GPS Antenna Design and Performance Advancements: The Trimble Zephyr

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New Antenna Technology from Trimble

The Trimble Zephyr and Zephyr Geodetic antennas are two new types of survey-grade, dual-frequency, GPS antenna. They are designed to match the performance of the choke ring antenna, while being smaller, lighter, and significantly less expensive.

Both antennas are the result of intensive research and development, and utilize recent innovations in high-performance GPS antenna technology, for which patents have been issued to Trimble. The new antennas incorporate major advancements in:

- Radio frequency antenna design
- Advanced materials technology
- High precision manufacturing techniques
- Trimble Stealth™ Ground Plane technology

The result is antenna phase center (APC) repeatability and multipath resistance comparable to the choke ring—and improved tracking of low elevation satellites and in difficult environments.

The use of advanced materials enables the Trimble Zephyr and Zephyr Geodetic antennas to be extremely compact and lightweight. Although the antenna element and low noise amplifiers used today will need to be modified in order to be compatible with the future L5 second civil frequency, the underlying design of the new Trimble Stealth Ground Plane is independent of frequency. This will make it much more effective for use with the new frequency than more conventional ground planes.

Patented Antenna Element Design Achieves Sub-millimeter Repeatability

The GPS antenna element is the part of an antenna that is sensitive to energy transmitted from GPS. For precise GPS surveying, this element is usually a flat piece of metal called a “patch” antenna. It is usually round or approximately square, and its dimensions make it sensitive to the GPS frequency being tracked. When a GPS receiver/antenna combination is tracking satellites and making code and carrier phase measurements, the actual points in space between which those measurements are taken are the instantaneous phase centers of the GPS satellite and GPS receiver antennas.

Nominally, the GPS receiver antenna phase center is located at the center of this square patch, that is, at the mechanical center of the antenna. However, in practice the effective electrical center of the antenna moves around in three dimensions.

This is a function of the apparent azimuth and elevation of the satellite being tracked, and the way that the antenna is fed, that is, how it is electrically connected to the rest of the circuit. Because multiple satellites are tracked at any time, and each one has a different azimuth and elevation, each measurement is taken from a slightly different location in space, somewhere near the mechanical center of the antenna. Thus, although surveyors require a measurement at a single point in space at any point in time, their antennas take measurements from a group of electrical phase centers that are all at slightly different locations.

The space in which these electrical phase centers may vary is something like an error ellipsoid; consequently, if an antenna’s variation is large, then its ellipsoid is also large.

An ideal GPS antenna for surveying would take all measurements from an exact, physically defined, mechanical location, regardless of satellite elevation angle or azimuth, or any other factor. Such an antenna would be said to have extremely good phase center stability.

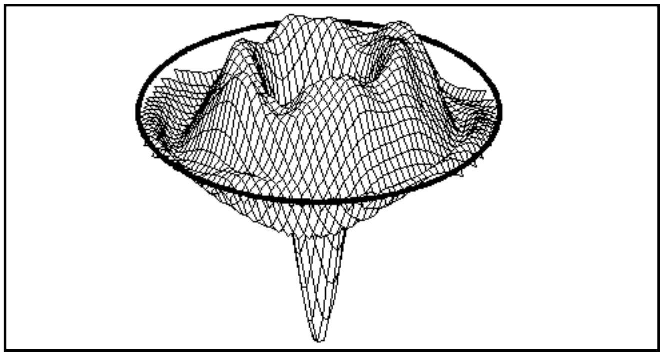


Figure 1. Typical Phase Center Variation Pattern as a function of Satellite Azimuth and Elevation angle

Although the phase center of all antennas has some variation, a high performance antenna varies minimally and in a predictable way that is consistent for all antennas of that type made, enabling variations to be cancelled or modeled in processing.

In practice, the electrical phase centers of all GPS antennas move—even those of choke ring antennas, as used for the most precise geodetic and scientific surveying. However, there is a two-fold difference between a precise, high-performance antenna (such as the choke ring) and a less accurate, low-performance antenna.

Firstly, in high-performance antennas, the variation of the phase center in the horizontal plane is limited to values of less than 1 millimeter, regardless of the direction from which the signal is received, or the rotation of the antenna. However, in low-performance, conventional, survey-grade antennas, the characteristics of an antenna are not consistent over the asymmetrical horizontal surface of the antenna, so the horizontal phase center is much less stable. Thus, the low-performance antenna experiences horizontal phase center shifts that vary depending on the direction to the satellite, and the direction in which the antenna is pointing. Furthermore, two antennas of the same type at each end of a baseline may be manufactured to slightly different tolerances, and be pointing in different directions, creating inconsistent relative horizontal phase center variations. This unpredictable behavior does not tend to cancel during double-difference processing. Its random nature also means that it cannot be effectively modeled either, leading to additional errors in the baseline solution.

Secondly, all antennas-including the choke ring-have significant vertical phase center variations as a function of satellite elevation angle in an absolute sense. However, in high-performance antennas, these variations are highly consistent, even across different antennas of the same type. This consistency means that two high-performance antennas at each end of a baseline will have almost identical phase center variations. In double-difference processing, this highly correlated error cancels out, effectively removing the error caused by the instantaneous offset.

As baselines become significantly longer than 50 km, the apparent satellite elevation and azimuth gradually become different for the antennas at each end of the line; that is, the apparent elevation angle de-correlates with range. In high-performance antennas, this effect can be accurately predicted using a simple correction table for the antenna phase center, and then removed during processing. Although conventional antennas can also have correction tables, because the variations in different antennas of the same type are inconsistent, as mentioned earlier, the offset cannot be predicted accurately and leads to errors in the solution.

If an antenna phase center moves very predictably as a function of satellite elevation, regardless of the azimuth of the satellite, and if this consistent behavior is held within very fine tolerances across all antennas of its type (even if thousands of them are produced), then the antenna has very good phase center repeatability.

For dual-frequency surveying, the patch antenna must be sensitive to both the L1 and L2 carrier frequencies on which the GPS satellites transmit. However, for optimum sensitivity, each frequency requires different dimensions for the patch.

One way to accommodate both frequencies is to stack an L1 patch on top of an L2 patch. Each patch is electrically connected to the antenna Low Noise Amplifier by a single feed point. GPS signals are transmitted by the satellite with a Right Hand Circular Polarization (RHCP) and, for optimal receiver performance, the receiving antenna must have the same polarization. RHCP is achieved in the conventional single point feed antenna by creating a 90 degree phase shift in two resonant modes on the patch. With a square patch antenna, this can be done by making two parallel sides resonant just under the center frequency (L1 for example) and the other two parallel sides resonant just over this center frequency.

Although this design solution works, it has significant limitations for precise survey accuracy applications: the conventional GPS antenna has lower phase center accuracy, and its ability to track satellites is affected. In practice, the solution only works well at the center design frequency. Also, because of the non-symmetrical patch, it loses the circular polarization required to effectively track the Right-Hand Circular Polarization (RHCP) of GPS signals. This loss of polarization leads to a reduced signal-to-noise ratio (SNR), so that received signals are weaker and contain more noise. It also makes 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 Polarization (LHCP). An antenna that is better tuned to RHCP is more likely to reject LHCP, and is therefore more immune to multipath.

Conventional antennas typically also have a single antenna feed point, which connects the antenna to the rest of the circuit at a single point, but which also makes the antenna asymmetrical, leading to inconsistent phase center variations.

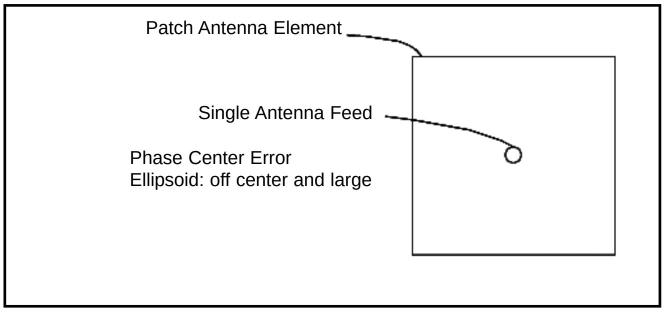


Figure 2. Conventional GPS Antenna Design

Unlike conventional antennas, the Trimble Zephyr and Zephyr Geodetic antennas utilize an innovative n-point antenna feed design that has n multiple feed points, where n is a positive integer greater than two, arranged on a symmetric patch antenna. This is a significant improvement on the single point feed design. The key advantage of this design lies in the almost perfect symmetry, achieved by combining a phased system of multiple, precisely located antenna feed points, and advanced, high-precision manufacturing.

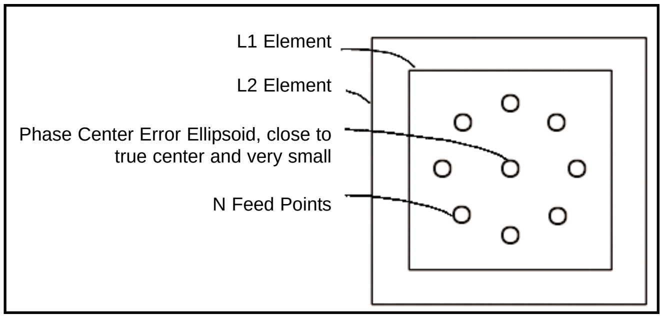


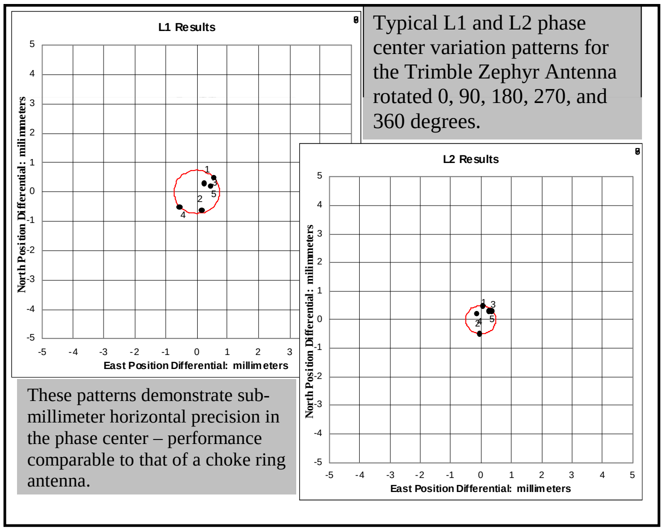
Figure 3. Trimble Zephyr with symmetrical n-point feed

The result: sub-millimeter phase center stability to match the accuracy of the choke ring. Furthermore, the excellent symmetry of this antenna significantly improves its RHCP and enables a much wider bandwidth (frequency range) to be tracked. This improves the ability of the antenna/receiver system to track and hold on to GPS signals under difficult conditions with an increased SNR. It also makes the antenna more immune to multipath.

Zephyr Antenna Rotation Tests

To test the L1 and L2 phase center repeatability and antenna symmetry in a Trimble Zephyr antenna, the antenna was set up on a mounting that automatically rotated the antenna by a total of 90 degrees every eight hours. The data collected from each eight-hour session was then individually processed using the double-difference model on a short baseline; a choke ring antenna located a few meters away functioned as a reference.

For each GPS frequency, this yielded a set of 5 results for the 0, 90, 180, 270, and 360 (back to zero) rotations, which differed slightly in position due to inconsistencies in the phase center position. As illustrated in Figure 4 overleaf, the results of the test demonstrated extremely good horizontal phase center stability—significantly less than 1 mm variation for both the L1 and L2 frequencies.



Typical L1 and L2 phase center variation patterns for the Trimble Zephyr Antenna rotated 0, 90, 180, 270, and 360 degrees.

These patterns demonstrate sub-millimeter horizontal precision in the phase center – performance comparable to that of a choke ring antenna.

Figure 4. Horizontal phase center stability for both the L1 and L2 frequencies

Zephyr Antenna Performance – High-Elevation Tracking

Tests also measured how well the highly symmetrical Trimble Zephyr and Zephyr Geodetic antennas track high- and low-elevation satellite signals.

A simple method for measuring and comparing the tracking performance of any GPS receiver is to take a large (at least 24 hour) data sample and compare the total number of *possible* observations to the total number of *actual* observations contained in the file. From this, the observed-to-expected ratio can be computed, as the ratio of the total number of observations *actually made* to the total number of *possible observations* during that period.

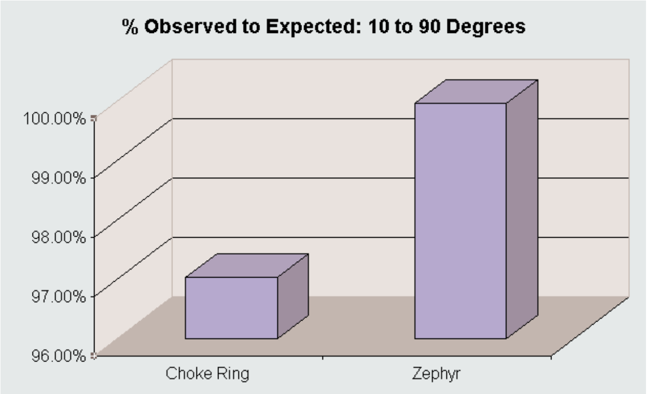
A perfect GPS receiver/antenna combination would always achieve a 100% observed-to-expected ratio, but in practice the following occur: cycle slips, low-elevation obstructions, and losses of lock. These cause small periods of missing data in the recorded file. Thus, a simple percentage expresses the observed-to-expected ratio. Results close to 100% indicate a better overall ability to acquire and continuously track satellites.

At low elevation angles, the GPS signals travel very obliquely through the earth's atmosphere. Refraction effects reduce the signal power significantly, increasing the noise and making the signals much harder to track. At very low elevation angles (typically below 10 degrees, and certainly below 5), this causes the number of losses of data to generally increase sharply. Therefore, it is common practice to estimate the statistics for high-elevation (10 to 90 degrees) and low-elevation tracking as separate data sets.

In order to benchmark the new Trimble Zephyr antenna against the well-known choke ring, data was logged by both antennas at the same position but on different days; both antennas using the same Trimble GPS receiver. In order to assess the performance in a sub-optimal GPS environment of the type typically encountered by the field surveyor, the data was collected in an area with various obstructions nearby, such as trees. Approximately 3 m away, data from a choke ring control antenna was collected on both days to ensure that the environment had not changed.

The results for the control antenna agreed on the two days, showing no statistically significant differences.

The graph below compares the observed-to-expected number of epochs for the Zephyr and choke ring antennas, for elevation angles of 10 to 90 degrees. The data consists of more than half a million measurements from a 24-hour data set, sampled at 1 Hz, and giving a total sample size of 86,400 expected epochs times the average number of satellites (~605,000 possible epochs).

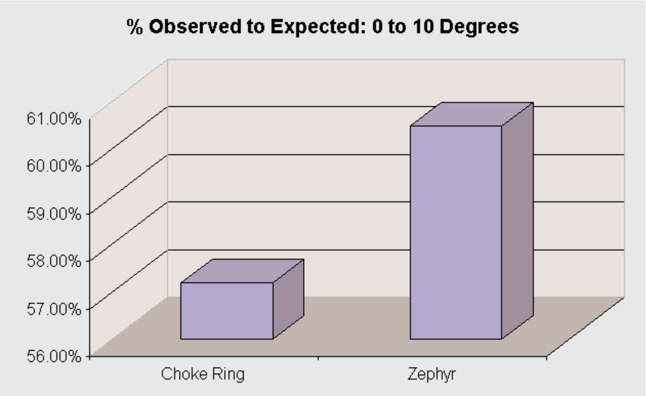


10 to 90 Degrees	Choke Ring	Zephyr
Observed to Expected Epochs (%)	97.02%	99.96%

The results show that the Trimble Zephyr (99.96%) achieves significantly better results than the choke ring (97.02%) antenna, when both antennas are combined with the same Trimble GPS receiver. On average, the choke ring antenna misses 75 times as many epochs as the Zephyr antenna.

Zephyr Antenna Performance – Low-elevation Tracking

The above test also produced data for elevation angles from 0 to 10 degrees from the same 24-hour data set sampled at 1 Hz. This data was analyzed to assess how well the Trimble Zephyr antenna tracks low-elevation satellite signals, where cycle slips and losses of lock become much more likely. The graph below compares the observed-to-expected number of epochs for the Zephyr and choke ring antennas, for elevation angles of 0 to 10 degrees:



0 to 10 Degrees	Choke Ring	Zephyr
Observed to Expected Epochs (%)	57.17%	60.47%

Again, the results show that a Trimble Zephyr antenna/Trimble GPS receiver combination achieves significantly better results for low-elevation tracking than a choke ring antenna with the same receiver.

Revolutionary Trimble Stealth Ground Plane Design

Although GPS receivers are designed to track the direct line-of-sight signal from any particular satellite, often a signal arrives at the GPS antenna via multiple paths, due to the tendency of RF (radio frequency) signals to reflect from some types of surface. For example, RF signals can reflect off water, earth, buildings, and vehicles. This signal multipath distorts the correlation peak from which pseudorange measurements are made, which can cause significant levels of error in L1 and L2 pseudorange measurement. Multipath also introduces errors in the L1 and L2 carrier phase measurements.

A GPS antenna ground plane can help to reduce the effects of multipath from reflections off objects beneath the antenna. On land, this may be from the ground or the roof of a building, while at sea, reflections may be from the water or the steel deck of a ship or offshore platform. Although the ground plane does not prevent multipath from objects located high above the antenna, such as from the side of a building, these multipath signals are usually weaker than those from the ground, which is generally in much closer proximity to the antenna and thus generates the multipath signals with the most power.

GPS antennas commonly use one of two types of ground plane: the conventional flat metal ground plane or the choke ring.

The flat metal ground plane is certainly more effective than having no ground plane at all, but it has an inherent weakness in that it is a good electrical conductor with low electrical resistance. If multipath signals reflected from the ground strike the underside of the ground plane at certain angles, the ground plane's electrical properties can actually conduct multipath to the antenna through diffraction or reflection.

The choke ring design consists of deep concentric wells in the ground plane, typically of a depth equal to 1/4 of the wavelength of the signal to which the antenna is tuned. These 1/4-wave wells act as traps for signals reflected from objects near the ground. The choke ring design is very effective, especially for single-frequency receivers, but it has two inherent weaknesses for dual-frequency GPS.

Firstly, the required depth of the choke rings is a function of the frequency of the antenna. This is fine for single-frequency receivers. However, for dual-frequency receivers, the antenna either has to be effective for only one frequency, or it has to compromise between the two frequencies, reducing effectiveness for both. Dual-frequency variations on the single-depth choke ring design have been attempted, but independent test results did not demonstrate superior dual-frequency performance. The planned GPS L5 second civil frequency will exacerbate this frequency-dependence problem, as the wider frequency spacing and desire to track three frequencies will make frequency-dependent designs even less effective.

Secondly, direct line-of-sight signals from low-elevation satellites are attenuated along with the offending multipath signals, reducing low-elevation tracking performance, as illustrated in the low-elevation tracking graph above.

The Zephyr Geodetic antenna uses the Trimble Stealth ground plane, the revolutionary design of which improves on both the conventional flat metal ground plane and the choke ring. The frequency independent nature of the design also has the potential to be used in high-performance future antennas capable of tracking the GPS L1, L2 and L5 frequencies. Trimble has been issued US patent No. 5694136 for this design.

The key to the Trimble Stealth ground plane's design is its use of electrical resistance to weaken multipath signals. An intricate pattern of tiny concentric rings exponentially increases electrical resistance as the distance from the center of the antenna increases. This makes the resistance from the inner edge of the ground plane to the outer edge extremely high, and makes the relatively small ground plane simulate one of infinite size. The advanced material technology that provides the ground plane with these properties was originally developed for the Stealth aircraft as a lightweight, radar-absorbent covering-hence the name, Trimble Stealth ground plane.

When multipath signals that are reflected to the underside or top of the Trimble Stealth ground plane encounter its extremely high electrical resistance, that resistance cuts off the electric field of the electro-magnetic wave, dissipating the energy as heat. The ground plane's design effectively burns up multipath, preventing a reflected signal of any significant power from reaching the antenna element. This action contrasts starkly with that of the flat metal ground plane, which has very little resistance and allows multipath signals to be diffracted or reflected, or conducted to the antenna element.

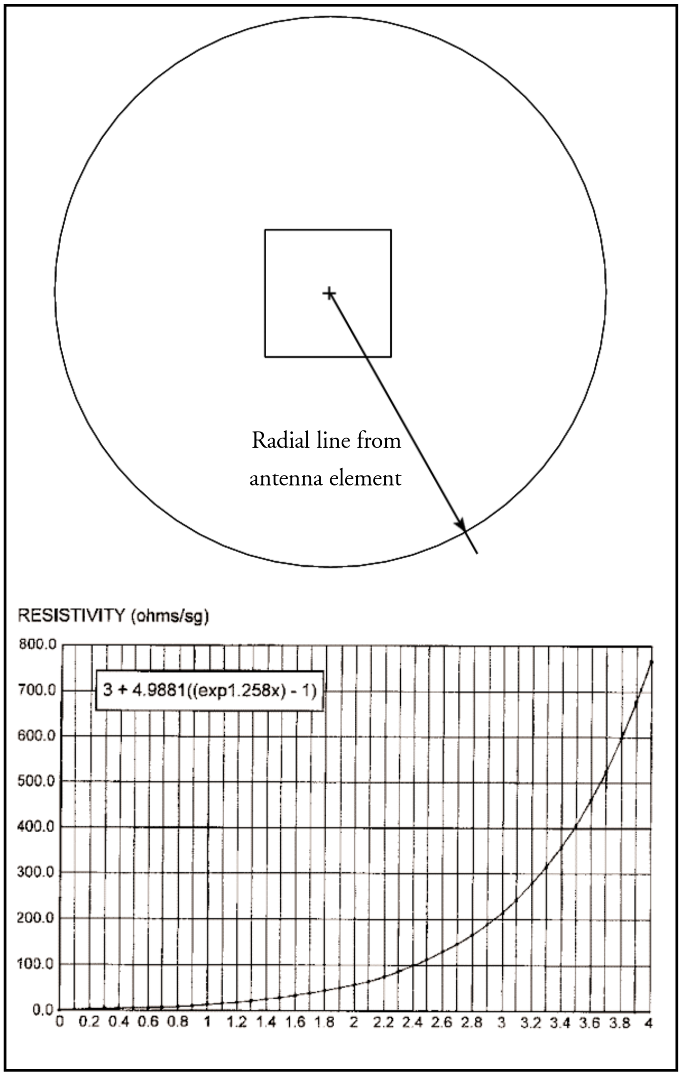


Figure 5. The Zephyr Geodetic antenna utilizes the revolutionary Trimble Stealth ground plane.

The ground plane is made of an advanced material in which the sheet resistance increases exponentially along any line radiating out from the antenna element. This electric field resistance burns up multipath as heat—similar to the method used by the Stealth aircraft to absorb radar signals to reduce reflections.

The underlying design of this new ground plane has the following key advantages over conventional and choke ring antenna ground plane designs:

- At the frequencies used for GPS-L1 (including WAAS/EGNOS), L2, and the future L5—the method is frequency-independent. It does not need dimensions tuned to a particular frequency, so it is equally effective for all three frequencies. (Note that antennas shipped today are not L5 compatible, as this requires changes to the antenna element and Low Noise Amplifier.)

- The low elevation tracking performance is not compromised as it is for the Choke Ring design
- The material and method used enable a more compact, lightweight, portable, and economical antenna that can be used for very high accuracy work that would have previously required a choke ring antenna.
- It is very effective for very high-precision applications both on land and off shore, in marine and construction environments, where large quantities of water and/or metal beneath the antenna cause severe multipath incidence to the underside of the ground plane.

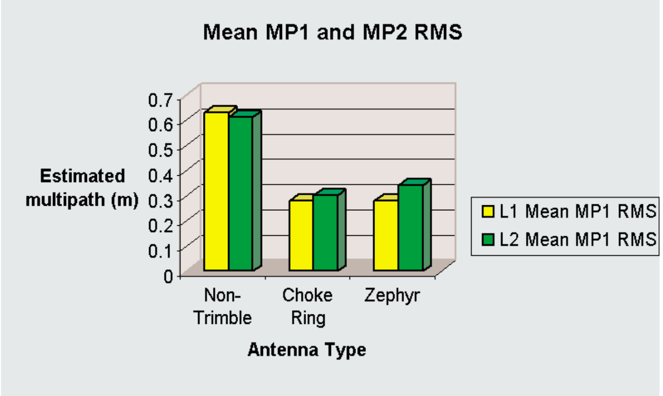
Trimble Zephyr Antenna Performance – Multipath Resistance Tests

To assess the combined multipath resistance of the Zephyr antenna and Trimble 5700 GPS receiver, a Zephyr/5700 combination and Trimble choke ring/5700 receiver combination were both tested and compared. A non-Trimble, survey-grade, dual-frequency GPS receiver and antenna combination was also tested as a comparison.

The MP1 and MP2 multipath estimation parameters[1] were used to assess the levels of multipath in the L1 and L2 data. The test took a complete 24 hours, with observations recorded at 1 Hz. The MP1 and MP2 values were calculated for each satellite and for each epoch, thus the total sample size for each antenna was 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 for the three GPS receiver/antenna combinations tested, in the following graph.

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.



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

This demonstrates that an advanced GPS antenna, coupled with an advanced GPS receiver, can achieve results comparable to that of a quality-milled choke ring antenna, but without the associated cost, weight and poorer low-elevation tracking performance.

Carrier Phase Multipath Resistance Compared to the Choke Ring

To assess how well the Trimble Stealth ground plane reduces carrier phase multipath error, a test was set up to compare the results from a choke ring control antenna with three other test antenna types. The test antennas were as follows: another choke ring antenna, a Trimble Zephyr Geodetic, and a non-Trimble, conventional, survey-grade GPS antenna.

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

For all baselines, 1-second data was collected for 24 hours and then processed using a PC compile of the Trimble RTK engine, which usually resides in the GPS receiver.

Multipath, especially the ground bounce multipath reduced by a ground plane, de-correlates very quickly as a function of baseline length, so the observations measured at each end of the 3 m baseline would show very little correlation, and

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[1] See the document located at http://www.unavco.ucar.edu/software/qc/#derivation for a derivation of the MP1 and MP2 equations.

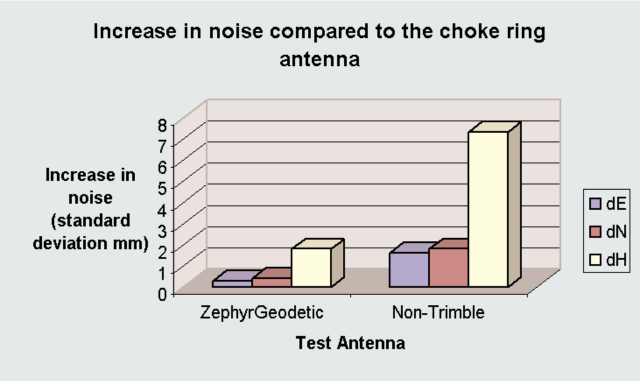
multipath noise would not be expected to cancel out during double-difference processing on an epoch-by-epoch basis. (The de-correlation is due to the short wavelengths of the L1 and L2 carrier frequencies-approximately 19 cm and 24 cm respectively.) However, multipath typically has a periodicity of just one minute. As the time span over which the sample data was 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. Put another way, 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 timescale, multipath can be treated as random, so the results can be expected to be free of multipath biases.

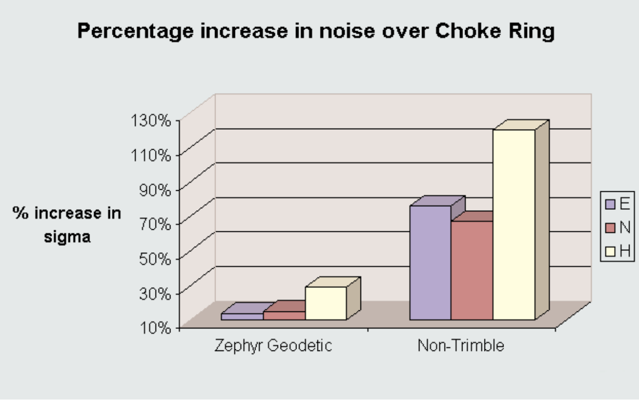
To yield an estimate of the error population for each antenna type, the mean baseline components and their associated standard deviations were computed from the entire 24 hours data sets. Although the mean estimates should be free of multipath due to averaging over the long timescale, the standard deviations should reflect the average levels of multipath in the data. The table below lists these standard deviation estimates in millimeters for the three antennas tested:

	E	N	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

% Increase over Choke Ring	E	N	H
Zephyr Geodetic	14%	15%	29%
Non-Trimble	76%	67%	120%

The results show that the choke ring to choke ring baseline contained residual noise of below approximately 3 mm horizontally and 6 mm vertically. The performance of the Zephyr antenna with the Trimble Stealth ground plane is extremely close to that of the choke ring, with approximately 3 mm of horizontal noise and 1.8 mm of vertical noise more than the choke ring. The non-Trimble antenna had more than twice the amount of vertical residual noise than the choke ring antenna, indicating multipath immunity that was significantly inferior. The graph below illustrates the increase in noise for the two antenna types, calculated by subtracting the derived component standard deviation for the choke ring from the derived standard deviation for the tested antenna:





Conclusions

The new Trimble Zephyr antenna introduces key new technologies into GPS surveying that enable users to benefit from improved accuracy resulting from sub-millimeter phase center repeatability, enhanced multipath resistance, and superior satellite tracking at all elevation angles and in difficult environments.

For Geodetic and Scientific GPS users, the Zephyr Geodetic antenna technology combined with the 5700 GPS WAAS/EGNOS receiver offers sub-millimeter, phase center repeatability and multipath resistance comparable to that of a choke ring antenna. The additional benefits include superior low-elevation tracking, reduced size, weight, and cost. Although Trimble antenna elements shipped today are not compatible with the future L5, the Trimble Stealth ground plane design is frequency-independent, making it equally effective for use with L1-, L2-, or L5-capable antenna elements (once they and the L5 signal are available)—this is a design with the future in mind.

For Real-Time Kinematic users, the performance of the Zephyr Geodetic antenna with the Trimble Stealth ground plane for the reference station reduces multipath and increases accuracy, especially when compared to using an antenna with no ground plane at all at the base station. For the roving RTK user, the superior high- and low-elevation tracking of the Zephyr antenna illustrated above enables the 5700 GPS WAAS/EGNOS receiver to keep lock on satellites during RTK surveys, with the effect of reducing the number of lost initializations in difficult environments. Also, the significantly reduced multipath, down to levels comparable with a choke ring antenna, improves RTK performance by improving accuracy, reducing initialization times, and further increasing RTK initialization reliability. The sub-millimeter, phase center stability enhances position accuracy, and the extremely compact and lightweight design increases portability and convenience.

Zephyr Antenna Technical Data

Zephyr

- Dimensions: 6" diameter x 2.25" maximum depth
- Weight: 1 lb
- Operating temperature range –40 to +70 C
- 100% humidity proof, fully sealed
- Shock tested for a drop of 2 m onto concrete
- Vibration tested to MIL-STD-810
- 4-point antenna feed for sub-millimeter phase center repeatability.
- Integral Low Noise Amplifier
- 50 dB antenna gain

Zephyr Geodetic Reference Station Antenna

- Dimensions: 13.5" diameter x 3" maximum depth
- Weight: 2.2 lbs
- Operating temperature range –40 to +70 C
- 100% humidity proof, fully sealed
- Shock tested for a drop of 2 m onto concrete
- Vibration tested to MIL-STD-810
- 4-point antenna feed for sub-millimeter phase center repeatability.
- Integral Low Noise Amplifier
- 50 dB antenna gain
- Trimble Stealth ground plane for reduced multipath

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