THE DESIGN AND PERFORMANCE OF THE ZEPHYR GEODETIC ANTENNA

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BIOGRAPHY

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ABSTRACT

The Trimble Zephyr Geodetic Antenna is a new high-performance GPS antenna utilizing two key technological innovations, for which US patents 5,515,057 and 5,694,136 have been issued to Trimble Navigation Ltd. This paper explains these GPS antenna technologies, their advantages and presents the results of performance testing on this new antenna design.

The n-point antenna feed technology is described. This is designed to reduce the electrical phase center error ellipsoid through enhanced antenna element and feed point pattern symmetry. This symmetry is also designed to improve the Right Hand Circular Polarization Characteristics of the antenna, resulting in enhanced GPS signal tracking and improved multipath rejection in cases where a polarization reversal has taken place as a result of the signal reflection.

The second key technology described is that utilized in the Trimble Stealth Ground Plane, an integral component of the Zephyr Geodetic Antenna. Conventional GPS ground planes typically use one of two designs; the circular metal ground plane or the choke ring ground plane. The method used for the Trimble Stealth Ground Plane is one whereby the e-field of the electromagnetic wave is cut off before it can reach the GPS antenna element. This is achieved through the use of a material in which the sheet resistivity increases exponentially along any radial line out from the antenna element to the edge of the ground plane. The use of this material offers the advantages of lighter weight and lower cost over conventional ground plane designs. As the name suggests, the material was developed out of research conducted as part of the development of the Stealth aircraft.

This method is frequency independent at L-band, so is expected to be equally effective at the L1 and L2 frequencies. This property also offers a potential advantage in future triple-frequency antennas capable of tracking L1, L2 and L5 signals, with the ability to reject multipath equally effectively at all three frequencies.

In order to test the performance of the new design, a number of tests were carried out with well known designs such as the choke ring used as a control. The results of these tests, including low and high elevation tracking performance, code and carrier phase multipath rejection, phase center repeatability and positioning precision are presented. Physical characteristics such as size and weight are also compared.

INTRODUCTION

A typical GPS antenna for survey grade applications has a microstrip patch design, which consists of a conductive patch, typically square and of approximately a half wavelength in dimensions, which is mounted upon a substrate.

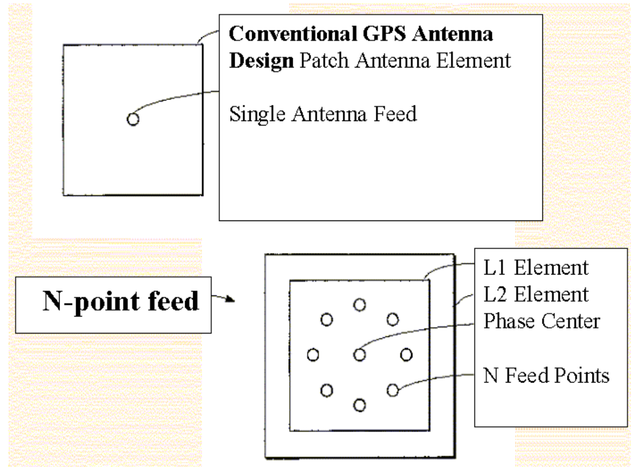
For dual frequency surveying, the patch antenna must be sensitive to both the L1 and L2 carrier frequencies and must be sufficiently broadband to accommodate the relatively wideband spread spectrum GPS signal. A typical solution to accommodate both frequencies is to stack an L1 patch on top of an L2 patch, e.g. as described in [Padros et. al., 1997].

In order to optimize the gain pattern of the antenna and to make the antenna less sensitive to ground-bounce multipath, which will be incident from below the horizon, it is also desirable to include a ground plane in the antenna design. Although some GPS receiving antennas have no ground plane, most antennas use either a flat metal ground plane of varying dimensions, or a ground plane of the well known choke ring design.

The new antenna design described in this paper takes a different approach to both the antenna element design and the ground plane design. The resulting development is the Trimble Zephyr Geodetic GPS antenna which, it is shown, is capable of out-performing the choke ring antenna in some aspects of performance and is comparable to the choke ring in others.

THE N-POINT ANTENNA FEED

The point at which the patch antenna is electrically coupled to the Low Noise Amplifier (LNA) is referred to as the feed point. A generic GPS patch antenna design has a single feed point for each patch. The Zephyr Geodetic Antenna employs an improvement on this generic design, where multiple symmetrically placed feed points are used for each patch, as described in [Lennen et. al 1996]. The basic geomtery of the single point feed and the n-point feed are illustrated below.



POLARIZATION

The electric and magnetic field vectors of the received GPS signal are rotating as a function of time, such that the polarization of the signal is considered to be Right Hand Circular Polarization (RHCP). Optimum Right Hand Circular Polarization of the receiving antenna is important for two reasons. One is that reduced polarization will result in a reduced signal-to-noise ratio and will make the antenna less sensitive to weaker signals. Another reason is that a loss of polarization will make the antenna more prone to multipath, as the reflection of the signal, for example off the ground, often results in a change in polarization to Left Hand Circular. Thus an antenna which is better tuned to RHCP and with better rejection of LHCP will be more immune to the cross-polarized multipath reflections of the signal

In the single point antenna feed design, the polarization is typically achieved by creating a 90 degree phase shift in two resonant modes on the path. With a rectangular patch antenna, this can be done by making two parallel sides resonant just under the center frequency and the other two parallel sides resonant just over the center frequency. However, disadvantages of this solution are that the asymmetry introduced tends to increase the phase center error ellipsoid and does not lead to optimum RCHP or optimum LHCP rejection of the antenna, particularly over the wide frequency bandwidth required for precision GPS.

RHCP is achieved in the Zephyr antenna by having symmetrically placed feed points driven from a feed network that forces the phase relationship required to generate RHCP. The frequency response of RHCP is limited by the bandwidth of the feed network and not the patch itself.
The near perfect symmetry of the n-point feed lends itself to enhanced RHCP and a higher degree of circular

polarization and cross-polarization rejection is achieved by this method. This is expected to enhance both the tracking performance of the antenna as well as the rejection of multipath signals in which the polarization has been reversed to LHCP as a result of the reflection.

THE TRIMBLE 'STEALTH' GROUND PLANE

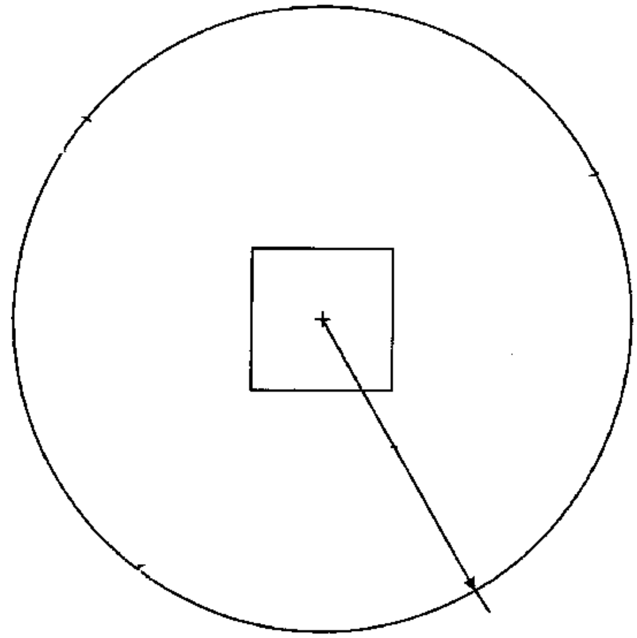
The generic GPS antenna ground plane is designed to shield the radiating element from near-field ground reflections of the GPS signal, i.e. local ground bounce multipath. The ground plane is typically fabricated from an electrically conductive material, which can have a detrimental effect in that signals which are diffracted at the ground plane edge (e.g from low elevation satellites or from behind) are directed towards the antenna element via surface waves. These diffracted surface waves distort the antenna pattern and contribute to unwanted backlobes in the gain pattern.

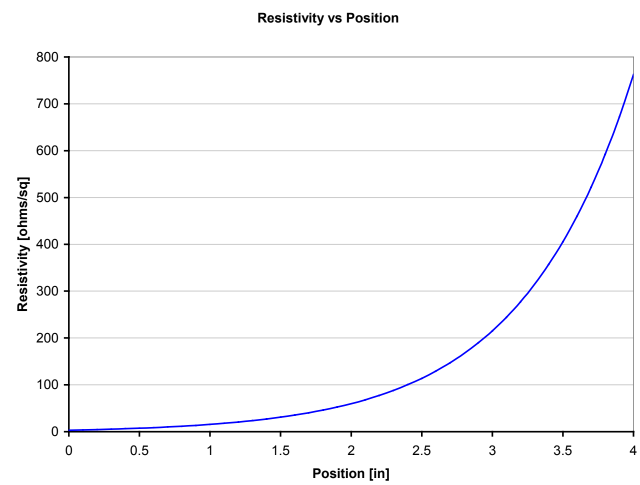
The Zephyr Geodetic Antenna utilizes a novel ground plane design as described in [Westfall, 1996]. This design takes advantage of resistive-card technology, which was originally developed for the Stealth Bomber aircraft, as a solution for the requirement to have a lightweight material covering which could absorb and dissipate as heat low powered electromagnetic signals such as enemy radar.

In the application of this technology to the problem of reducing GPS multipath reflections, the ground plane is constructed of a non-conductive material which acts as a supportive structure, onto which is applied a conductive material. The application of the conductive material is such that the sheet resistivity is not constant; it increases non-linearly as measured on any radial line from the center of the antenna to the edge of the ground plane.

Note that sheet resistivity in most conductive materials is constant for a square sheet of that material, regardless of the size of the square. Thus sheet resistivity is measured in Ohms Per Square, which is usually invariant to the size of the square. [cf Westfall, 1996]. The resistive-card differs from most conductive sheets in that the sheet resistivity is variable across the sheet. One method of achieving this variable resistivity is to vary the thickness of the conductive layer which is applied to the non-conductive supporting structure. The variation in thickness is chosen such that the increase in sheet resistivity is approximately quadratic, as a function of the distance from the center of the antenna.

This function is graphed in the figure below. It can be seen that the sheet resistivity increases from zero to 800 Ohms / Square for a ground plane of this design with a distance of about 10cm from the inner radius point to the outer radius point and an overall radius of about 16.5cm.





This design is effective in preventing multipath signals reflected from below the antenna from reaching the antenna element. Signals reflected from the ground which are incident on the underside of the antenna structure are absorbed by the ground plane and dissipated as heat, with the e-field of the electromagnetic wave cut off before it can interact with the antenna element itself. This method is frequency independent at L-Band, therefore the dimensions are not related to the wavelength of the signals. This has advantages both for equal effectiveness at the L1 and L2 frequencies and for the ability to build a more compact antenna without compromise in the multipath mitigation properties of that antenna. The varying sheet resistivity means that the Trimble Stealth

Ground Plane, although physically small, essentially simulates a ground plane of infinite dimensions.

A further difference in the design is the use of a capacitive coupling between the ground plane and the antenna element, as opposed to the use of an ohmic coupling as is typical in a conventional design.

TRIPLE FREQUENCY POTENTIAL

Another advantage of this frequency independent approach is that the underlying ground plane design is inherently suited to application in a three frequency antenna design, as will be required for simultaneous reception of L1, L2 and L5 signals. Other designs, including the choke ring, are frequency dependent and so dual frequency antennas are a compromise between L1 and L2 performance, a design problem which will be further exacerbated by the introduction of L5.

It should be noted that L5 compatibility of the current Trimble Zephyr Geodetic Antenna is not claimed, only that the underlying design of the ground plane has the potential to be adapted to a triple frequency model.

LOW ELEVATION TRACKING

An inherent disadvantage of the choke ring design is the reduced antenna gain at low apparent elevation angles. This reduced antenna gain makes the antenna less sensitive to direct line-of-sight signals from satellites at low elevation angles, which reduces the available signal power at the antenna element and increases the number of cycle slips experienced. This effect is not expected to be so apparent in the Zephyr Geodetic antenna design.

In order to make a comparison between the two designs in this aspect of performance, a choke ring antenna and a Zephyr Geodetic Antenna were located in very close proximity to one another and each was connected to an identical GPS receiver. Both antennas had an identical view of the horizon. Data were collected for 24 hours at 1Hz, yielding a sample data set of 86,400 epochs.

The UNAVCO TEQC software [Estey et. al (1998)] was used to compute the Actual vs. Expected number of epochs for both data sets, for all data between zero and ten degrees elevation. As might be expected from theory, the choke ring antenna caused a larger number of cycle slips for this low elevation data and yielded a data set with a larger number of missing epochs. The Zephyr Geodetic antenna had more than 2,000 fewer missing epochs, demonstrating better low elevation tracking than the choke ring.

0 to 10 degrees	choke ring	Zephyr
Actual vs. Expected epochs (%)	57.17%	60.47%

HIGH ELEVATION TRACKING

The same data set was also analyzed in an identical fashion for the data between 10 degrees and 90 degrees, to compare the high elevation tracking performance of the Zephyr Geodetic Antenna with the well known choke ring design. The table below shows the results. Again, the Zephyr Geodetic exhibited better tracking performance than the choke ring, with more than 2,000 fewer missing epochs.

10 to 90 degrees	choke ring	Zephyr
Actual vs. Expected epochs (%)	97.02%	99.96%

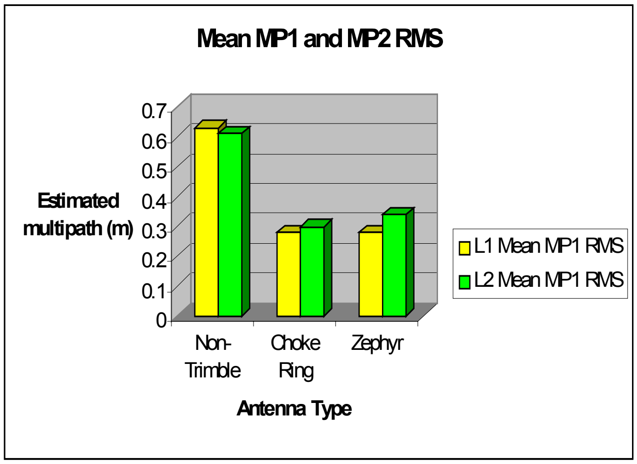
PSEUDORANGE MULTIPATH ESTIMATION

In order to assess the combined multipath resistance of the Zephyr antenna and Trimble 5700 GPS receiver, the Zephyr / 5700 combination was tested with a Trimble choke ring / 5700 receiver combination used as a benchmark. A third, non-Trimble survey-grade dual frequency GPS receiver and antenna combination was also tested for the purposes of comparison.

The MP1 and MP2 multipath estimation parameters [Estey et. al.] were used to assess the levels of multipath in the L1 and L2 data. The test was run over a complete 24 hour period, with observables recorded at 1Hz. The MP1 and MP2 values are calculated for each satellite and for each epoch, thus the total sample size for each antenna is more than 500,000 samples.

The Mean MP1 RMS value is the mean of the RMS MP1 values calculated for each satellite, which in turn are calculated as the RMS of all MP1 values for that satellite over the entire 24 hour data set. The Mean MP2 RMS is calculated in the same way, from all the MP2 estimates. The estimated mean MP1 and MP2 values express the average level of multipath present over the entire data set and are shown in the graph below for the three GPS receiver / antenna combinations tested.

The MP1 and MP2 values for the choke ring antenna and the Zephyr antenna are equal to within 1/7500 of a single C/A code chip, demonstrating the choke ring level pseudorange multipath resistance of the Zephyr antenna.

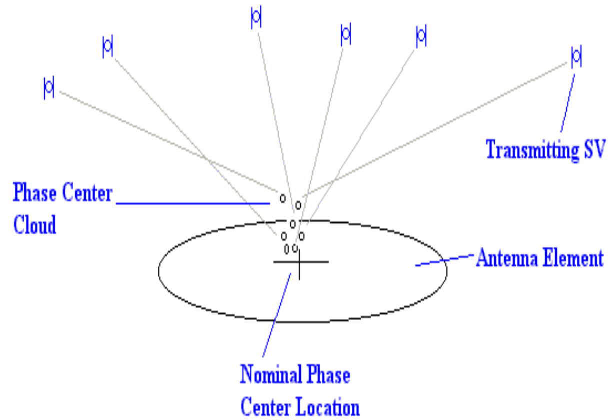


The non-Trimble conventional antenna design results contained approximately twice the levels of L1 and L2 multipath than those seen in both the choke ring and Zephyr antennas, in this large data sample of more than half a million measurements.

PHASE CENTER VARIATION

In the case of a GPS receiver being used to measure geodetic accuracy positions, it is necessary to relate a physical measurement center to the electrical center, from which the phase measurement is actually made. As well as some systematic offset from a physical reference point to a nominal L1 and L2 phase center location, all GPS antennas have a variable phase center response to the apparent elevation and, to a lesser extent, azimuth of the transmitting satellite. This effect is also frequency dependent, thus the response of the L1 and L2 phase centers will be different, even when the two signals are transmitted from the same satellite, so that both signals have an identical apparent elevation and azimuth at the receiver.

In fact, as the receiving antenna is simultaneously tracking a number of transmitting satellites at any one time, each of which has a different apparent elevation angle and azimuth, the instantaneous measurement space actually resembles a phase center cloud as shown in the figure below. This cloud consists of *n* discrete phase center measurement locations in space, where *n* is the number of satellites being tracked for an L1 receiver and nominally twice the number of satellites being tracked for an L2 receiver.



NGS RELATIVE CALIBRATION RESULTS

By taking measurements on a well known baseline, with a reference antenna (typically a Dorne Margolin Model T choke ring) at one end of the line and a test antenna at the other, it is possible to estimate a relative Phase Center Variation (PCV) table, e.g. [Mader (a)]. The tables below show this relative calibration for the Zephyr Geodetic Antenna, as published by the National Geodetic Survey [NGS (a)]:

TRM 41249.00 — TRIMBLE ZEPHYR GEODETIC with Ground Plane — NGS (4) 01/04/11

	.3		.5	71.4														
.0	.6	1.4	2.3	3.2	4.1	4.9	5.6	6.1	6.4	6.4	6.1	5.5	4.5	3.1	1.3	-.9	.0	.0
	-.4		.1	68.2														
.0	-.5	-.6	-.5	-.2	.1	.5	.8	1.0	1.1	1.0	.9	.6	.2	-.2	-.6	-.8	.0	.0

RMS mm (1 sigma) — 4 MEASUREMENTS

	.2		.3		.2													
.0	.1	.2	.2	.1	.1	.1	.1	.2	.2	.2	.2	.2	.2	.2	.2	.3	.0	.0
	.2		.2		.2													
.0	.3	.5	.5	.5	.5	.4	.4	.3	.3	3	.3	.3	.4	.4	.4	.5	.0	.0

The RMS values show the repeatability over four measurements, with all values for L1 at 0.3mm or less and all values for L2 at 0.5mm or less.

The values in the relative PCV table only show the variations relative to the reference antenna. If the absolute variations of the reference antenna are unknown, no inferences can be made about the phase center stability of the test antenna in an absolute sense.

ABSOLUTE PHASE CENTER VARIATION

A number of different approaches have been taken to attempt to measure the absolute variation of a GPS antenna. Recent work by [Wübbena et. al (2000)] has yielded an absolute calibration of the choke ring Antenna, published by IfE Hannover [IfE (a)].

With an absolute phase center variation (PCV) table available for the Dorne Margolin choke ring Model-T, it is possible to indirectly estimate the absolute phase center variation for any antenna for which a PCV has been measured relative to the DM-T. This is the case for many antennas, including the Zephyr Geodetic antenna type.

Taking the absolute PCV table due to [IfE (a)] and adding to each discrete L1 and L2 elevation dependent variation the relative value from the table due to [NGS], yields an indirect absolute PCV table for the Zephyr Geodetic Antenna. These indirect absolute PCV tables for L1 and L2 are as follows:

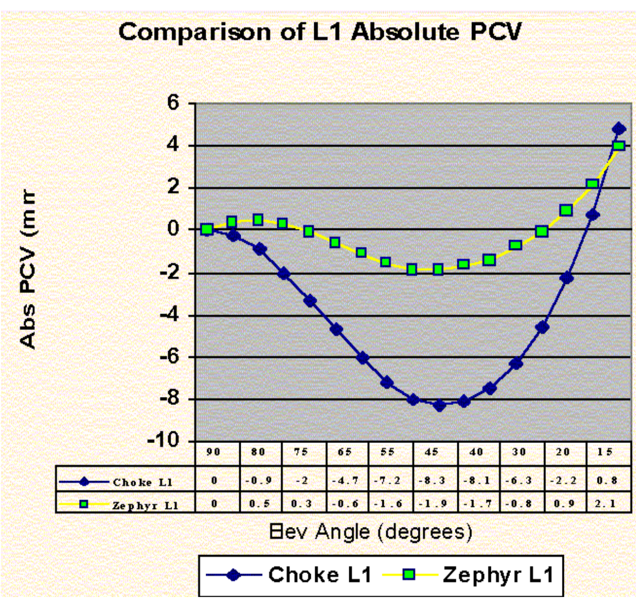
Indirect L1 PCV Table Zephyr Geodetic

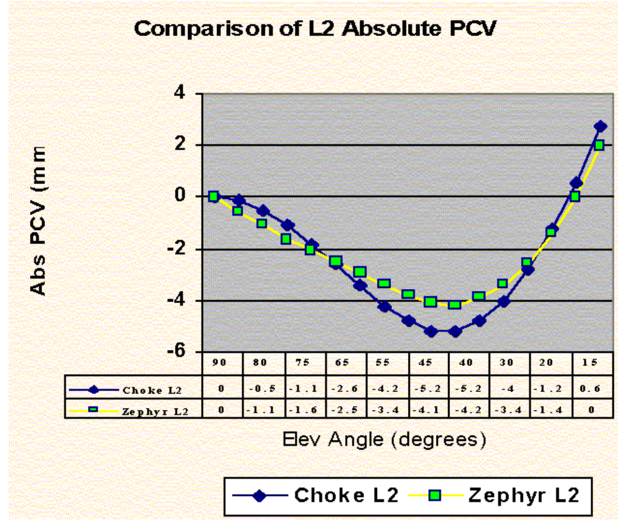
EL	90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
	0.0	0.4	0.5	0.3	–0.1	–0.6	–1.1	–1.6	–1.9	–1.9	–1.7	–1.4	–0.8	–0.1	0.9	2.1	3.9

Indirect L2 PCV Table Zephyr Geodetic

90	85	80	75	70	65	60	55	50	45	40	35	30	25	20	15	10
0.0	–0.6	–1.1	–1.6	–2.0	–2.5	–2.9	–3.4	–3.8	–4.1	–4.2	–3.9	–3.4	–2.6	–1.4	0.0	2.0

The L1 and L2 absolute elevation dependent phase center responses are graphed below, as estimated by this method.





It can be seen that the absolute L1 phase center variation is significantly larger for the choke ring than for the Zephyr Geodetic Antenna. The L2 response is approximately the same for both antennas, within about 1-2mm.

However, absolute stability of the phase center is far less important than repeatability of the phase center. If we take a random sample of antennas of the same type, the response of each of those antennas to the elevation angle and azimuth would ideally be identical. If it were, then errors in the positioning solution could be eliminated once a PCV calibration had been carried out and a PCV correction table produced. In practice, however, there will be some variation between the model and the actual responses of an individual antenna of any given type. Some of these variations are due to the modeling process itself, while others are due to the antenna design.

The strength of the choke ring antenna design does not lie in the absolute phase center stability. In fact, the absolute variations of the choke ring phase center are relatively large, at more than 20mm. Rather, the strength lies in the repeatability of those variations. In other words, even though the absolute variations are large, those variations are very repeatable and very predictable, typically within 1mm. [Bock et al, 1988] report phase center repeatability of 0.1-0.2mm horizontal and 0.5mm vertical for a sample of different choke ring models.

REPEATABILITY OF RANDOMLY SELECTED PRODUCTION ANTENNAS

The inferred absolute PCV table for the Zephyr Geodetic Antenna suggests that the phase center of this antenna exhibits significantly less variation, and thus has better absolute stability, than the choke ring. In order to assess the repeatability of the Zephyr Geodetic phase center response, ten production antennas of this type were randomly selected and a relative calibration with respect to the choke ring antenna was carried out independently for each antenna over a period of fourteen days. The relative PCV derived from all the measurements agrees well with the NGS elevation dependent model results, although it should be noted that the model of choke ring reference antenna is different, which along with site dependent effects, would lead us not to expect identical results. (Note that the format in the table below is reversed with respect to the NGS format, i.e. from zero to ninety degrees from left to right). Elevation corrections (mm) 0 to 90 degrees @ 5 deg:

L1									
---	---	---	0.6	2.7	3.7	4.6	5.4	6.0	6.2
5.9	5.4	4.6	3.8	3.0	2.2	1.4	0.7	0.0	
L2									
---	---	---	2.3	0.5	0.4	1.0	1.5	1.8	1.9
1.7	1.5	1.3	1.2	1.1	1.0	0.8	0.5	0.0	

However, of more interest here are the residuals to the mean PCV for each of the fourteen days of the test, as these provide an indication of the repeatability of the PCV model across a random selection of antennas of this type. The tables below show the residuals by elevation angle for each of the fourteen days of the test, the first table for the L1 frequency and the second for the L2 frequency.

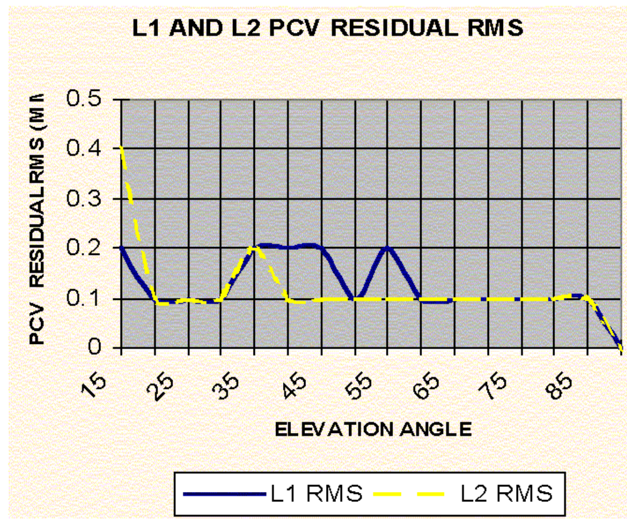
L1

EL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	RMS
15	-0.2	-0.4	0.1	-0.0	-0.2	-0.2	-0.0	0.1	0.1	0.1	-0.2	-0.0	0.5	0.4	0.2
20	-0.2	-0.1	0.1	-0.0	-0.1	-0.1	-0.1	0.2	0.1	0.1	-0.0	-0.1	0.3	-0.0	0.1
25	-0.1	-0.1	0.2	-0.0	-0.2	-0.1	-0.1	0.1	0.1	0.2	-0.0	-0.0	0.2	-0.0	0.1
30	0.0	-0.2	0.2	-0.1	-0.2	-0.2	-0.2	0.1	0.1	0.2	0.0	0.0	0.2	0.0	0.1
35	0.0	-0.1	0.2	-0.1	-0.3	-0.2	-0.2	0.2	0.1	0.3	0.0	-0.1	0.2	0.0	0.2
40	0.0	-0.1	0.1	-0.1	-0.3	-0.3	-0.3	0.2	0.1	0.2	0.0	-0.2	0.2	0.0	0.2
45	0.0	-0.1	0.1	-0.1	-0.3	-0.2	-0.3	0.2	0.0	0.2	0.0	-0.2	0.2	-0.1	0.2
50	-0.0	-0.1	0.1	-0.1	-0.2	-0.1	-0.2	0.2	0.1	0.2	-0.0	-0.1	0.3	-0.0	0.1
55	-0.1	-0.1	0.1	-0.1	-0.3	-0.1	-0.2	0.2	0.1	0.2	0.0	-0.1	0.2	0.0	0.2
60	-0.0	-0.1	0.2	-0.0	-0.2	-0.0	-0.1	0.2	0.1	0.2	-0.0	-0.0	0.3	0.1	0.1
65	-0.1	-0.1	0.2	-0.1	-0.2	-0.1	-0.1	0.2	0.1	0.2	-0.0	-0.0	0.3	0.1	0.1
70	-0.2	-0.2	0.1	-0.1	-0.2	-0.1	-0.1	0.1	0.0	0.2	-0.1	0.0	0.2	0.0	0.1
75	-0.1	-0.1	0.1	-0.1	-0.2	-0.1	-0.1	0.1	0.0	0.1	-0.1	0.0	0.2	0.0	0.1
80	-0.1	-0.1	0.1	-0.1	-0.1	-0.1	-0.1	0.1	0.0	0.1	0.0	0.0	0.3	0.0	0.1
85	-0.1	0.0	0.1	-0.1	-0.1	-0.1	-0.1	0.0	0.0	0.1	0.0	-0.1	0.1	0.0	0.1
90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

L2

EL	1	2	3	4	5	6	7	8	9	10	11	12	13	14	RMS
15	0.6	-0.1	0.3	0.6	-0.2	-0.7	-0.2	-0.5	0.0	-0.4	0.1	-0.1	0.1	0.1	0.4
20	0.1	0.0	0.0	0.0	0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.1	-0.1	0.2	0.0	0.1
25	0.2	0.1	0.1	-0.1	0.1	-0.0	-0.1	-0.0	-0.2	-0.1	0.1	-0.1	0.2	-0.1	0.1
30	0.2	0.1	0.1	-0.1	0.0	-0.1	-0.2	-0.1	-0.3	-0.1	0.2	-0.1	0.1	-0.2	0.1
35	0.2	0.1	0.2	-0.0	0.1	-0.1	-0.1	-0.1	-0.2	-0.1	0.4	-0.0	0.1	-0.2	0.2
40	0.2	0.1	0.1	0.1	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.4	-0.0	0.2	-0.1	0.1
45	0.1	0.0	0.0	0.0	0.1	-0.1	-0.1	-0.1	-0.1	-0.1	0.3	0.0	0.1	-0.2	0.1
50	0.1	0.1	0.1	0.1	0.1	-0.0	-0.0	-0.0	-0.1	-0.1	0.3	-0.0	0.2	-0.1	0.1
55	0.2	0.1	0.1	0.1	0.1	-0.0	-0.1	-0.0	-0.1	-0.1	0.2	-0.0	0.2	-0.1	0.1
60	0.2	0.1	0.1	0.1	0.1	-0.0	-0.1	-0.0	-0.1	-0.1	0.2	-0.0	0.2	-0.0	0.1
65	0.2	0.1	0.1	0.0	0.0	-0.1	-0.1	-0.1	-0.1	-0.2	0.2	-0.1	0.2	-0.1	0.1
70	0.2	0.1	0.1	0.0	0.0	-0.2	-0.1	-0.1	-0.1	-0.2	0.2	-0.1	0.2	-0.1	0.1
75	0.2	0.0	0.0	0.0	0.0	-0.2	-0.1	-0.1	-0.2	-0.2	0.1	-0.1	0.1	-0.1	0.1
80	0.2	0.0	0.0	0.0	0.0	-0.2	-0.1	0.0	-0.1	-0.1	0.1	-0.1	0.1	-0.1	0.1
85	0.1	0.0	0.0	0.0	0.0	-0.2	0.0	0.0	-0.1	-0.1	0.1	-0.1	0.0	-0.1	0.1
90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

It can be seen that the RMS values are of the order of 0.1 - 0.2mm for L1 and 0.1 - 0.4mm for L2. The graph illustrates the RMS values for the residuals as a function of elevation angle. These results demonstrate sub-0.2mm repeatability of the PCV across a random selection of ten production antennas for L1 and sub-0.4mm for L2. These results are comparable to those reported by [Bock et. al, 1998] for the choke ring models tested.



CARRIER PHASE POSITION DOMAIN PERFORMANCE COMPARISON

To assess the reduction in carrier phase multipath error achieved with the Stealth Ground Plane, a test setup was created to compare the results from a choke ring control antenna to three other test antenna types. The test antennas were (i) another choke ring, (ii) a Trimble Zephyr Geodetic and (iii) a non-Trimble survey grade GPS antenna of conventional feed and ground plane design.

Three sets of static data were collected using the same survey mounts with approximately 3m separation, each with the reference choke ring antenna at the "base" end and the test antenna at the other.

For all baselines, 1 Hz data were collected for 24 hours and then processed using a PC compile of the Trimble RTK engine, usually resident inside the GPS receiver.

Multipath, especially the ground-bounce multipath reduced by a ground plane, de-correlates very quickly as a function of baseline length. This de-correlation is due to the short wavelengths of the L1 and L2 carrier frequencies (approximately 19cm and 24cm respectively). Consequently, the observables measured at each end of the 3m baseline would be expected to show almost zero correlation of multipath on average. Therefore, multipath noise would not be expected to cancel out during double-difference processing on an epoch-by-epoch basis..

However, multipath typically has a periodicity of the order of several hundred seconds. As the time span over which the sample data were taken was 24 hours, multipath effects as a whole would average out for the baseline components, as estimated from all the data over the entire 24 hour sample. Thus the mean baseline components are estimated from all the data, 24 hours in this case, which is several orders of magnitude larger than the typical frequency of multipath error. Over this time-scale, multipath can be treated as random and the results can be expected to be free of biases caused by multipath.

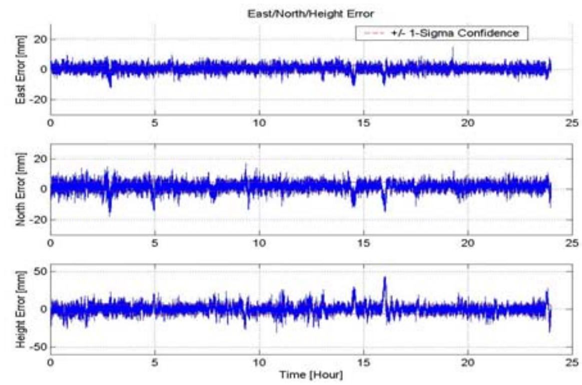
The mean baseline components and their associated standard deviations were computed from the entire 24 hours data sets, to yield an estimate of the error population for each antenna type. Although the mean estimates would be expected to be free of multipath due to averaging over the long time period, the standard deviations would be expected to reflect the levels of carrier phase multipath in the data on average. The table below lists these standard deviation estimates (in mm) for the three antennas tested.

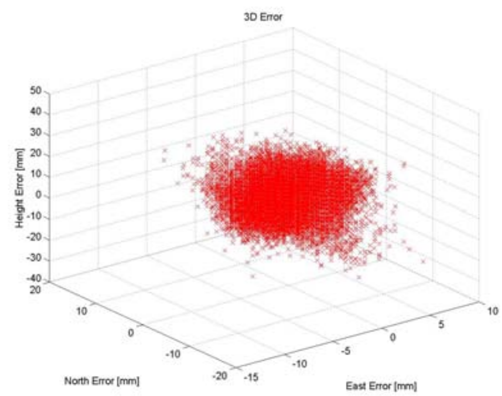
Antenna	Sigma E	Sigma N	Sigma H
choke ring	2.1	2.7	6.1
Zephyr Geodetic	2.4	3.1	7.9
Non-Trimble	3.7	4.5	13.4

It can be seen from the table below that the data taken with the Zephyr Geodetic Antenna is within 15% of the noise levels of the data from the choke ring and within 30% in height. The other test antenna shows more than a 75% increase in noise horizontally and a 120% noise increase in the vertical.

%age increase in noise over choke ring	E	N	H
Zephyr Geodetic	14%	15%	29%
Non-Trimble	76%	67%	120%

The repeatability can also be tested in the position domain. For this analysis, five production antennas were randomly selected and each one was deployed on a precision mounting along with a reference antenna on a known baseline and data collected for 24 hours. Each of the five 24 hour data sets were then run through the same PC compile of an RTK engine as described above. The NGS derived PCV model was used in the processing. This yields epoch-by-epoch vector solutions which can be compared against a well known dE, dN, dH vector for the test setup to generate an E, N, H error time series as plotted below in both E,N,H and 3-D form.





As multipath geometry is known to repeat itself once per sidereal day and as other error sources such as those induced by atmospheric propagation will be almost perfectly correlated on such a short baseline, the time series for each of the five antennas is expected to be very highly correlated. With all other environmental parameters constant over the five day period of the test, variations in the antenna PCV are detectable as variations in the sigma values across the individual samples of the antenna type. The table below lists the differences in the E,N,H sigma values for the five sample antennas, referenced to antenna #8907. It can be seen that the horizontal values are consistent to within 0.1mm and the vertical to within 0.2mm when the PCV model is used. Once again this suggests that a random production antenna of this type will have elevation dependent responses which are within +/- 0.2mm of the standard PCV model for this type.

Zephyr Geodetic Antenna Serial #	Mean # SVs	Delta Sigma East (mm)	Delta Sigma North (mm)	Delta Sigma Height (mm)
8907	6.98	- ref -	- ref -	- ref -
8357	6.98	0.0	0.0	+0.1
0491	6.98	0.0	+0.1	+0.1
2118	6.98	0.0	0.0	+0.1
8878	6.98	0.0	0.0	+0.2

COMPARISON OF MECHANICAL AND PHYSICAL DESIGN

The Zephyr Geodetic antenna has a number of improvements over conventional antennas in terms of the physical design.

First, the resistive ground plane is wholly encased in an environmentally sealed housing. The plastic housing consists of an upper radome and lower housing that are glued together to form a completely sealed unit, thus there is no reliance on o-ring seals and screws that can fail over time.

Second, unlike a metal ground plane, whether removable or not, the antenna performance is not dependant on an ohmic connection between the antenna element and the ground plane. The Zephyr Geodetic antenna uses capacitive coupling to connect the element to the ground plane. While any corrosion at the joint may cause an increase in the resistance across the transition for a metal ground plane, the capacitance of the same joint is much less affected.

Third, the resistive ground plane is constructed to minimize any changes to the surface resistance. The resistive layer is sputtered onto a plastic film and then adhesively attached to another layer of plastic film, such that the resistive material is doubly protected from environmental exposure.

Several studies have been performed to look at environmental ruggedness of the ground plane. One of the studies took an exposed ground plane without the outer radome housing, attached to an antenna element which was mounted outside for a period of 4 months. The ground plane was subjected to rain, wind and hot sun during the test, following which no detectable degradation of the ground plane, either physically or electrically, was found. In another study, a complete Zephyr Geodetic antenna with the sealed housing was subjected to a week of temperature cycling from -55 to +125 degrees Celcius (-131 to +257 F) at a half an hour per temperature. At the conclusion of the test the unit was surveyed and compared with a survey prior to the test. Again, no detectable degradation was found in the ground plane performance either physically or electrically.

Despite the ability to withstand exposure to such extreme environmental conditions, the antenna itself is considerably more compact and lightweight than the choke ring design. The table below compares the weight and dimensions of the two designs. The Zephyr Geodetic antenna is also more economical than the choke ring, due to significantly reduced manufacturing costs, which can be passed on to the end user.

Antenna	Weight	Diameter	Height
Choke ring	10 lb 4.5 kg	15" 38mm	6" 15mm
Zephyr Geodetic	2.2 lb 1 kg	13.5" 34mm	3" 7.5mm

CONCLUSIONS

The Zephyr Geodetic utilizes two novel designs in the n-point antenna feed and the Trimble Stealth Ground Plane. The results of a number of performance tests have been presented which demonstrate that:

- The absolute phase center stability of the Zephyr Geodetic antenna is considerably better than the choke ring at L1 and approximately equal at L2.
- The phase center repeatability of the Zephyr Geodetic antenna is consistent with the PCV model to +/- 0.2mm for any random production antenna of this type. This repeatability equals or exceeds previously reported results for the choke ring antenna.
- The Trimble Stealth Ground Plane, which utilizes a resistivity tapered material to resist multipath, has demonstrated comparable multipath rejection performance to the choke ring ground plane.
- The Zephyr Geodetic antenna has better low elevation tracking than the choke ring, due to the gain drop-off at low elevation angles for the latter. The Zephyr Geodetic antenna also demonstrated better high elevation tracking in our tests.
- The Zephyr Geodetic antenna design utilizes electrical and mechanical methods which are extremely rugged and resistant to extreme

environmental conditions, while still being significantly more compact and lightweight than other antennas with comparable performance.

These results demonstrate that this advanced GPS antenna design can achieve results comparable to that of a quality milled choke ring antenna design, but without the associated cost, weight and reduced low elevation tracking performance.

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