon_0}\right) - \sin^2\theta}} \end{aligned} \tag{3}$$

where ε_0 denotes free space dielectric constant, ε_r is relative dielectric constant, σ is conductivity, and θ represents the incoming zenith angle.

The spherical coordinates are then transformed into rectangular coordinates as

$$\begin{bmatrix} E_{ix} \\ E_{iy} \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\phi & -\sin\phi \\ \cos\theta\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} E_{i\theta} \\ E_{i\phi} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} E_{rx} \\ E_{ry} \end{bmatrix} = \begin{bmatrix} \cos(-\theta)\cos(\phi) & -\sin(\phi) \\ \cos(-\theta)\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} E_{r\theta} \\ E_{r\phi} \end{bmatrix} \tag{5}$$

where E_{ix}, E_{iy}, E_{rx}, and E_{ry} denote the LP component on the x-axis and y-axis of incoming and reflected wave, respectively. The angle ϕ represents the incoming azimuth as shown in Fig. 1.

The details of specular reflections of circular polarized wave are widely known and have been fully introduced in Leick et al. (2015). As shown therein, the magnitude of the reflection factor for an incident circularly polarized signal is large when the signal is from large zenith angle closer to the horizon, and the variation is dependent of the type of ground. The reflection phase for the vertically polarized component changes 180° across the Brewster angle. For dry ground, the Brewster angle is about 64° while for wet ground it is 76°.

Assume that the LOS signal is RHCP and the axial ratio is zero. The axial ratio of the multipath, taking as the ratio of vertical polarized and horizontal polarized component, is shown in Fig. 2. The magnitude of the vertical polarized and horizontal polarized component for the LOS signal is nearly equal. However, the balance is broken when the ground reflects the signal. Around the Brewster angle, the axial ratio gets worse significantly. For the same reason, the magnitude ratio of the two orthogonal LP components on the x-axis and y-axis of the multipath is also very different from that of the LOS signal.

For small zenith angle near the vertical, the axial ratio changes slowly while the reflected magnitude of multipath is small. For large zenith angle near the horizon, the reflected magnitude of multipath is nearly equivalent to that of the LOS signal, but the axial ratio changes acutely. Since the target to detect is the strong multipath at around the Brewster angle, the worsening axial ratio can be used to distinguish the multipath from the LOS signal when the two orthogonal LP components on the x-axis and y-axis can be received individually.

Multipath detection based on single antenna

In this section, the parallel cross-cancellation receiver is proposed. The receiver has a single orthogonal dual-polarized antenna to receive the two orthogonal LP components of the LOS signal and the multipath on the x-axis and y-axis individually. Then the LOS signal is removed from the received signal by cross-cancellation. First, the signal model based on parallel cross-cancellation receiver is introduced. Then the process of cross-cancellation is analyzed.

The following assumptions are made to simplify the analysis, and all the following is based on the special case meeting these assumptions:

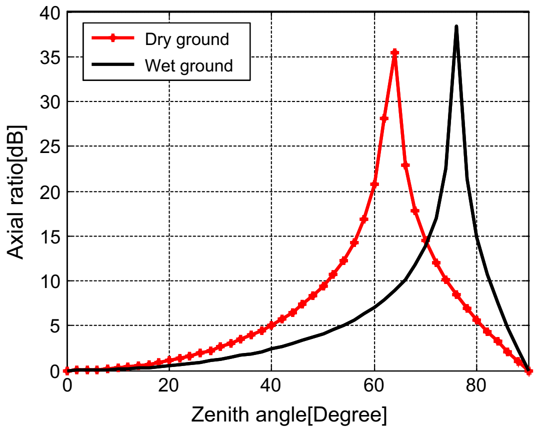

Fig. 2 Axial ratio of ground multipath versus zenith angle

- The receiver has prior knowledge about the DOA of the LOS signal. Initial weights can be set to make sure that the receiver could achieve positioning. It is reasonable to assume that the DOA is measured when the receiver platform attitude is known with the help of other sensors, such as inertial navigation unit.
- The antenna has a pure LP channel on the direction of *x*-axis and *y*-axis, respectively. The patterns of the two channels are the same both in gain and in phase, and are azimuth-independent.
- The down-to-up gain ratio (D/U) of the antenna is larger than 2 dB for any azimuth when the incoming zenith angle is smaller than 80°, which means that the gain of antenna in down direction is 2 dB greater versus that in up direction.

Signal model of orthogonal dual-polarized antenna

The parallel cross-cancellation receiver and its receiving channels are shown in Fig. 3. The antenna has two channels to individually receive the LP signal on the *x*-axis (XP) and the LP signal on *y*-axis (YP). In the parallel cross-cancellation receiver, each port is followed by an independent RF front-end. Each LP component received by the antenna is then down-converted to baseband by low noise amplifier, filters, and mixers in the RF front-end. The base band signal is converted by the analog-to-digital converter (ADC) to a digital signal. Cross-cancellation can be achieved by the two parallel receiving channels. The residual signals are then transmitted to the tracking channel.

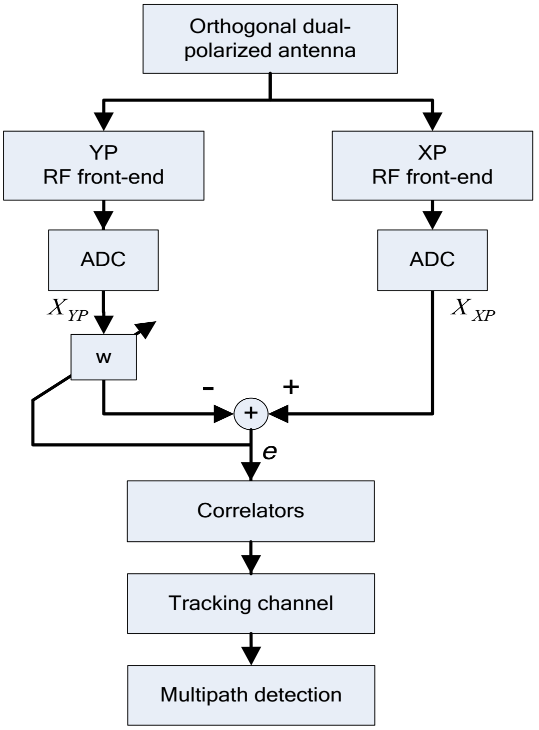

Fig. 3 Parallel cross-cancellation receiver with orthogonal dual-polarized antenna

The LOS signal $x_i(t)$ and multipath $x_r(t)$ arriving at the orthogonal dual-polarized antenna can be expressed as

$$\begin{aligned} x_i(t) &= x_{ix}(t) + x_{iy}(t) \\ &= s(t).\begin{bmatrix} (\cos\theta\cos\phi\sin\gamma e^{j\eta} - \sin\phi\cos\gamma)+ \\ (\cos\theta\sin\phi\sin\gamma e^{j\eta} + \cos\phi\cos\gamma) \end{bmatrix} \end{aligned} \tag{6}$$

$$\begin{aligned} x_r(t) &= x_{rx}(t) + x_{ry}(t) \\ &= s(t)e^{-j2\pi f\Delta\tau}\cdot\begin{bmatrix} (\cos\theta\cos\phi\Gamma_{\mathrm{HP}}\sin\gamma e^{j\eta} - \sin\phi\Gamma_{\mathrm{VP}}\cos\gamma)+ \\ (\cos\theta\sin\phi\Gamma_{\mathrm{HP}}\sin\gamma e^{j\eta} + \cos\phi\Gamma_{\mathrm{VP}}\cos\gamma) \end{bmatrix} \end{aligned} \tag{7}$$

Assume that $s(t)$ represents the LOS signal of the GNSS satellite arriving at the receiver, and we have

$$s(t) = Ap(t - \tau_0)\cos(2\pi ft + \varphi_0) \tag{8}$$

where A denotes the magnitude, *p(t)* denotes the pseudo-random code, τ_0 denotes the propagation delay of the LOS signal, and φ_0 denotes the carrier phase of the LOS signal.

The signal received by vertical polarized port X_{XP} and horizontal polarized port X_{YP} can be expressed as

$$X_{\mathrm{XP}} = G(\theta)x_{ix} + G(\pi - \theta)x_{rx} + n_1 \tag{9}$$

$$X_{\mathrm{YP}} = G(\theta)x_{iy} + G(\pi - \theta)x_{ry} + n_2 \tag{10}$$

where $G(\theta)$ and $G(\pi - \theta)$ denote the pattern of antenna at incoming zenith angle θ and $\pi - \theta$, while n_1 and n_2 denote the white Gaussian noise with zero mean. Then the signal after cross-cancellation is

$$\begin{aligned} e(t) &= X_{\mathrm{XP}} - wX_{\mathrm{YP}} \\ &= G(\theta)s(t)e_d + G(\pi - \theta)s(t)\cdot e^{-j2\pi f\Delta\tau}e_m + n_3 \end{aligned} \tag{11}$$

On the right of (11), the first term is the residual LOS signal, while the second term is the residual multipath. The ideal RHCP signal can be expressed with $\gamma = 45°$, $\eta = -90°$. However, the actual GNSS signal is not an ideal RHCP signal, so the polarization has some bias. The complex residual factor is defined as

$$\begin{aligned} e_d = {} & \cos\theta\sin(\pi/4 + \Delta\gamma)e^{-j(\pi/2+\Delta\eta)}(\cos\phi - w\sin\phi) \\ & - \cos(\pi/4 + \Delta\gamma)(w\cos\phi + \sin\phi) \end{aligned} \tag{12}$$

$$\begin{aligned} e_m = {} & \cos\theta\Gamma_{\mathrm{HP}}\sin(\pi/4 + \Delta\gamma)e^{-j(\pi/2+\Delta\eta)}(\cos\phi - w\sin\phi) \\ & - \Gamma_{\mathrm{VP}}\cos(\pi/4 + \Delta\gamma)(w\cos\phi + \sin\phi) \end{aligned} \tag{13}$$

where $(\Delta\gamma, \Delta\eta)$ denotes the polarization bias of actual signal. So $(\Delta\gamma, \Delta\eta)$ represents the non-ideal characteristic of actual GNSS signal.

Multipath detection

Multipath detection must remove the LOS signal from the received signal. The proposed method is to adjust the weight to make the residual factor of the LOS signal to be too small to influent the detection of multipath. Two cases are analyzed regarding prior knowledge about polarization of the LOS signal.

Case 1: Polarization of the LOS signal is precisely known

In this case, the quantity $(\Delta\gamma, \Delta\eta)$ is precisely known, and the weight is adjusted as

$$w = \frac{\cos\theta\cos\phi\sin\gamma e^{j\eta} - \sin\phi\cos\gamma}{\cos\theta\sin\phi\sin\gamma e^{j\eta} + \cos\phi\cos\gamma} \tag{14}$$

then the LOS signal is removed. As shown in Fig. 3, because the axial ratio of the multipath is large, the cross-cancellation cannot remove the multipath completely. The residual multipath is still strong enough to be detected.

The correlation can be expressed as

$$IR_p(\varepsilon) = G(\pi-\theta)AT_cR_{es}(\varepsilon-\Delta\tau_0)e_m\cos(\varphi_e+\Delta\varphi_1) \tag{15}$$

$$R_{\mathrm{es}}(\varepsilon) = \frac{1}{T_{\mathrm{c}}}\int_0^{T_{\mathrm{c}}} p(t)p_s(t-\varepsilon)\mathrm{d}t \tag{16}$$

where T_{c} represents the coherent integration time, φ_e denotes the residual carrier phase, and $\Delta\varphi_1$ denotes the extra phase as a result of multipath. Since the correlation of the LOS signal is removed in the right of (15), the multipath can be detected easily by detection of the correlation peak in the DLL.

Case 2: Polarization of the LOS signal is unknown

When the polarization of the LOS signal is unknown, the weight is adjusted as

$$w = \frac{\cos\theta\cos\phi e^{-j\pi/2} - \sin\phi}{\cos\theta\sin\phi e^{-j\pi/2} + \cos\phi} \tag{17}$$

Since the GNSS signal is RHCP, the quantity $(\Delta\gamma, \Delta\eta)$ is very small. The correlation is expressed as

$$\begin{aligned} IR_p(\varepsilon) = {} & G(\theta)AT_cR_{es}(\varepsilon)e_d\cos\varphi_e + G(\pi-\theta)AT_cR_{es} \\ & \times(\varepsilon-\Delta\tau_0)e_m\cos(\varphi_e+\Delta\varphi_1) \end{aligned} \tag{18}$$

On the right of (18), the first term is the correlation of residual LOS signal while the second term is the correlation of residual multipath. Since the first term is much smaller than the second term, the multipath can be detected by detection of correlation peak in the DLL. Otherwise, the down-to-up gain ratio can be used to strengthen the multipath further as

$$D/U(\mathrm{dB}) = G(\pi-\theta)/G(\theta)(\mathrm{dB}) \geq 2\,\mathrm{dB}. \tag{19}$$

Simulation and results

A simulation was carried out based on GPS L1 signals to verify the effectiveness of the proposed method. According to the interface control document of GPS (IS-GPS-200H 2013), the axial ratio of GPS L1 signals shall be no worse than 1.2 dB for Block IIA and shall be no worse than 1.8 dB for Block IIR/IIR-M/IIF/GPS III satellites. So the ranges of $\Delta\gamma$ and $\Delta\eta$ were set to $|\Delta\gamma| \leq 6^{\circ}$ and $|\Delta\eta| \leq 10^{\circ}$. First, the numerical analysis of residual signal was carried out. Then the correlation curve and phase discrimination curve based on regular DLL were simulated at different incoming zenith angle.

Numerical analysis of residual signal

Multipath detection is mainly based on the fact that the magnitude of residual multipath is much larger than that of residual LOS signal after cross-cancellation. This is the key point of the proposed method.

The magnitude of residual LOS signal and residual multipath was sufficiently analyzed. Based on the analysis, the cutoff angle of the incoming zenith angle was 78° to make sure that the residual multipath was stronger than the residual LOS signal. The magnitudes of residual LOS signals are shown in Fig. 4 when signals come from first quadrant in the rectangular coordinate system.

In Fig. 4, the magnitude of residual LOS signal is smaller than 0.19, and it is influenced seriously by $\Delta\gamma$. We have found that the magnitude of residual LOS signals is small when the axial ratio of LOS signals is small. Moreover, the residual LOS signal is influenced by the DOA. The residual LOS signal is stronger when the LOS signal comes from a larger azimuth and a smaller zenith angle. However, when the azimuth increases, the impact of zenith angle reduces.

Because of the reflected factor, the residual multipath is stronger than the LOS signal and also varied while the DOA and the bias of polarization changed. As shown in Fig. 4, the LOS signal is already weakened significantly by cross-cancellation. Further, the ratio of the residual multipath to the residual LOS signal (RMLR) is calculated, and the RMLR on dry ground is shown in Fig. 5.

The figure shows that the RMLR is larger than 4.5 dB when the incoming zenith angle is smaller than 78°. The incoming azimuth does not influence the RMLR. The RMLR is large when the bias of polarization of LOS signal is small. For a large zenith angle, for example 78°, although the residual multipath is stronger than the residual

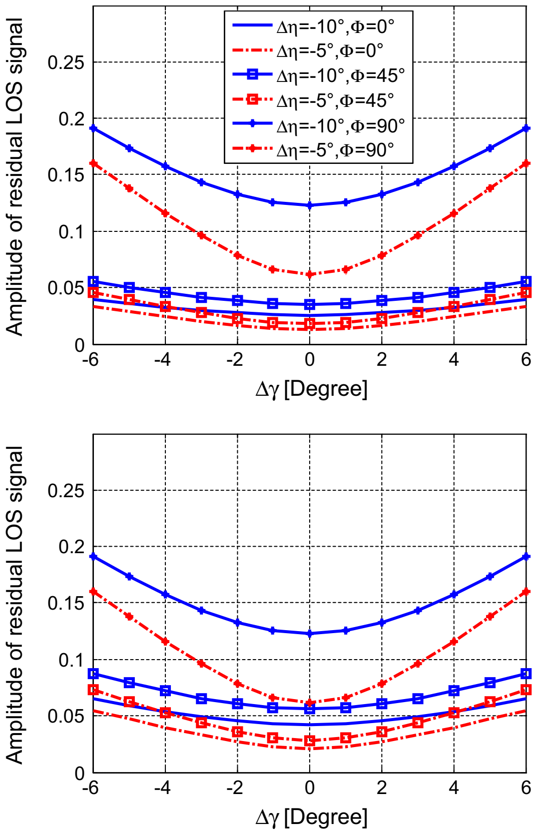

Fig. 4 Magnitude of residual LOS using zenith cutoff angle of 78° (*top*) and 70° (*bottom*)

LOS signal, it is not enough to ignore the influence of LOS signal while detecting multipath. In such a situation, the designed D/U can strengthen the multipath while weaken the LOS signal. When the zenith angle is smaller than the Brewster angle, the residual multipath is almost two times larger than the residual LOS signal.

When the reflector is on wet ground, the RMLR is greater than 9 dB when the incoming zenith angle is smaller than 78°. For the same incoming zenith angle, the RMLR on wet ground is larger than that on dry ground. So the performance of multipath detection is only analyzed in the condition of dry ground in the following section.

Performance for multipath detection

The code tracking loop in the GNSS receiver is a DLL called an early–late tracking loop (Elliott and Christopher 2006). The performance for multipath detection is shown by the correlation curve and phase discrimination curve in the DLL.

In the simulation, the incoming zenith angle of the LOS signal is the Brewster angle and the extra delay of the multipath is set to 0.4 T_{c}. The RF front-end is treated to be ideal and the error of carrier tracking loop is ignored; the correlation curve and phase discrimination curve are shown in Fig. 6.

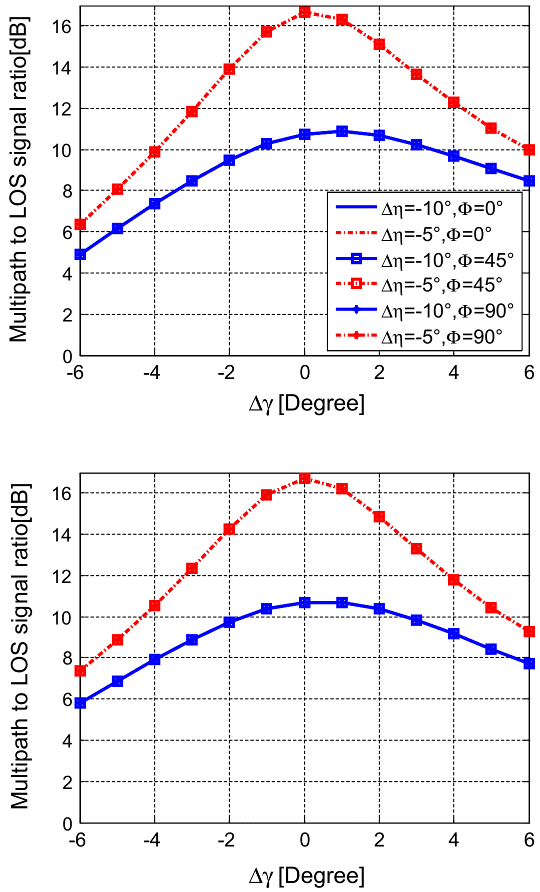

Fig. 5 Residual multipath-to-residual LOS signal ratio on dry ground with zenith cutoff angle of 78° (*top*) and Brewster angle (*bottom*)

For conventional GNSS receiver, the received signal is a combination of the multipath and the LOS signal. The correlation curve and phase discrimination curve of the mixed signal are shown by a solid line with square marks in Fig. 6. In the figure, the conventional receiver without cross-cancellation is locked on the mixed signal without cancellation. Since the coordinate on the *x*-axes, where the phase discrimination curve crosses the zero point of the *y*-axes, represents the error of measured pseudorange, the error caused by multipath is about 0.1 T_{c}.

For parallel cross-cancellation receiver, the LOS signals can be removed completely when the polarization of the LOS signal is precisely known. In such a case, the received signal can be simplified to be represented by multipath after cancellation as shown in Fig. 6. When the polarization of the LOS signal is unknown, the bias of polarization of LOS signal was set to $|\Delta\gamma| \leq -6^{\circ}$ and $\Delta\eta = -10^{\circ}$. Because the RMLR is not influenced by the azimuth of the incoming signal, the correlation curve and phase discrimination curve

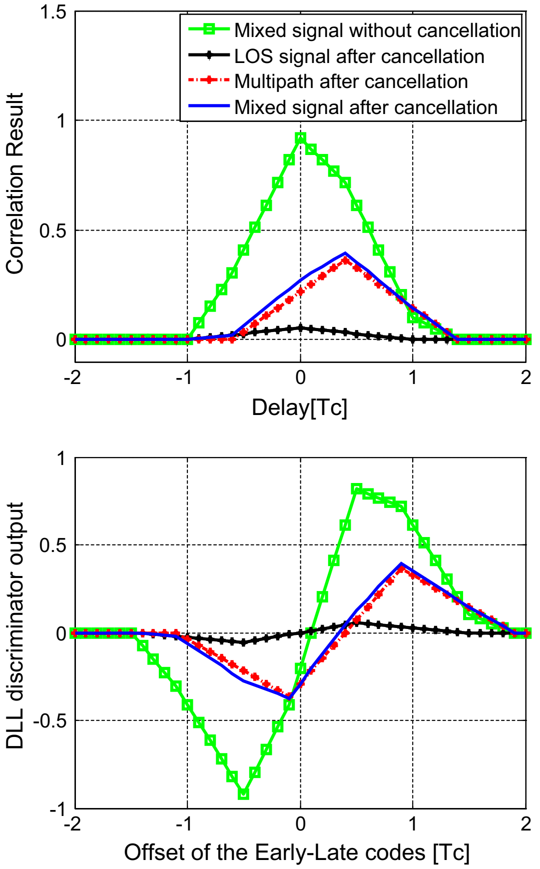

Fig. 6 Correlation results at Brewster angle showing correlation curve (*top*) and phase discrimination curve (*bottom*)

are shown in the figure as mixed signal after cancellation when incoming azimuth is 45°.

The residual LOS signal after parallel cross-cancellation is weakened heavily, and the curve of mixed signal mainly depends on the characteristic of multipath in Fig. 6. So the receiver is locked onto the multipath. Once the threshold of code acquisition is set to be larger than the residual LOS signal but smaller than residual multipath, the parallel cross-cancellation receiver can acquire the multipath easily. Moreover, the parallel cross-cancellation receiver could not acquire any signals when the multipath is absent.

Then, the incoming zenith angle of the LOS signal is set to be the cutoff angle. The correlation curve and phase discrimination curve are shown in Fig. 7. Though the residual LOS signal and multipath are weakened further after cancellation, the residual multipath is much stronger than the residual LOS signal. In this situation, the multipath can be detected by using weak signal acquisition technology.

A reasonable threshold of code acquisition is required to make sure that the parallel cross-cancellation receiver could not acquire any signals when the multipath is absent. As a general case, the threshold is set to be larger than the correlation peak of the residual LOS signal but smaller than the correlation peak of the residual multipath during one code chip period. Based on the analysis above, the threshold is a function of the DOA. In this research, the threshold is the mean of the minimum peak of multipath and the maximal peak of the LOS signal during one code chip period in any incoming angles. The numerical results are shown in Fig. 8. Though the bias of polarization influences the correlation peak, the peak of the LOS signal is smaller than the multipath in any incoming angles whatever the bias of polarization is.

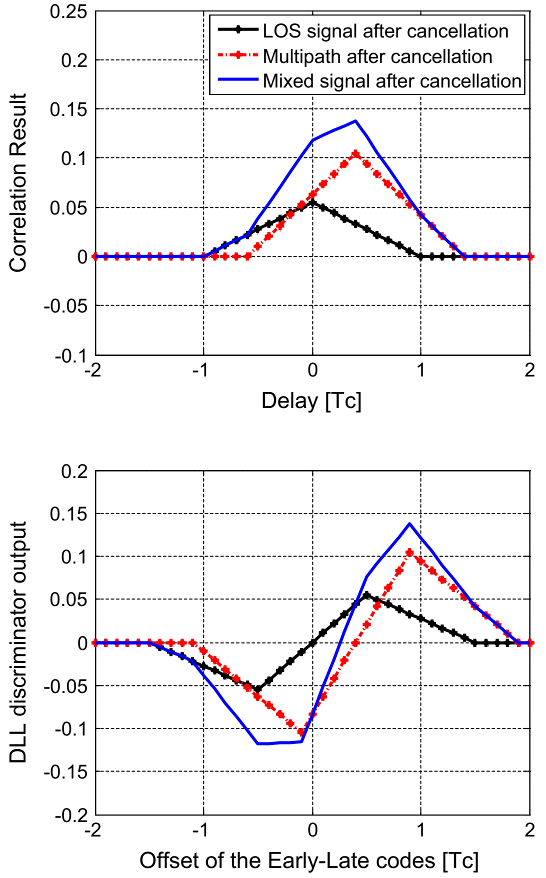

Fig. 7 Correlation results at cutoff zenith angle showing correlation curve (*top*) and phase discrimination curve (*bottom*)

In Fig. 8, the acquisition threshold varies with DOA. Because the residual multipath is much weak for small azimuth and large zenith angle, the threshold must be a small value. The biggest threshold occurs when the LOS signal comes from the YOZ plane (Fig. 1) and near zenith angle.

The simulation results and the analysis can be summarized as follows:

- When the incoming zenith angle is smaller than 78°, the residual multipath is stronger than the residual LOS signal. The RMLR is always larger than 4.5 dB for dry ground and larger than 9 dB for wet ground.

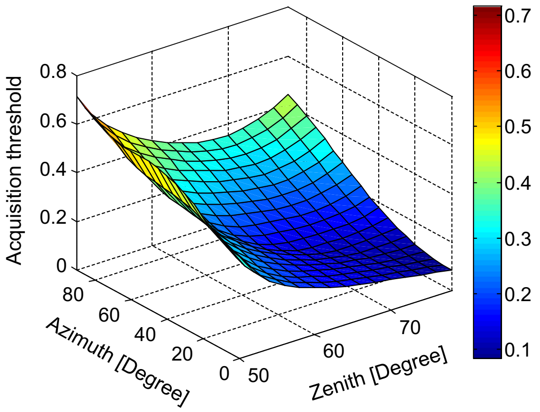

Fig. 8 Threshold of code acquisition during one code chip period

- With parallel cross-cancellation, the received signal mainly depends on the characteristic of the multipath. The receiver is locked on multipath when it is present. So the correlation results and DLL discriminator output of multipath are detected.
- When the threshold of code acquisition is set to be the mean of the minimum peak of multipath and the maximal peak of the LOS signal in any incoming angles, the receiver with parallel cross-cancellation cannot acquire any signals when the multipath is absent.
- Once the correlation results of multipath are detected, it can be used to assist the conventional GNSS receiver to mitigate the multipath.

Conclusions and future work

By taking advantage of the polarized diversity between the horizontal polarized and vertical polarized component of a RHCP signal, the LOS signal is removed by parallel cross-cancellation with prior knowledge of DOA. The residual multipath is strong enough to be detected by the conventional GNSS tracking channel in real time. The parallel cross-cancellation receiver cannot acquire any signals when the multipath is absent. The proposed method is based on a theoretical model of orthogonal dual LP antenna and does not cause an increased computational burden when having no previous knowledge of multipath characteristics. The parallel cross-cancellation receiver can be used as a high precision terminal to decrease the influence of multipath since the correlation results of multipath are detected. For future work, the orthogonal dual-polarized antenna, as well as the impact of actual antenna characteristics for practical implementation, requires further analysis.

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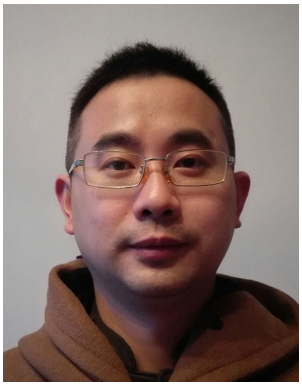

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