EFFECTS OF THE ROOFTOP ENVIRONMENT ON GPS TIME TRANSFER

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Abstract

We examine the effects of the rooftop environment on GPS time transfer, in particular the effects of multipath reflections from nearby metallic objects. Three different antenna sites on the roof of the NIST laboratories at Boulder, Colorado, were selected, each with different multipath characteristics that we discuss. Simultaneous tests were conducted at each site with the same model of L1 band GPS receiver, but with different types of antennas. Four different types of active antennas with low-noise amplifiers were used at each site: a patch antenna, a patch antenna with a simple choke ring attached, a quadrifilar helix, and a "pinwheel" antenna with an aperture coupled slot array design. Results are presented that demonstrate how each antenna performs in each multipath environment, with the time deviation ($\sigma_x(\tau)$) used as a metric. We also discuss the potentially harmful effects on time transfer caused by RF interference from other active GPS antennas located on the same roof.

I. INTRODUCTION

During the past several years, we have assembled a number of inexpensive time transfer systems that use identical GPS receiving equipment. These systems are used both for international comparisons between national metrology institutes **[1]** and for a time calibration service provided to NIST customers **[2]**. At various times, as many as seven of these systems have run simultaneously from the same building at NIST in Boulder, Colorado, with their antennas located in several different locations on the building's roof. When comparing the received time from these systems to the UTC (NIST) time scale, we have found that the amount of noise present on the satellite tracks can vary considerably, even though all of the systems use identical hardware and have had their antenna coordinates carefully surveyed to within 20 cm.

Our goal was to make each system that we assembled perform identically, so we began studying a number of system parameters that could introduce time transfer noise. We surveyed and resurveyed our antenna coordinates until we were convinced that there was no possibility of an error. We improved laboratory temperature control by having new air conditioning equipment installed. We regulated and conditioned the AC voltage that was fed to the receiver power supplies. We experimented with different antenna cables and connectors, and rerouted several antenna cables. All of this work was educational and helped improve the quality of our measurements, but none of our experiments appreciably reduced the amount of time transfer noise on the systems with the noisiest satellite tracks. Finally, we began to experiment with different types of antennas designed to mitigate multipath reflections. From this work, we determined that the source of our problem was indeed multipath, but more specifically, our problem related to the way that different antennas handled the multipath reflections produced by different rooftop environments. We found that an antenna that works well in one rooftop location can perform much worse when moved to another location only a few meters away.

This paper summarizes our work and illustrates the effects of the rooftop environment on GPS time transfer. It describes an experiment conducted from three different antenna sites located on the roof of the same building at NIST. During this experiment, we installed identical GPS antennas at each site, and made measurements comparing GPS timing signals to UTC (NIST) from each site for 10 days. We repeated this process with four different models of GPS antennas. Section II describes the four types of antennas that were tested, and Section III describes the three antenna sites used for the test. Section IV presents the measurement results. Finally, Section V describes how RF interference from other GPS antennas is another potential hazard of the rooftop environment that can degrade time transfer results.

II. THE GPS ANTENNAS UNDER TEST

The four antenna types used in our test were a patch antenna, a patch antenna with a simple choke ring attached, a quadrifilar helix, and a “pinwheel” antenna with an aperture coupled slot array design. These antennas are described below, and pictured in Figures 1 through 4.

2.1. PATCH ANTENNA

The patch antenna used in our experiment (Figure 1) is typical of those sold with GPS-disciplined oscillator products. These antennas are inexpensive, durable, easy to install, and widely used. This particular model is 9 cm in diameter, is powered by 5 V dc from the receiver, and works with the L1 carrier frequency (1575.42 MHz) only. It has a gain of more than 30 dB, which is useful for driving the long antenna cables often found in laboratory timing installations. As can be seen in Figure 1, the actual antenna is flat and the cone-shaped radome is empty. The purpose of the radome is simply to prevent snow and debris from settling on the antenna.

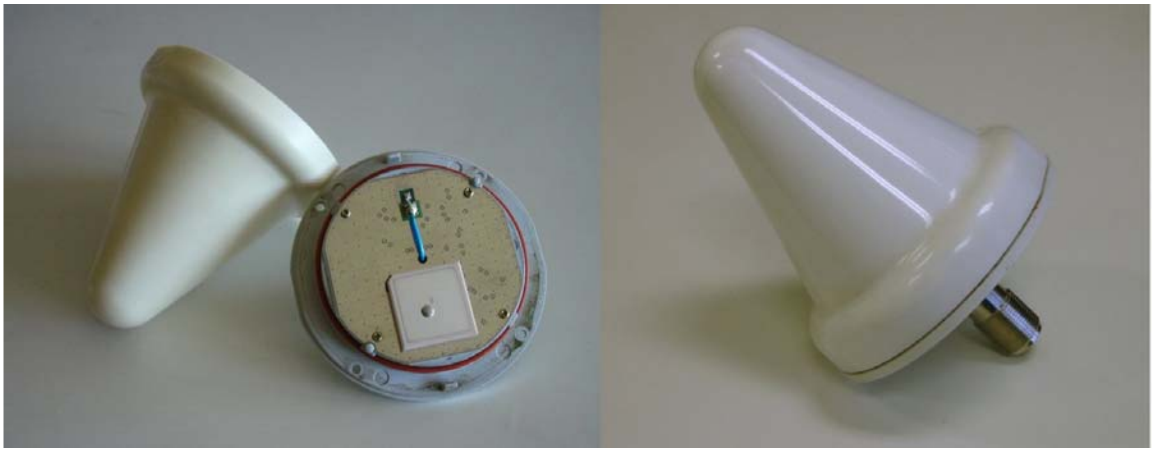

Figure 1. Patch antenna with radome removed (left) and with radome attached (right).

2.2. PATCH ANTENNA WITH SMALL CHOKE RING

Originally designed by the Jet Propulsion Laboratory (JPL) **[3]**, a choke ring is a ground plane containing a series of concentric circular troughs one-quarter wavelength deep. In the timing community, choke rings have long been added to GPS antenna elements to help mitigate multipath reflections and reduce time transfer noise **[4]**. Choke rings work by preventing traveling surface waves from forming, thus providing protection from signals bouncing off the ground or arriving from near-horizontal directions. However, they are less effective at rejecting multipath signals reflected from above the antenna **[5]**.

For this experiment, we modified the patch antenna described in Section 2.1 by adding a small choke ring with a ground plane that is 24 cm in diameter. This choke ring was fabricated at NIST by milling a solid cylinder of aluminum (Figure 2). It was designed to be small and light enough to add to the patch antennas without reinforcing the antenna mount. Unlike commercially available choke rings that often have five or more concentric rings; our simple design has only two. The rings are spaced by multiples of 4.76 cm from the center of the ground plane, or about one-quarter of the 19.03 cm wavelength of the L1 carrier. The depth of each ring is also 4.76 cm.

Figure 2. Simple choke ring by itself (left) and attached to patch antenna (right).

2.3. QUADRIFILAR HELIX ANTENNA

The quadrifilar helix antenna predates GPS. It was originally described by Kilgus in 1968 **[6]**, and a variation was later used with early GPS timing receivers developed at NIST **[7]**. The model used in our test (Figure 3) is a low-cost device that is 9.2 cm in diameter. Like the patch antenna, this particular model is powered by 5 V dc from the antenna cable, and works with L1 only. It has 37 dB gain, and is righthand circularly polarized (RHCP). Multipath signals change polarization during the reflection process, and are often lefthand circularly polarized (LHCP) when they arrive at the antenna. A quadrifilar helix well designed for RHCP often does a good job of rejecting LHCP signals, thus mitigating some effects of multipath **[8]**.

Figure 3. Quadrifilar helix antenna with radome removed (left) and with radome attached (right).

2.4. PINWHEEL ANTENNA

The "pinwheel" type antenna is a patented commercial design that uses a phased array of aperture-coupled spiral slots that are optimized to receive RHCP signals. This type of antenna has a very stable phase center, and is able to provide multipath rejection of LHCP signals over a wide range of elevations and all azimuth directions **[9]**. In addition, pinwheel antennas have the advantage of being much smaller, lighter, and usually less expensive than a choke ring, and tests have shown that they provide comparable rejection of multipath signals **[9,10]**. For these reasons, their use in the timing community seems to be growing rapidly. The model we tested is 18.5 cm in diameter. It receives only the L1 frequency and provides 27 dB gain.

Figure 4. "Pinwheel" antenna.

III. THE GPS ANTENNA SITES

Our GPS antennas are mounted on rooftop locations at NIST that are relatively close to our timing laboratories, with the antenna cables ranging from about 15 to 30 m in length. Our receivers are located in two different laboratories, and antenna cables are run either to the very top of the building, six stories above the ground, or to a large flat roof area above the fourth floor. For this experiment, three specific antenna sites were chosen (Table 1). Sites 1 and 2 were located at the top of the building, and Site 3 was located on the fourth floor roof area. Note that Sites 1 and 2 are 7.8 m higher in elevation than Site 3, and that the longest baseline between the sites is just 34.9 m.

Table 1. Coordinates of antenna sites used for experiment.

Site	Latitude	Longitude	Altitude (meters)	Distance to other sites (meters)		
				Site 1	Site 2	Site 3
1	39° 59’ 43.494” N	105° 15’ 44.108” W	1653.3	----	12.7	31.8
2	39° 59’ 43.725” N	105° 15’ 44.552” W	1653.3	12.7	----	34.9
3	39° 59’ 44.291” N	105° 15’ 43.322” W	1645.5	31.8	34.9	----

Figure 5 is a photograph of the three antenna sites taken from the north side of the fourth floor roof. Note that Sites 1 and 2 are located atop the large concrete structure above the fifth floor that houses the elevator shaft. We refer colloquially to this structure as the “penthouse.” Antenna cables pass through the interior of the penthouse from our laboratory, which is located nearly directly below the penthouse on the fourth floor. The antenna cables that run to Site 3 originate in a second laboratory located on the fourth floor, just slightly below and about 10 m to the west of the antenna site. The orientation of the three sites with respect to each other can be confusing. Coloradoans in the Denver-Boulder area are accustomed to looking for the mountains to determine which way is west, but when standing on the NIST roof the mountains appear to wrap around the building. To gain perspective, note that Site 3 is the farthest site to the north and that Site 2 is the farthest site to the west.

A closer look at Sites 1 and 2 is provided in Figures 6 and 7. A guardrail made of PVC pipe runs along the perimeter of the penthouse. The Site 1 antenna is mounted on this guardrail; the Site 2 antenna is mounted on a pole just inside of the guardrail. The two antennas are at the same elevation (1653.3 m) and separated by a baseline of 12.7 m (Table 1), which is the approximate width of the penthouse.

Site 1 (Figure 6) is a challenging multipath environment. There are several reflective metal objects on the rooftop, including the hood of a ventilation system, and the door that provides access to the roof. There are also several other antennas in the vicinity, including a 10 m tall whip. More prominently, a large audio horn used by an emergency warning system (upper right corner of Figure 6), is just a few meters away and can reflect signals from above the antenna.

Site 2 (Figure 7) has fewer reflecting objects above the antenna to contend with. However, the site is adjacent to a large metal smokestack that descends into an underground boiler room. The smokestack has numerous reflective metal surfaces that are located below the antenna under test.

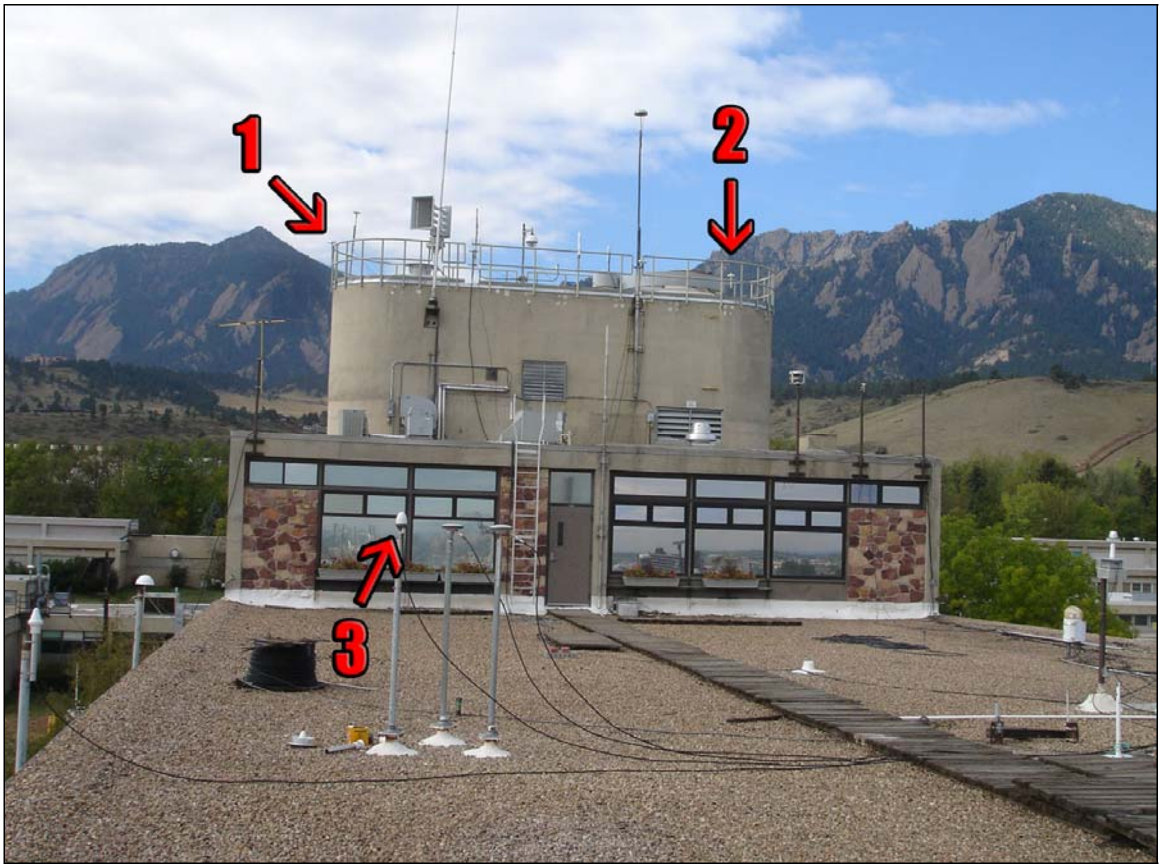

Figure 5. The three antenna sites.

Figure 6. Antenna Site 1 (the arrow points to the choke ring antenna under test).

Figure 7. Antenna Site 2 (the arrow points to the choke ring antenna under test).

Figure 8. Antenna Site 3 (the arrow points to the choke ring antenna under test).

Site 3 (Figure 8) is located below and to the north of the penthouse and is a less hazardous multipath environment than Sites 1 and 2. The surface of the roof is non-metallic, covered with tar and rock, and there are no reflecting objects directly overhead. As shown in Figure 8, there are many antennas, mounting poles, and metallic objects nearby that can reflect signals. However, the small size of these objects and/or their distance from the Site 3 antenna limits the amount of multipath noise that they generate.

IV. MEASUREMENT RESULTS

We tested the four antenna types at each of the three sites by connecting them to identical GPS receivers. Each test ran for 10 days, with the results summarized in Table 2. We chose the time deviation, $\sigma_x(\tau)$, **[11]** as our metric for time transfer noise, and note that guidelines for timing receiver manufacturers published by the Bureau International des Poids et Mesures (BIPM) state that "contributions due to multipath noise should have time deviation (TDEV) values below 1 ns when averaged across satellites" **[12]**. Using an averaging time of 10 minutes, only the pinwheel antenna met the 1 ns requirement at Site 1. Only the patch antenna failed to meet the requirement at Site 2, and all four antennas easily met the requirement at Site 3.

Table 2. Time deviation of GPS data (obtained by averaging tracks from all satellites in view).

Antenna Type	Dates of Comparison (10-day tests)	$\sigma_x(\tau)$ (nanoseconds) at $\tau = 600$ s		
		Site 1	Site 2	Site 3
Patch	08/24/06 to 09/02/06 (MJD 53971 to 53980)	1.27	1.21	0.69
Patch w/choke ring	09/06/06 to 09/15/06 (MJD 53984 to 53993)	1.06	0.98	0.62
Quadrifilar helix	09/19/06 to 09/28/06 (MJD 53997 to 54006)	1.10	0.91	0.72
Pinwheel	09/30/06 to 10/09/06 (MJD 54008 to 54017)	0.81	0.77	0.57

Table 2 shows $\sigma_x(\tau)$ at $\tau = 600$ s, the default averaging time used by our systems **[1,2]**. Figures 9 through 12 graph $\sigma_x(\tau)$ for the four antenna types for τ values ranging from 600 s to 86400 s (one day). The patch antenna (Figure 9) performed similarly at Sites 1 and 2, but had much less noise at Site 3, with the noise remaining lower for averaging times out to about two hours. Adding the choke ring to the patch did not notably reduce noise at Site 3 (Figure 10), suggesting that Site 3 had few ground reflection problems to begin with. However, the choke ring did reduce noise at Site 2 at short averaging times, and surprisingly made Site 1 the least noisy of the three sites after about 1 hour of averaging. At longer averaging times, the performance of the patch/choke ring antenna varied considerably at the three sites. This suggests that our simple choke ring is not an optimal match for the patch antenna, and that it could be rejecting some non-multipath signals.

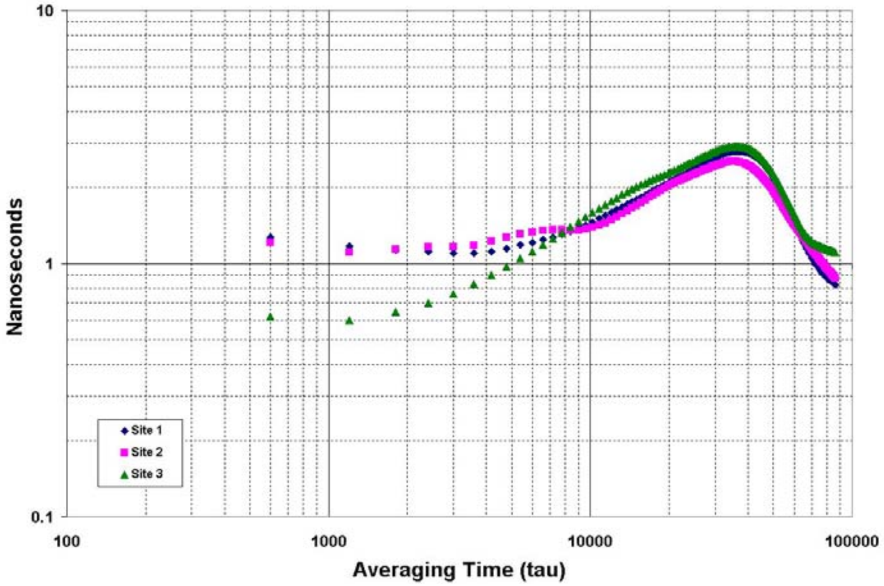

Figure 9. Time deviation of GPS receiver using patch antenna.

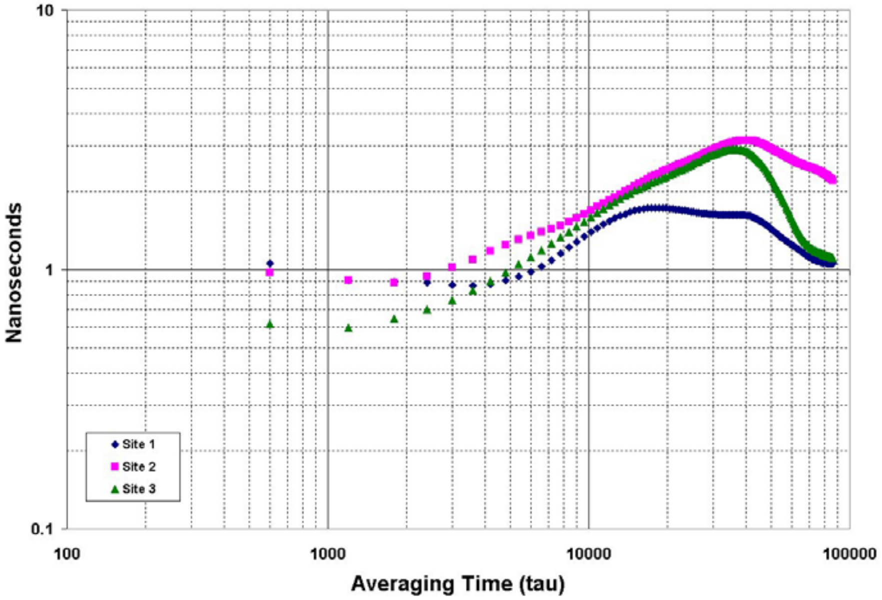

Figure 10. Time deviation of GPS receiver using patch/choke ring antenna.

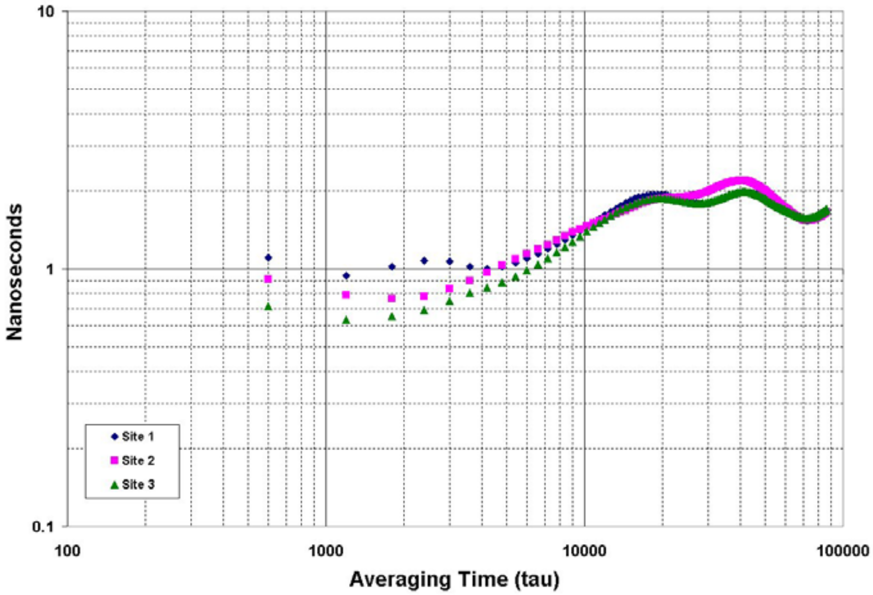

Figure 11. Time deviation of GPS receiver using quadrifilar helix antenna.

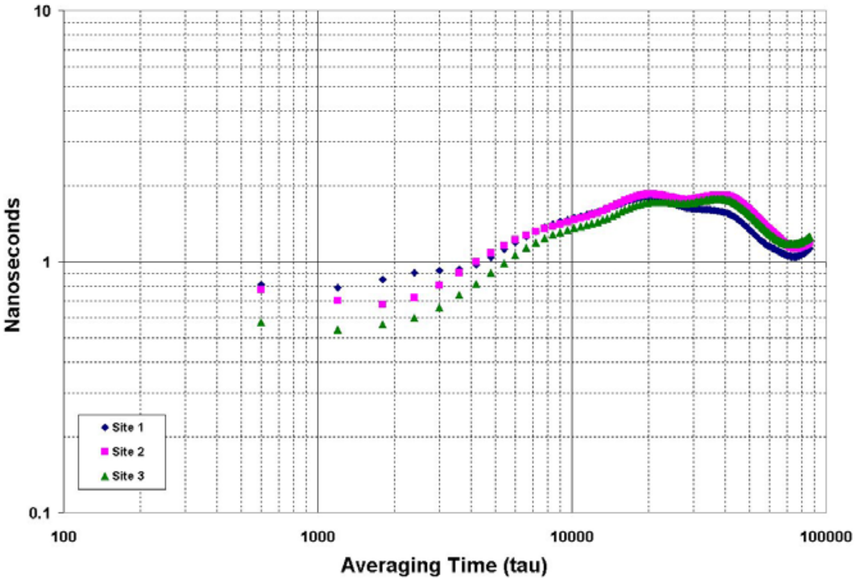

Figure 12. Time deviation of GPS receiver using pinwheel antenna.

The quadrifilar helix antenna (Figure 11) rejected more multipath noise than either the patch or patch/choke ring antenna combination at Site 2, perhaps dealing better with the reflections coming from multiple angles off of the boiler room smokestack. It exhibited consistent behavior at all three sites after about four hours of averaging. However, the pinwheel antenna (Figure 12) was the best performer. Like the quadrifilar helix, it fared better at Site 2 than at Site 1, but was still able to stay below 1 ns at Site 1 for averaging times of up to 1 hour.

When examining the data presented in Figures 9 through 12, it is important to realize that our time transfer systems average 10-minute tracks from as many as eight satellites using an “all-in-view” approach, and that this averaging has already attenuated the multipath noise. The individual satellite tracks are usually noisier than the composite average, often containing large phase “spikes” from multipath reflections. The phase of the individual satellite tracks often reveals more about the multipath conditions than can be seen from time deviation graphs. To illustrate this, Figures 13 through 16 show daily 1-hour tracks (consisting of 60 1-minute averages) recorded from PRN 14 at Site 1 using each of the four antenna types. The graphs have identical y-axis scales for comparison purposes, and each graph includes nine daily tracks. All data sets were normalized to 0, and the tracks were aligned by shifting them by 4 minutes each day, to compensate for the sidereal orbit of the satellite. The patch antenna graph (Figure 13) shows a phase spike of about 100 ns in amplitude caused by multipath reflections from objects on the roof. These same reflections caused a similar phase spike in data from the quadrifilar helix (Figure 15), but both the choke ring/patch combination (Figure 14) and the pinwheel antenna (Figure 16) were able to attenuate much of this type of multipath noise. Using all available data from PRN 14 over the 10-day test period, $\sigma_x(\tau)$ at τ = 600 s was 4.05 ns for the patch, 1.51 ns for the choke ring/patch combination, 1.97 ns for the quadrifilar helix, and 1.31 ns for the pinwheel.

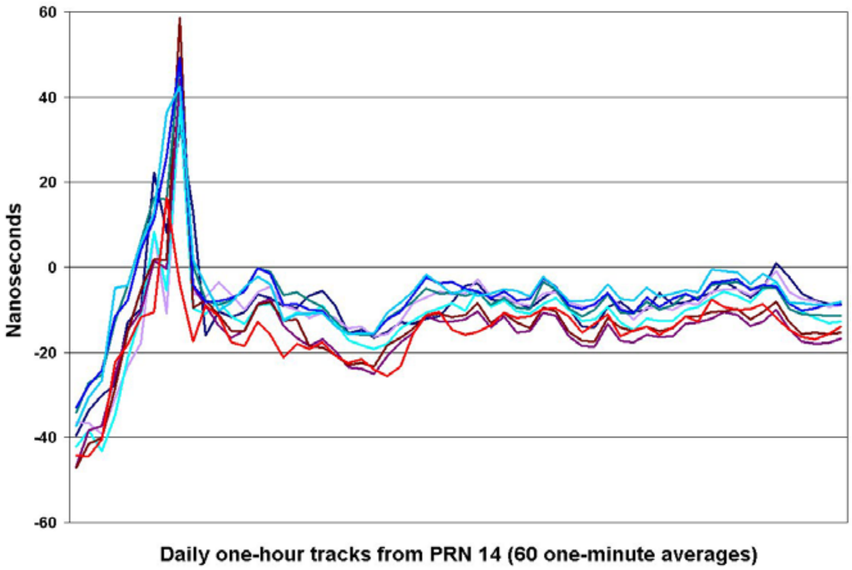

Figure 13. One-hour satellite tracks recorded for patch antenna at Site 1.

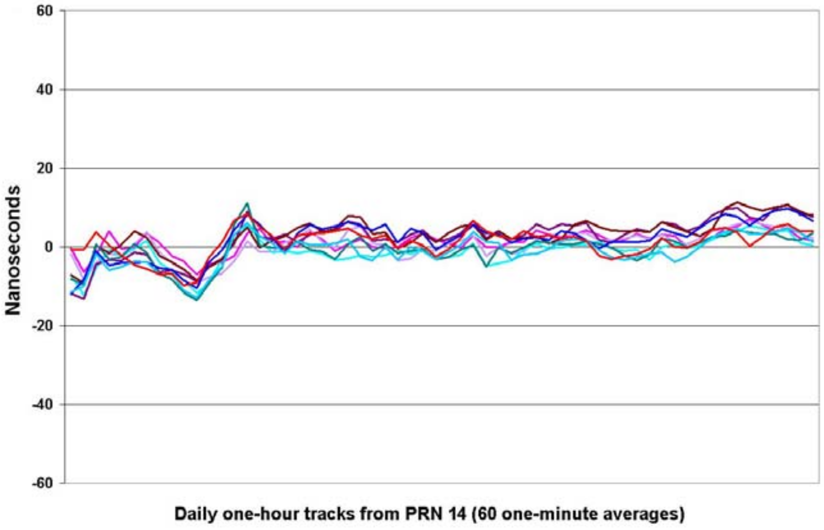

Figure 14. One-hour satellite tracks recorded for patch/choke ring antenna at Site 1.

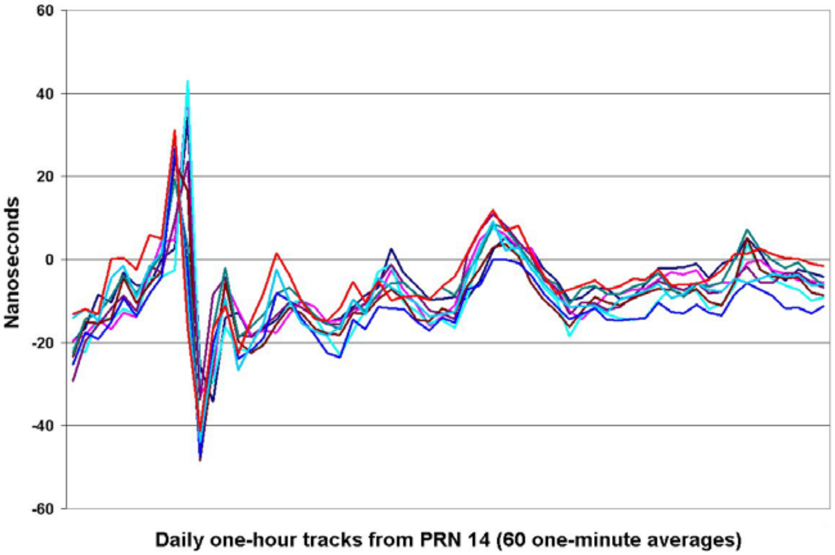

Figure 15. One-hour satellite tracks recorded for quadrifilar helix antenna at Site 1.

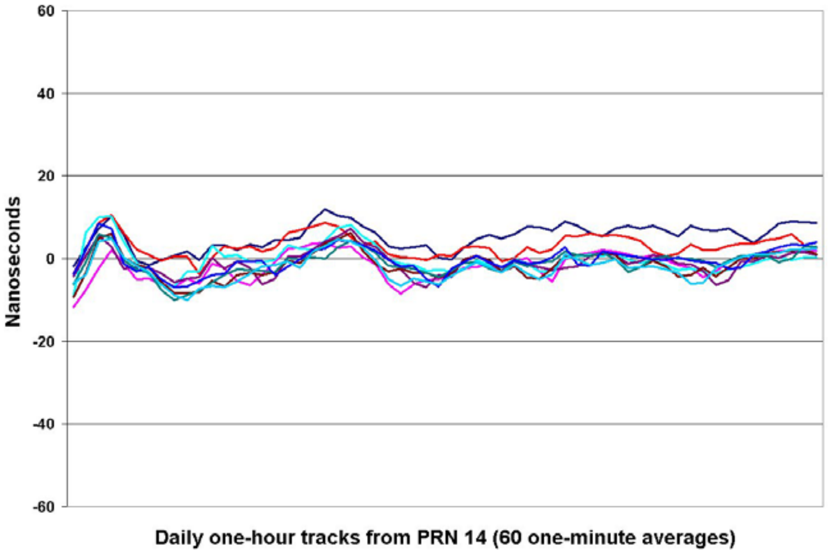

Figure 16. One-hour satellite tracks recorded for pinwheel antenna at Site 1.

The data shown in Figures 13 through 16 are obtained from one-way GPS comparisons of the receiver's output to UTC (NIST). In a common-view comparison involving two GPS receivers, any phase spikes contributed by multipath that affect one receiver differently from the other will not cancel when the data are reduced, and will add a systematic uncertainty to the measurement. As we have seen from experience, this can occur even if two antennas of the same type are located in different multipath conditions on the same roof, and is likely to be a problem if common-view common-clock calibrations are made between two identical receivers using different types of antennas.

Our time transfer systems **[1,2]** collect more than 1000 10-minute satellite tracks per day on average (1152 is the maximum possible number of tracks if eight satellites are recorded at all times). Web-based software developed at NIST allows us to quickly view individual satellite tracks and to page through them by either the date or the satellite PRN number. Using this software, we have seen numerous examples similar to Figures 13 through 16, where a given antenna can handle multipath better than the others in a particular environment, and yet can still perform worse than the others in a different environment. This makes it necessary to look at more than one situation before drawing conclusions about which antenna does the best job of rejecting multipath. However, the measurements presented in this section appear to be thorough enough to indicate that the patch antenna was the worst performer overall when tested at three sites, and worked well only in the mostly reflection-free environment of Site 3. The pinwheel appeared to be the best performer overall, and did a good job of rejecting multipath in all three environments. The pinwheel antenna is several times more expensive than the patch or the quadrifilar helix, but is still relatively inexpensive when compared to commercially available choke rings, and less labor-intensive than making our own choke rings at NIST. We had previously deployed patch antennas with time transfer systems delivered to other laboratories, but plan to deploy pinwheel antennas with future systems, and have already retrofitted some of the systems that we have in the field.

V. RF INTERFERENCE FROM OTHER GPS ANTENNAS

Multipath is not the only hazard of the rooftop environment. GPS is vulnerable to RF interference, and there has historically been much discussion and concern about the threat of intentional jamming of the GPS signals. Unintentional jamming is perhaps a more likely threat to time transfer applications due to the extremely low power of the GPS signals. The guaranteed minimum received signal level on earth is near –160 dBW for the C/A code on the L1 carrier [**13**], equivalent to 10^{-16} W. When unintentional jamming occurs, finding the source of interference can be difficult and time consuming. One published account describes how GPS was unintentionally jammed for more than two months in a California harbor area, with the source finally identified as commercially available television antennas located on private boats **[14]**. While it seems unlikely, on at least two occasions at NIST we have seen interference caused by other GPS receiving antennas located on the same roof. The most recent of these incidents is described here.

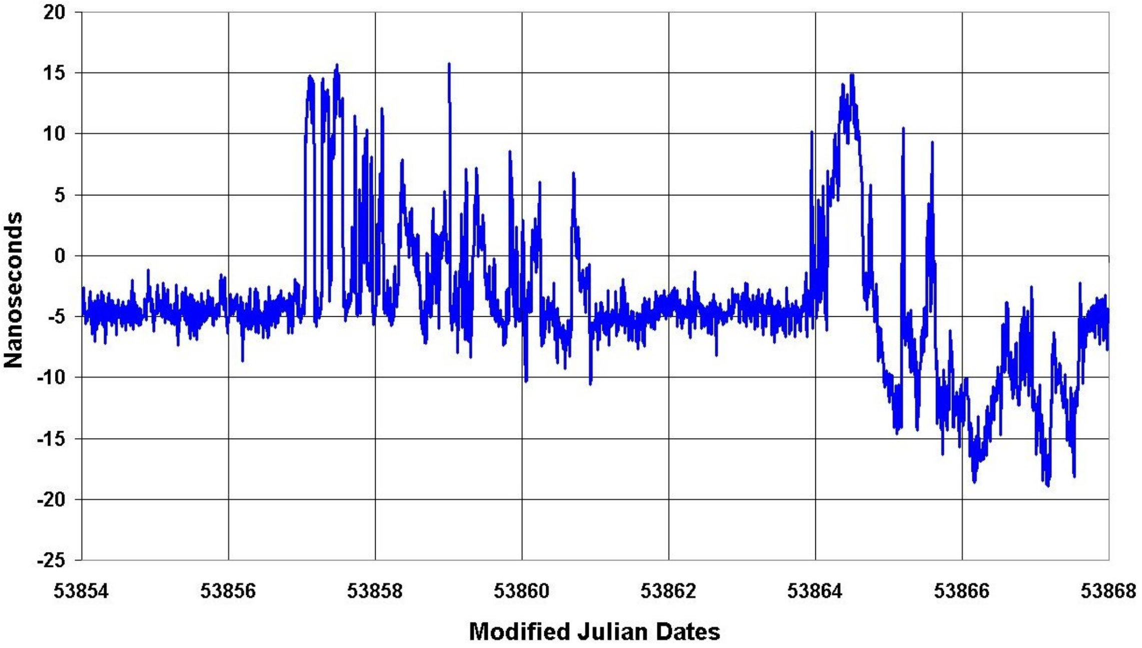

Figure 17. Common-clock common-view data contaminated by noise from RF interference.

Beginning about 2 May 2006 (MJD 53857), several of our GPS receivers began experiencing intermittent interference and signal outages. During the next 2 weeks, these multi-channel receivers routinely tracked fewer than their normal number of satellites, and in some cases, completely lost the GPS signal. Two of the outages at Site 2 lasted for more than 1 hour, and two at Site 3 lasted for more than 30 minutes (no receiver was operational at Site 1 during this period). The interference was intermittent throughout the day, but suspiciously disappeared for about 72 hours beginning on May 6 (MJD 53861). Figure 17 shows results from a common-view common-clock calibration that was being conducted during this period of interference between two receivers located at Site 3. The graph begins about 3 days prior to the start of the interference and extends for about 4 days past the "quiet" period. During the initial period and the "quiet period", the true differential delay (~5 ns) between the two receivers can be seen.

Out initial attempts to find the source of the problem were unsuccessful. At first, we were not convinced that the interference was coming from an outside source, and we focused on looking for problems with our own receivers, turning some of our equipment off to try to isolate the problem. Eventually, a measurement made with a spectrum analyzer during one of the outages revealed a intermittent source of interference moving around 1.579 GHz, with peak amplitude 5 dB higher than the C/A code amplitude. By carrying a broadband horn antenna (0.7 to 18 GHz) and a spectrum analyzer to the roof, the direction and source of the interference was found on 16 May 2006 (MJD 53871). The problem was traced to a GPS antenna located on another part of the roof that had a loose connector on its antenna cable. Tightening the connector completely stopped the interference. When the owner of the bad antenna was located and interviewed, he revealed that he had turned off his GPS receiver during the weekend beginning on 6 May, which explained the "quiet" period. The "bad antenna" was located about 100 m from Site 3, and Figure 18 shows its relative position with respect to the antenna sites described in Section III.

Figure 18. Location of the "bad antenna" (circled) with respect to our three antenna sites.

VI. SUMMARY AND CONCLUSIONS

The rooftop environment can have a negative impact on the quality of GPS time transfer results. Multipath reflections from rooftop objects can introduce a significant amount of time transfer noise. Some antennas are much at rejecting multipath signals than others, but all antennas benefit from being located as far from reflecting objects as possible. Unintentional RF interference, even from another GPS receiving antenna, can generate time transfer noise and even entirely block reception. Although the options available to a given laboratory are often limited, the type of antenna and the location of the antenna site should each be carefully selected to obtain the best time transfer results.

VII. ACKNOWLEDGMENTS

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