Dual-polarization GNSS observations for multipath mitigation and better high precision positioning

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BIOGRAPHIES

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Peter Clarke is Professor of Geophysical Geodesy and works at the interface of geodesy and geophysics, using precise GPS positioning to study the deformation of the Earth due to plate tectonics, tides, and surface mass loading. His interests span the applications of these areas to geohazards such as earthquakes, tsunamis and climate change (changes in the global hydrological cycle, ice sheet mass, and atmospheric water vapor).

Stuart Edwards is a Senior Lecturer in Geomatics specializing in Engineering Geodesy. His career commenced in industry where he was heavily involved in the development and application of GNSS based survey techniques to open-pit mining. Switching to academia in 1994, he has focused on engineering survey related topics in both teaching and research. His research interests focus on GNSS solutions for displacement monitoring, GNSS quality indicators and satellite altimetry, although latterly he has applied his research to further the study of ice-mass balance in Greenland.

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ABSTRACT

We demonstrate the use of GNSS signal tracking with a dual-polarization antenna for evaluating the multipath condition of the survey location, and suggest using this information to improve the quality of positioning. As GNSS use right-hand circularly polarized signals (RHCP), changing partly into left-hand polarized (LHCP) upon undesirable reflection or scattering, measurements of the level of LHCP can be used as a proxy for the level of multipath contamination of the useful RHCP signal. This information can be used to apply realistic weights to the individual ranging measurements, leading to improved accuracy, precision, reliability, and availability of coordinate measurements. We discuss the procedure of obtaining a multipath indicator in an experiment reproducing a realistic high-precision surveying scenario and the potential directions of further research into dual-polarization GNSS technology.

INTRODUCTION

GNSS technology is ubiquitous in navigation, surveying, and science, and its importance continues to grow. GNSS technology is being continuously improved: new hardware and software aim at reducing the errors and increasing productivity, robustness, reliability, and availability. The effects of multipath are currently among the most significant uncorrected error source in precise GNSS – as used in surveying and science – and also constitute a significant accuracy and precision limiting factor in consumer-sector GNSS applications.

GNSS positioning algorithms assume that the ranges to the satellites are measured by the receivers accurately and directly along the line of sight. Multipath (MP) is the effect of GNSS ranging distorted by indirect (reflected or scattered from the objects surrounding the antenna) signals (non-line of sight—NLOS, in contrast with the line-of-sight—LOS signals). Major MP sources are the ground and water surfaces, buildings, walls, other engineering constructions, etc. Severe MP is frequently observed in cities, especially in "urban canyons" where the walls of tall buildings are situated either side of narrow streets. Uncorrected MP leads to systematic and random errors in the measured pseudoranges and phase

measurements, and consequently to computed coordinates of surveyed points, due both to distortions of measured ranges and to the ability to correctly resolve integer carrier phase cycle ambiguities. In many cases MP can significantly delay or even prevent reliable positioning.

Although the important GNSS design decision of using circularly polarized signals was initially taken to obviate the need for specific orientation of user receiving antennas, it also happens to be an MP countermeasure. Current and planned GNSS constellations use Right-Hand Circular Polarization (RHCP) radio signals. Circularly polarized signals change direction and/or degree of polarization when reflected or scattered, e.g. the larger part of the power of an initially RHCP signal becomes Left-Hand Circularly Polarized (LHCP) after a reflection [Nievinski and Larson 2014]. The use of GNSS antennas sensitive dominantly to RHCP signals reduces the influence of unwanted reflected signals. Some of the reflected MP signals are still able to pass through the polarization filter and influence the ranging measurements though.

The probable direction of arrival of MP signals is from below the local horizon, after reflection or scattering (ground wave) [Tranquilla et al 1994]. Commonly used measures to reduce the influence of the ground wave include the use of hardware techniques (such as ground planes, choke-ring structures and varying impedance ground planes), and introducing the elevation cut-off angle for ranging measurements in the position computation stage. Both these approaches are ineffective when the MP reflectors/scatterers are located above the horizon or the elevation cut-off angle.

Other approaches to tackling MP have been proposed. Some examples are: sidereal filtering, which relies on repeating GPS (but not other GNSS) satellite tracks and multipath patterns from day to day [Choi et al 2004]; analysis of phase residuals: use of wavelet analysis,

adaptive filters, experiment-specific weighting, including MP in estimation algorithms [Liu et al 2011, King and Watson 2010]; and use of the RHCP carrier-power-to-noise density ratio (C/N_0) allowing detection of MP and choice of optimal data-weighting strategies [Lau and Cross 2006, Bilich and Larson 2007].

Attempts at MP mitigation based on modelling MP errors based on the knowledge of reflector/scatterer geometry have not had much success because of the very high sensitivity of MP error to geometry and the properties of reflectors/scatterers, which are never precisely known in practice. Some advance has been made in qualitatively explaining typical MP error behavior based on the modelling of radio signal reflection and scattering [Elósegui et al 1995, Bilich and Larson 2007, King and Watson 2010, Nievinsky and Larson 2014]. However, these methods are hardly applicable in practice. It will be safe to state that the level of our understanding of MP is still very low and more research is needed into the ways its influence can be characterized and mitigated using both hardware and software approaches.

Overall, the difficulty of MP mitigation comes from the inability of the antenna/receiver combination to extract the information related to the LOS signal from the mixture of LOS and NLOS signals. Manandhar et al (2001) and Brenneman et al (2007) proposed a way of overcoming this difficulty by analyzing GNSS observations made in two circular polarizations: the RHCP, which is the primary component of the initially emitted satellite signal, and LHCP, which is mostly expected in the NLOS signals. Jiang and Groves (2014) demonstrated in practice the ability to discriminate NLOS from LOS signals using the dual-polarization (DP) technique. In the present work, we demonstrate a way of obtaining the MP index using a dual-polarization antenna in a realistic scenario.
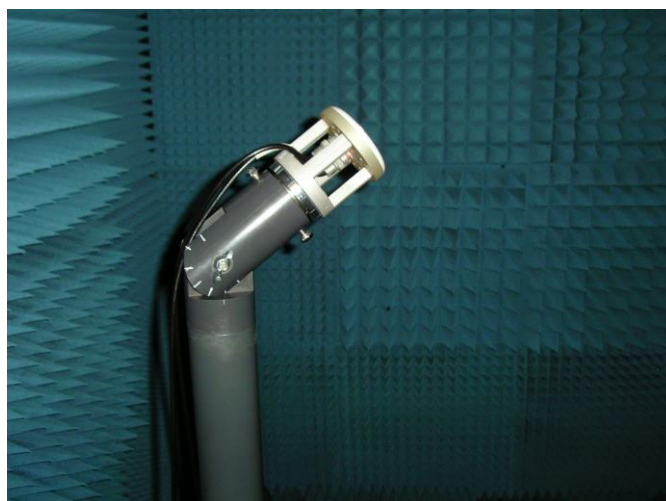

Figure 1 Photographs of the emitting circular polarization antenna (left) and receiving dual-polarization antenna in the anechoic chamber during the initial DP antenna evaluation

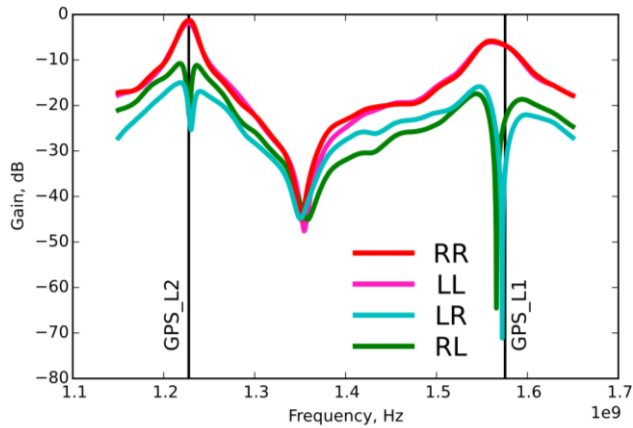**DUAL-POLARISATION ANTENNA EVALUATION**

Figure 3 Amplitude gain of the AntCom 3G1215RL antenna as a function of frequency, for different emitting and receiving polarizations. GPS frequencies are represented by black vertical lines.

We used AntCom 3G1215RL DP antennas (http://www.antcom.com/documents/catalogs/Page/3G12 15PJ2-XS-1_RHCP-LHCP-V-H-L1L2GPSAntennas.pdf) to collect the experimental data. The antennas were first evaluated for their polarization filtering properties in an anechoic chamber. We used EMC Test Systems model 3102 LHCP and RHCP helical antennas as the reference signal emitters and an Agilent Technologies E8363B Network analyzer to collect the amplitude response of the dual-polarization antennas at various azimuths and elevation angles (Figure 1).

The amplitude gain as a function of frequency for reception at the zenith is presented in Figure 3. The in-polarization results show clear peaks around the nominal GPS frequencies L1 and L2. The cross-polarization gains are much lower at GPS frequencies. Although precise
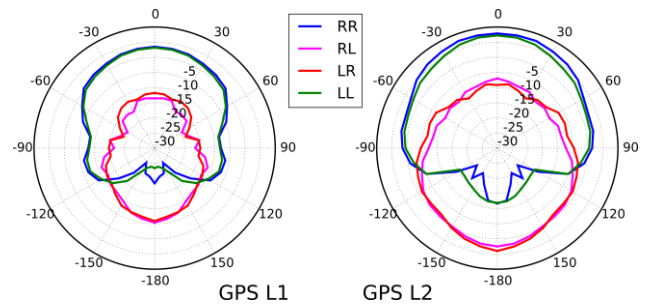

Figure 2 Sensitivity of the AntCom 3G1215RL for different emitting and receiving polarizations, for two GPS frequencies. Concentric circles represent gain in dB.

interpretation of these results should depend on the calibration results of the emitting antennas, which were not taken into consideration, we conclude that the given receiving antenna provides cross-polarization selectivity at the level of approximately 15 dB or better for reception of a signal coming from the zenith.

Figure 2 presents the sensitivity diagrams of the dual-polarization antennas for in- and cross-polarizations on two GPS frequencies. It appears that the efficiency of polarization filtration decreases drastically for the signals coming from lower elevation angles: for the signals from the lower hemisphere of the antenna, the gain of the cross-polarized signal becomes higher than that of the in-polarization signal. The consequence for positioning applications is inability of the particular antenna to effectively reject LHCP MP signals reflected from objects situated below the antenna, leading to reduced coordinate measurement quality. We expect that a similar conclusion will be also valid for other comparable antennas with RHCP-only tracking.
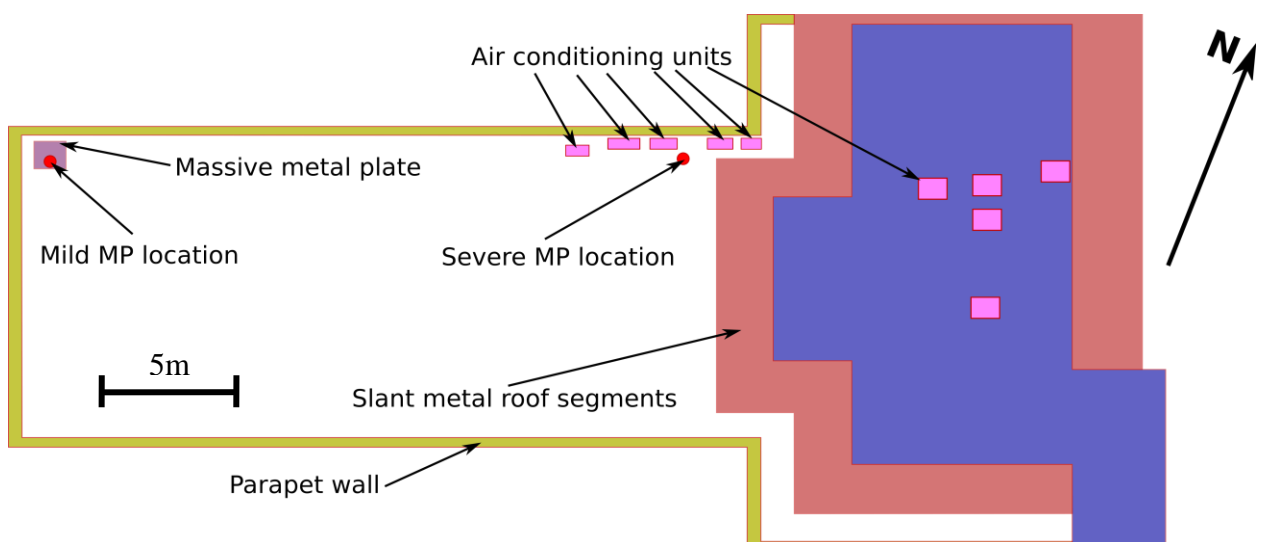

Figure 4 Sketch of the experimental data collection locations.

EVALUATING GPS SITE MP CONDITIONS USING A DUAL-POLARISATION ANTENNA

As the NLOS signals undergo reflection or scattering from the objects surrounding the antenna, they experience power reduction in the RHCP and increase in the LHCP components. Therefore the presence of significant proportion of LHCP in the ranging signal can indicate its contamination by MP caused by NLOS signals.

Conventional GNSS antennas are designed to be mostly sensitive to RHCP to reduce the received level of NLOS power in the receiver input. As it is demonstrated in the previous section, such efficiency is significantly reduced for the lower hemisphere of the antenna. If an antenna is designed to provide output for both RHCP and LHCP signals independently, the measured power of the LHCP signal can be interpreted as the proxy for the level of MP contamination in the received RHCP signal and further used to assign more realistic weights to the tracking measurements obtained for RHCP signal.

Readily available GNSS receivers provide a signal-to-noise ratio (C/N_0 observable) that can be used as a measure of the signal power. Specifically, C/N_0 of the LHCP signal can be used to produce the estimates of the NLOS signal power.

The estimation of the MP level using dual polarization (DP) observations, with subsequent application of derived weights, has a number of advantages over other MP mitigation techniques (e.g. sidereal filtering or temporal filtering). It is in principle able to work with multiple GNSS, in real-time, and with moving antennas and/or a changing MP environment.

EXPERIMENT DESIGN AND DATA COLLECTION

We used a DP antenna to collect an experimental dataset at two static locations in Newcastle, UK (Figure 4). Photographs of the two dual-polarization antenna setups are presented in Figure 5. Both setups use geodetic pillars on the roof of Drummond Building, Newcastle University (54.981715°N, 1.613184°W), but differ significantly in the character of MP conditions.

We recorded tracking data (code pseudorange, phase, and C/N_0) for each (RHCP and LHCP) polarization using a separate (but identical and identically set up) GPS receiver for each polarization channel.

Each receiver was set up for clock steering to the GPS time independently. The sampling rate was set to 1 s. About 1 week of data was collected for each location. RHCP data from these sites are thought to be comparable to data from a typical surveying or scientific measurement session taken with a single (RHCP) polarization antenna.

In both cases the number of satellites tracked by LHCP channels was significantly lower than that for RHCP. The typical reported signal to noise ratio was significantly lower for LHCP channel, which is explained by the low content of LHCP in the LOS (primarily RHCP) satellite signal, and the lower power of the reflected and scattered signals. The LHCP channel experienced much more frequent cycle slips and data gaps, presumably due to lower C/N_0 therein, and the behavior of the LHCP phase differing from the expected due to the difference in propagation geometry of LOS and NLOS signals, confusing the tracking circuits of the receiver. Probability density histograms of C/N_0 for the mild MP site are

Figure 5 Photos of GPS sites with relatively mild (left) and severe (right) MP conditions. MP is due to NLOS signals reflected/scattered from the flat roof surface below the antenna, parapet walls, the massive metal plate below the antenna (for the mild MP site), air conditioning units and metal walls and roof of the bulkhead construction (for the severe MP site)

presented in Figure 6a and b.

As the antenna sensitivity is strongly dependent on the elevation angle (see Figure 2), raw C/N_0 measurements cannot be used as a signal-in-the-air power proxy without normalizing them. As signal from the RHCP antenna channel is used for ranging and most of the power of the pristine signal is RHCP, in-polarization calibration results were used to normalize RHCP C/N_0 values.

In the assumption of all the power registered by the LHCP antenna channel resulting from LHCP MP signal the normalization should be done using the in-polarization gain pattern. C/N_0 PDFs normalized in this way are presented in Figure 6c and d. The power of the

normalized LHCP is still lower than RHCP, which is in agreement with the hypothesis of the NLOS being weaker than the LOS signals.

In the assumption of all the power registered by the LHCP antenna channel resulting from it picking up the RHCP EM wave, the normalization should be done using cross-polarization gains. C/N_0 PDFs obtained in this way are shown in Figure 6e and f. In the case of absence of the NLOS reception the peaks for RHCP and LHCP should appear at the same locations, however normalized LHCP power exceed normalized RHCP power for both frequencies. This can be interpreted as an indication the presence of NLOS signals in the power received by the LHCP antenna channel.
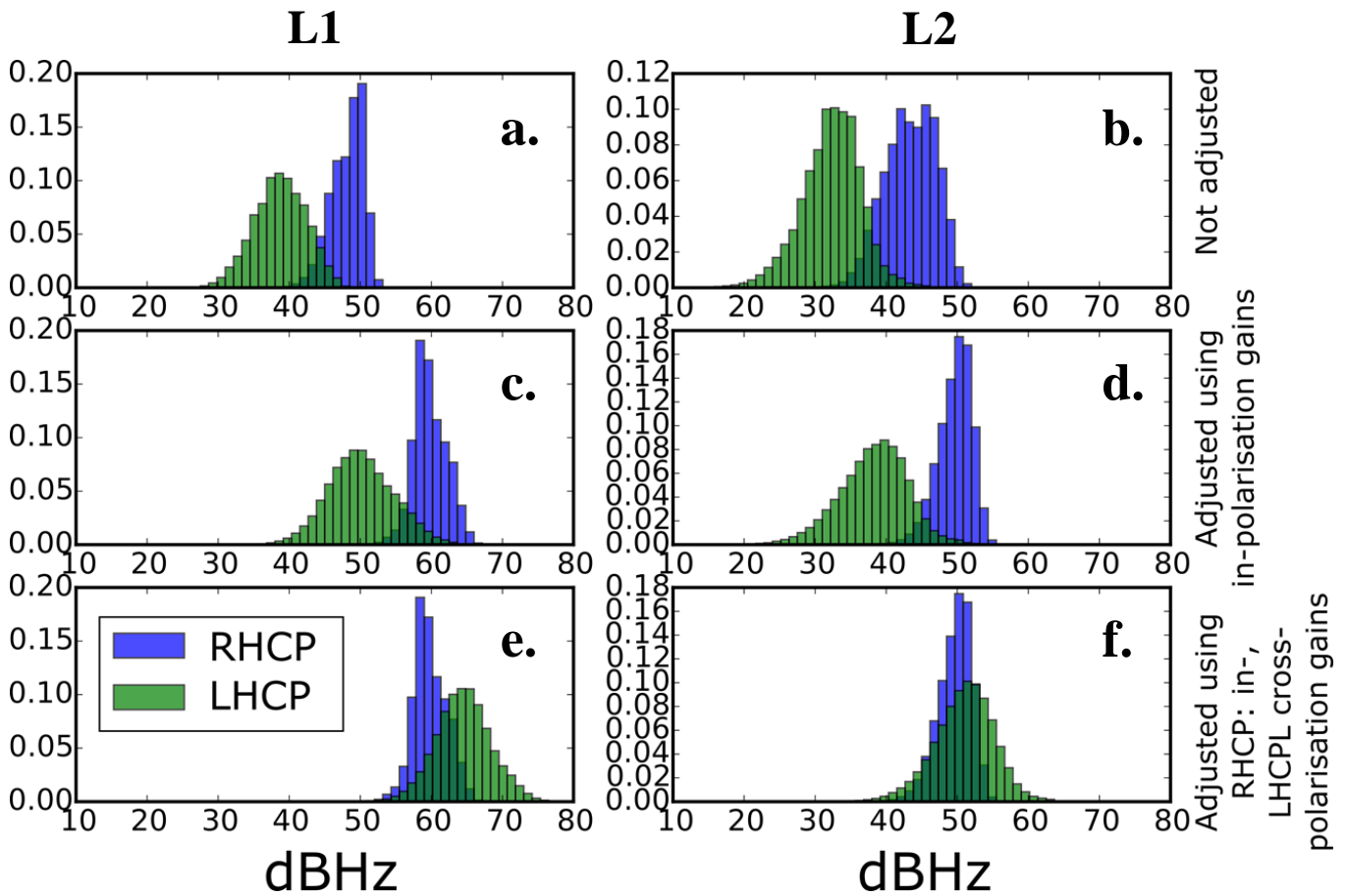

Figure 6 C/N_0 observable probability distribution density for both GPS frequencies (L1 on the left and L2 on the right) for RHCP and LHCP polarization channels for the mild MP site. Panels a and b show raw C/N_0 PDFs, c and d — C/N_0 PDFs adjusted in the assumption of using the in-polarization, and e and f — in PDFs adjusted using cross-polarization antenna gain calibrations.
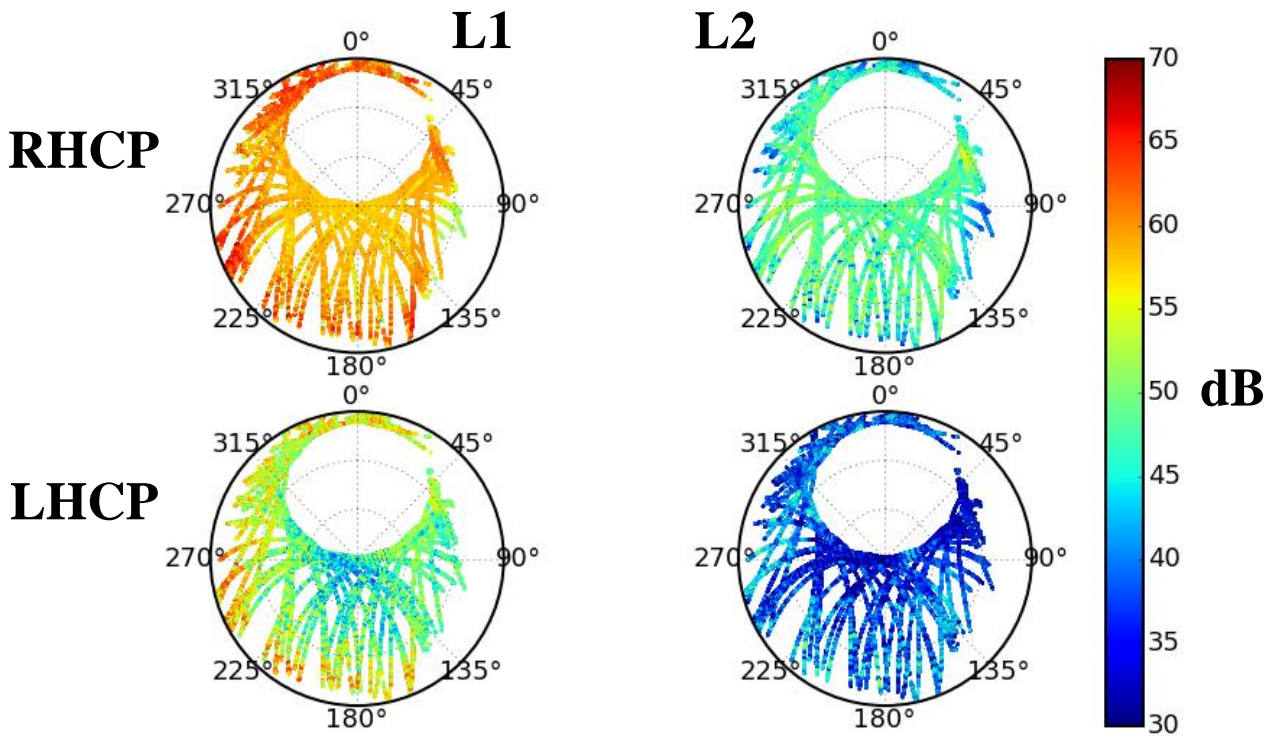
Figure 7 Sky maps of normalized C/N$_0$ values for the severe MP site

The PDFs of the observed C/N$_0$ values for the severe MP site have the similar characteristics, with even higher level of cross-normalized LHCP power.

In Figure 7 we present the sky maps of the of normalized C/N$_0$ values for the severe MP site for one day of observations. The gap in the eastern sector of the sky is due to sky view obstruction. Small scale features are present, especially in LHCP, where they are also more irregular and dissimilar for L1 and L2. This is in

agreement with the hypothesis of higher sensitivity of LHCP channel to MP signals, generated by the presence of signal scatterers of arbitrary geometry.

Although some dependence of the normalized C/N$_0$ on the elevation angle still exists, it is much weaker than for the raw C/N$_0$. Normalized C/N$_0$ grow at low elevations in both RHCP and LHCP, which is probably due to a combination of genuine increase of the NLOS power at low elevation angles and a systematic error in anechoic
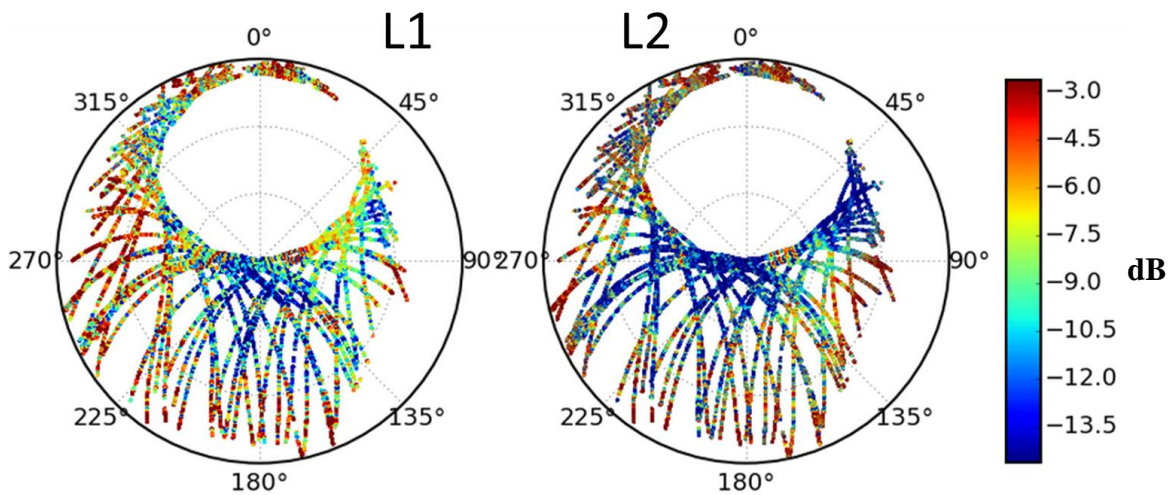

Figure 8 Sky maps of the MP index for the severe MP site

calibration results. To exclude the latter we propose to use the difference between the normalized LHCP and RHCP values as the MP index. Sky maps of such difference for one day of observations for the severe MP site are presented in Figure 8.

As expected, the MP index shows increase for the lower elevation angles. However, a number of local maxima are present at high elevations as well. Many of them coincide for both frequencies, although a high value of the index on one frequency does not necessarily cause its increase on another. At some of the elevated MP index spots the characteristic striped structures can be seen on more than one adjacent satellite passes, presumably produced by the interference of the direct and NLOS signals.

CONCLUSIONS AND FUTURE DIRECTIONS

We have demonstrated the potential of DP GNSS data in determining the degree of MP contamination of the satellite ranging signals. In contrast to other MP estimation strategies, this method relies on independent measurements. The MP index based on the DP observations can further be used in reweighting tracking data for high-precision positioning applications. The optimal form of the MP index to weights conversion is still to be found.

This approach to MP mitigation is expected to have some advantages over other techniques, with most important being:

- Ability to work both in kinematic and static modes

- Ability to work with multi-system GNSS

We anticipate that the introduction of the weighting derived from DP observations will not only improve the precision of the measurements, but also strengthens their reliability, in particular due to lower probability of incorrect integer ambiguity resolution.

It is worth noting that the availability of additional GNSS (GLONASS and Galileo), allowing GNSS positioning in more obstructed environments, does nothing for the reduction of MP. Indeed, this development is likely to increase the amount of precise GNSS positioning that is attempted in such high-MP locations, making the proposed technology even more advantageous.

This research should enable GNSS equipment manufactures to produce enhanced hardware i.e. dual polarization antennas together with enhanced receivers and receiver firmware, at moderate extra cost as receiver hardware would not need to change significantly: notably the use of the signals of both polarizations will require doubling the number of tracking channels, which should be relatively cheap to achieve. However, the channels designated for LHCP tracking should be designed to have higher sensitivity and wider bandwidth to measure primarily the signal power rather than precisely track code/phase.

More research is needed into the properties, advantages, disadvantages, and specific ways of performing observation reweighting based on DP observations. Specifically, we intend to investigate its performance in both the cases of kinematic and static positioning, and both in high-precision setup and code-only positioning mode with typical customer-grade hardware (both antennas and receivers).

Combination of the observation reweighting based on DP measurements with other (both hardware-based and signal processing) MP mitigation methods should also be researched.

We expect our research to benefit all surveyors, who will be able to produce more accurate and reliable measurements in less time, especially in harsh MP conditions such as urban environments where effective measurement is sometimes impossible with current technology. Further applications include precise vehicle guidance e.g. construction machinery. Scientific users will also benefit from reducing the error levels as it will lead to greater accuracies in shorter time spans in applications like tectonic strain estimation and volcano monitoring, both saving research funds and enabling new science.

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