Multipath Analysis Using Code-Minus-Carrier Technique in GNSS Antennas

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***Abstract*—Global Navigation Satellite System (GNSS) broadcasts messages that enable the user's GNSS receiver to determine the antenna position at the time of the signal transmission. The signals sent from a GNSS satellite have multiple paths to arrive at the receiving antenna. They can arrive directly in a line of sight method, which is the desired method, or they may be reflected off surfaces. These reflected signals can be delayed in time and add error to the position data. This is called multipath and needs to be avoided or minimized.**

Most GNSS receivers are unable to process multipath signals in order to reduce the multipath effect in GNSS system. However, well-designed antennas can mitigate multipath signals and enhance the performance of GNSS receivers. Most of the antennas available in the current market have inadequate multipath rejection, or brute-force impractical methods of improving them. In this study, a variety of compact, ground-plane independent, dual/triple-band, GNSS antennas with improved multipath rejection have been designed and field-tested along with the effect that ground planes have on theses antennas.

Multipath signals have a huge effect on code and carrier phase measurements. This paper uses dual frequency code-minus-carrier technique (CMC) to isolate the effect of multipath from the rest of the GNSS errors.

The field-tests showcase that GNSS antennas CAN be designed and optimized to reject multipath waves, providing better quality signals to the receivers without having to be the larger and more expensive geodetic antennas.

Keywords*—GNSS, GPS, Galileo, satellite tracking, multipath, multi-band, dual-frequency, code-minus-carrier, pseudo-range, radiation pattern, axial ratio, RHCP, geodetic antenna, patch antenna, crossed dipole, helical antennas.

I. Introduction

Global Navigation Satellite System (GNSS) allows users to determine their location and the location of other people or objects at any given time, along with the ability to determine their velocity and the current system time. The range of envisaged applications of GNSS has been increasing in the recent years, spanning both the public and private sectors across numerous market segments, e.g., pedestrian navigation, drones, autonomous driving and Internet-of-Things (IoT) [1].

Multipath is one of the main error sources in GNSS systems and can occur in all environments. It is particularly noticeable in urban locations with buildings, vehicles, people, etc, which can cause signal reflections and affect the Time-To-First-Fix (TTFF) performance and accuracy of determining the position in the real-world.

A GNSS receiver determines the travel time of a signal from a satellite by comparing the pseudo-random noise code (PRN) generated by the receiver, with an identical code in the signal from the satellite. The code generated by the receiver is shifted until it syncs up with the received satellite code. The signal's travel time is calculated based on the frequency used to generate the code and the number of cycles that the code is shifted. This processing technique results in 1-5 meters accuracy [2].

The carrier phase measurement is a measure of the range between a satellite and receiver expressed in units of cycles of the carrier frequency f_C. In the case of GPS (L1 [1575.42 MHz], L2 [1227.60 MHz] and L5 [1176.45 MHz]), this processing technique derives in sub-meter accuracy, as a result of the high frequency used.

In the process of transmitting signals from the satellites to computing a position, several errors are introduced. The effect of most of errors can be reduced, however multipath (MP) error remains an unsolved problem even after efforts by many investigators. Multipath signals introduce a distortion in the correlation curve between received signal and receiver-generated replica used for acquisition and tracking [3,4].

In the recent years, different approaches have been taken into account to mitigate the multipath effects [5]. Various techniques were proposed to mitigate multipath in GNSS measurements such as hardware, software and hybrid approaches.

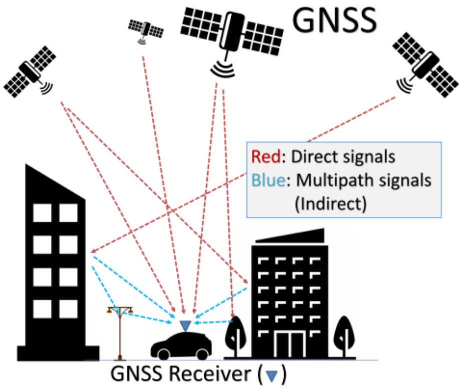

Fig. 1. GNSS multipath error

The approach discussed in this paper is based on multipath error estimation and measurement correction. The well-known Code-Minus-Carrier (CMC) metric is used to extract and measure code multipath errors by subtracting carrier phase measurements from corresponding pseudo-ranges [6]. Since the pseudo-range multipath error is considerably larger than that of the carrier phase, the CMC results in an indication of the multipath in the pseudo-range. To carry out this technique, a dual-frequency receiver is required to eliminate the ionospheric contribution.

II. Multipath Error Estimation

This approach is based on a direct measure of code range multipath error. Direct and indirect signals received at the GNSS receiver have relative phase offsets and the phase differences, which are proportional to the differences of the path lengths. By combining code and carrier phase measurements, it is possible to estimate the multipath error [7].

A. Code-Minus-Carrier (CMC) Method using Dual frequency

In this data analysis we calculate the code multipath error using the dual-frequency approach. The formula to estimate the pseudo-range multipath error on L1 and L2 frequencies using CMC method is the following:

$$MP_{L1} = \rho_{L1} - \phi_{L1} - \frac{2 \cdot f_{L2}^{2}}{f_{L1}^{2} - f_{L2}^{2}} \cdot (\phi_{L1} - \phi_{L2}) + K_1 + \eta_1 \quad (1)$$

$$MP_{L2} = \rho_{L2} - \phi_{L2} - \frac{2 \cdot f_{L1}^{2}}{f_{L2}^{2} - f_{L1}^{2}} \cdot (\phi_{L2} - \phi_{L1}) + K_2 + \eta_2 \quad (2)$$

Where ρ_{fi} and ϕ_{fi} are the corresponding code and carrier phase measurements converted to units of length. The η_i is the noise error accumulated in the code and carrier measurements. The variable K_i is the unknown integer ambiguity which can be assumed constant [7]. The dual-frequency linear combination removes ionospheric error from the equation.

III. EXPERIMENTAL SETUP

A multiband high precision GNSS receiver (Septentrio, AsteRx-U) was used to carry out this study. The system was tested on a roof top (building 43 meters tall) in an open sky scenario at Taoglas office in Dublin, Ireland. The antennas were mounted on a plastic base 1.7m from the floor of the roof top.

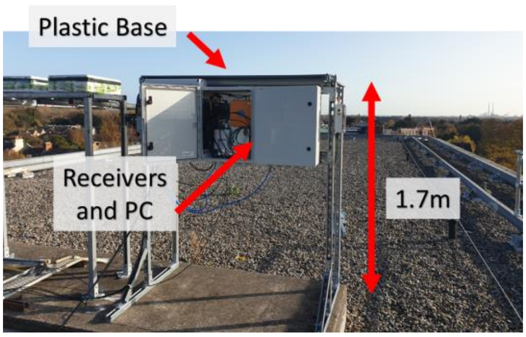

Fig. 2. GNSS receiver setup, Taoglas Office Dublin, Ireland.

For any static GNSS base station, multipath effects re-occur with repeating satellite ground track with a constant phase shift during the successive days. The multipath error is almost the same when the satellite view is in the same position during each orbital pass. This tracking technique is especially useful with GPS satellites. The semi synchronous characteristic of the GPS satellites, with a period of one-half of a sidereal day gives to the test the repeatability desired.

By knowing the test location, a GNSS planning tool can be used to select the best satellite for the study. A wider elevation range can help to carry out a more in-depth analysis of the multipath capabilities of the antenna. It is a well-known fact that the contribution of long-range multipath is significant at low elevation angles and at negative angles (below the horizon plane).

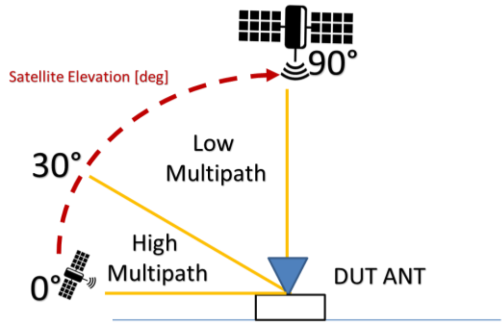

Fig. 3. Multipath vs satellite elevation angles

In this study the satellite G01 in the GPS constellation was chosen to carry out this test. As it can be seen in Figure 4, the satellite G01 gives us a very good elevation angles range where the GNSS base station is located. It is also important to check the band capabilities of the satellite to be tracked. In the G01 case, it covers L1-C/A, L1-P(Y), L2-P(Y), L2C and L5.

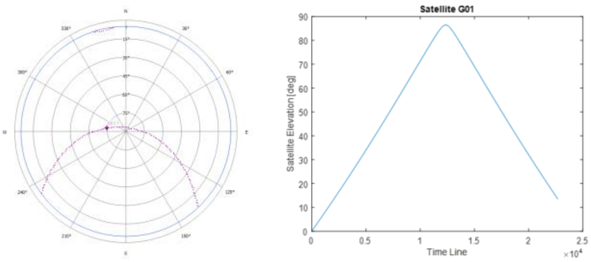

Fig. 4. Satellite GPS G01 elevation angles based on base station location.

IV. Field Test Results

The GPS raw data was recorded and saved in Septentrio binary format (SBF). The SBF file was downloaded and converted to ASCII (American Standard Code for Information Interchange) using the function *"bin2asc"*. This ASCII file processing can be done by any post-processing software. In this study, the SBF converter tool was used for the format conversion as this tool also has the possibility to convert the file into RINEX (Receiver Independent Exchange) for quality-checking purposes. The converted data was imported into Matlab® [8] to carry out the multipath calculations and correlate the data with the satellite elevation angle.

The antennas shown in Fig.5. were used for this study, a description of each is given below:

- Reference antenna (Dimensions: Ø170 x 195mm): Geodetic choke ring antenna for survey use.
- Taoglas XAHP.50A (Dimensions: Ø94 x 57mm): an active multi-band GNSS antenna has been carefully designed to work on the full GNSS

spectrum, as well as SBAS, and L-band correction services. The XAHP.50 has excellent performance across the full bandwidth of the antenna and its design has an even gain across the hemisphere giving almost excellent, broad axial ratio which in turn makes it resilient to multipath rejection and excellent phase centre stability.

- Taoglas AA.200 (Dimensions: 63x67x26mm): active GNSS magnetic mount antenna for use across most major constellations including GPS (L1/L2/L5), GLONASS (G1/G2/G5), Galileo(E1/E5a/E5b) and BeiDou(B1/B2). The antenna exhibits excellent gain and good radiation pattern stability leading to a reliable GPS fix in areas of weaker signal strength.

Fig. 5. GNSS antenna tested from left to right: Taoglas XAHP.50.A, Taoglas AA.200 and 2 euros coin.

A. *Taoglas XAHP.50A and AA.200 vs Geodetic Antenna*

All the antennas were mounted on the support structure, which is positioned higher than the other objects on the rooftop, Fig.2. It is necessary to highlight any ground plane structure was used in this test.

The multipath error estimate on frequency L1-C/A for the satellite GPS G01 obtained by dual frequency code and phase measurement with CMC technique using Eq. (1) and (2) are depicted in Fig.6.

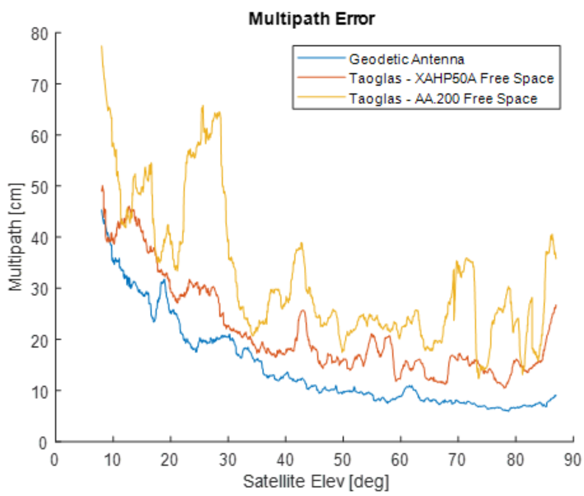

Fig. 6. Standard deviation of the multipath error for GPS L1-C/A signal.

The difference between the curves shown in the Fig.6. can be seen as a measure of difference between multipath rejection capabilities and the size of each antenna. A comparison of low-elevation and high-elevation multipaths is also presented in Table 1.

B. *Effect Of Ground Plane in Multipath*

The Taoglas XAHP.50.A was designed to work in free space or on a metal surface. The L1-C/A multipath error obtained when the antenna was mounted on a metal ground plane is shown in Fig.7. The geodetic antenna is also shown for reference.

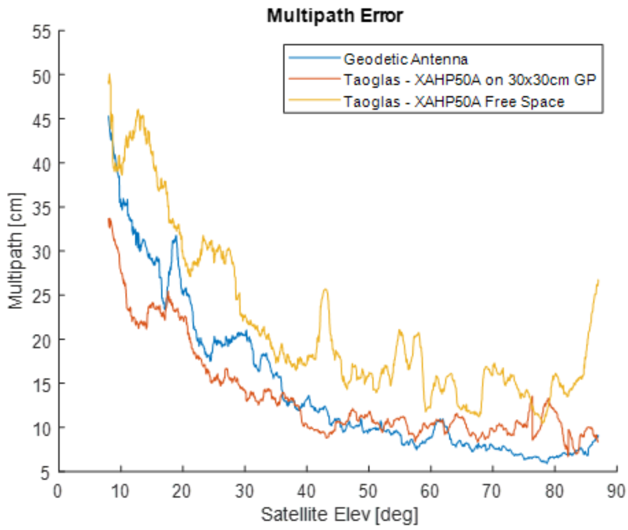

Fig. 7. Standard deviation of the multipath error for GPS L1-C/A signal.

The same study was done with the Taoglas AA.200 antenna. The multipath error when the antenna was tested in free space and on a 30x30 cm ground plane is shown in Fig.8. The geodetic antenna is also shown for reference.

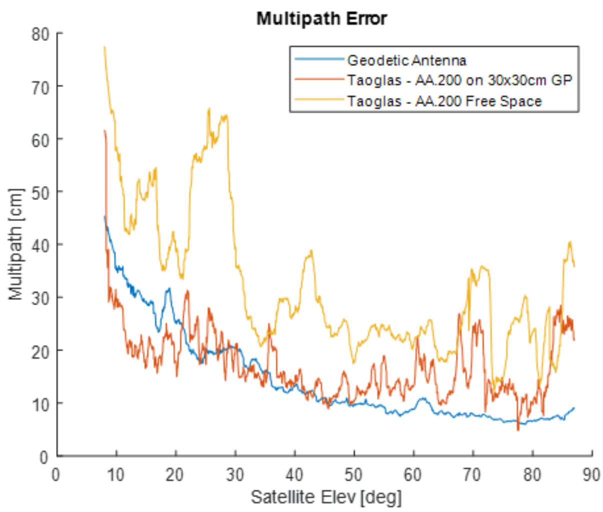

Fig. 8. Standard deviation of the multipath error for GPS L1-C/A signal.

V. ANALYSIS OF THE RESULTS

A. Comparison Table

Antenna	Average multipath at Elevation Angles [deg]			
	0° to 20°	20° to 40 °	40° to 60 °	60° to 90°
Geodetic Antenna	34.37cm	21.26cm	10.32cm	8.64cm
XAHP.50.A **Free Space**	41.24cm	24.96cm	16.96cm	13.39cm
XAHP.50.A **30x30cm GP**	24.31cm	15.66cm	10.57cm	11.39cm
AA.200 **Free Space**	54.88cm	45.18cm	23.44cm	22.8cm
AA.200 **30x30cm GP**	28.88cm	20.59cm	13.90cm	18.25cm

Table 1. Average of the standard deviation multipath error (cm) at different range of elevation angles.

The comparison results in Table 1 above shows how well-designed compact antennas can mitigate the multipath effect. This table highlights the correct balance when integrating an antenna with a ground plane and the improvement on multipath rejection performance.

VI. CONCLUSION

Multipath in GNSS signals limits the speed and accuracy of determining the receiver position. Multipath errors have a direct impact in the positioning accuracy. In a good multipath environment, 2-3 meters of positional accuracy is typically achievable; under an adverse multipath environment, the positional accuracy can be degraded up to 10 meters or more.

To mitigate multipath interference, GNSS antennas can be designed and optimized to reject multipath waves, providing better quality signals to the receivers.

In the current market, antennas with multipath rejection are generally heavy and large structures, whether these are choke-ringed or contoured. In general, these options are bulky and rather heavy.

A relatively simple, lightweight, well-designed, cheaper and compact antenna can obtain similar levels of multipath rejection compared to conventional and expensive geodetic antennas. An optimal combination between the antenna characteristics and a ground plane integration can provide to the system an immunity to multipath from objects in the “near field”.

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