P R O P R I E T A R Y   I N F O R M A T I O N

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DOCUMENT IDENTIFICATION NUMBER: WP 5033-3

ISSUE: 3 DATE: 05/01/2024

TITLE: THEORY, DESIGN AND TEST MEASURMENT FOR GNSS COMPASS BASED ANTENNA ALIGNMENT TOOL ACCURACY

ABSTRACT

THIS DOCUMENT DESCRIBES THE GENERAL THEORY, DESIGN AND MEASURED ACCURACY OF GNSS COMPASS BASED ANTENNA ALIGNMENT TOOLS AS WELL AS DISCUSSION OF SPECIFIC PERFORMANCE AND IMPLEMENATION OF THE SUNIGHT INSTRUMENTS ANTENNALIGN ALIGNMENT TOOL (AAT)

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CHANGE HISTORY

ISSUE	SECTION	DESCRIPTION
1		Original Issue - (11/14/2016)
2		Updated for clarity and clerical issues – (08/14/2017)
3		Updated with new data base on Rover AAT units (05/01/2024)

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1. INTRODUCTION

This document was created to discuss the history of antenna alignment methods, as well as the methodology for accurately aligning antennas in the real world. The scope of the document is to discuss the device theory for highly portable GNSS based alignment systems, the possible accuracy of these devices, as well as the practical results to be expected when using such devices in real-world situations. The document draws on theory, measured results and real-world observations.

Examples will be given as to why specific alignment tools give better results as well as an explanation on how much results can vary based solely on the alignment tool's performance.

Important Points

- **Alignment Tool Performance can be a major contributor to alignment results.**
- **The single most important item that determines the accuracy of any GNSS-based alignment product is the physical distance between the GNSS antennas mounted on the unit**
    - **The smaller the GNSS alignment product's antenna spacing, the less azimuthal accuracy is possible**

2. DEFINITION OF ANTENNA ALIGNMENT

- **Antenna Alignment: the following parameters fully specify the alignment of a given antenna:**
    1. **Azimuth:** also referred to as "heading" or "bearing"; measured in degrees
    2. **Tilt:** refers to mechanical tilt (above/below horizon).
    3. **Roll:** refers to mechanical roll (aka "plumb").
    4. **Height:** specifies the height of an antenna above the base of the structure supporting the antenna, typically referred to as "AGL" for "above ground level". For RF engineering purposes, this height is typically measured from the middle of the antenna radome.

        Tower companies sometimes request multiple height measurements (top, middle, bottom of antenna)

All four of the above components affect antenna alignment

3. TYPICAL NETWORK ALIGNMENT GOALS

From Sunsight's experience, the typical requirements for cellular panel antenna alignment below are for installed antennas in the field. These values represent the absolute maximum final variance. These measurements are taken when the antenna is in its final mounted position and has been affected by all factors that contribute to misalignment.

- +/-2 or +/-3 degrees in azimuth
- +/- .5 degrees in tilt and roll (plumb)

- +/- 1 foot (.3 meter) in height

These specifications vary from carrier to carrier.

It is important to note that the more accurate the alignment tool, the more margin for error the installers have for meeting the goals above. The tolerance of the alignment tool very much limits the actual amount of installation error the users have to work with.

Example:

If the alignment tool has an azimuth accuracy of +/- 1 degree, the installer must be within 1 degree of a perfect alignment to maintain a tolerance of +/- 2 degrees overall.

In essence **Final Alignment = tolerance of alignment tool + installer's offset error during installation**

So the more accurate the tool, the more tolerance for the installer.

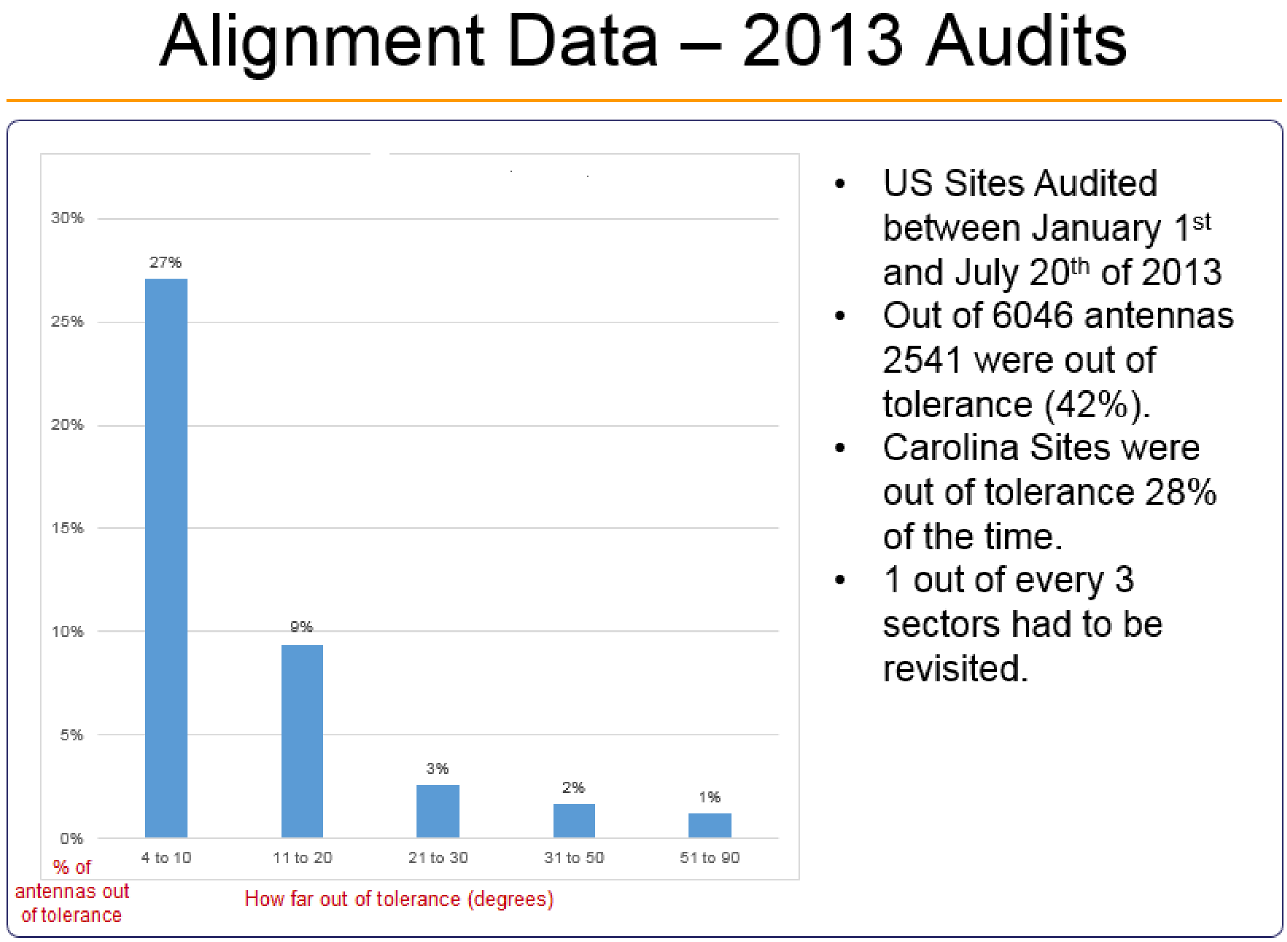
4. GENERAL OVERVIEW OF GNSS BASED ANTENNA ALIGNMENT DEVICES AND SYSTEMS

In the early 2000s, portable antenna alignment systems based on GPS compasses began to appear commercially. The market driver for these devices was the poor alignment results that were being observed when using traditional aligning mechanisms. The biggest problem with alignment prior to the advent of the GPS based compass systems was due to the use of magnetic compasses to determine azimuthal alignment of antennas. Magnetic compasses were being used on towers, rooftops or from the ground to measure azimuth.

The issues with magnetic compasses are:

- Interference from nearby ferrous (iron) materials
- Improper use of compass
- Required correction of magnetic measurements (declination compensation)
- Naturally occurring declination changes (declination changes over time)
- Lack of traceability of results
- Lack of repeatability of results

It was well understood that results using magnetic compasses were poor. The following graphic was the result of independent alignment auditing of a major U.S. carrier. These results were measured by a third-party auditing company after installers had installed and aligned the antennas using magnetic compasses. The results were taken across the U.S. using a ground-based GNSS and LASER surveying instrument, which is expensive and slow, but very accurate.



In addition to azimuth inaccuracies, it was also found that there were major discrepancies in the tilt, roll (plumb) and Above Ground Level (AGL) height accuracy of the audit antennas. Subsequently, the GPS compass-based alignment tools began integrating measurement of tilt and roll values into their product offerings as well as some systems also including the ability to measure industry-acceptable AGL height as well.

The more advanced alignment systems offer the ability to track multiple satellite constellations beyond the U.S. based GPS system. When more than one constellation of satellites is used by a system, it is generally referred to as a GNSS system rather than a GPS based system. Compared with a GPS-Only system, a GNSS system will be more accurate and much more robust in difficult environments that may include physical obstructions and high multipath conditions. Both obstructions and high multipath conditions are commonly encountered when performing antenna alignments.

Only one of the available commercial systems (Sunsight AAT family of products) uses **five** positioning satellite constellations (**GPS/Beidou/GLONASS/ Galileo/QZSS**). More satellite constellations improve robustness as well as accuracy of the azimuth results. In addition, the AAT uses multiple frequencies to receive satellite data which mitigates near-band interference from other RF sources. The real-world problem is that some cellular frequencies are very close to L1 frequency bands used by single frequency alignment systems. This means standard RF filtering cannot be employed, which is a very significant problem in the field.

5. EXPECTATION FOR GNSS COMPASS BASED ALIGNMENT SYSTEMS

The following paragraphs will provide an understanding of how the various measurements (azimuth, tilt, roll, and height) are made as well as describe the expected accuracy.

Azimuth

GNSS and GPS based compasses have become the common solution for determining the azimuth of antenna installations.

The strengths of GNSS and GPS compasses are:

- Always report in true North, avoiding the need for declination corrections
- Not affected by ferrous (iron-based) materials which are commonly found on tower structures and embedded in rooftops
- Portable enough to be attached directly and firmly to antennas
- More consistent results than magnetic compasses
- Removes the "art" of azimuth measurements, eliminating the need for highly skilled workers
- Can provide traceability and detailed reporting of results

The weaknesses of GNSS and GPS compasses are:

- Require line-of-sight to at least 5 satellites simultaneously to determine azimuth
- Azimuth results are always statistical probabilities
- Require battery power
- Results can be affected by signal reflection from nearby objects (multipath), line-of-sight obstructions, and/or high output of nearby RF noise sources
- For single frequency systems (L1), the center band is very near that of some cellular frequencies increasing the difficulty of filtering out near-band interference. This is perhaps the most difficult issue with GNSS/GPS based systems.

6. OTHER METHODS FOR MEASURING AZIMUTH

Other methods have been used for determining azimuth, including optical scopes, Google Earth, landmarks, building plans and blue prints. Google Earth has been discussed frequently, but is not usable for accurate alignment of antenna azimuth per Google. Sunsight has made available, via its corporate website, a separate white paper dedicated to the subject of the issues of using Google Earth for antenna alignment.

7. DISCUSSION OF AZIMUTHAL ACCURACY FOR GNSS COMPASS BASED ALIGNMENT TOOLS

Having established that GNSS based compasses are the best solution available at this time, it is important to understand the expected accuracy of the systems.

The single most important item that determines the accuracy of any GNSS-based alignment product is the physical distance between the GNSS antennas mounted on the unit

The smaller the GNSS alignment product's antenna spacing, the less azimuthal accuracy is possible

Azimuth measurements from all GNSS/GNSS based systems are statistical in nature meaning they have a probability of being accurate within a certain range or tolerance. Statistical results for these measurements have various units assigned to them based on the probability that they fall in a range of measurements. Three common ranges are:

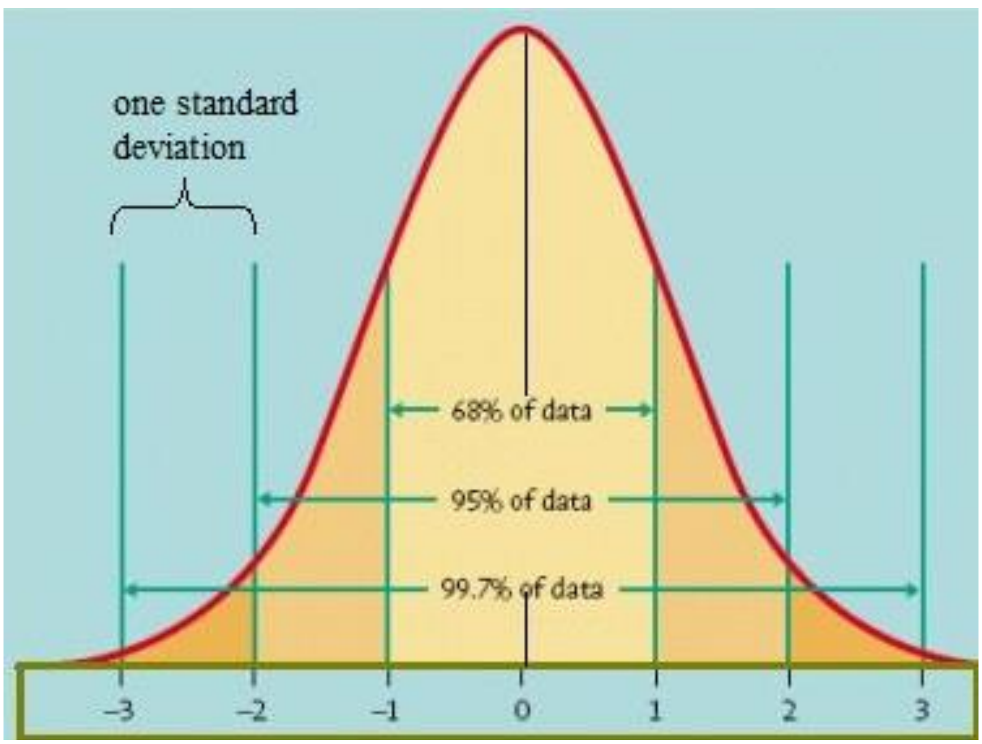
- **Root Mean Squared (RMS)** – which implies that any one measurement will fall within a specific range about 68% of the time (also known as 1 sigma probability or 1 standard deviation - STD)

- **R95** - which implies that any one measurement will fall within a specific range about 95% of the time (also known as 2 sigma probability, or 2 standard deviations)

- **R99** - which implies that any one measurement will fall within a specific range about 99.7% of the time (also known as 3 sigma probability, or 3 standard deviations)

The following graph shows the various probabilities:

The empirical rule describes what percentage of the data falls within a certain number of standard deviations from the mean:
• 68% of the data falls within one standard deviation of the mean.
• 95% of the data falls within two standard deviations of the mean.
• 99.7% of the date falls within three standard deviations of the mean.



As a real-world example, consider the following:

An instrument with a stated accuracy of .8 degrees RMS would imply that any one measurement would fall within +/- .8 degrees of the actual azimuth being measure 68% of the time. This also means for about 32% of the time the single measurement would fall <u>outside</u> of +/- .8 degrees.

For this same instrument, the R95, or 2 sigma, measurement would have a range of +/-1.6 degrees of the actual measurement 95% of the time.

Finally, for the same instrument, the R99, or 3 sigma, measurement would have a range of +/-2.4 degrees of the actual measurement 99.7% of the time.

Example

Device A has an RMS value of +/-1 degree, implying an R95 value of +/-2 degrees and an R99 of +/- 3 degrees

Device B has an RMS value of +/- .3 degree, implying an R95 value of +/-.6 degrees and an R99 of +/- .9 degrees

The first example below uses the RMS values for the devices;

For an antenna physically pointing at **exactly** 180 degrees:

Device A - 180.8, 180.7, 180.8 (all within stated accuracy of the device)
This yields an average (mean) of 180.76 degrees, which would likely be rounded to 180.8 or 181

Device B - 180.3, 180.2, 180.3 (all within the stated accuracy of the device)
This yields an average (mean) of 180.27 degrees, which would likely be rounded to 180.3 or 180

The second example uses the R99 values for the devices

For measuring at 180 degrees of azimuth, the devices measure:

Device A - 182.9, 182.8, 182.9
This yields an average (mean) of 182.86 degrees, which would likely be rounded to 182.9 or 183

Device B - 180.9, 180.8, 180.9
This yields an average (mean) of 180.87 degrees, which would likely be rounded to 180.9 or 181

The point of the examples is to show the actual expected range of measurement accuracy. When reviewing the performance of various GNSS/GPS compasses it is quite important to pay close attention to the unit applied to any accuracy number. If an azimuth accuracy is published with no unit attached, the manufacturer should be contacted to provide the stated accuracy in writing.

To take the examples further, device A can and will display an azimuth value of 183 degrees when the antenna is physically pointing at 180, which is at the limit of the design goal for the final alignment. **However, if the installer sets the antenna to a displayed value of 182 degrees (still within written design goal), the actual azimuth could be off 5 degrees (182+3 degrees of device error = 185 degrees).**

**** Another very important point is that while some device manufacturers display a resolution of .1 degree in no way should that be taken as device has an accuracy of .1 degree. **** Simply displaying values to 1/10 of a degree is misleading for devices having accuracy poorer than .1 degrees. **This false precision is seen frequently in various commercial alignment devices.**

The Sunsight AntennAlign Alignment Tool (AAT) family of products have the following azimuth accuracy specifications:

AAT

.15 degrees RMS
.3 degrees R95
.4 degrees R99

AAT Mini

.3 degrees RMS
.5 degrees R95
.75 degrees R99

AAT Max

.08 degrees RMS
.16 degrees R95
.25 degrees R99

8. METHODS TO STATISCALLY IMPROVE THE ACCURACY OF THE AZIMUTHAL MEASUREMENT

There are various techniques for using many individual measurements to increase the likelihood of getting a reading that is closer to the actual measurement. Regardless, it is imperative to have as narrow of a possible range to start with to maximize the quality of the results.

Averaging results that have a large tolerance can still result in highly skewed measurements when compared to the results of a device that has a narrow tolerance range.

Most GNSS compasses report at a fairly frequent rate. Some typical values are 5Hz, 10Hz and 20Hz. Manufacturers will collect and use these measurements to attempt to lessen the impact of any one measurement and this is done with some effectiveness. The typical method is to use a "**sliding window**" of values where samples collected for a set period of time are averaged in an attempt to lessen the impact of any one measurement. For example, sliding windows might take 3 seconds of data (perhaps 15 measurements) and average these for the displayed measurement. 3 seconds is a fairly typical averaging value for GNSS compasses, but again, if the device has a poor accuracy tolerance to start with, averaging a few seconds of data will have less positive affect than a device that has a much better accuracy tolerance range.

9. CHARTERISTIC ERRORS OF GNSS COMPASS SYSTEMS

GNSS compasses are subject to some azimuthal errors. These errors are seen for multiple reasons including atmospheric disturbances, celestial disturbances, propagation characteristics, multipath, competing RF interference, obstruction, etc. Sunsight has observed two dominant characteristics of errors:

1) Impulse error that has to do with the basic noise floor of the GNSS/GNSS electronics. This noise floor level is very tiny, but varies erratically. The difficulty of the situation is that a receiver is attempting to receive and decode a signal from over 16 thousand kilometers in distance. The received signals are so small, they are very near the noise baseline of the receiver itself. The GNSS signal is very likely competing with local RF sources from the cell tower that might be literally a million times larger in power. The result is that the

RF receiver in the GNSS system must be extremely sensitive, but at the same time reject any near band RF signals. Regardless of effort, there is still some noise present in all receivers.

2) A sinusoidal error that typically cycles once every 6-12 minutes that is a characteristic of satellite positions and atmospheric induced errors. This error is not easily corrected by sliding window averaging due to the length of time for one cycle of error to occur. It is not practical to continually average over several minutes as the GNSS/GNSS compass will become very slow to respond to small changes in actual azimuth. This presents a problem when making small adjustments of an antenna.

10. SUNSIGHT AAT IMPLEMENTATION OF THE GNSS/GNSS COMPASS

Sunsight addressed the accuracy of its azimuth measurements in multiple ways.

- **GNSS/GNSS accuracy is directly affected by the offset between the two GNSS antennas used by all GNSS/GNSS compasses**. Greater spacing between the antennas produces more accurate azimuth results (up to a limit). Sunsight offers three different devices with different antenna spacing which produce different azimuth accuracies. The issue is the practical trade-off between azimuth accuracy and the overall size of the GNSS/GNSS compass device. For example, the most accurate Sunsight product, the AAT Max, is over 1 meter in length, making it inconvenient to use on a tower. The AAT Mini is about .4 meters in length, making it much more convenient. The trade-off is azimuth accuracy, as seen in the accuracy specifications for the devices. The AAT, at about .66 meters in length, balances both convenience and accuracy.

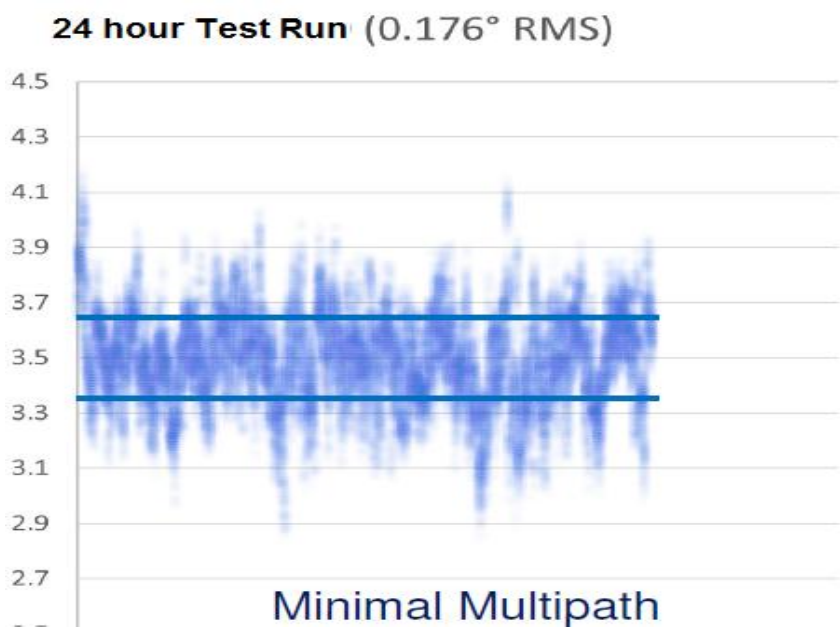
- Sunsight is the first and only antenna alignment systems to use **five GNSS satellite systems and at multiple frequencies**. Using five satellite systems improves the azimuth accuracy over GPS or GPS/GLONASS only systems. Using multiple frequencies mitigates the problems of cellular-band RF overriding the incoming GNSS signals. It also makes the azimuth results more accurate and repeatable by performing better in obstructed and high multipath environments. The AAT works in conditions where other systems cannot. As previously stated, GNSS/GNSS compasses require a minimum of 5 viewable (line-of-sight) satellites to calculate an azimuth. The more viewable satellites the better. Further, using multiple frequency bands makes for a more robust alignment system.

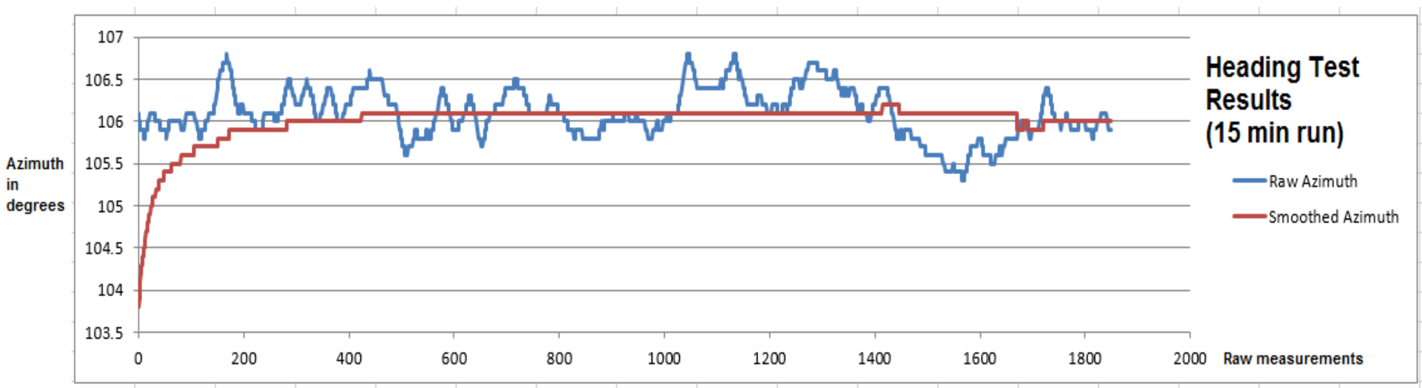
- Data collection and processing for the Sunsight products are more advanced than a "sliding window" only. The Sunsight products use a proprietary algorithm and hardware to average over greater periods of time to dramatically increase the likelihood of an accurate azimuth measurement.

- RF/EMI shielding and filtering – the Sunsight products all incorporate extensive internal shielding against RF interference that is quite common during antenna installation. GNSS and GPS are both RF technologies that operate near the same frequencies as cellular systems. In addition, the Sunsight products use very high quality and expensive RF band filtering devices to filter out unwanted RF signals from the azimuth measuring subsystem.

11. PERFORMANCE

Find below several graphs indicating the accuracy of the azimuth subsystem used in the Sunsight products:





12. REAL WORLD EXPECTATIONS FOR USING ANY GNSS/GPS ALIGNMENT TOOL

While it is important to get the most accurate alignment products, it should be considered that regardless of the accuracy of the testing device, there are limitations on the ability to measure the alignment of antennas. Sunsight can provide a PowerPoint presentation on the problems that can and will be encountered in the field. Some of the issues include:

The accuracy of the actual antenna housings –Antenna housings are typically extruded plastic and may vary in dimension. They may also change shape when devices are attached. This primarily affects the accuracy of downtilt, as inconsistencies in the housing can drastically affect tilt.

Time of Day – Towers are moving structures. As the sun strikes the surface of the tower, the tower will bend away from the sun due to unequal heating of the tower. This can affect downtilt significantly.

Weight of the climber – The weight of a tower climber can affect downtilt during installation and alignment

Wind – Wind can produce difficult conditions for measuring antenna alignment. Towers and antennas move significantly with wind and gusts

Azimuth – can be affected by the number of viewable satellites, RF interference in the near field and multipath from nearby reflective objects.

Height – Traditional height measurements are done using tape measures. This process can be inaccurate due to tape stretching or blowing in the wind. Deriving AGL using GNSS-measured MSL (Mean above Sea Level) height is very inaccurate as it involves taking two separate MSL estimates (one on the ground and the other at the antenna and subtracting the distance to determine AGL). MSL height accuracy is typically about half as good as horizontal accuracy, so if a GNSS system had a lat/long accuracy of +/- 1 meter, the vertical height (or MSL) accuracy would be +/- 2 meters. Then subtracting two MSL heights from each other, the potential error is doubled again to +/-4 meters. Sunsight is not aware of any carrier that would accept a 4-meter error in reported height of an antenna above ground (AGL). Sunsight employs a LASER rangefinder. It is available in two models with accuracies of +/-1 foot (.3 meter) or +/- .2 foot (5 centimeters).

13. ADDRESSING THE REAL-WORLD LIMITATIONS

Having identified issues with issues that affect accurate alignment, Sunsight has endeavored to address these issues in the following ways:

Alignment Tool Accuracy – Sunsight uses five satellite constellations and multiple frequencies, RF/EMI filtering, multipath filtering, and multiple product size options to provide the most accurate and practical alignment tool commercially available.

Antenna Housing Accuracy – No alignment method can produce good alignment results if it cannot be mounted accurately and securely to the antenna while referencing the antenna backplane correctly. The Sunsight mounting system produces firm contact with both the back and side of the antenna. Sunsight also provides specialty brackets for certain antennas that do not readily accept brackets. Some examples of these antennas include Ericsson AIR antenna systems, Nokia FASB, KMW, small cells. Sunsight has worked directly with Ericsson personnel with regard to the accuracy and suitability of the Sunsight mounts. Sunsight produces more brackets for various antennas than any other manufacturer.

Time of Day – Sunsight does not have a solution to tower deflection in the tilt plane due to unequal heating from the sun.

Weight of Climber(s) – Sunsight Alignment products employ a timer when the actual measurement data is being recorded. The Sunsight AAT is typically operated from an Android device over WiFi. This allows the user to move away from the antenna and more towards the center of tower mass to minimize the effect of the climber's weight on tilt.

Wind - Sunsight Alignment products employ a timer when the actual measurement data is being recorded. During the measurement time the AATxx collects continuous data points and averages the results. Choosing an extended collection time minimizes the effect of the tower twisting or buffeting in the wind.

Height - Sunsight alignment products accept an optional LASER rangefinder for measuring height from the antenna to the ground to an accuracy of +/- 1 foot (.3 meters) or +/- .2 feet (5 centimeters). The results are recorded in the AAT. The rangefinder can also be tilted when being used to avoid obstacles directly below the antenna being aligned that would affect the accuracy of the height measurement. Examples of obstacles are undergrowth/vegetation, porches, and shelters). When the rangefinder is tilted, the results are used to determine the actual vertical height of the antenna using the distance and angle measured. Only the vertical AGL height is recorded in the AAT.

14. QUALITY

Every Sunsight AAT is tested for accuracy. For azimuth, the AAT is compared to a solar noon measurement. The tilt and roll functions are measured and calibrated on a granite surface plate. Results are recorded in the QA records at Sunsight. Subsequently, the user may calibrate tilt and roll in the field as necessary using the onboard instructions.

No return to the manufacturer for calibration is required. The date of the last calibration by the user is stored in the AAT and displayed on alignment reports.

Sunsight AAT products carry a three-year warranty.

15. ACCEPTANCE

Sunsight products are specifically documented as accepted by AT&T in the U.S. for use on both cellular panel antennas and microwave links. They are also mandated for use in many regions of Verizon and Sprint where other tools are not accepted.

Sunsight alignment products are in use on five continents and have been accepted by all major U.S. carriers as well as Orange, France Telecom, Deutsche Telecom and many others.