Multipath Mitigation Performance of Planar GPS Adaptive Antenna Arrays for Precision Landing Ground Stations

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BIOGRAPHY

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Robert J. Davis is a Communications Engineer at MITRE. He received his AS degree from Northeastern University and manages the Near-Field antenna range where the antennas described in this paper were tested. Since joining MITRE in 1981 he has tested antennas ranging in frequency from VLF to EHF and also conducted EMI, SATCOM and scale model investigations

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ABSTRACT

GPS precision landing systems require significant multipath mitigation performance from ground station antennas to achieve the desired accuracy. Recently, multipath-limiting antennas have been designed specifically to meet requirements of the Local Area Augmentation Systems (LAAS) Ground Facility (LGF) specification. The most promising designs incorporate a linear-vertical array of antennas weighted to form a fixed beam with a steep total-power gain slope at the horizon. The spatial filtering properties of the antenna array are exploited to reduce the amplitude of ground-based multipath, which arrives from angles that are below the antenna horizon. Military GPS antenna arrays, however, are currently configured as planar arrays to mitigate hostile interference through adaptive spatial filtering. These systems have yet to address the issue of multipath mitigation. In this paper, the multipath mitigation performance of a planar GPS adaptive antenna array is presented. Several techniques for improving the performance are implemented on the array and compared quantitatively using figures of merit proposed for ground-station environments. An implementation of fixed pattern shaping is demonstrated by mounting the antenna array on a prototype resistivity tapered groundplane. Multipath mitigation performance is compared to the performance of the same antenna array mounted on a highly conductive groundplane. Adaptive pattern shaping and fixed pattern filtering are simulated from the antenna array patterns measured on both types of groundplanes. The figures of merit are calculated and presented for each technique and for the combined techniques. Recommendations are given for areas of further improvements in multipath mitigation performance given the limitations of the techniques found in this study.

INTRODUCTION

The multipath environment present on the ground of a military landing site can vary from the benign open field, devoid of structures, to the densely populated steel structures found on a carrier deck. Each environment presents a different challenge for multipath mitigation techniques. One technique used to mitigate structural reflections may increase the vulnerability to diffuse diffraction. A technique for mitigating ground reflections may also reduce the signal to noise ratio. One way to compare the performance of different mitigation techniques without bias-

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ing the results towards a particular scenario is through the use of figures of merit. The most common figure of merit for antenna multipath mitigation performance is the up-to-down ratio introduced in [1]. When applied at the boresight of an antenna pattern this ratio is commonly specified as the front-to-back ratio and indicates not only the directivity or gain of the antenna, but also its ability to reject certain interference. In particular, the up-to-down ratio specifies the ability to reject ground reflection interference, which comes at an elevation angle equal to the negative of the source elevation angle, assuming a locally flat ground. Interference can also come from structural reflections at angles that are 180 degrees from, directly behind, the source. Diffraction can enter the antenna from any angle, however most near-in scatterers can be assumed to be sited below the antenna horizon. Each of these scenarios can be associated with a figure of merit and used to evaluate the performance of different multipath mitigation techniques. In this paper we propose using four types of multipath: ground and structural reflections, and diffuse and peak diffraction. Diffraction terms are calculated for all angles below a certain elevation angle. If all types of multipath are considered, then it may become evident which mitigation techniques work best in a particular multipath environment.

After developing the figures of merit, they will be used to quantify the multipath rejection performance of several fixed pattern antennas. The first antenna is a typical patch antenna on a metal groundplane used as a baseline to gauge improvement for other multipath rejection techniques. The first mitigation technique investigated is the resistivity-tapered laminate, a groundplane treatment that has been used to improve the pattern shape including the front-to-back ratio. The next technique is to double the size of the metal groundplane. This is an impractical brute force technique, however it can be effective. A third technique is a choke ring, an "artificially soft" groundplane implemented in a commercial surveying antenna. The last technique evaluated is a proprietary commercial antenna alternative to the choke ring. These fixed pattern shaping techniques are representative of what is currently available for application to planar arrays, however areas of new research in groundplane treatments are showing promise such as Photonic Band-Gap (PBG) materials [2], lossy magnetic coatings, and dual-frequency choke rings [3]. Non-planar fixed pattern antenna designs such as stacked turnstiles [4], multi-mode conical spirals [5], and linear dipole arrays [6], show the most promise however these designs will have to be modified for military applications to include adaptive hostile interference mitigation.

Adaptive pattern shaping and filtering for multipath mitigation is demonstrated using the antenna array patterns measured on a two foot metal and a two foot resistivity tapered groundplane. Adaptive beam steering was used as the primary pattern shaping technique. Adaptive array pattern filtering is demonstrated using two constraints: a fixed angle constraint and a ground reflection angle constraint. The effect of combining a groundplane technique with adaptive shaping and filtering was also investigated.

The results of the present study are summarized for each multipath mitigation figure of merit and conclusions are drawn about the viability of significant multipath mitigation using only planar antenna technologies.

MULTIPATH REJECTION FIGURES OF MERIT

Four figures of merit will be used to quantify the multipath rejection performance of a given antenna corresponding to four different types of multipath present at a military ground-station environment. The first two are specular reflections that follow Snell's law of reflection and therefore the angle of reflection is equal to the source angle of incidence relative to the tangent to the surface. For the ground reflection this angle is the negative of the source elevation angle. For a vertical structure the angle of reflection is equal to the source elevation angle at 180 degrees in azimuth, opposite the source. Figure 1 shows the relationship between the antenna and the proposed ground (R_g) and structural (R_s) reflections. The structural reflection, for low elevation satellites, is at near normal incidence angle causing the structural bounce to become cross-polarized to the source or Left Hand Circular Po-

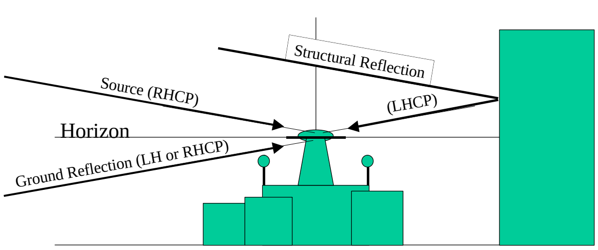


Figure 1. Sources of Multipath Reflections for GPS Ground Reference Antenna.

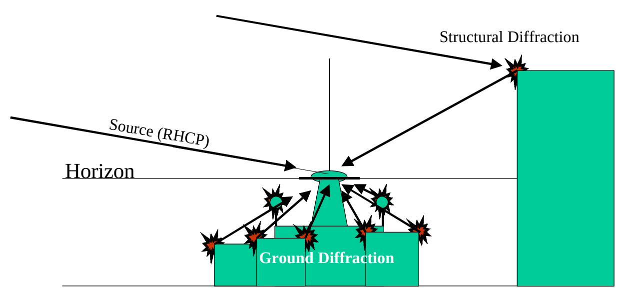


Figure 2. Sources of Multipath Diffractions for GPS Ground Reference Antenna.

larization (LHCP) while the ground bounce can be unaffected in polarization and remain Right Hand Circularly Polarized (RHCP). Many multipath mitigation techniques assume the multipath is LHCP and therefore can be discriminated by using the inherent antenna polarization mismatch loss. However, the ground bounce "grazing" angle can be below the Brewster's angle and therefore the polarization of the reflected signal depends on the geology of the surface: sand, snow, or water [7]. For this reason we are using a total power ground bounce figure of merit, and leaving the structural reflection LHCP. The amplitude of a reflection can be as high as 100% of the source amplitude leading most people to believe that this term is the chief cause of destructive interference that is observed in receivers as slow fading.

The last two figures of merit capture multipath diffraction. For this study we calculate the mitigation of diffraction from all structures that are below a "cut-off" elevation angle of 0°. We can assume that the ground-station antenna is sited above any obvious scatters, forcing the diffraction to come from below the antenna horizon as shown in Figure 2. The cumulative effect of diffuse scatterers, many scatterers covering all angles below the horizon, is noise like and is often modeled as such [8]. The figure of merit that will capture reductions in this type of multipath is the average total power received below the cut-off elevation angle (D_{ave}). Diffracted signals are arbitrarily polarized by the scatterer so the figure of merit should be total power rather than polarized power. A single near-in scatterer can couple very strongly into the side lobes or main lobe of an antenna, therefore it is also beneficial to measure the peak total power side lobe (D_{peak}). For most of the antennas in this study the strongest multipath component is the peak total power back lobe. Upon investigation it was found that this term was not a back lobe; rather it was the roll off of the main beam at the horizon. This term is therefore critical for low elevation satellites because it is the most difficult to mitigate.

All of the above figures of merit are measured relative to S, the RHCP gain of the antenna at the satellite look angle. The figures of merit are independent of the absolute antenna gain, which can be misleading as will be shown in one of the simulated cases. The multipath figures of merit are defined below for a satellite at elevation angle θ preceded by the color and symbol used to differentiate them in the plots.

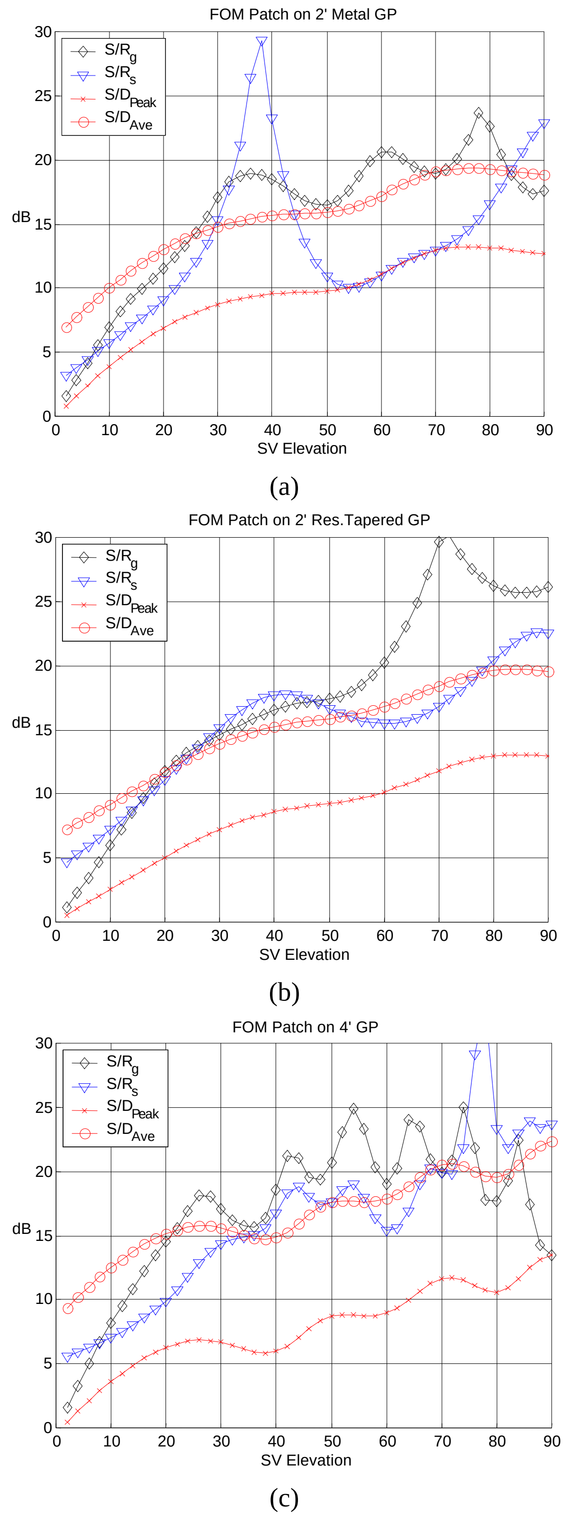
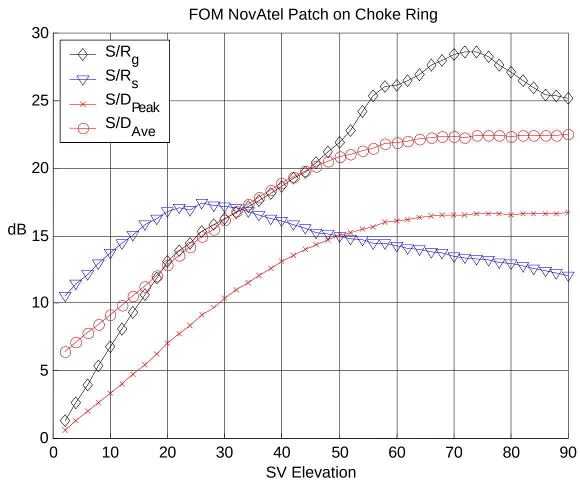


Figure 3. Multipath FOM for a) patch antenna on 2' SQ. metal groundplane, b) patch antenna on 2' SQ. resistivity tapered groundplane and c) patch antenna on 4' circular metal groundplane.



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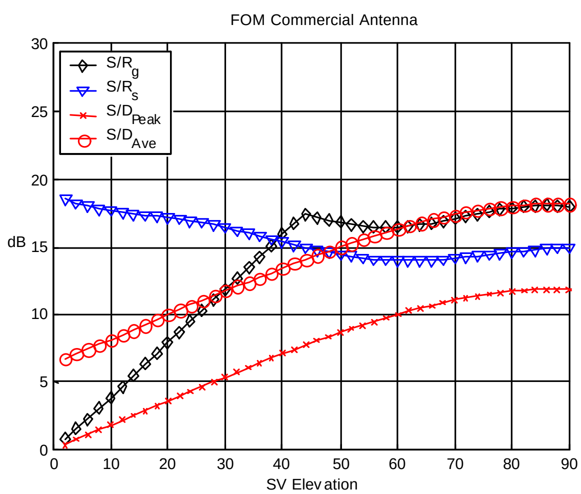
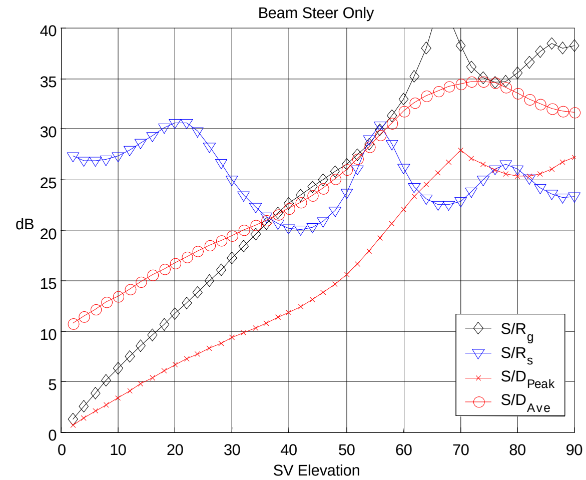


(b)

Figure 4. Multipath FOM for a) patch antenna on choke ring groundplane and b) proprietary commercial antenna alternative.



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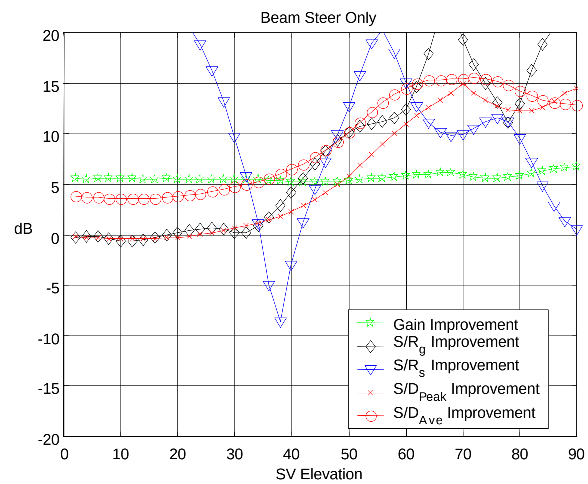


(b)

Figure 5. a) Multipath FOM for adaptive array pattern shaping on a 2' SQ Metal GP b) relative FOM improvement over non-adaptive pattern.

◊ S/R_g = Source power / Total power at angle (- θ)

∇ S/R_s = S / LHCP power at angle (180 - θ)

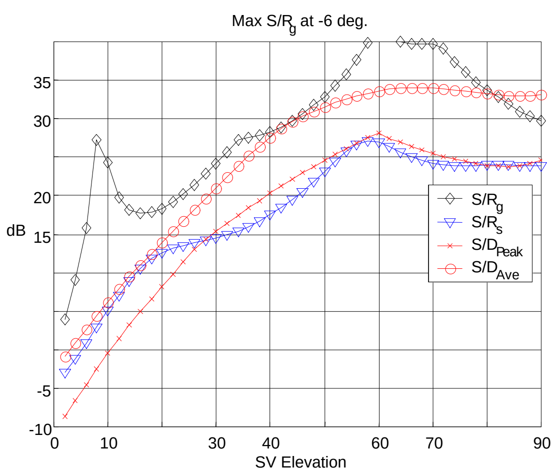
o S/D_{Peak} = S / Peak total power below horizon

× S/D_{Ave} = S / Average total power below horizon

FIXED ANTENNA PATTERN SHAPING

The far-field polarimetric complex antenna patterns were measured in two degree increments using the MITRE L-band anechoic chamber for the following 5 antennas: 1) patch-array antenna elements on a two-foot square metal groundplane, 2) patch-array antenna elements on a two-foot resistivity-tapered groundplane, 3) patch-array antenna element on a 4' metal circular groundplane, 4) single patch antenna on a choke ring groundplane, and 5) the latest commercially available precision antenna. The four figures of merit defined previously were used to quantify the multipath mitigation performance of each antenna and are shown in Figures 3 and 4. Shown in Figure 3a is the baseline performance of the array element with no multipath mitigation other than the inherent performance of the patch antenna. In all figures the four FOM are plotted on a 10*log10 scale for the y-axis verses the satellite elevation angle in degrees on the x-axis. Figure 3b shows the result of using a resistivity-tapered groundplane for multipath mitigation. This technique has been used with single element antennas to remove the finite groundplane effects of scalloped patterns, degraded axial ratio and reduced front-to-back ratio [9]. When used on the adaptive array it improves structural reflection rejection by nearly 5 dB for most of the pattern, and ground reflections above 65 degrees elevation also by 5 dB. However the ground reflections below 65° elevation and both of the diffraction FOM are not improved. This technique may be useful for sites that have strong structural reflections, and are mounted relatively high above any reflecting surfaces. The situation described would occur on a terminal building or antenna farm where other towers and structures are above the GPS antenna. Unfortunately environments with large structural reflections also have structural diffractions and this antenna does not mitigate the diffraction. The four-foot groundplane is shown in Figure 3c for comparison purposes. Note the improvement in rejection of average back energy (S/D_{ave}) by 3-4 dB while the peak back lobe

Figure 4 shows the FOM from two commercial antennas that have been design for traditional multipath mitigation. Figure 4a shows the FOM for a patch antenna mounted on a choke ring groundplane. The choke ring presents an 'artificially soft' surface to a wave propagating along the groundplane. The effect is reduced total power at and below the horizon. The technique achieves an 8 dB improvement in structural reflection mitigation at the horizon but the other FOM have not changed. Figure 4b shows that the proprietary commercial antenna improves the structural reflection mitigation by 15 dB at the horizon however all other FOM are worse. The fixed antenna pattern shaping techniques studied here can provide up to 5 dB improvement for one or two FOM but the overall multipath mitigation performance is not significantly improved. In particular, for precision landing systems, the multipath rejection for low elevation satellites below 12°



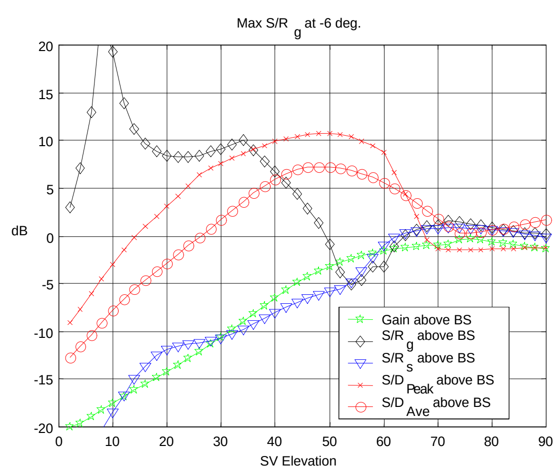


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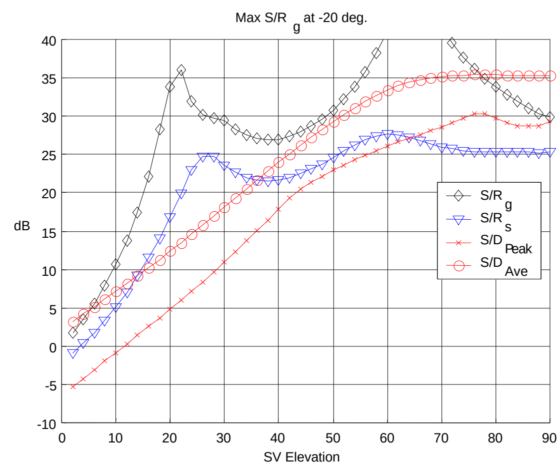
Figure 6. a) Multipath FOM for adaptive array pattern filtering with fixed angle constraint at -6° on resistivity tapered groundplane and b) relative FOM improvement over non-adapted



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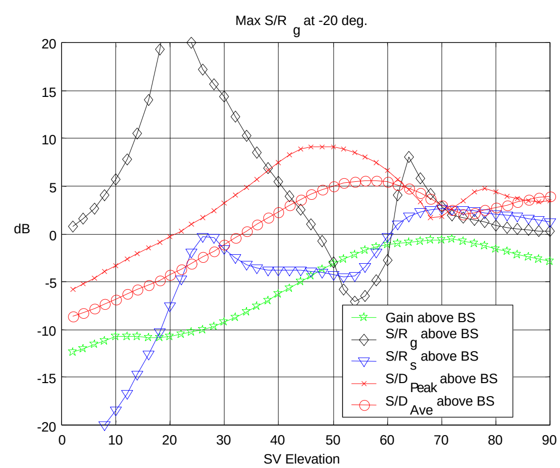


(b)

Figure 7. a) Multipath FOM for adaptive array pattern filtering with fixed angle constraint at -20° on resistivity tapered groundplane and b) relative FOM improvement over non-filtered adapted performance.

The far-field polarimetric complex antenna patterns were measured in two degree increments using the MITRE L-band anechoic chamber for a seven element GPS antenna array mounted on a two foot square metal groundplane. The seven complex antenna signals were optimally combined in a computer program to form an adaptive "beam" on the satellite angle of arrival. The four figures of merit defined previously were calculated for each adapted antenna pattern over the entire set of elevation look angles, as shown in Figure 5a. The relative FOM improvement over the non-adapted pattern is shown in Figure 5b. The relative pattern gain to the satellite is shown to improve by 6dB for all elevation angles due to the coherent gain provided by the beamforming algorithm. Gain is shown in these plots to indicate that receiver noise is not the dominant source of error. The average back lobe energy and the structural reflection is also reduced for all elevations, ignoring the few angles where the baseline antenna exceeds 20 dB. For precision landing systems the two FOM which are the most significant for low elevation satellites, S/R_g and S/D_{peak}, did not improve below 32° elevation.

ADAPTIVE ARRAY PATTERN FILTERING: FIXED ANGLE CONSTRAINT

The measured array patterns described previously were used to optimally form a beam on the satellite and simultaneously cancel the total power at a fixed angle below the horizon. A new pattern was created for each satellite elevation angle and the four figures of merit were used to quantify the multipath mitigation performance for two fixed cancellation angles, negative 6° and negative 20°, as shown in Figures 6 and 7 respectively. Examining Figure 6a, the ground reflection mitigation has been improved by an order of magnitude for elevation angles between 6° and 16°, and by 8 dB up to 37°. Unfortunately at 6° the peak diffraction is 5 dB above the signal and the average diffraction is 11 dB above the signal. The relative signal gain shown in Figure 6b explains the problem. At 6° the signal has been reduced to –19 dB relative to the non-adapted signal strength. Loss of signal gain at the horizon is caused by the cancellation of the beam in the adaptive algorithm. A horizontal planar array has limited vertical aperture when viewed from the horizon and therefore the adaptive array has limited 'resolution' in the elevation plane near the horizon. The adaptive algorithm cannot achieve both constraints optimally, and therefore it achieves a null at the expense of the beam. The problem of main-beam cancellation can be overcome by separating the two constraints in elevation. This leads to the next scenario where the fixed constraint is moved to –20 degrees in an attempt to achieve a more optimal beam gain. As seen in Figure 7b the gain is still reduced by 10 dB near the horizon, and all of the FOM are worse than the

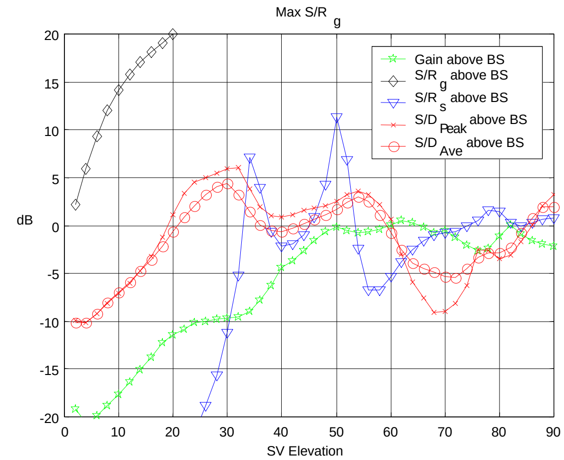


Figure 8. Multipath FOM for adaptive array pattern filtering with ground reflection constraint measured on 2' metal groundplane: Maximize S/Rg performance relative to non-filtered adaptive performance.

beam-steered performance, except for ground bounce rejection, which is only improved by 5 dB at 10°. The fixed angle constraint results indicate that results for any angle constraint near the horizon will be poor but a final constraint was investigated for completeness.

ADAPTIVE ARRAY PATTERN FILTERING: GROUND REFLECTION ANGLE CONSTRAINT

The same measured array patterns were used to optimally form an adaptive beam on the satellite and simultaneously cancel the total power at the ground reflection angle, below the horizon. A new pattern was created for each satellite elevation angle and the four figures of merit were used to quantify the multipath mitigation performance as shown in Figure 8. This constraint is interesting because it optimizes the S/R_g FOM for each elevation angle. An improvement of 14 dB at 10 degrees can be seen in Figure 8, however all other FOM have been made worse. As stated earlier, the reason for failure is the loss in signal gain attributed to the opposing constraints placed too close for the horizontal planar array to resolve. Since all of the FOM are relative to the signal gain, if the gain is cancelled by trying to cancel multipath, then all the other FOM will degrade. Since the peak diffraction angle is even closer to the beam than the ground reflection, a null constraint on the peak diffraction will also yield poor results. A null constraint on the structural reflection, or multiple null constraints on the diffuse diffraction, would not have the problem of gain loss, however the beam-steering results already indicate very good mitigation performance against these types of multipath without using up degrees of freedom.

COMBINATION ADAPTIVE ARRAY AND GROUNDPLANE TECHNIQUES

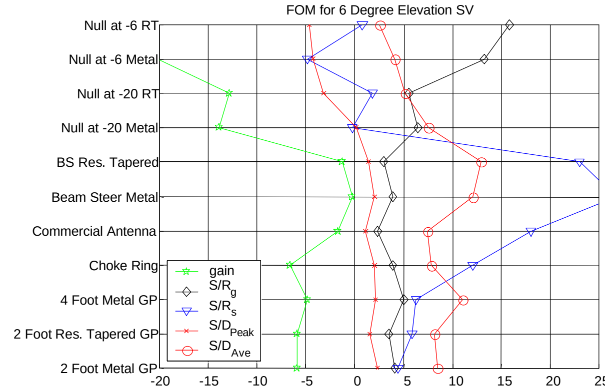
The three adaptive array techniques were repeated using the measured array element patterns mounted on a two-foot square resistivity-tapered groundplane. Results of the multipath figures of merit for low elevation angles are shown in the summary in Figure 9. It is of interest to point out that antenna element mitigation techniques applied in addition to adaptive array techniques do not always yield the expected improvement as seen in Figures 9a and 9b for the beam-steering array. For low elevation angles, the resistivity-tapered groundplane results are slightly worse than those found with a metal groundplane.

SUMMARY

A set of four multipath figures of merit have been developed to quantify the multipath mitigation performance of a precision landing ground station. The FOM were used to investigate the performance of multipath mitigation techniques used on a planar adaptive antenna array. Multipath reduction performance for the various techniques is summarized at two low angle satellite elevations, 12° and 6° as shown in Figures 9a and 9b respectively. None of the techniques improve the peak diffraction rejection above the baseline, and none improved the ground reflection rejection by more than 3dB, excluding the adaptive filtering results which were all poor due to loss of signal gain.

CONCLUSION

The multipath mitigation performance of a planar adaptive array has been characterized using a new set of merit figures, namely the ground and structural reflection ratios, and the peak and average diffraction ratios. Using these figures of merit it was concluded that fixed pattern shaping techniques provide only incremental improvement. Adaptive array filtering techniques provide significant improvements in the figures of merit at the expense of signal gain. Adaptive array shaping techniques do not improve ground reflection multipath or peak diffraction multipath however structural reflection multipath and average diffraction multipath were reduced by 25 and 15 dB at 12 degrees elevation. When compared to precision landing ground-station antenna requirements, mitigation techniques were not found to be adequate. Non-planar fixed pattern shaping antennas developed to meet LAAS ground facility requirements provide 32 dB of ground reflection mitigation and 23 dB of peak diffraction mitigation for an SV at 10 degrees elevation, using the assumed cut-off angle for peak diffraction of 0° elevation [10]. To meet this degree of multipath mitigation, further improvements should be sought using non-planar antenna techniques, which provide the promise of elevation pattern shaping without decreasing the signal gain.



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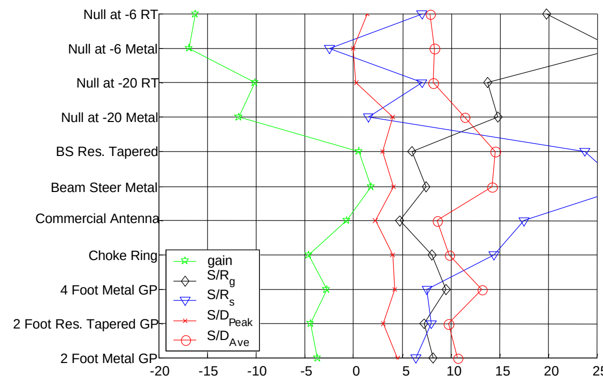

(b)

Figure 9. Multipath FOM summary for all planar adaptive array techniques a) at SV elevation angle 6° and b) at SV elevation angle 12°.

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