SOME CHARACTERISTICS OF ALFA's FIXED PATTERN NOISE (FPN)

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Contents

1. INTRODUCTION

Accuracy of the spectra taken with ALFA and LBW are limited by systematic baseline wiggles that change slowly, or perhaps not at all, with time. After a few second of integration, this *fixed pattern noise*, or *FPN*, dominates the uncertainty in the spectrum. It tends to have frequency structure of width $\gtrsim 1$ MHz, which is comparable to time delays of $\lesssim 1$ μsec in the autocorrelation function. We have strongly believed, and prove it here, that the structure results from reflections, the path differences are $\lesssim 300$ m. 1 MHz corresponds to 200 km/s at the HI line—a velocity scale in which lots of interesting things happen, scientifically speaking, so this FPN signifantly affects the science. We performed some experiments to determine some of its characteristics, of which we report in this document.

2. SUMMARY OF IMPORTANT FINDINGS

In this section we briefly summarize our most interesting findings. We document each in later sections with data and more discussion.

1. The FPN arises from reflections and is 100% polarized. (§4, 5, 7)
2. Most of the FPN arises from reflections involving shorter path lengths. The spectrum of delays is essentially continuous and looks random. (§8; figures 9, 10, 12, 13, 15)
3. A small component of the FPN arises from reflections between the bowl and the feed and associated structures; this component depends on the feed and the ALFA turret angle. This component of the FPN has sharp time-delay features in the 0.90, 1.04, and 1.16 μs. There seem to be additional time delays but the results look suspicious and should be repeated. (§8; figures 9, 10)
4. The FPN changes when the ALFA turret is rotated. The further the rotation, the larger the change. (§6)
5. The FPN changes with zenith angle za. The further the move, the larger the change. (§9)
6. Over the limited range in azimuth (az) that we tested, the FPN changes: the further the move, the larger the change. (§10)
7. The FPN amplitude increases noticeably towards lower frequencies. (§11)

3. EXPLANATION OF THE PLOTS IN FIGURES 1, 2, and 3

The formats of these three figures are identical. Each figure shows a pair of spectral plots in two panels to save space. The spectra are polynomial-flattened RF powers obtained from the

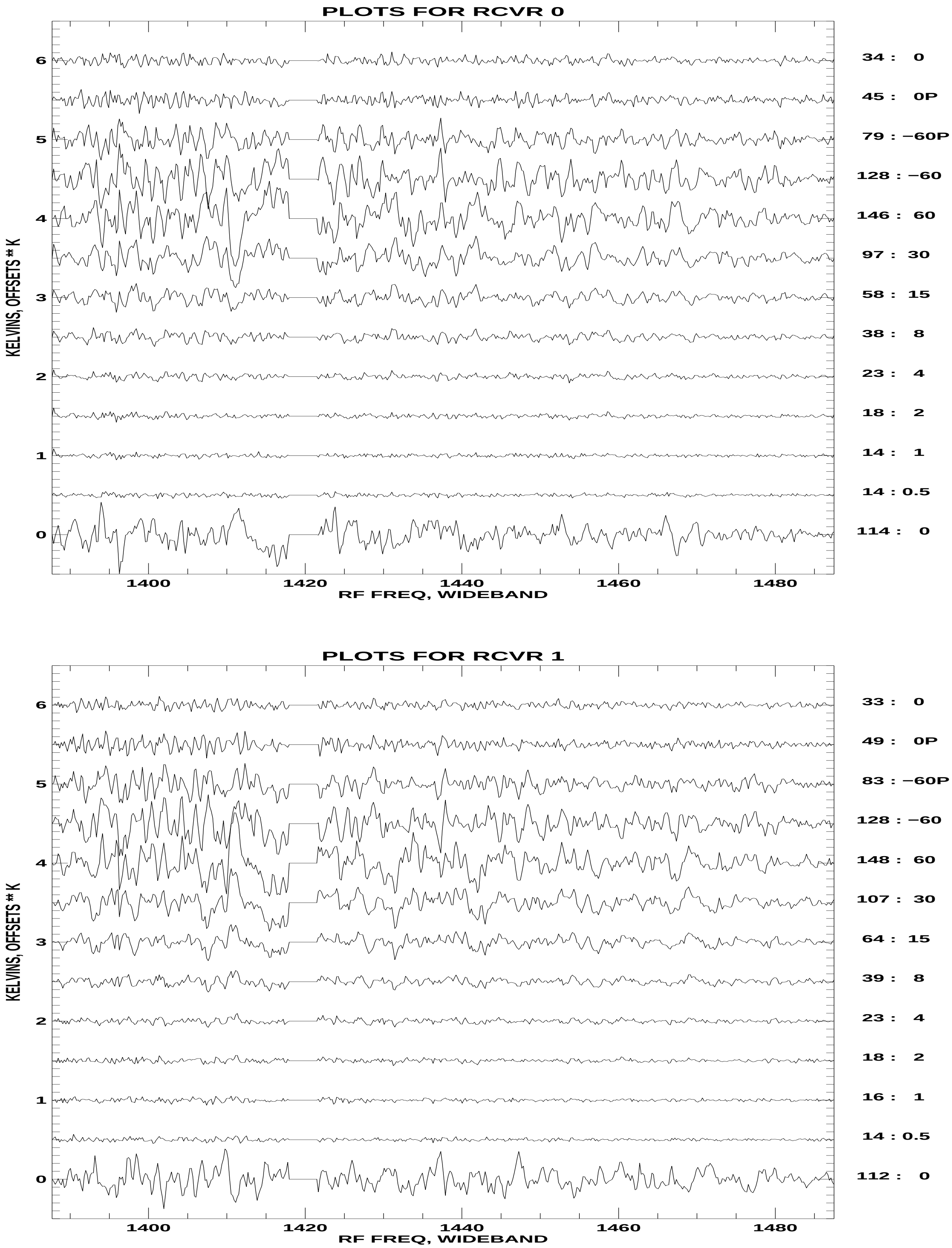


Fig. 1.— Spectra for receivers 0 (top), 1 (bottom) on beam 0. Labels on the right indicate ALFA turret angle; "P" indicates that the platform was lowered ~ 3 inches.

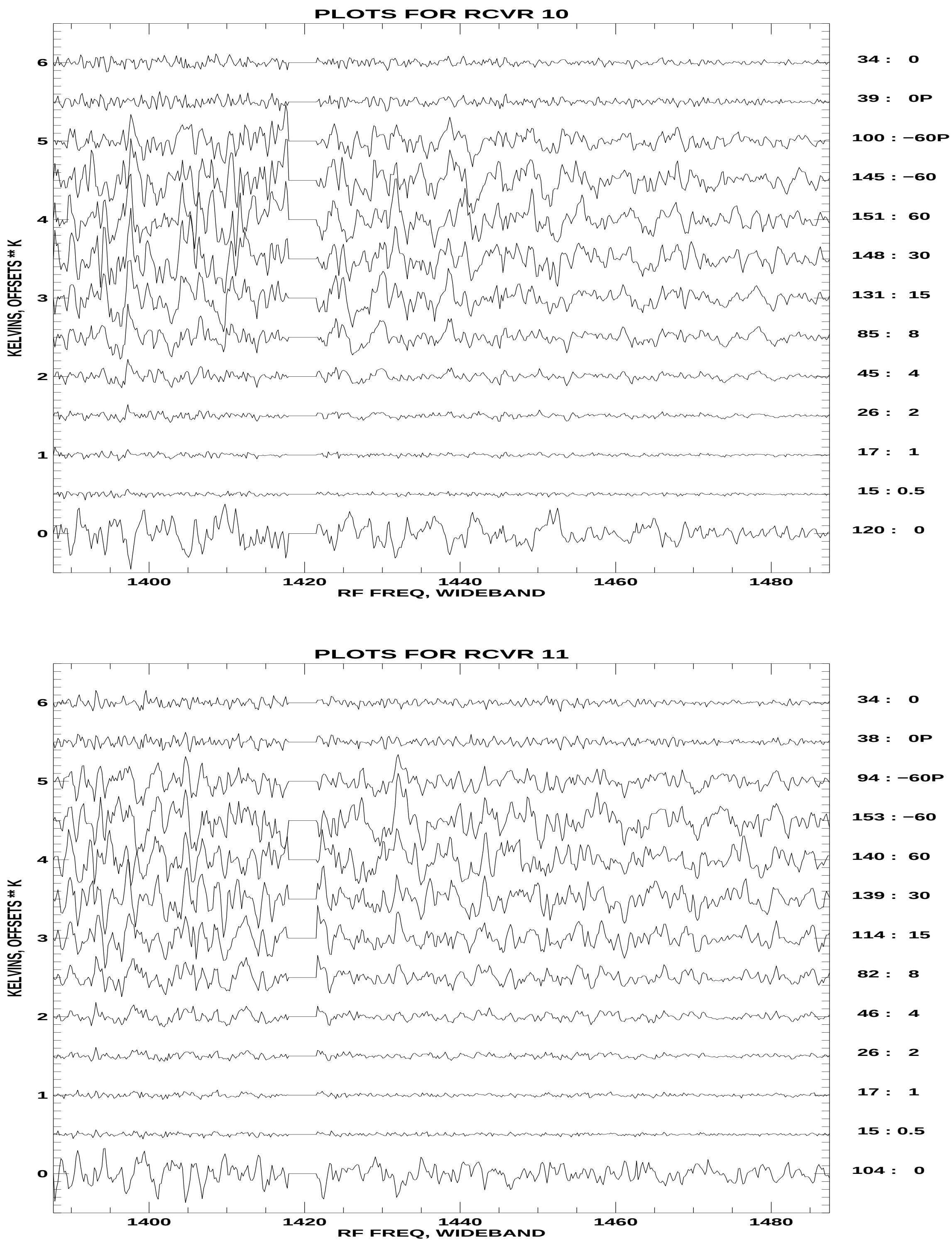
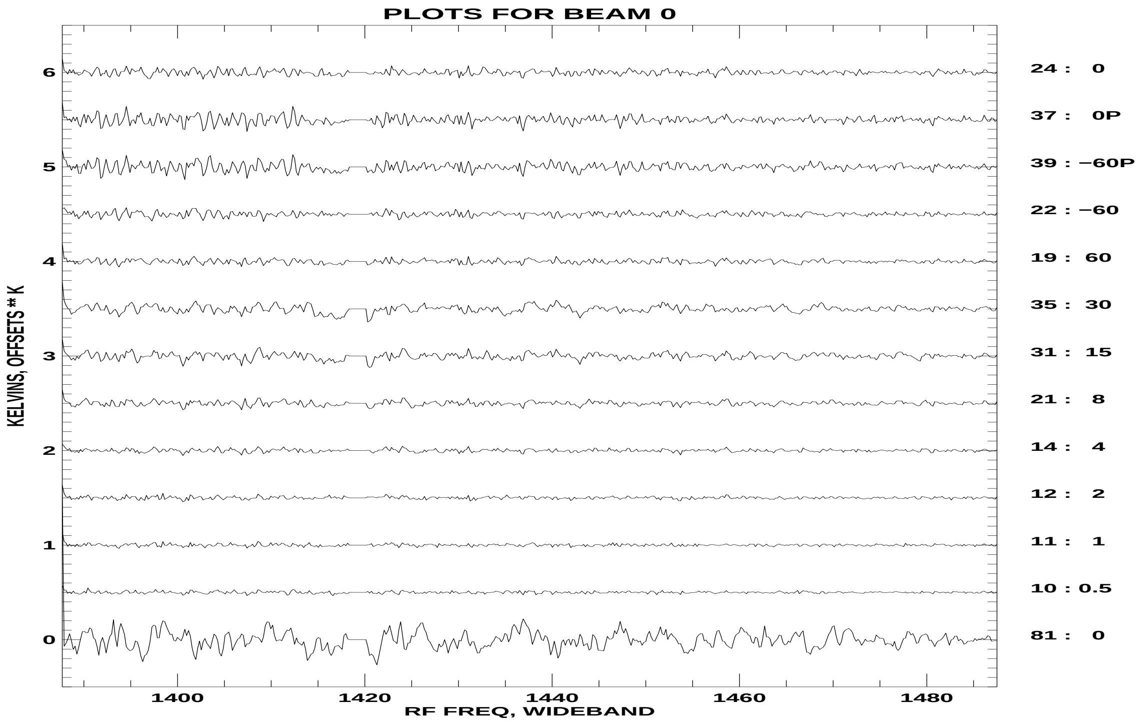


Fig. 2.— Spectra for receivers 10 (top), 11 (bottom) on beam 5. Labels on the right indicate ALFA turret angle; "P" indicates that the platform was lowered ~ 3 inches.



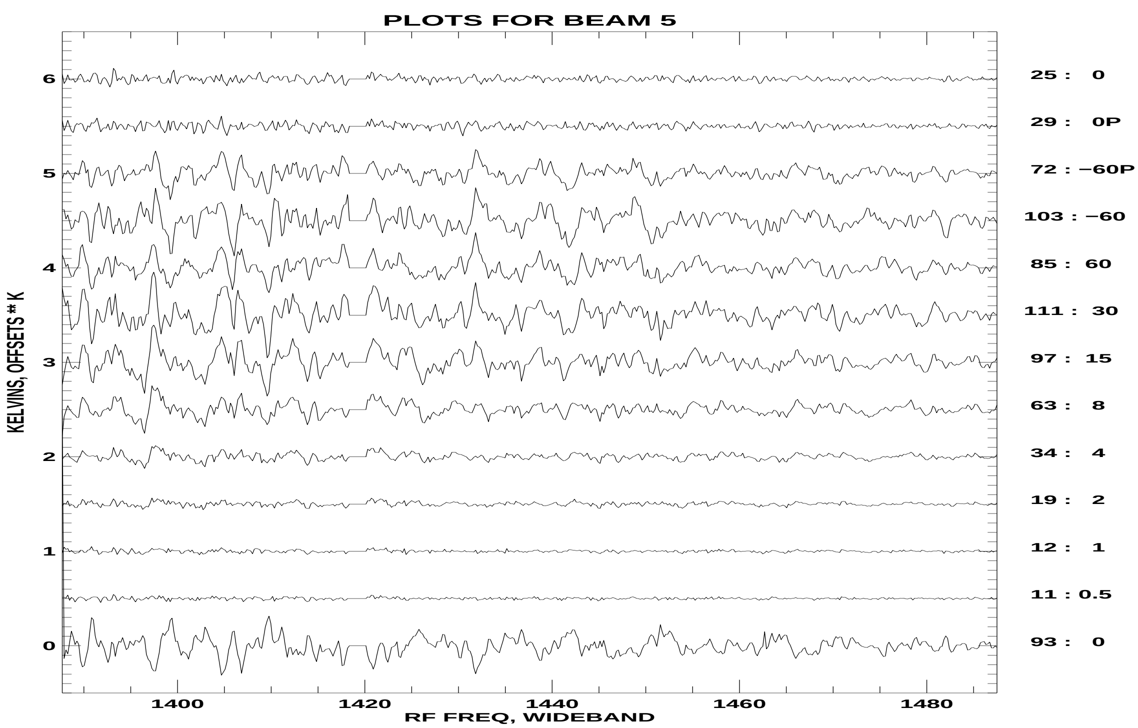


Fig. 3.— Spectra for beams 0 (top) and 5 (bottom). Labels on the right indicate ALFA turret angle; "P" indicates that the platform was lowered ~ 3 inches.

Least-Squares Frequency Switching (LSFS, a.k.a. SMARTF) procedure. They are shown versus r.f. frequency and the area near the 21-cm line (1420.4 MHz) has been zeroed. Each panel shows 12 plots for a specific receiver or feed; the zeros are offset by 0.5 K for clarity and the tags on the right, outside the plot boundary, indicate the conditions for that plot. Each plot shows a specific condition and time ordering of the measurements increases from bottom to top, with about 60 seconds integration for each plot.

The tags on the right show two quantities. For each spectrum, the first is the rms of that spectrum in milliK. The second indicates the ALFA turret angle, which steps in geometric increments from 0° to $+60^\circ$, then to -60°, and then back to 0°. Near the top, the two plots labeled with a "P" indicate that the platform was lowered by ~ 3 inches. The first plot, at the bottom, is the spectrum for the first measurement of the series of 13; it has ALFA turret angle 0°. All the other plots are *differences* between its particular spectrum and the first spectrum. This is why the very top plot, which was also taken at ALFA turret angle 0° (but about 30 minutes later), is so small.

4. BEAM 0 SHOWS THAT THE FPN IS 100% POLARIZED

First let's take a look at the on-axis feed 0, which is served by receivers 0 and 1. This feed is almost on-axis, so when we rotate the ALFA turret all that happens is the feed rotates with only a little translation—in other words, the polarization position angle changes. Look at Figure 1, which shows the difference between receivers 0 and 1 for different position angles. As we move away from ALFA angle 0, the difference spectra rms's get larger. This reflects the polarization of the FPN, and shows that the FPN is polarized.

The fluctuations in the two receivers, which have orthogonal linear polarizations, are completely uncorrelated. For the ALFA turret angle 0° spectrum, the rms of the difference between the two receivers' spectra is 163 milliK and that of the sum is 164 milliK, which is close enough to equality to consider the spectral fluctuations in the two receivers to be completely uncorrelated and independent. If the FPN were randomly polarized, then the FPN wouldn't change at all with position angle; the rms of the difference between the two receivers would be zero. The fact that the rms's of the difference and sum are identical means that the FPN is 100% polarized.

For off-axis feeds we can make the equivalent of Figure 1; for feed 5 we show the plots for its receivers 10 and 11 in Figure 2. We show this for fun only because it doesn't mean much: the native linear polarizations in all feeds are oriented identically on the sky, so as we rotate the ALFA angle we also rotate the orientation of the linear polarizations to which a feed responds. Because the FPN is itself polarized, the response of individual receivers contains this changing polarization. Instead of looking at individual receivers for a feed, we have to look at their sum so that the polarization of the FPN doesn't confuse us.

5. DEPENDENCE OF FPN ON ALFA TURRET ANGLE

Figure 3 shows the spectra for the on-axis feed 0 (top panel) and the off-axis feed 5 (bottom panel). Note that these are averages of both receivers, so FPN polarization plays no role in these plots. As we increase the ALFA turret angle away from 0°, the FPN of the difference spectra rise. (These are difference spectra, each spectrum minus the one for turret angle 0). The rms for feed 0 rises modestly, by no more than a factor of 2. This as it should be: when we rotate the ALFA turret, all we are doing is rotating feed 0, so when we add the polarizations we expect zero effect. The residual effect that we do see is almost certainly produced by feed 0 being slightly off-axis (by design; Cortéz-Medellin 2002).

For the outrigger feeds the FPN changes quite rapidly with turret angle. For example, for turret angle 8°, for beam 5 the rms of the difference spectrum is almost half the value of the turret-angle 0 spectrum. Thus, even at 8° turret angle, the FPN has changed a lot from its pattern at 0°.

6. DEPENDENCE OF FPN ON FEED

The FPN of each feed is statistically independent of the others. Figure 4 shows one set of spectra all 14 receivers, together with the mean at the top. The FPN for the mean is much smaller than the FPN of the individual receivers. In fact, a detailed look at a set of data (not those in the figure) shows that the statistical reduction in the rms of the mean spectrum is almost exaclty what's expected if the FPN's are statistically independent. Thus, the rms of the FPN of the average of all receivers is about $\sqrt{14}$ times smaller than the average rms of each, which is what we expect for statistical independence.

There is no comprehensible systematics in variation of the FPN rms from beam to beam. A grand average over *all* of the 12 measurement conditions gives, for the 7 beams, rms's of [83, 62, 79, 83, 81, 84, 78] milliK. This average mixes all of the ALFA turret angles that we sampled. If we restrict the average to turret angle 0, we obtain [81, 66, 82, 89, 78, 93, 86] milliK. For both cases, feed 1 is significantly smaller than the others; the others are comparable to each other. Feeds 1 and 6 are the "downhill" feeds, closest to the center of the Gregorian dome. Feeds 3 and 4 are the "uphill" feeds. But it doesn't seem to matter.

7. THE FPN STAYS FIXED IN SPACE WHEN WE ROTATE ALFA BY 60 DEGREES

If the FPN is from reflections, then it should be fixed in space. When we rotate the ALFA turret by 60°, thus interchanging one feed for another, the newly-interchanged feed should see the same FPN that the original one did. This is, in fact, the case. However, the FPN interchanges are

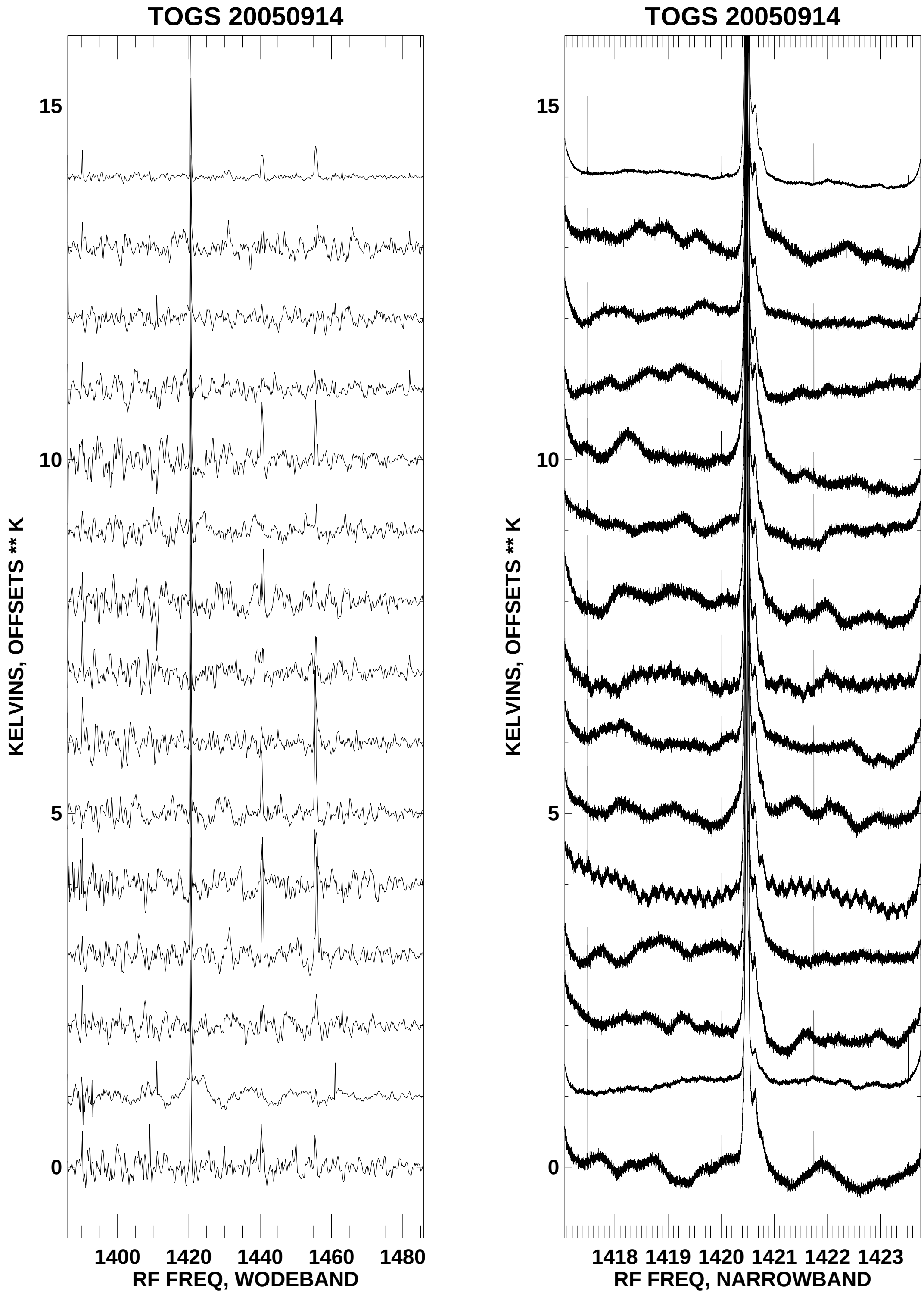


Fig. 4.— An example of spectra for each of the receivers. The mean of all receivers is at the top. Each receiver's spectrum is stastically independent of the others'.

not quite perfect

First, let us define the terms *self difference* and *interchange difference*. These differences are between receivers at two different turret angles that differ by 60° or 120°. The self difference is between the same feed at the two angles. The interchange difference is the difference between the original feed and the one that occupied the same physical location after the rotation.

We show three representive cases in Figure 5. The top panel compares turret angles $[-60°, 0°]$; the middle, $[+60°, 0°]$; and the bottom, $[60°, -60°]$. We subtract feed 5's spectrum at the first angle from its spectrum at the second angle (upper plot in each panel); and from the spectrum of its interchange partner (lower plot).

For each panel, the interchange difference (lower plot) looks much less noisy than the self difference. This proves that the FPN stays fixed in space and as the feeds rotate they sample the same reflections in space. However, the interchange difference isn't just thermal noise, so there is more to the story. The ACF plots figure 6 show that the differences are primarily associated with short time delays. In particular, for the lower two plots the ACF shows a well-defined peak at a delay of 0.075 μs (22.5 meters round trip, 11.25 meters one-way), and you can clearly see the associated low-frequency ripple on the right-hand half of the frequency spectrum.

Either there is an additional contributor to FPN that is receiver-based, or there are mechanical imperfections or anomalies. We don't think the receivers themselves have any intrinsic FPN because of tests we did in July 2005, when we observed with the ALFA cover on and found *no* FPN. The 11.25 meter one-way distance perhaps offers a hint about what might be happening to someone who knows the mechanical structural details.

8. BEHAVIOR OF THE FPN WITH PLATFORM HEIGHT

A well known reflection is that between the bottom of the bowl and the feed, Gregorian, or platform. If we change the platform height while keeping all other conditions the same, we change the phase of these reflections and we can see what happens. Here we look at two feeds, the on-axis feed 0 and feed 5 as a representative; all of the off-axis feeds looked similar. We have two platform-moved datasets, one at ALFA turret angle $-60°$ and one at angle $0°$; the mighty Phil grabbed hold of the platform, moved its great weight of the platform down by ~ 3 inches[1] and held it there for a few minutes to make our measurements, and then lifted it back up.

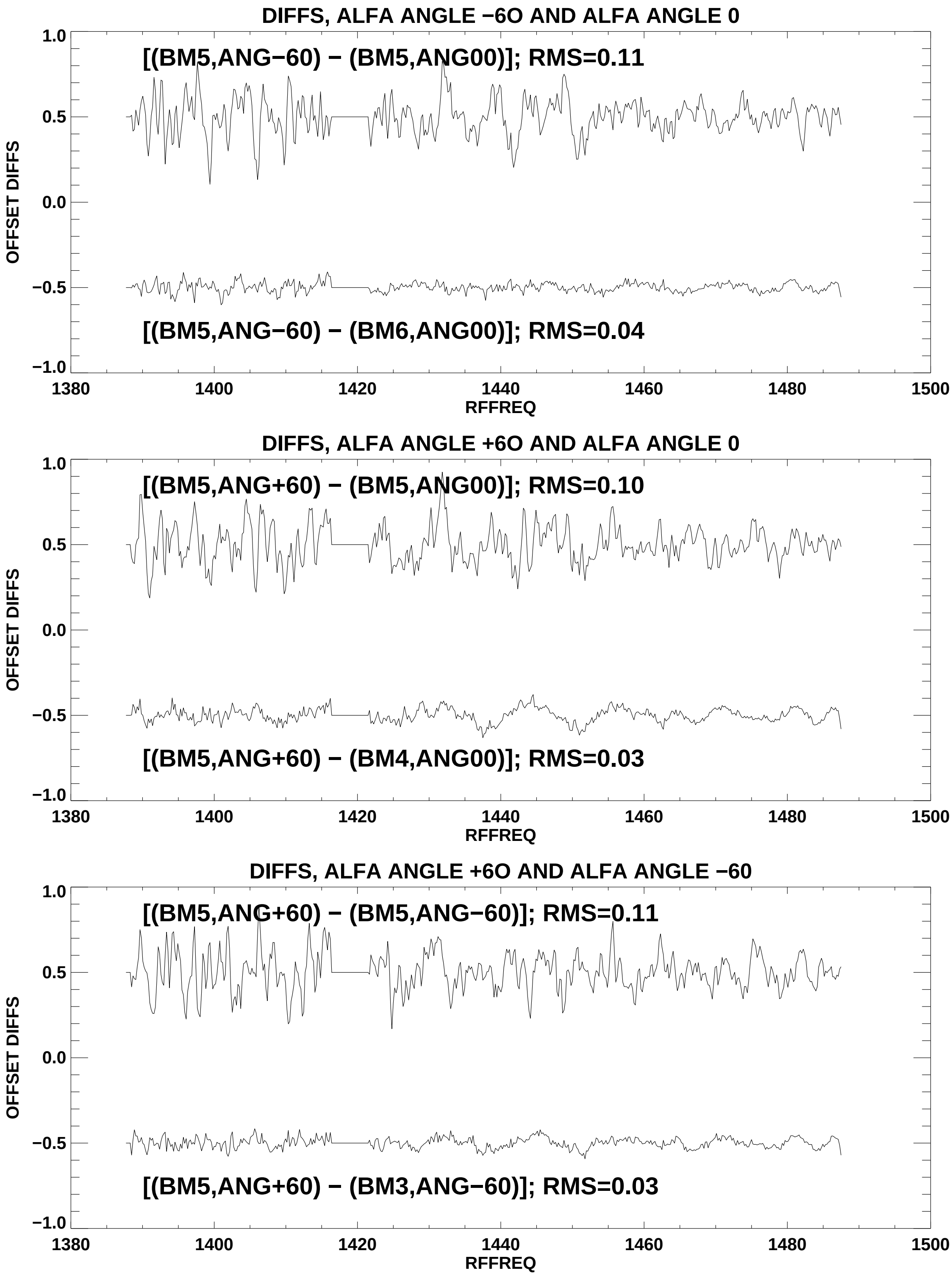


Fig. 5.— Difference spectra for ALFA turret angles $-60°$, $0°$, and $60°$. In each panel, the top spectrum is the "self difference" and the bottom one the "interchange difference". The latter is the spectrum of the interchanged receiver minus that of the original. See text!

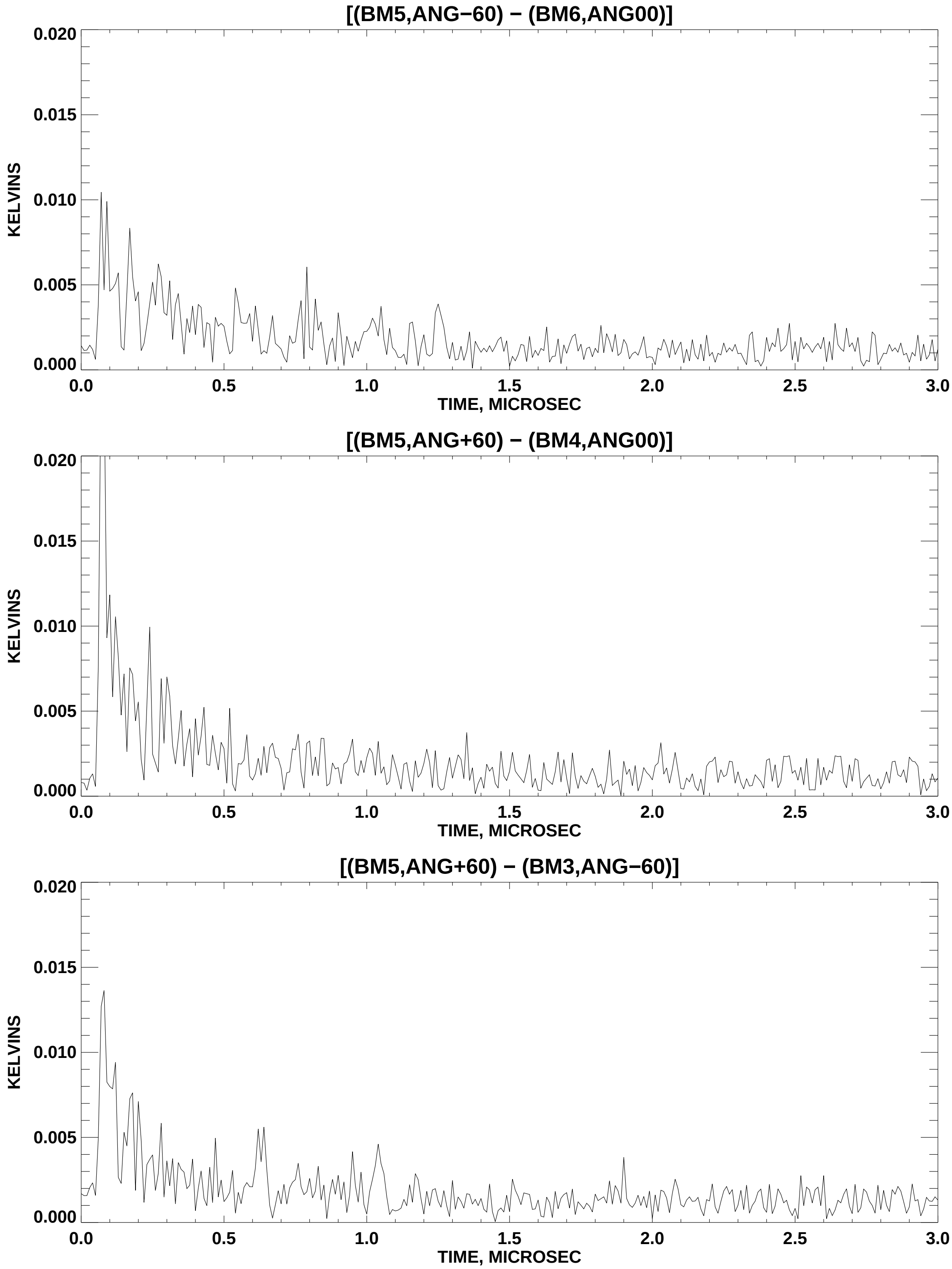


Fig. 6.— ACF's of interchange difference spectra for ALFA turret angles $-60°$, $0°$, and $60°$

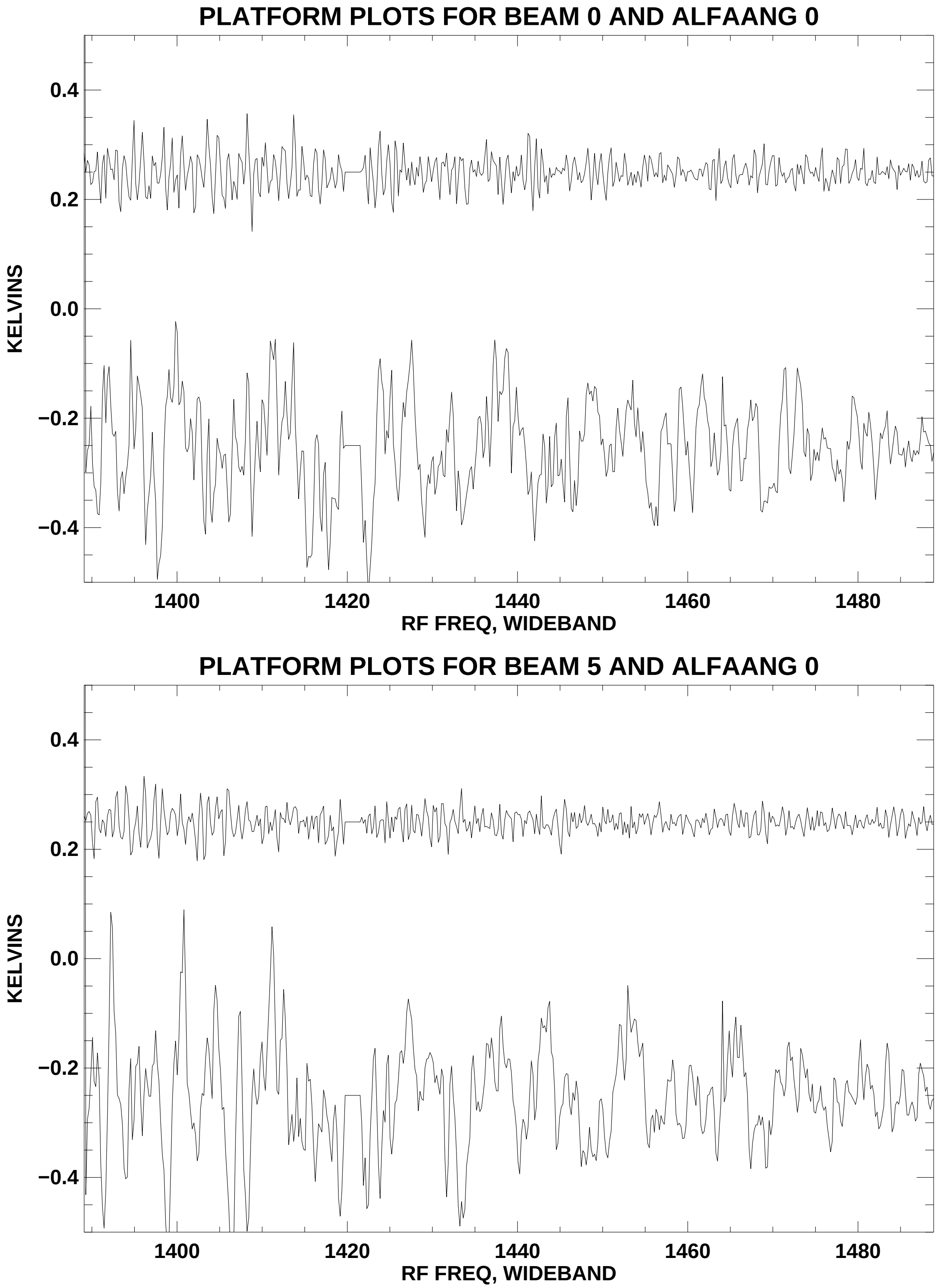


Fig. 7.— Difference spectra for ALFA turret angle 0°. The top panel is feed 0 and the bottom feed 5. In each panel, the top spectrum is the difference spectrum for the two platform heights and the bottom spectrum is one of the spectra.

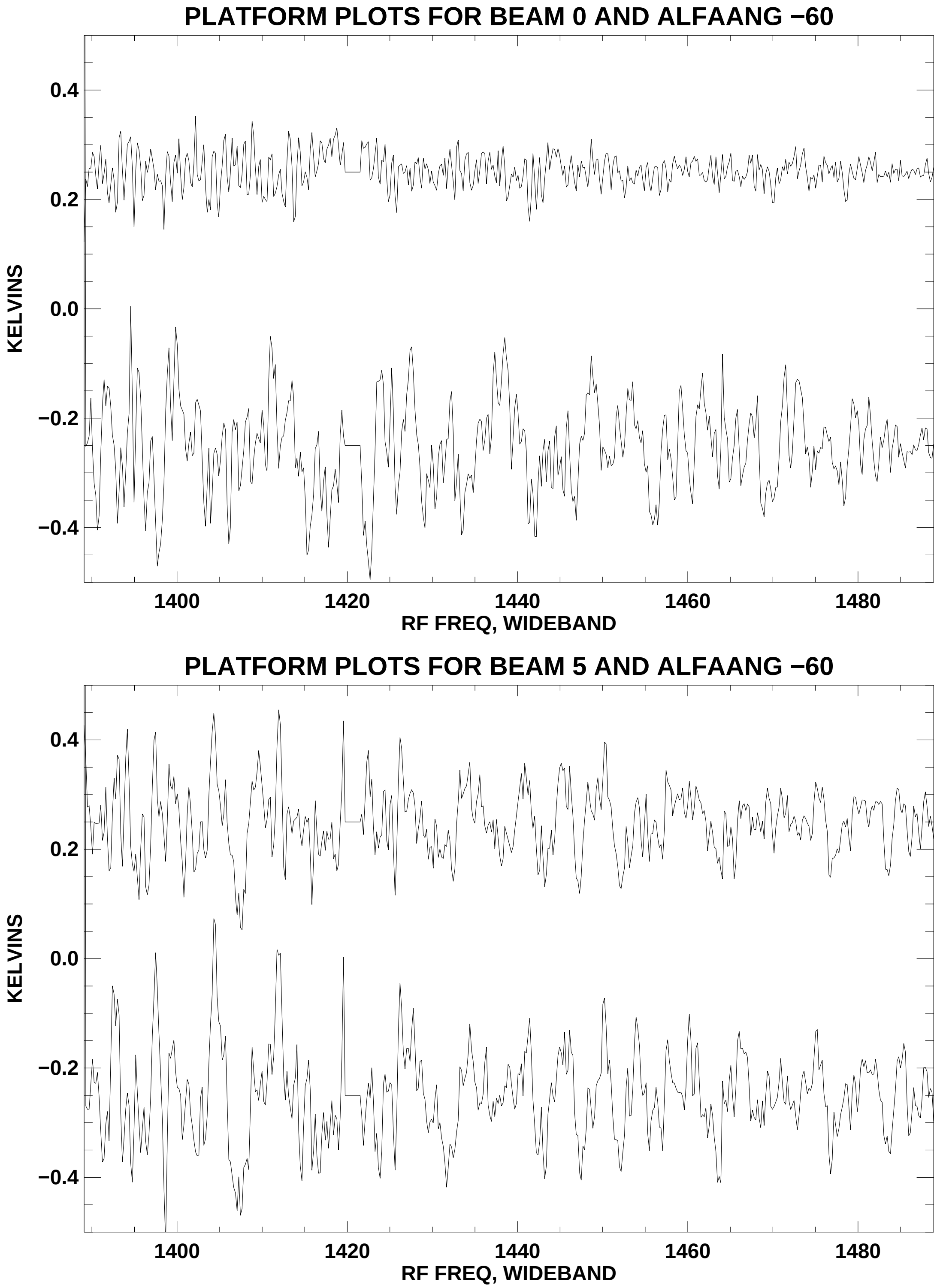


Fig. 8.— Difference spectra for ALFA turret angle $-60°$. The top panel is feed 0 and the bottom feed 5. In each panel, the top spectrum is the difference spectrum for the two platform heights and the bottom spectrum is one of the spectra.

8.1. Plots of spectra—Kelvins versus frequency

Figure 7 shows the dependence on platform height for ALFA turret angle 0. This is what we'd expect: nearly everything should cancel out in the upper difference plots, and what remains should be a rapid ripple with period ~ 1 MHz, which reflects the ~ 1 μsec delay time of the feed-to-bowl reflection. Both the on-axis and off-axis beams have roughly the same behavior.

Figure 8 is a completely different story. Feed 0 shows the same, expected, behavior as in Figure 7. But look at feed 5—it's completely different! The difference spectrum doesn't cancel out at all. Rather, it looks similar in shape to the actual spectrum! *All* of the off-axis feeds show this same effect!

8.2. Plots of autocorrelation functions—Kelvins versus time delay

Figures 9 and 10 are the autocorrelation function (acf) equivalents of figures 7 and 8. The acf is the Fourier transform of the power spectrum and vice-versa. A peak in the acf indicates a reflection with a corresponding round-trip time delay. The distance for 1 μsec is about 1000 ft, which is about twice the distance between the feed and the bottom of the bowl.

Figure 9 shows the acf's for feed 0 (top panel) and feed 5 (bottom panel) for ALFA turret angle 0. The behavior is somewhat curious. For beam 5, the difference acf has a single sharp spike at 0.91 μsec. For beam 0, the difference has a dominant peak at 0.91 μsec but it's rattier, with substantial peaks at 1.04 and 1.16 μsec, as well as a broader underlying shelf running from about 0.7 to 1.4 μsec. (We conservatively estimate the accuracy of all quoted times to be ± 0.005 μsec; the time resolution is 0.01 μsec).

Figure 10 shows the acf for feed 0 (top panel) and feed 5 (bottom panel) for ALFA turret angle $-60°$. The behavior is a lot weirder than in Figure 9 for angle $0°$. Here, for the difference acf for feed 5, instead of the nice single sharp peak in figure 9 we have a very broad response that covers roughly the same time delays as the acf's themselves. The two peaks near 0.9 μs are barely recognizable; they have delays 0.90 and 0.94 μs. The 0.90 μsec peak differs from the prominent turret angle 0 peak by 0.01 μs, equivalent to a total path of ~ 10 feet. This ratty behavior for feed 5 is, of course, exactly what we expect from looking at the frequency spectra in Figure 8. For beam 0, we have the same three dominant spikes as before at 0.91, 1.04, and 1.16 μsec, together with the broad underlying shelf, but there is also substantial power below ~ 0.4 μs.

It's hard to understand why there should be such a difference between turret angles $-60°$ and $0°$. It is worth trying this experiment again. These experiments were done during the daytime, and perhaps a Solar reflection interfered with the data for ALFA turret angle $-60°$. On the other hand, the large power for the platform difference spectra for feed 5 occurs for all the off-axis feeds

[1]The tiedowns moved 5 inches.

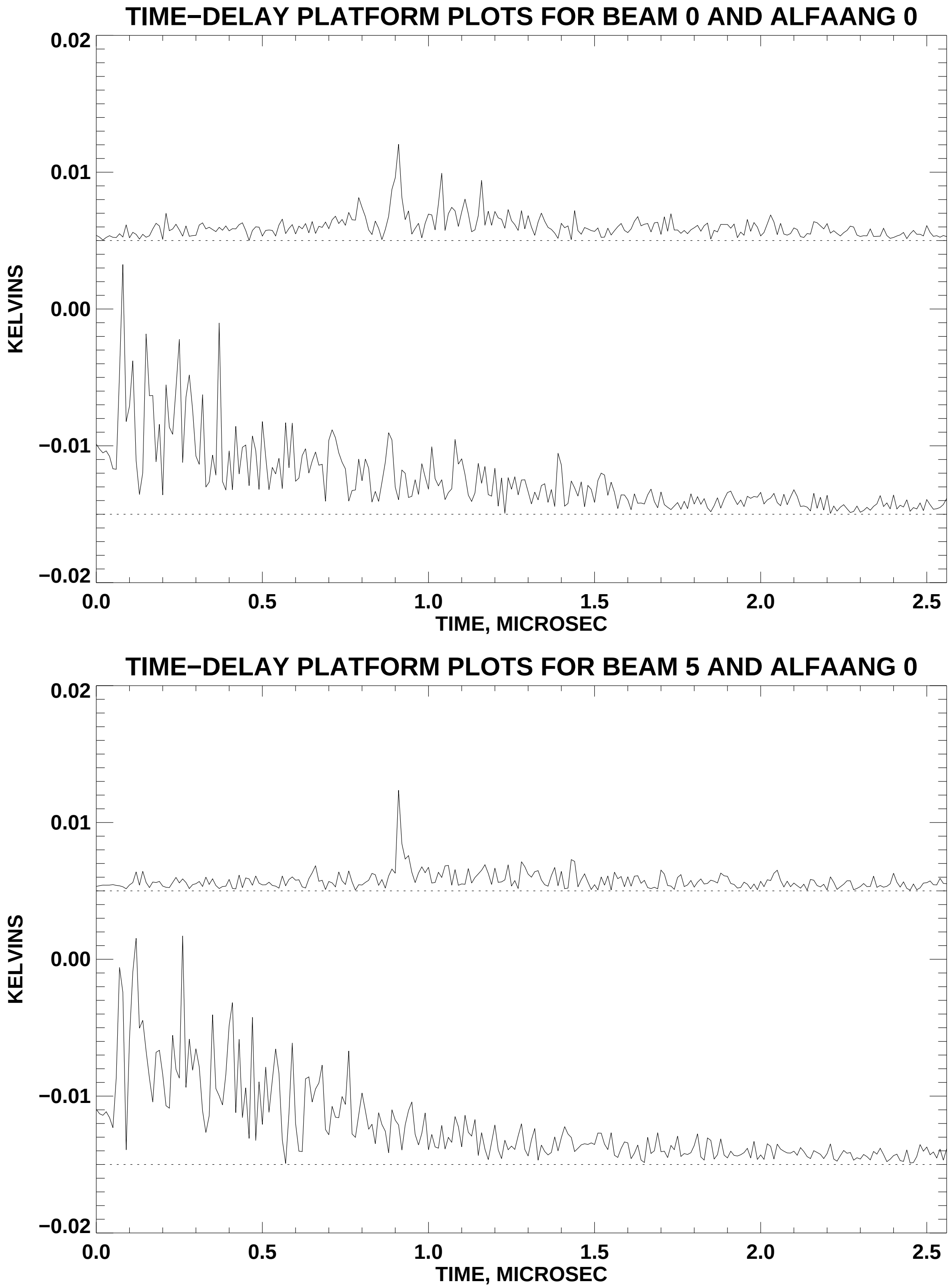


Fig. 9.— ACF's for ALFA turret angle 0°. The top panel is feed 0 and the bottom feed 5. In each panel, the top acf is the difference between acf's for the two platform heights and the bottom acf is one of those acf's. Time delay in μsec; KELVINS is the amplitude of the Fourier component.

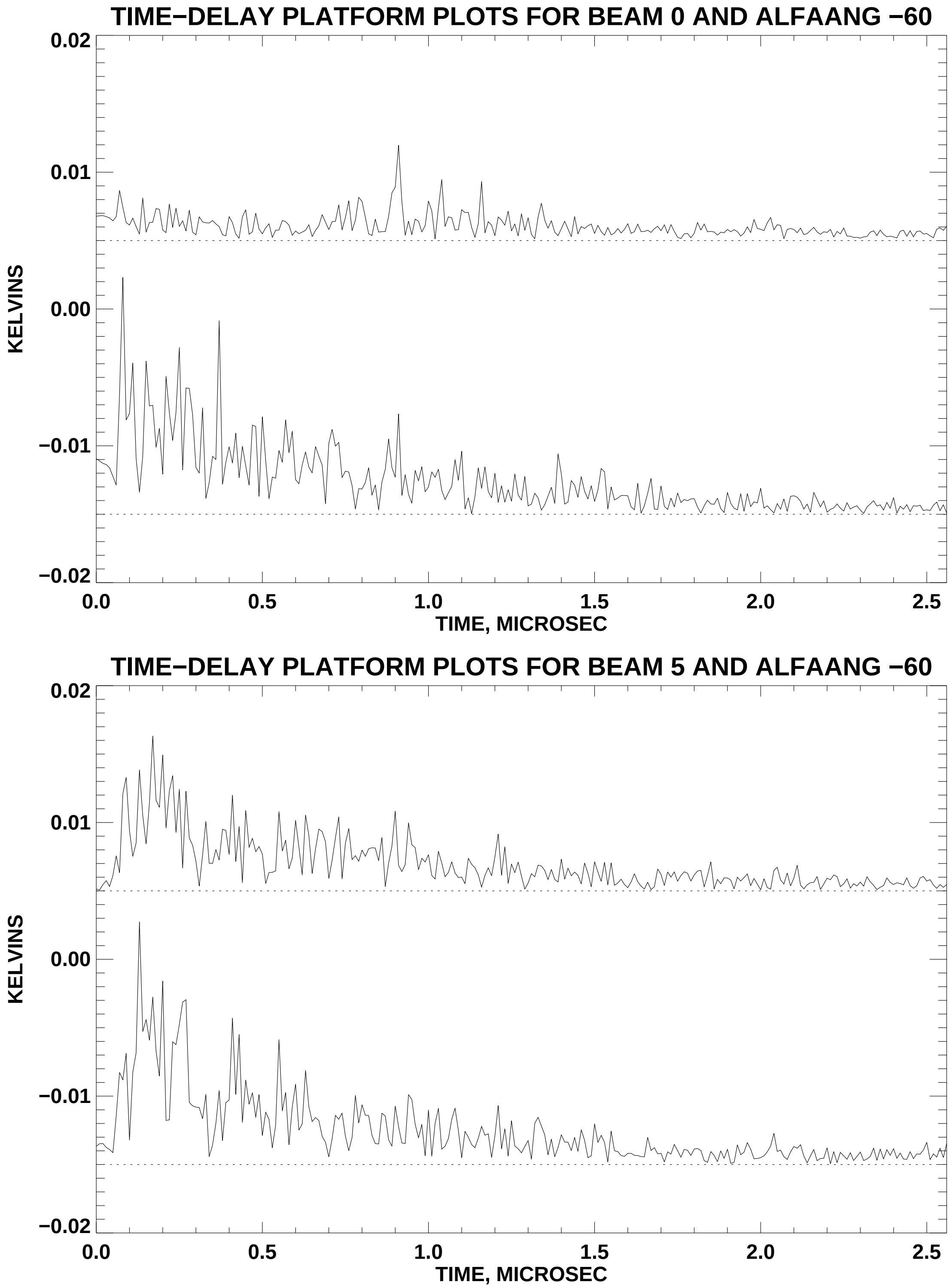


Fig. 10.— ACF's for ALFA turret angle -60°. The top panel is feed 0 and the bottom feed 5. In each panel, the top acf is the difference between acf's for the two platform heights and the bottom acf is one of those acf's. Time delay in μsec; KELVINS is the amplitude of the Fourier component.

as well, and why should their behavior differ from that of feed 0? Who knows.

9. ZA DEPENDENCE OF FPN

Here we examine the za dependence of the FPN. Figure 11 shows the FPM for 7 different intervals of za ranging from $3.0°$ to $19.7°$. The FPN changes slowly with change from one extreme to the other is comparable to the FPN itself. All feeds have about the same behavior.

Figures 12 and 13 show, for all feeds, the acf's of the difference between the spectra at $\langle za \rangle = [4.0°, 19.7°]$ and those at $\langle za \rangle = 12.5°$. Most of the energy resides below delays of a μs, and there are few prominent peaks. In Figure 12, the prominent peaks for feed 0 are at 0.91 and 1.04 μs; the prominent peak for feed 6 is at 0.90 μs. In Figure 13, the prominent peak in several spectra is at 1.04 μs; the prominent peak for feed 3 is at 0.79 μs.

10. AZ DEPENDENCE OF FPN

Here we examine the az dependence of the FPN. Figure 14 shows the FPM for 7 different intervals of az ranging from $269°$ to $189°$ in increments of $\sim -20°$. The columns of numbers on the right hand side of the plots indicate, first, the rms of the spectrum; and second, the mean az. All of these except the third from the bottom (which is the reference spectrum) are difference spectra, equal to the spectrum itself minus the reference spectrum. All of these data are at $za = 18°$ except the bottom one, which is at $za \sim 19.5°$; this za difference probably explains the larger difference spectrum.

If everything were perfect, the FPN would not change with az. In fact, as az changes the spectra do indeed change slowly; you need to go $\sim 40°$ before the differences become comparable to the FPN itself. We examined the rms's for all feeds and found that the uphill feeds 3 and 4 have a $\sim 30\%$ larger rms for the top spectrum than the other feeds. This probably occurs because these feeds see a bit more of the ground than the other feeds. If so, these small feed-to-feed differences with az should disappear at smaller za.

Figure 15 shows the acf's for the topmost spectra in Figure 14, for all 7 feeds. The prominent peaks occur at 0.79, 0.90, 0.98, and 1.04 μs; some peaks appear in some feeds and not others. Feed 0, the on-axis feed, has the most prominent peaks.

11. FREQUENCY DEPENDENCE OF FPN

Look at all of the preceding plots: the amplitude of the FPN increases towards lower frequencies. This suggests that the reflections are not purely specular, but at least partly diffractive, and

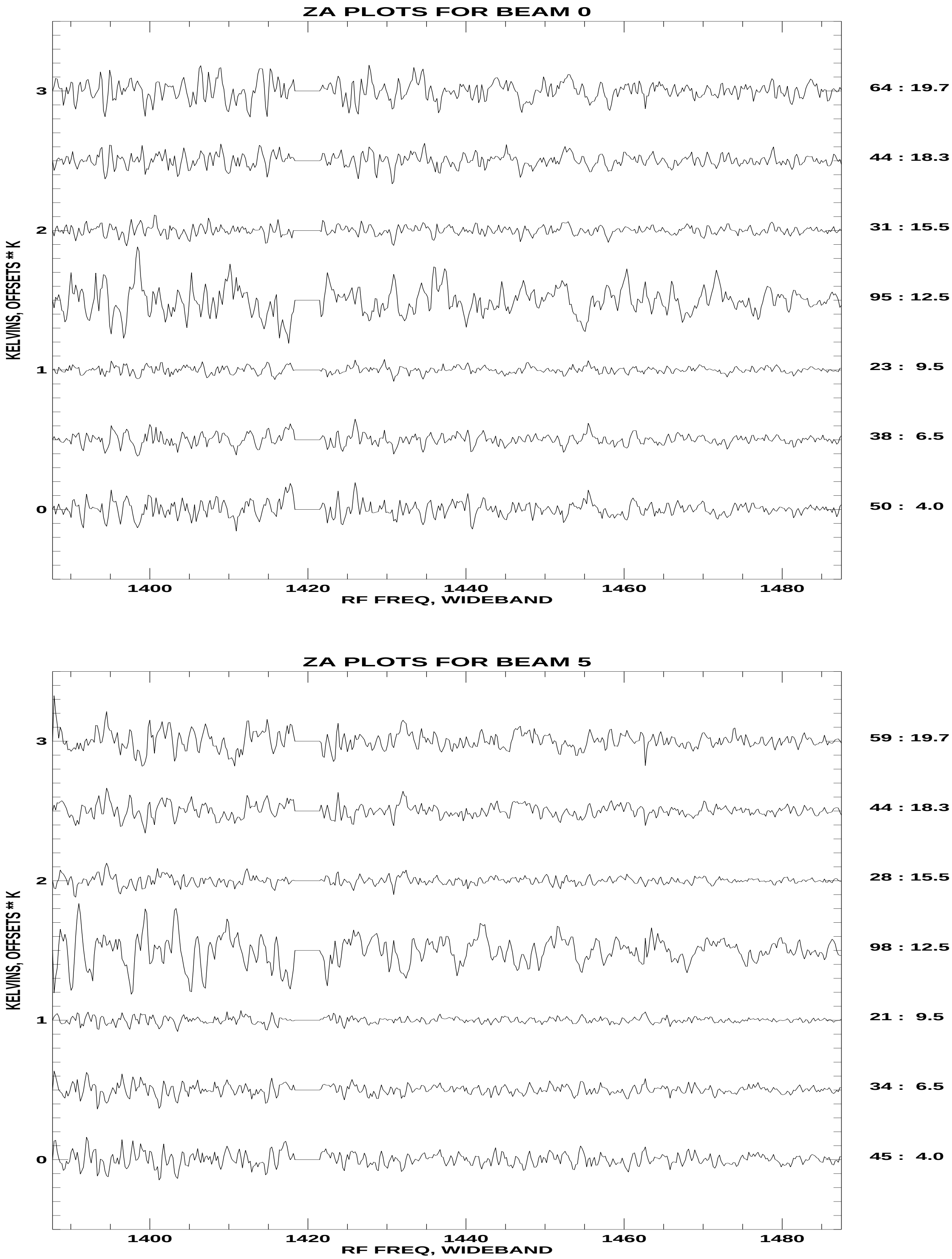


Fig. 11.— ZA dependence of FPN for feeds 0 (top) and 5 (bottom). All spectra except the middle one are difference spectra, equal to that spectrum minus the middle one. Labels on the right indicate: first the rms in milliK, and second the mean za for the spectrum.

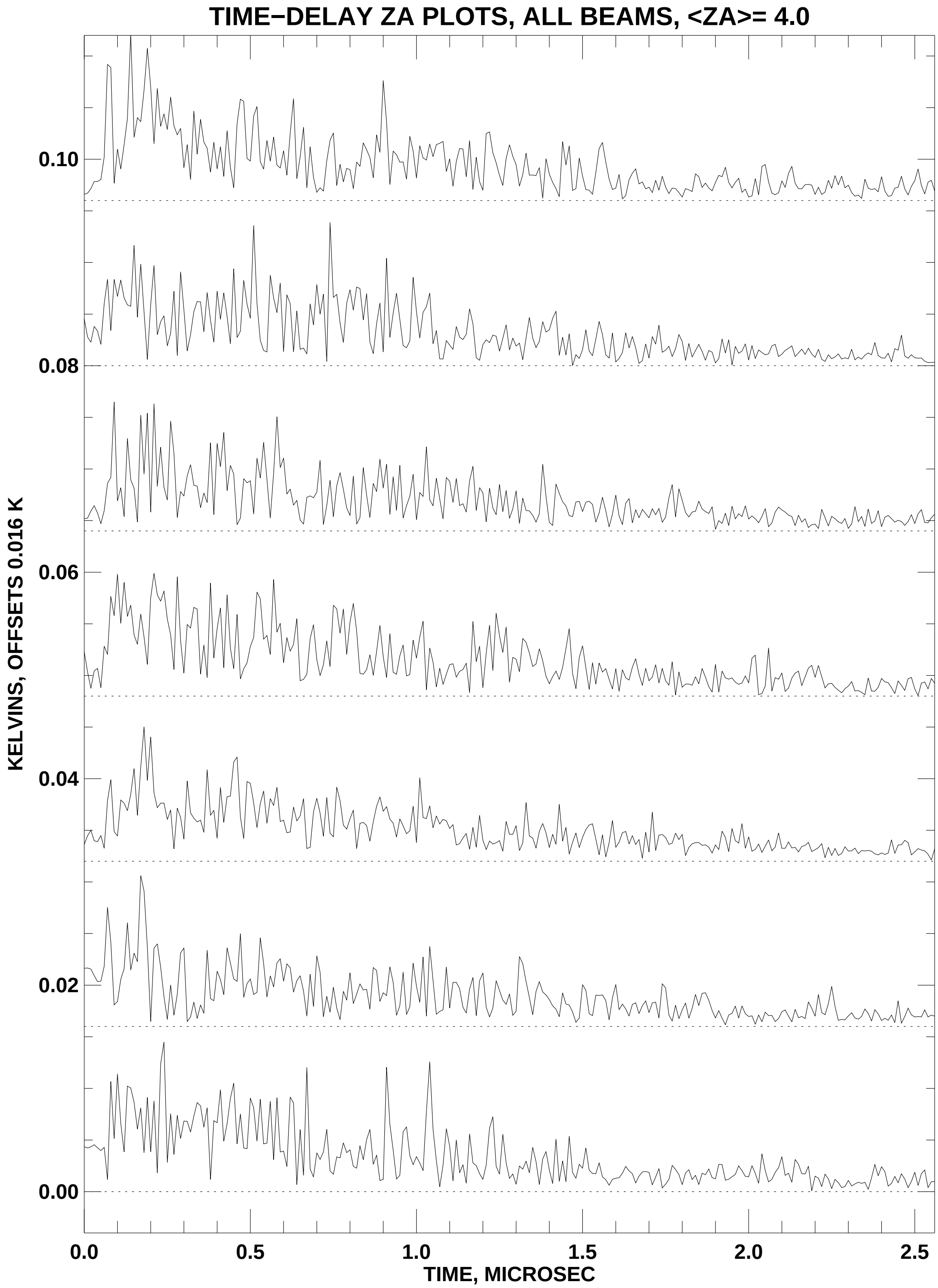


Fig. 12.— Difference acf's for all feeds at $\langle za \rangle = 4.0°$, where the FPN is large (Figure 11). Feed number increases upwards. The difference acf is the Fourier transform of the spectrum minus the spectrum at $za = 12.5°$. Feed number increases upwards.

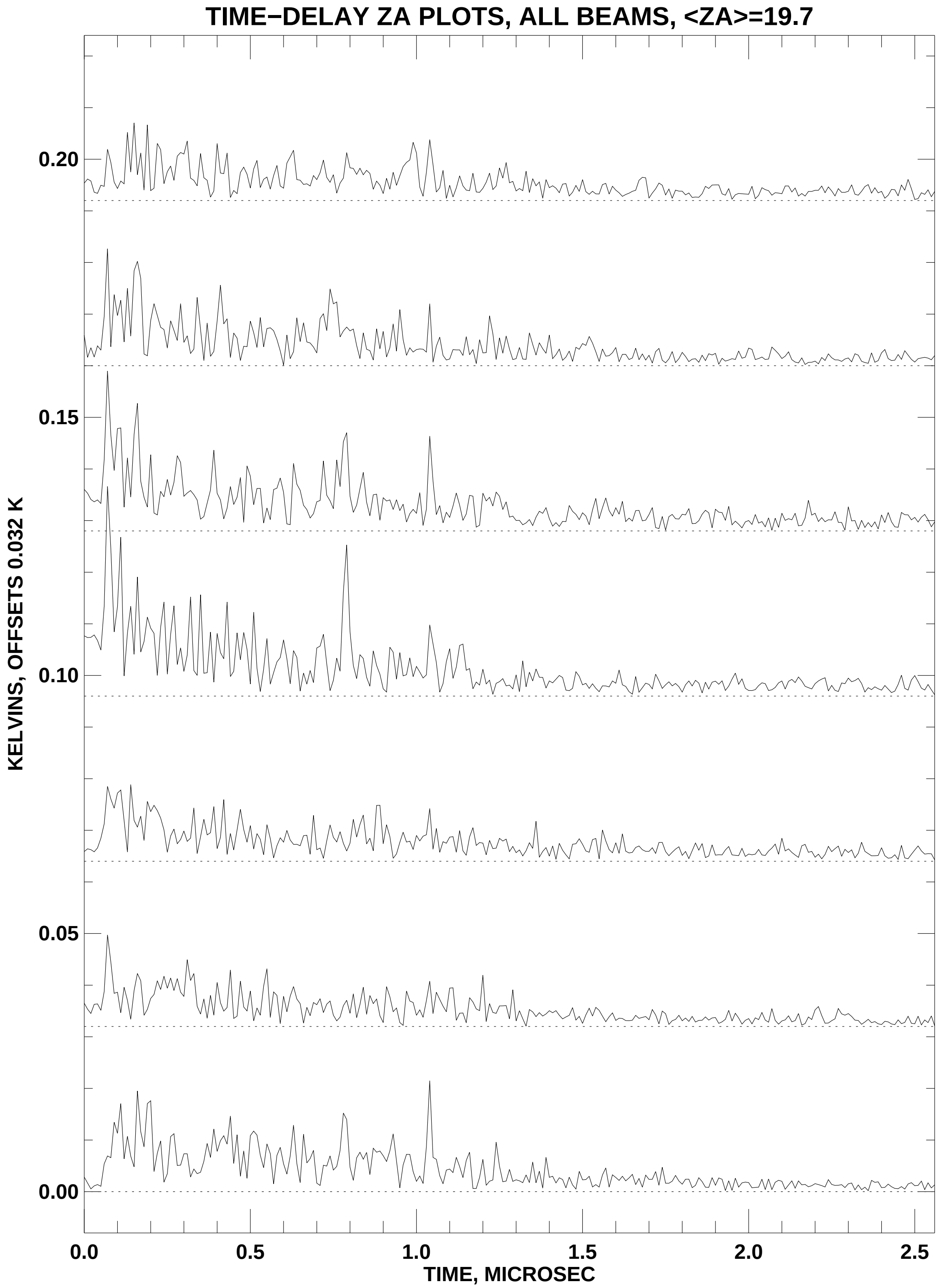
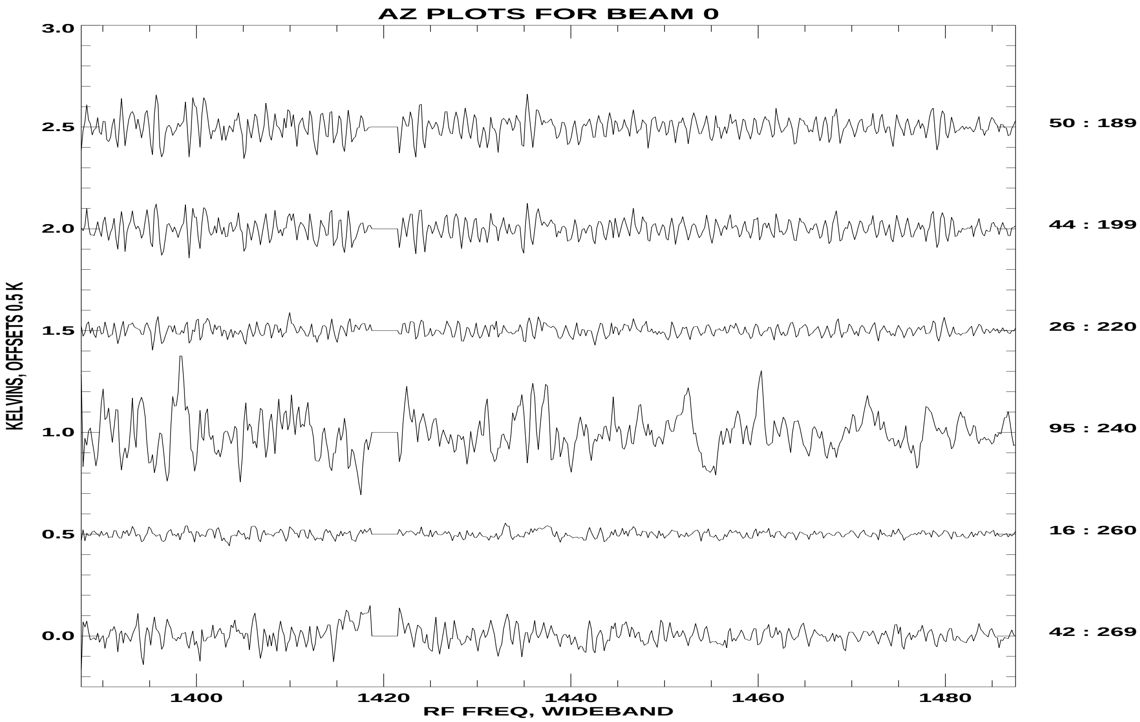


Fig. 13.— Difference acf's for all feeds at $\langle za \rangle = 19.7°$, where the FPN is large (Figure 11). Feed number increases upwards. The difference acf is the Fourier transform of the spectrum minus the spectrum at $za = 12.5°$. Feed number increases upwards.



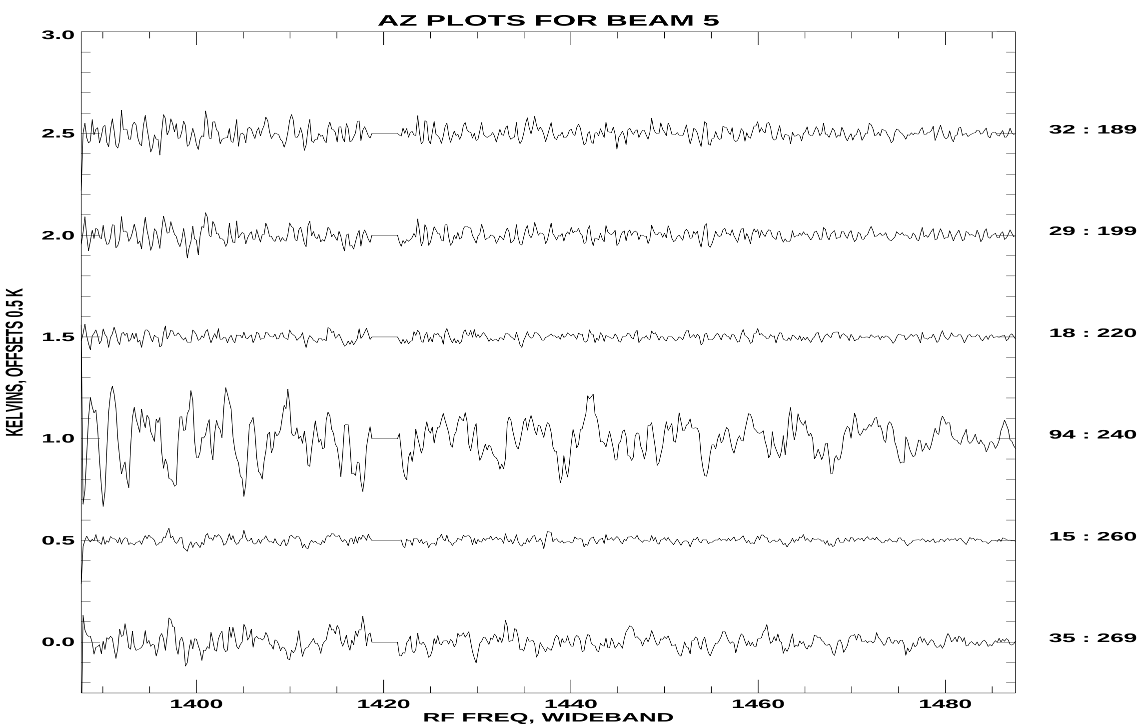


Fig. 14.— AZ dependence of FPN for feeds 0 (top) and 5 (bottom). Labels on the right indicate: first the rms in milliK, and second the mean az for the spectrum. All spectra except the third from the bottom (the reference spectrum); difference spectra, being the spectrum itself minus the reference spectrum.

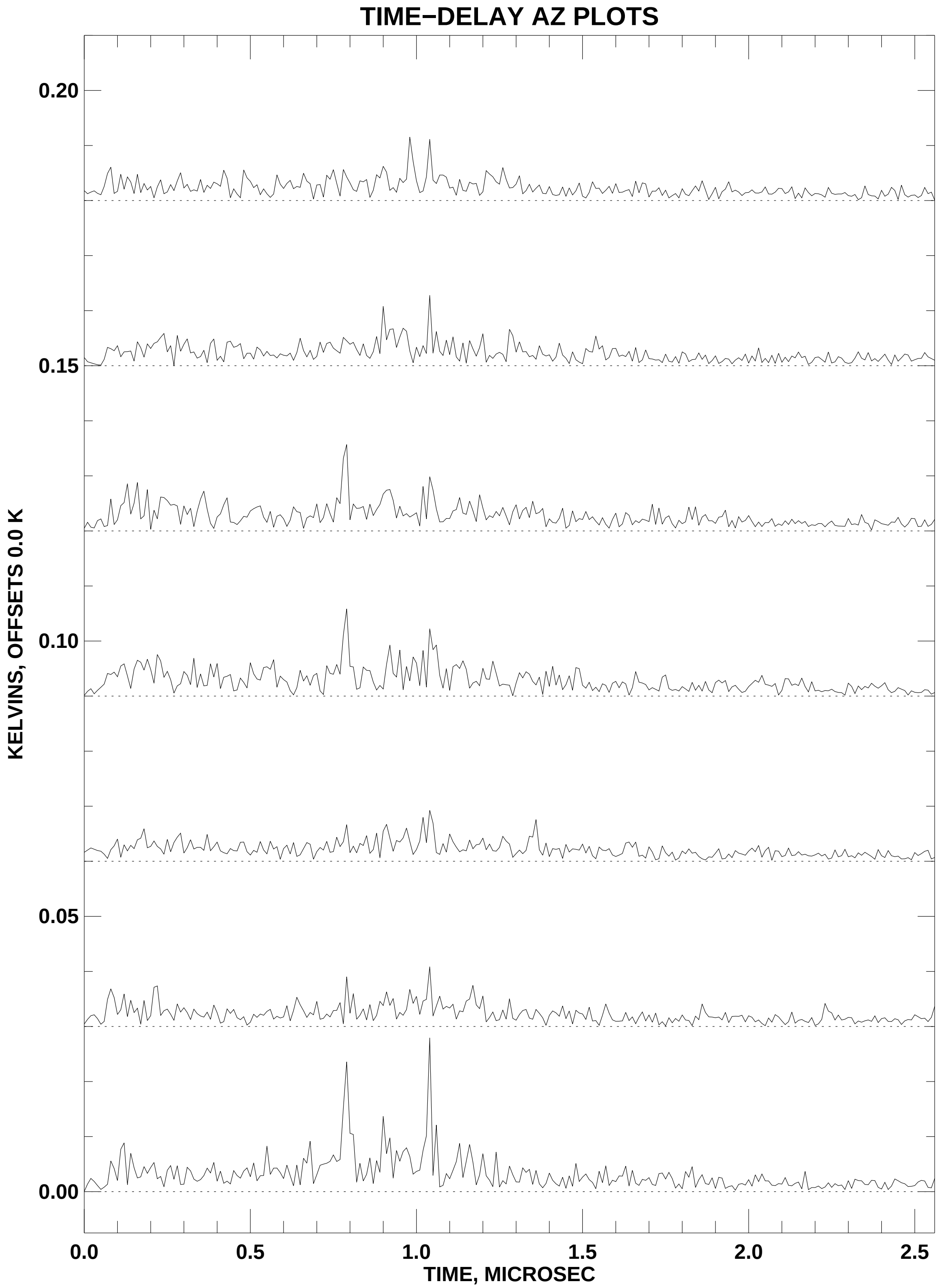


Fig. 15.— ACF of the az difference spectra for all feeds at $az = 189°$ (Fourier transforms of the topmost spectra in Figure 14). For all feeds, the prominent peaks occur at 0.79, 0.90, 0.98, and 1.04 μs.

that they are produced by structures whose sizes are comparable to the wavelengths involved—maybe the structural beams on the platform.

This frequency dependence has important ramifications for the representation of the FPN by Fourier modes. The Fourier representation is a natural one for reflections because of the acf/power spectrum relationship. However, the frequency variation of the FPN indicates that the strength of the reflections varies across our 100 MHz band, which implies that the Fourier coefficients decrease in amplitude with increasing frequency—contrary to the basic assumption in Fourier transforms that the coefficients apply all across the interval being analyzed. This suggests that a modification of the Fourier representation is required. Hmmmmmmmmmmm...

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