THE UNIVERSITY OF TEXAS AT AUSTIN
RADIONAVIGATION LABORATORY

# Centimeter Positioning with a Smartphone-Quality GNSS Antenna

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The University of Texas at Austin | ION GNSS+ 2014

## Motivation

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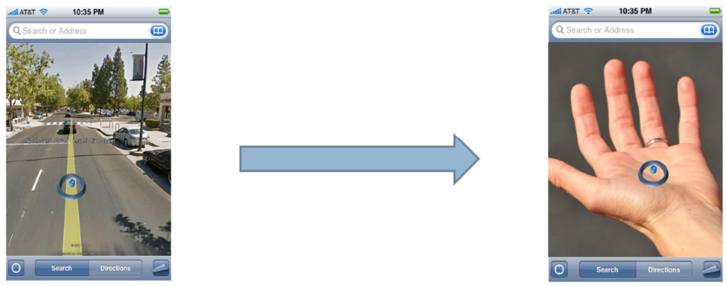

"I predict that by the *GPS World* dinner in 2020, carrier-phase differential GNSS, will be cheap and pervasive. We'll have it on our cell phones and our tablets. There will be app families devoted to decimeter- and centimeter-level accuracy…This will be the commoditization of centimeter-level GNSS."

–Todd Humphreys, GPS World Dinner 2012

Two years ago, in 2012, at the Institute of Navigation Conference GNSS+ conference, the director of our University of Texas Radionavigation Lab, Todd Humphreys, predicted that centimeter-level GNSS would make its way into smartphones by 2020. For the past year or so, we've been working with a major smartphone manufacturer to bring this about. You can think of this presentation as a summary of what we've learned so far.

## Focus

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Our focus has been on single-frequency carrier-phase differential GPS techniques. Why?

1. Our smartphones have single-frequency antennas
2. As compared to PPP, CDGPS/RTK has faster convergence times
3. Reference stations will eventually proliferate, making dual-frequency less important
4. Single-frequency RTK is quite often good enough


Our initial focus has been on single-frequency carrier-phase differential techniques, for four reasons. First, the smartphones on which we've experimented have single-frequency antennas, and we anticipate that single-frequency will forever remain the cheapest option. Second, as compared to PPP, CDGPS (or RTK) has faster convergence times, and convergence time will matter a great deal to impatient smartphone users. Third, we anticipate that as cm accurate GNSS moves into the mainstream, reference stations will proliferate so that users can count on being within a few kilometers of one. Thus, ionospheric errors will be a minimal concern, making dual-frequency observables less important. Finally, single-frequency RTK is quite often good enough for many users. This isn't to say that we've given up on multiple-frequency RTK for smartphones: we'd welcome the faster convergence times and improved robustness that multiple frequencies would bring, but for our initial evaluation, single frequency has been our focus. In fact, we've focused on single-frequency GPS L1 RTK to keep our initial analysis as simple as possible and eliminate confounding factors.

## The Primary Challenge: Awful Antennas

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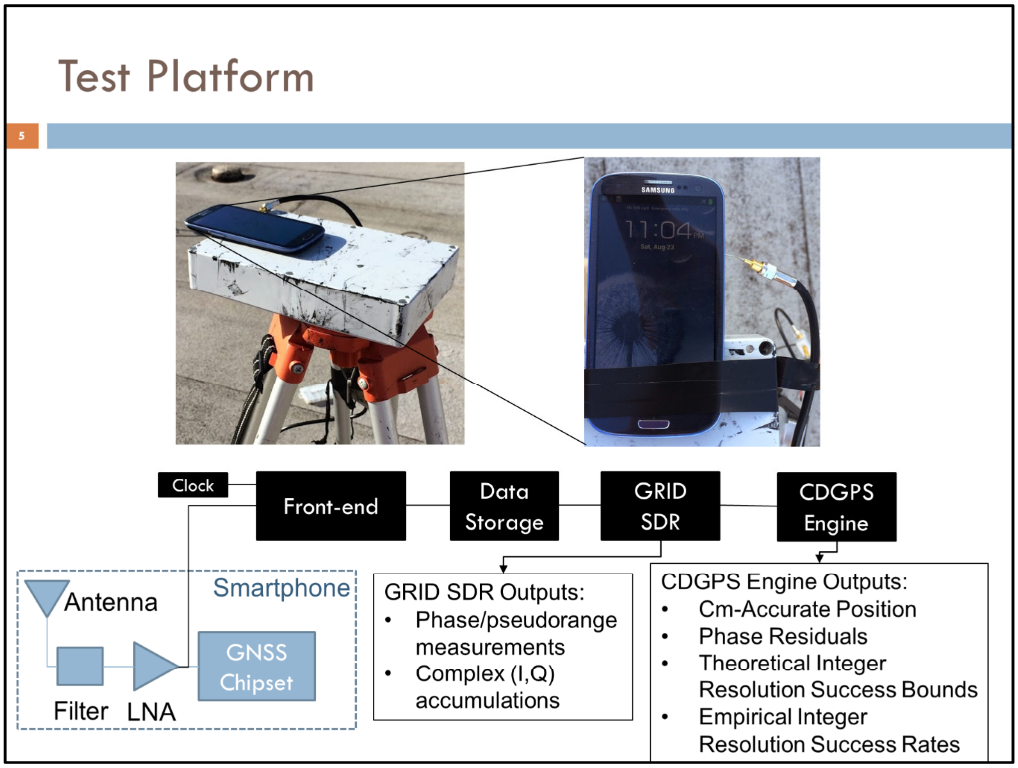
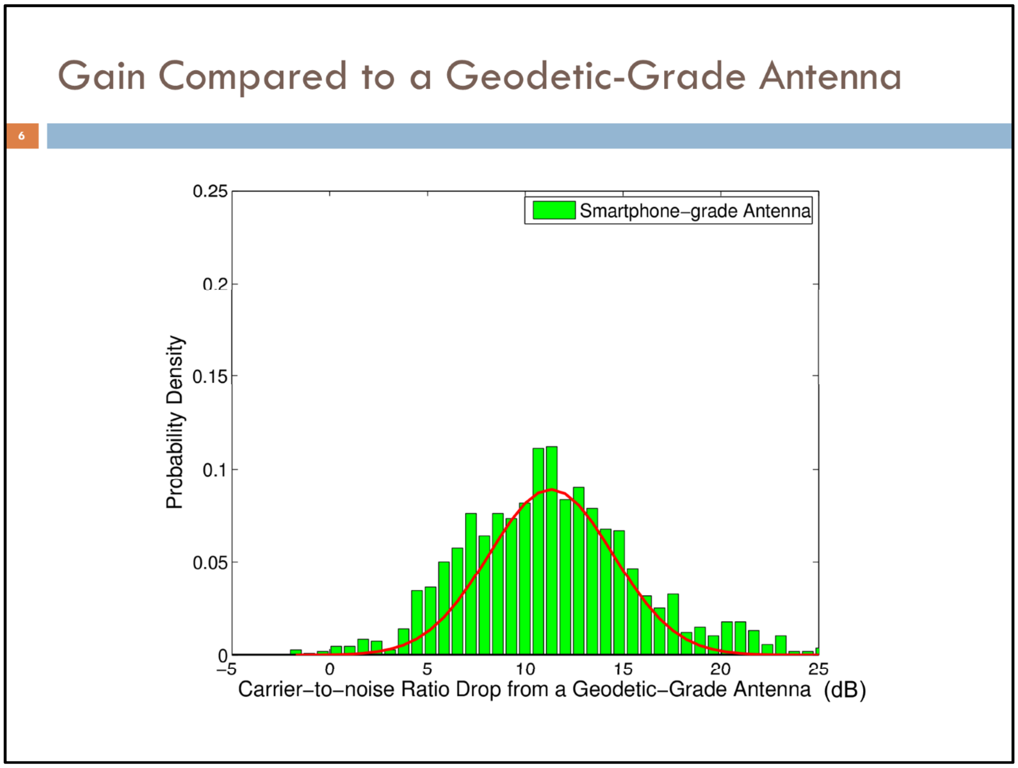
| Antenna | Axial Ratio | Polarization | Loss in Gain compared to Survey-grade | |
|---|---|---|---|---|
| Survey-grade | 1 dB @ 45° | RHCP | 0 dB |  |
| High-quality Patch | 2 dB @ 45° | RHCP | 0 – 0.5 dB |  |
| Low-quality Patch | 3 dB (average) | RHCP | 0.5 – 1 dB |  |
| Smartphone-grade | 10+ dB | Linear | 5 – 15 dB |  |

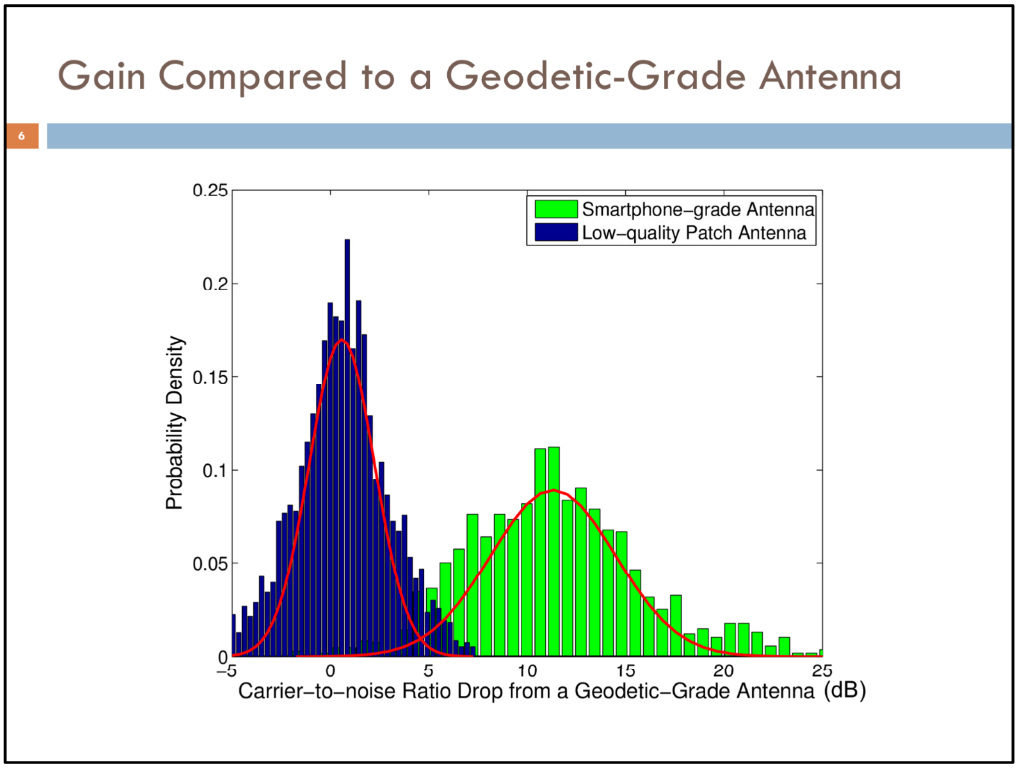
The primary challenge of introducing centimeter-accurate location into smartphones lies not in the commodity chipsets, which actually outperform survey-grade chipsets in some respects, but in the antenna. Let’s consider a range of antennas of decreasing quality. Survey-grade antennas, one of which is shown in the top row, have a nice uniform quasi-hemispherical gain pattern, right-hand circular polarization, a stable phase center, and a good axial ratio. These are all important properties for RTK. Unfortunately, these desirable properties are intrinsic to the antenna’s large size: the laws of physics dictate that smaller antennas will typically be worse in each of these properties. In addition to the survey-grade antenna, I list here 3 other antennas that we’ve worked with over the past few months. In the second row is a high-quality patch antenna, which has many similar properties and loses, on average, less than ½ a dB in sensitivity as compared to the survey grade antenna. Next I list a low-quality patch antenna, which again, has similar properties, and loses, on average less than 1 dB in sensitivity. Last, I list properties for a smartphone-grade antenna. You’ll notice smartphone-grade antenna loses between 5 and 15 dB in sensitivity as compared to the survey-grade antenna. The smartphone’s linear polarization means that it has extremely poor multipath rejection, which, as we’ll discuss, severely complicates RTK.




This slide describes our test platform, which was designed for an in situ study of the GNSS antenna on the popular smartphone pictured here. We left the antenna undisturbed within the phone, tapping off its analog signal just after the phone's internal filter and amplifier. We directed this analog signal to our own RF front end and signal processor because we trust these and didn't want our study to be confounded by the limitations of the phone's internal chipset. The external clock attached to our front-end was a good-quality OCXO, however, even a lower quality oscillator would suffice as we only ended up need to coherently integrate the signal out to between 20 and 40 milliseconds. We stored many hours of raw high-rate (6 Mhz) IF samples to disk for post-processing. We also stored to disk high-rate data from a geodetic-grade antenna, which served as the reference antenna for our CDGPS processing. Our software-defined GNSS receiver, GRID, generates high-quality carrier phase observables. We can adapt GRID to squeeze the most out of each signal tracked, and to maintain carrier lock despite severe fading. Our CDGPS engine is implemented as a square-root information Kalman filter. Within the filter, we model antenna motion as a velocity random walk process, or model the antenna as static when appropriate. The complex accumulation outputs from GRID allow us to closely study the signal and tracking loop behavior. The CDGPS engine takes in the carrier phase observables from GRID and outputs a few things: the centimeter-accurate position of the mobile antenna, a time history of the phase residuals, the integer ambiguities, theoretical integer resolution success bounds, and empirically computed integer resolution success rates.




This figure quantifies one of the obvious drawbacks of a smartphone-grade antenna, namely, its low gain. The drop in carrier to noise ratio as compared to a geodetic-grade antenna is on average 11 dB, capturing only 8% of the power captured by its geodetic-grade counterpart.




Now, shown, for comparison, is a similar drop in carrier-to-noise ratio, but for the low-quality patch antenna. Its mean is much closer to zero, and only suffers about a 1 dB drop in power on average. You might be wondering why the standard deviation is so large, and this is likely because of the multipath-induced power variations in the signal as well as the differing gain patterns between the two antennas. Given a smartphone antenna's extremely poor gain as compared to the higher-quality antennas and its multipath-welcoming linear polarization, you might stop here and question whether there is any point in proceeding. So allow me to lift some of the gloom by revealing that we have been able to achieve centimeter-accurate positioning on a cell phone, despite these antenna properties.

## Centimeter accuracy is achievable on a smartphone

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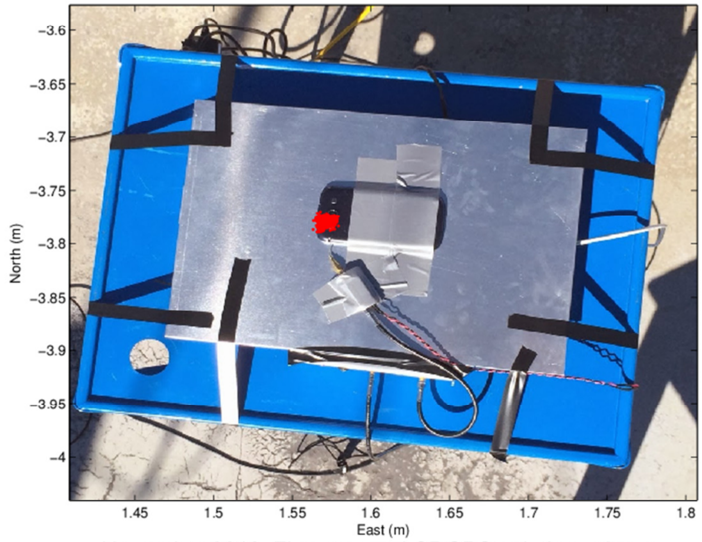
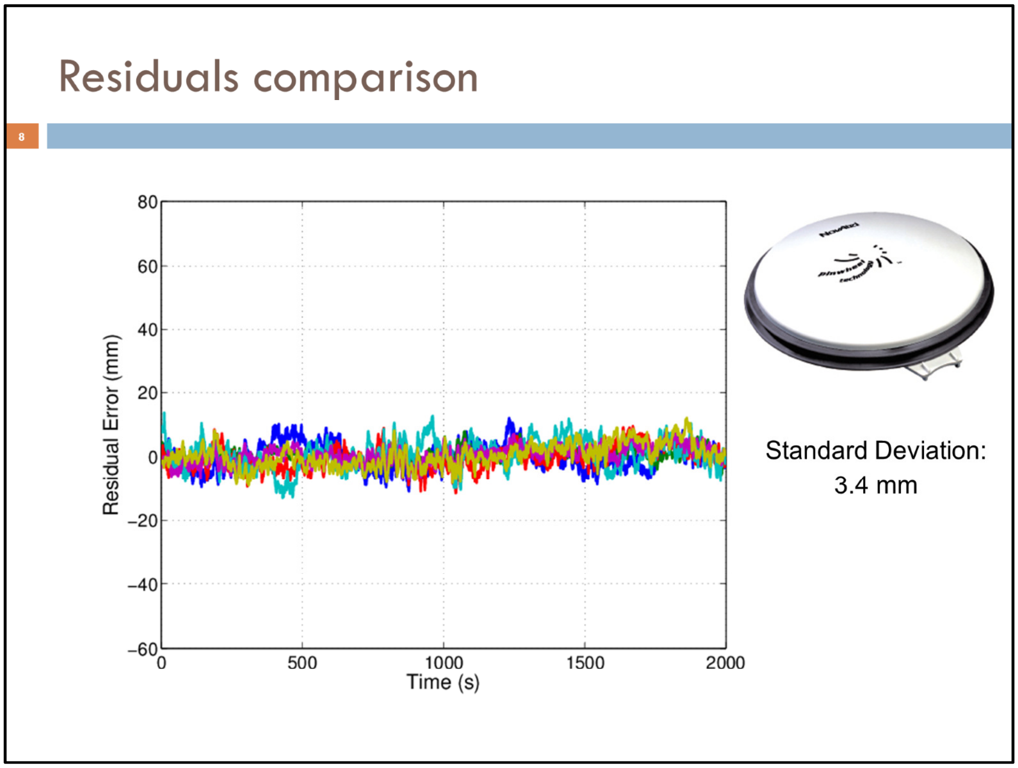


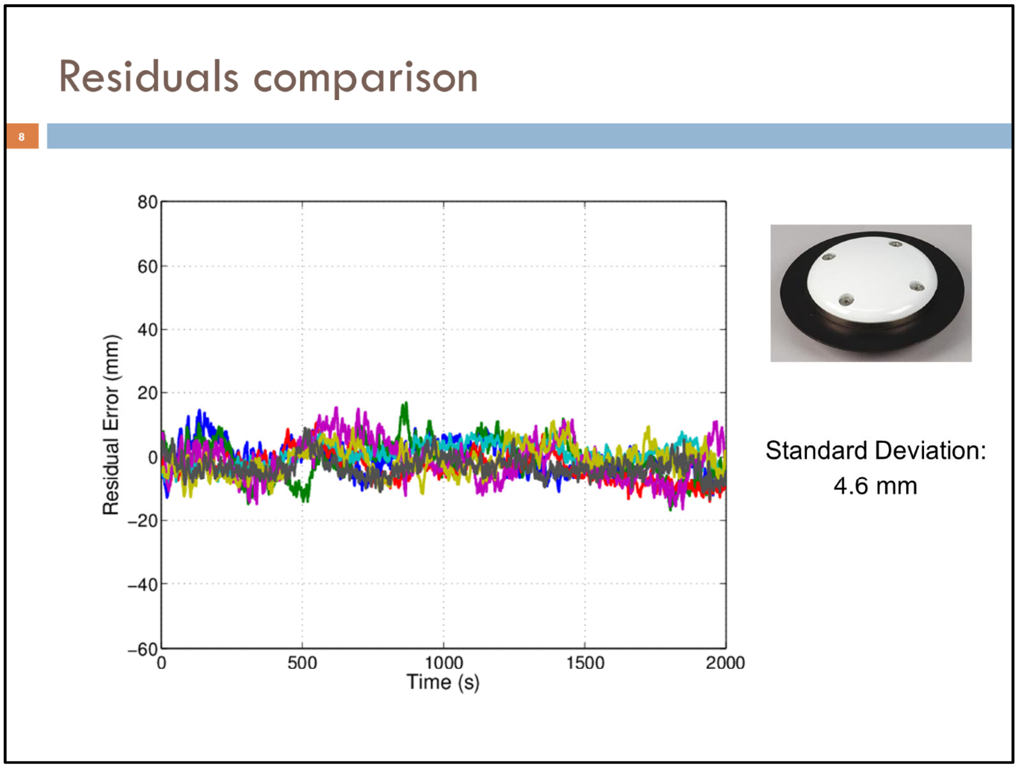

November 2013: First reported CDGPS solution using a smartphone antenna

The result shown here is from one of our first attempts. The cluster of red near the lower left-hand corner of the phone represents 500 CDGPS solutions over an 8 minute interval, superimposed on the photo and properly scaled. The integer ambiguities were resolved correctly; we verified this by analysis of the phase residuals and by physical measurement. Early experiments were done with the large backplane shown here, but later experiments showed this to be unnecessary. Also, whereas the phone was oriented face down here, we later discovered that the phone's irregular gain pattern is better oriented when the phone is face up. Furthermore, although we had a very short baseline to our reference antenna in this scenario, similar ambiguity resolution performance would be seen for all baselines under approximately 5 kilometers, those which are of primary interest to us.

This is a significant result. It is, to our knowledge, the first public demonstrations of RTK using a smartphone antenna. It is also repeatable: we now perform such solutions routinely in our research. But I wish to stress that this figure is not a declaration of 'mission accomplished.' To understand why, let's take a closer look at the phase residuals.




Shown here is a 2000-second segment of phase residual time histories for data collected from a survey-grade antenna. To produce these residuals, we locked the antenna position to its true value within the CDGPS filter, so that all integer ambiguities were resolved correctly and so that the residuals you see represent departures from phase alignment at the true average phase center of the antenna. You'll notice that the phase center variations have a standard deviation of 3.4 millimeters.




Now shown are residuals for the high-quality patch antenna. You'll notice that the standard deviation has increased slightly.

# Residuals comparison

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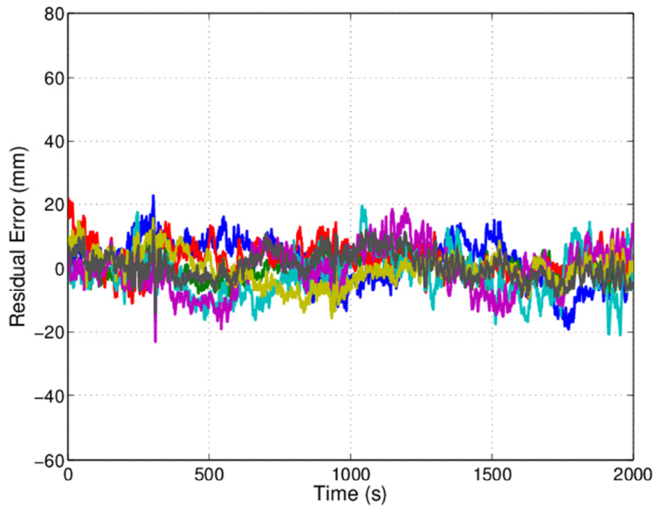
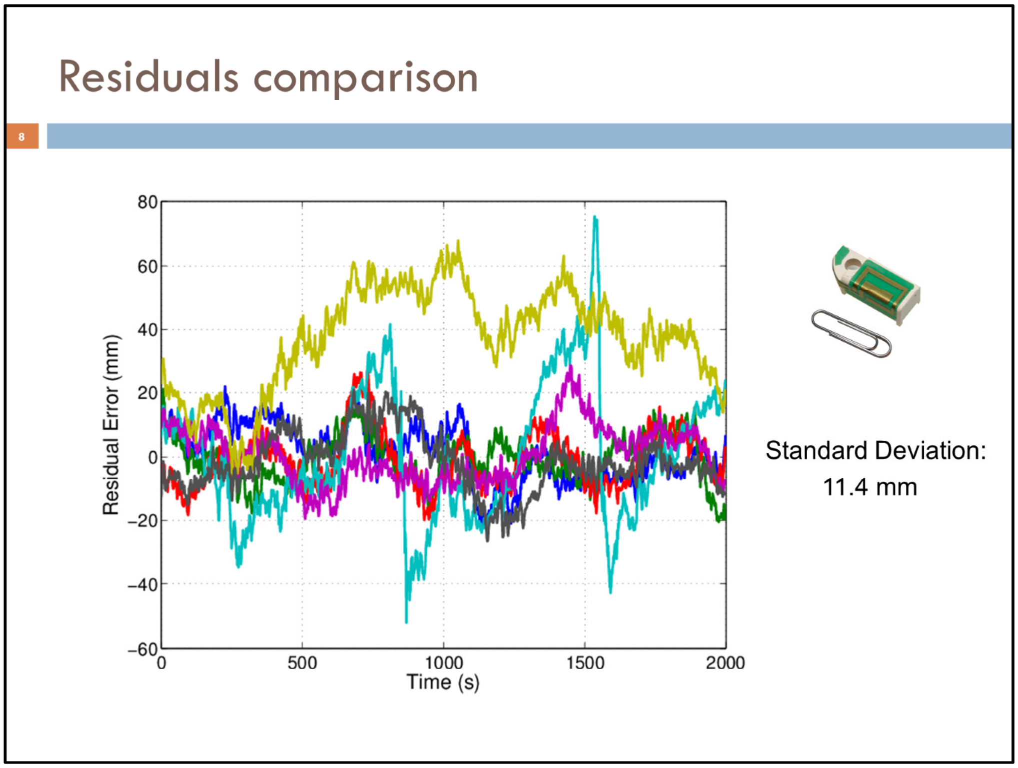


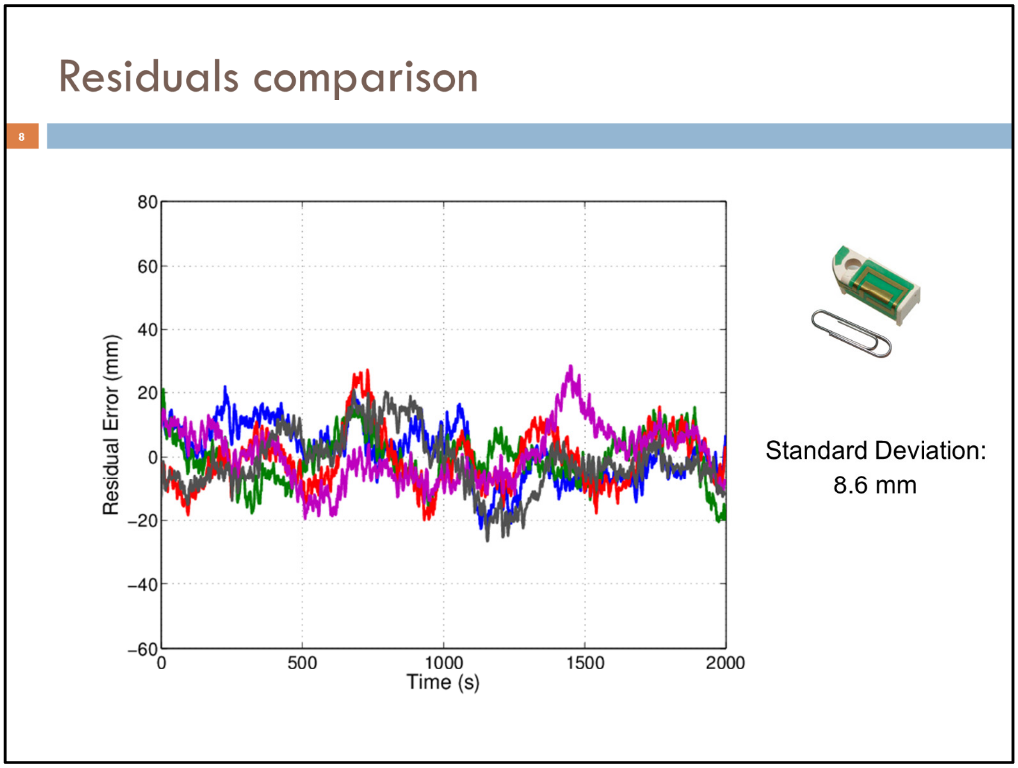


Standard Deviation:
5.5 mm

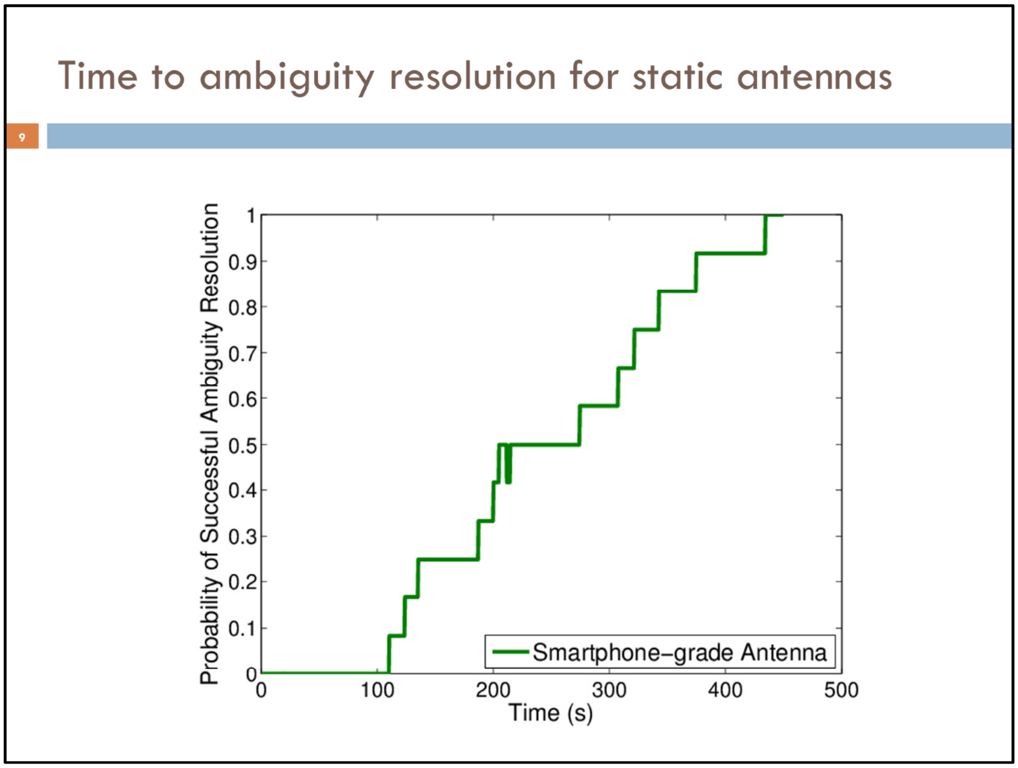
Now shown are the residuals for the low-quality patch, and [next slide]



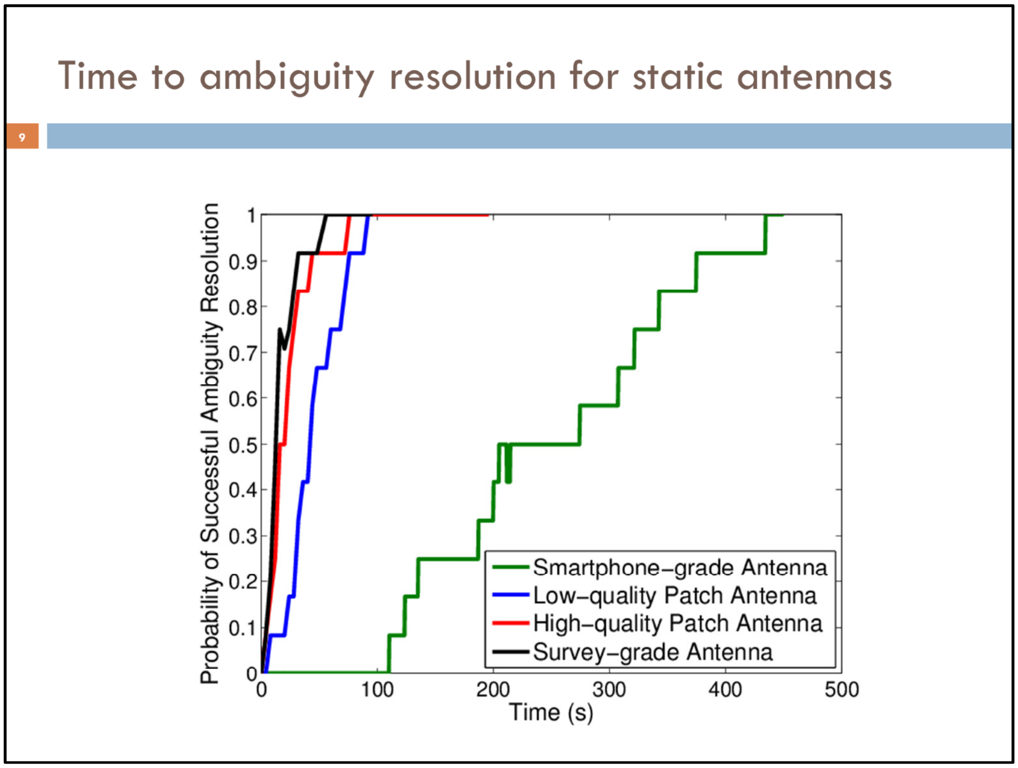

finally, for the smartphone-grade antenna. Looking at these residuals, you'll first notice the presence of a few outliers whose large errors persist for thousands of seconds. It's hard to believe that these large residuals are due to antenna phase center variations, as the phone itself is not much larger than 6 centimeters in extent. We continue to investigate such outliers -- we wish to understand them better. It may turn out to be a combination of poor antenna gain in the direction of the satellite, coupled with healthy gain in the direction of a multipath bounce. This type of outlier residuals is not uncommon for the smartphone antenna. We see them often. Obvious outliers such as these can be excluded by an innovations test.



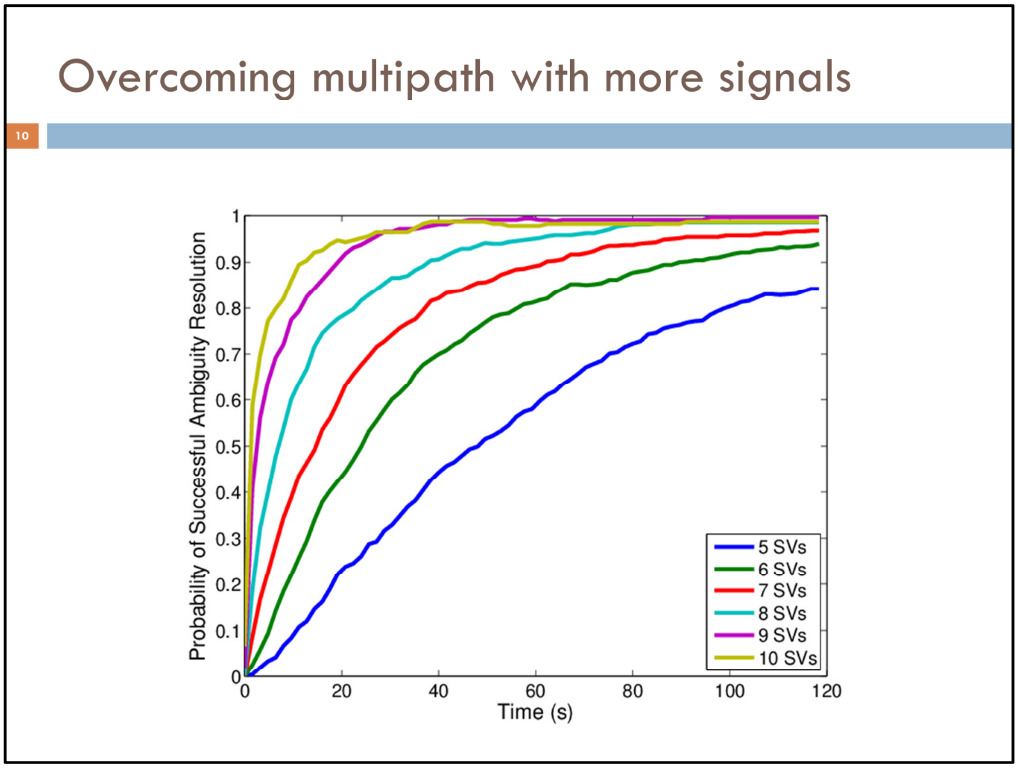

BUT, even if they are excluded, as I've now done, the standard deviation of the remaining residuals remains large compared to the other antennas. For residuals with such a large ensemble standard deviation, the time correlation in the residuals becomes very important. This long time correlation (100-200 seconds as is shown here) is a well studied phenomenon. It is due to carrier phase multipath. Such correlation is present in the residuals of all four antenna types with about the same decorrelation times. But it is more of a problem for low-quality antennas because their residuals have a higher ensemble standard deviation. What is the effect of this time correlation? An increase in the time to ambiguity resolution.



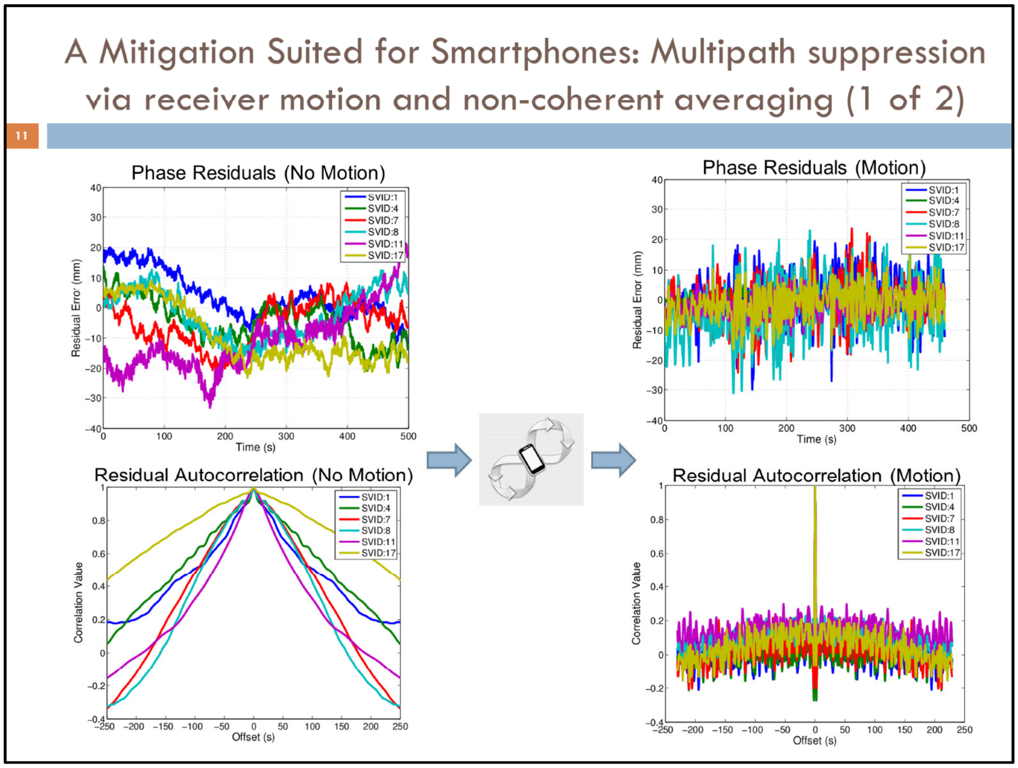

This plot shows the empirical probability of successful ambiguity resolution for the smart-phone grade antenna tracking seven satellites. On the y-axis we have the success-rate probability and on the x-axis we have time. The green trace represents an empirically-computed success rate computed from 12 – 400 second batches of phase data with small overlap. We form this trace by asking the filter, at each 1-second step within a given 400 second batch, to provide us with its best estimate of the integer ambiguities on the basis of the data ingested thus far. We then compare this estimate with the true set of integer ambiguities and, if correct, set a flag at that time step to 1; if incorrect, even if only by one integer, we set the flag to 0. We then average these flags from all 12 batches of data to arrive at the green trace seen here, representing an empirical integer ambiguity success rate. For smartphone applications, a 90% success rate would usually be good enough, and we call the time to get to 90%, the time-to-ambiguity-resolution. So we're looking at a 400 second time to ambiguity resolution for a static smartphone. Obviously, this would exceed the patience of the average user. [next slide]



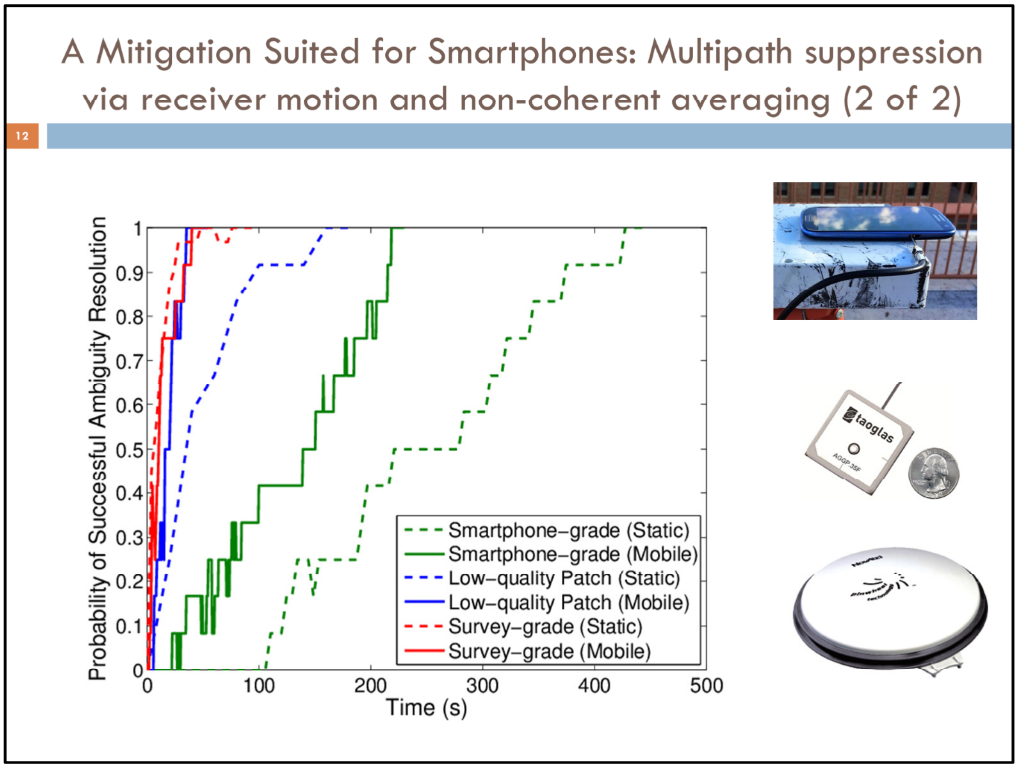

Shown now, are similar traces for the other three antenna types. It is clear that higher-quality antennas give shorter times to ambiguity resolution, as they are able to better combat multipath. So, the outstanding challenge is the severe time-correlated multipath errors in the double-differenced carrier phase data. The loss in carrier-to-noise ratio we can deal with, we can track these signals fine, with no cycle slips. Multipath-induced variations are the much bigger challenge.




Even with the wretched multipath experienced by low-quality antennas, if we had enough double-differenced signals, we could get to an acceptable time-to-ambiguity resolution. Seen here is a series of traces representing the time-to-ambiguity resolution for an increasing number of signals tracked. As can be seen, every additional GNSS satellite decreases the time-to-ambiguity resolution. Although these traces were produced from data collected by the survey grade antenna, as it was easier to collect a days worth of data using this antenna than using the smartphone-grade antenna, a similar trend would apply for the smartphone-grade antenna: More signals tracked equates to a shorter time to ambiguity resolution. We estimate that if we could track 15 or more satellites using the smartphone, then the time to ambiguity resolution could be brought to under 30 seconds. Multiple-frequencies and multiple-constellations would obviously be necessary to achieve these numbers.



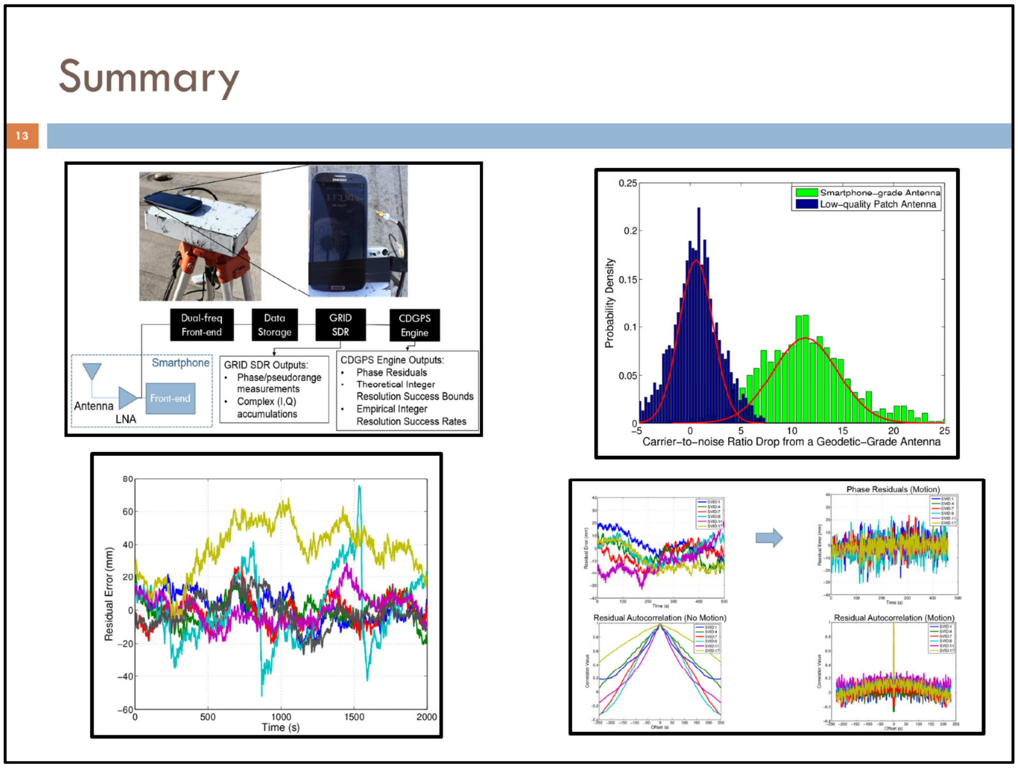

A second way to mitigate multipath, which is especially well-suited for smartphones, is through receiver motion. By simply moving the antenna, in random small movements, on the order of a cycle, while attempting to resolve the integer ambiguities, you change the nature of the phase residuals from slowly-varying as shown in the top left-hand plot for a static antenna to quickly-varying as shown in the top right-hand plot for a moving antenna. Consequently, as shown in the bottom two plots the autocorrelation time for the phase residuals decreases from hundreds of seconds, for the static antenna, to much less than a second, for the moving antenna. A shorter residual autocorrelation time, enabled through random antenna motion, effectively increases the information content provided to the filter at each measurement epoch, allowing it to more swiftly resolve the underlying phase ambiguities.



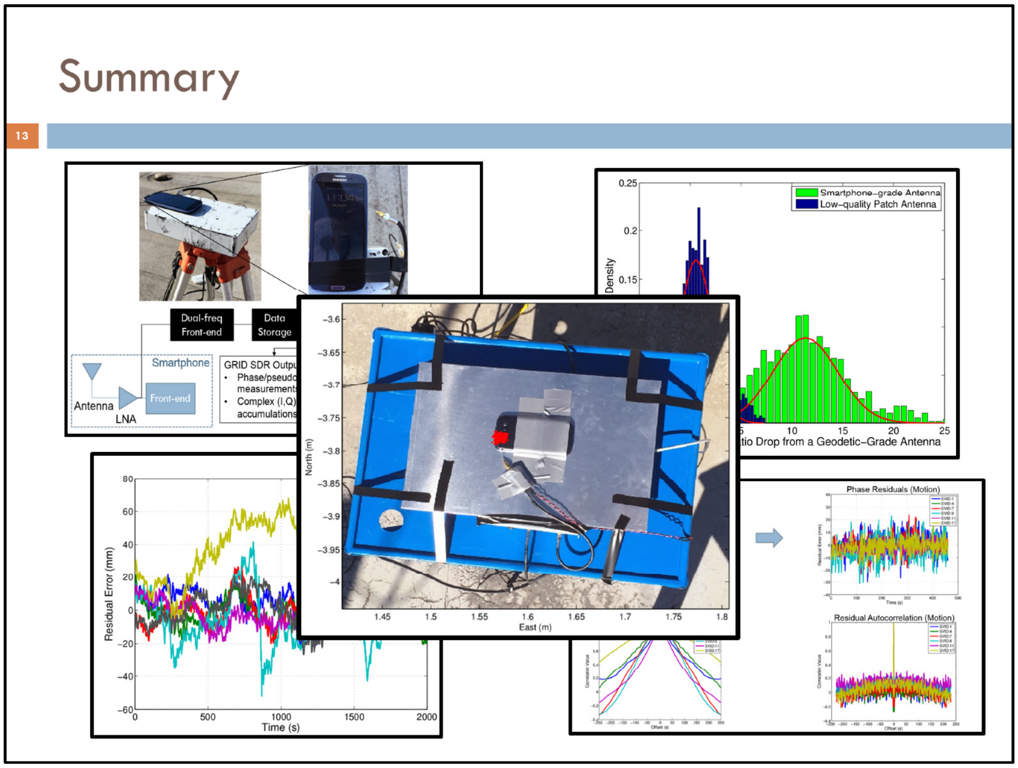

Shown here is a plot comparing the empirical success rates derived from data collected from three of the antennas under two different scenarios: when static and when moving. It is clear that motion benefits the time-to-ambiguity resolution for all three antenna types, but in particular, it is very beneficial for the smartphone-grade antenna, which suffers from large multipath errors. If motion is also coupled with more signals, only 7 signals were tracked in the plots shown here, it is easy to imagine that the ambiguity resolution times could be reduced even further, eventually to a few seconds or less, even for smartphone-grade antennas.

I wish to point out, however, that for the survey-grade antenna, motion provided little benefit. The reason for this is that there is a trade-off that occurs within the CDGPS filter. While the phase residuals do indeed decorrelate much faster when the antenna is moving, the filter can no longer use the knowledge that the antenna is static throughout data collection, a valuable constraint that it can apply to lower the time to ambiguity resolution. As it turns out, the survey grade antenna is already so good at mitigating multipath that the benefit of decorrelating what little multipath errors there are via antenna motion is approximately offset by no longer being able to assume that the static motion profile is known.

Now, if the filter could reconstruct how the antenna was moved, possibly using the phone’s internal sensors, then it could exploit both motion, to decorrelate the residuals and a motion constraint. We have applied this type of synthetic aperture technique and have seen some modest benefit even beyond the unconstrained motion technique.




In summary, we've described our setup for collecting and analyzing data from a smartphone-grade antenna. We described the properties of such antennas, namely their poor gain pattern and poor multipath mitigation, by looking at the carrier-to-noise ratio drop between these antennas and a geodetic grade antenna and by studying the phase residuals, which can often be in excess of 50 millimeters and persist for thousands of seconds under a static-antenna scenario. Finally we looked at ways to overcome these properties through more signals and through antenna motion.




Many challenges still remain before RTK positioning can become mainstream in smartphones and tablets, but we have showed that it is possible compute an RTK solution with data collected from a smartphone grade antenna, the first public demonstration of such and a significant step in the right direction.