Aligning an Array of Receiving Radio Antennas in the Presence of an Interfering Source: Taking Advantage of Differences in Spectral Shape

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An interfering radio source present in the primary beam of an array of receiving radio antennas intended to track a spacecraft telemetry signal can cause the array to point off the spacecraft in the direction of the interferer when the incoming signal is used to align the array. By using the narrow spectral shape of the spacecraft signal relative to the (usually) broad shape of the interfering signal, it is possible to separate the two signals and track the spacecraft in the face of this interference. Analysis and simulations are presented to demonstrate how this can be accomplished in a variety of cases.

I. Introduction

In a previous article [1], the SIMPLE and SUMPLE algorithms for aligning an array of radio receiving antennas, especially in the face of a weak telemetry signal, were analyzed and discussed. Alignment was achieved by a process that used the cross-correlation of the various antenna signals with each other to derive their phase offsets. These offsets were then fed back to the individual antennas to achieve alignment. Both of these algorithms were considered advantageous because they did not require correlation of all antenna pairs, with a consequent reduction in hardware and data-processing demands.

In this article, we investigate a modification to the same two algorithms to achieve proper alignment in the presence of an interfering radio source near (in angle) to the source of the desired telemetry signal. The approach assumes the telemetry signal is band-limited while the interfering source is broadband. It is further assumed that the receiver at each antenna is multi-channel, providing a cross-correlation spectrum of the incoming signal with sufficient bandwidth and resolution to cover the telemetry signal using several of its inner channels while at the same time covering the broadband interferer, devoid of significant narrowband telemetry, using its remaining outer channels. The correlation characteristics

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of the interferer can then be derived using the outer channels and subtracted from the inner channels, yielding telemetry correlations without the interferer. The actual approach performs a least-squares fit of a phase verses frequency model for both the telemetry and interferer using all the channels. The fitting process permits the derivation of residual delays for the telemetry and the interferer when there is sufficient signal-to-noise strength. It should be noted that the process outlined here guarantees only that the array is aligned to form a "pencil beam" that points at the telemetry source, undisturbed by the interferer. It does not eliminate or reduce the effects of the interferer on the overall system noise.

In this investigation, we also include two further refinements to our approach. The first is when a slight misalignment of the array pencil beam can, under the right circumstances, improve the combined telemetry signal-to-noise ratio (SNR). The second is when a slight reshaping of the array pencil beam can also, under the right circumstances, improve the combined telemetry SNR. These improvements occur when the change in the pencil beam causes greater attenuation of the interferer than of the telemetry.

II. Description

The algorithms discussed in [1] treated the case when the telemetry was narrowband and the cross-correlation between antennas to derive their phase offsets was performed in the time domain. In the new arraying systems being designed and constructed in NASA's Deep Space Network (DSN), the correlation portion of the digital receivers in each antenna performs a Fourier transform (FT) of the signal in real time so that the cross-correlations between antennas are accomplished in the frequency domain. Consequently, the array provides cross-correlation spectra for each antenna pair that have been averaged and output, typically once per second. The alignment algorithms can then simply use the channel containing the strongest peak of the telemetry for deriving the alignment weights. However, better SNR can be achieved by using a weighted average of all of the channels containing telemetry signals.

The approach taken here is to least-squares fit the correlation spectrum of each antenna, for each correlation averaging interval, with a telemetry model (usually a sinc-squared function will do, where its width and position, corresponding to the telemetry rate and carrier, are known) having adjustable amplitude and phase. In the case when the measurement of any residual delay is desired, a phase slope across the frequency band is added to the parameter list (this addition, however, requires going to a non-linear fitting algorithm). Finally, when an interferer is present, it can be modeled with a flat spectrum, and the parameter list grows by another amplitude, phase, and phase slope, for a total of six model parameters. To begin with, it will be assumed that the interferer is a point source. A more complicated source will be discussed later.

Normally, it is expected that the telemetry predicts are sufficiently accurate to guarantee that the phase slope for the telemetry signal is quite small, and often can be ignored. However, a potential interferer may occupy a position coincident with the telemetry source or hold a position many pencil beamwidths away. Its corresponding phase offset will go from zero to many cycles, and its phase slope will go from zero to a value corresponding to a phase differential of several cycles across the spectral band. In the latter case, the amplitude derived for the interferer will be reduced, both from its being outside the pencil beam (if SUMPLE is being used) and from its being "filtered" by the fit, because the non-linear fit cannot follow a slope beyond about a cycle or two across the band when its starting point is zero slope. Fortunately, for this case, the fit parameters for the telemetry are still adequate to align the array.

In summary, a parameter fit is performed for each correlation averaging time interval, for each antenna correlation (against a reference antenna in SIMPLE or against the combined set of the other antennas for SUMPLE). The telemetry model fit of amplitude, phase, and phase slope is used to derive the antenna weight and delay residuals, which, in turn, are used to align the array.

III. Analysis

At each antenna, the total signal, downconverted to an intermediate frequency band, can be represented by the sum of three components, the signal, the interferer, and the receiver noise:

$$\hat{S}_a[t] = \hat{s}_0[t - \tau_{sa}] \tag{1}$$

where $\hat{s}_0[t]$ is a time sequence of pseudo-random symbols coming from the ath antenna and τ_{sa} is the residual delay for this telemetry signal;

$$\hat{R}_a[t] = \hat{r}_0[t - \tau_{ra}] \tag{2}$$

where $\hat{r}_0[t]$ is a time sequence of Gaussian random noise representing an external interfering radio source coming into the same antenna and τ_{ra} is the residual delay for the interferer signal; and

$$\hat{N}_a[t] = \hat{n}_a[t] \tag{3}$$

where $\hat{n}_a[t]$ is a time sequence of Gaussian random noise representing the receiver noise for the same ath antenna.

In the DSN array design, the digital receiver applies model phases and delays corresponding to the geometry of the array and signal source at each antenna, and forms an FT of the resulting signal over 512 time points to get 512 frequency bins. The frequency bins are then averaged over a time of usually one second to give a single spectrum for this antenna correlation and time interval. This FT can be represented by

$$F_a[\nu] = \int \left[\hat{S}_a + \hat{N}_a + \hat{R}_a\right] e^{[-2\pi i t\nu]} dt \tag{4}$$

where ν is the frequency within the spectrum. Putting in the signals from above and making an appropriate change of variables to simplify the equations yields

$$F_a[\nu] = e^{[-2\pi i\tau_{sa}\nu]} F\left[\hat{s}_0, \nu\right] + e^{[-2\pi i\tau_{ra}\nu]} F\left[\hat{r}_0, \nu\right] + F\left[\hat{n}_0, \nu\right] \tag{5}$$

The correlation operations become a multiply and average, which yields

$$\hat{V}_{a\rho}[v] = F_a[\nu] F_\rho^*[\nu] = \left\{ \begin{array}{l} e^{[-2\pi i(\tau_{sa}-\tau_{s\rho})\nu]} F\left[\hat{s}_0, \nu\right]^2 + \\ e^{[-2\pi i(\tau_{ra}-\tau_{r\rho})\nu]} F\left[\hat{r}_0, \nu\right]^2 \end{array} \right\} + \text{noise} \tag{6}$$

In this equation, the FTs on the right represent the power spectra of the telemetry, interferer, and noise, respectively. The cross-terms in the correlation all average to zero because of the incoherency of the components. They contribute to the noise and are represented in the *noise* term. If the reference signal, represented by the ρ subscript, is coming from a combination of antennas, as in SUMPLE, then a sum of exponentials will multiply each term but will not change the equation's basic form.

If we represent the frequency by the sum $\nu = f_0 + f$, we can write

$$\hat{V}_{a\rho}[f] = \left\{ \begin{array}{l} e^{[-2\pi i f_0(\tau_{sa}-\tau_{s\rho})]} e^{[-2\pi i f(\tau_{sa}-\tau_{s\rho})]} A_S S[f] + \\ e^{[-2\pi i f_0(\tau_{ra}-\tau_{r\rho})]} e^{[-2\pi i f(\tau_{ra}-\tau_{r\rho})]} A_R R[f] \end{array} \right\} + \text{noise} \tag{7}$$

The two spectral shapes, S and R, are assumed to be known. The S is typically a sinc-squared function, and the R is a constant function, across the bandpass. The phase and phase slope are represented by the two exponential factors of S and R, and the A's are the amplitudes of S and R. In particular, the fitting parameters are

$$\begin{aligned} fcoef[1] &= A_S \cos\left[-2\pi i f_0(\tau_{sa}-\tau_{s\rho})\right] \\ fcoef[2] &= A_S \sin\left[-2\pi i f_0(\tau_{sa}-\tau_{s\rho})\right] \\ fcoef[3] &= A_R \cos\left[-2\pi i f_0(\tau_{ra}-\tau_{r\rho})\right] \\ fcoef[4] &= A_R \sin\left[-2\pi i f_0(\tau_{ra}-\tau_{r\rho})\right] \\ fcoef[5] &= -2\pi(\tau_{sa}-\tau_{s\rho}) \\ fcoef[6] &= -2\pi(\tau_{ra}-\tau_{r\rho}) \end{aligned} \tag{8}$$

The first four coefficients represent the two phases and the two amplitudes, and can be fit with a linear algorithm. The last two coefficients correspond to the two phase slopes, and require a non-linear fitting algorithm.

IV. Simulations

The above-described algorithm was incorporated into the simulation software developed for testing SIMPLE and SUMPLE in [1]. This required expanding from a narrowband to a broadband treatment of the signals, adding FTs for doing the correlation in the frequency domain, and then incorporating a non-linear fit routine ("dnlsfb" from the MathC90 library) to extract the various model parameters from the correlation spectra. For the following simulations, a total of 64 frequency channels were used (instead of the 512 that are in the DSN array design) with up to 37 antennas spread uniformly over a plane with maximum baselines of 500 m. The antenna size was assumed to be 12 m with a receiver temperature of 20 K. The amplitude reduction due to the shape of the primary beam of the antennas was ignored in determining the intensity of the interfering radio source. The nominal radio frequency of the signals was set to 8 GHz. For all of the point source interferer simulations, the interferer strength in each channel was set equal to the telemetry strength at its peak, and the telemetry symbol SNR was 0 dB in the peak frequency channel.

In the following discussion, only the SUMPLE algorithm results will be shown and discussed. Similar results can be obtained with SIMPLE, but with poorer SNRs in the correlation spectra and, consequently, larger combining losses. To serve as a control experiment, the first example, seen in Fig. 1, is a fit to the spectrum from one of the longest baselines, where there is no interferer and no residual delay. The combining loss for this case is less than 0.1 dB.

Figure 2 shows a fit where, again, there is no interferer, but a residual delay for the telemetry source has been included. In this case, the residual delay appears as a slope in the phase of the telemetry signal.

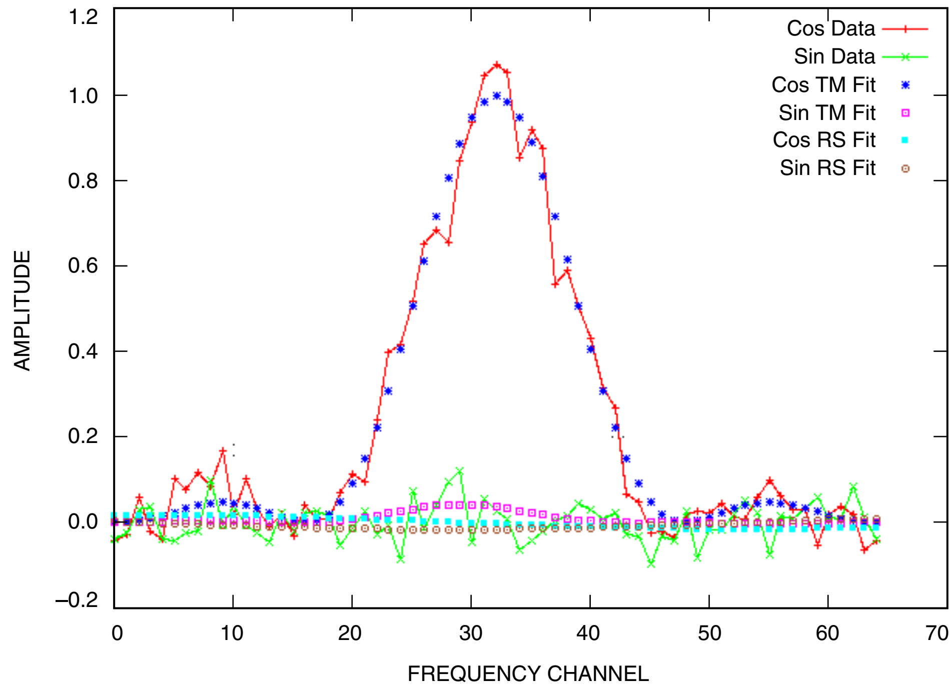

Fig. 1. A fit to the correlation spectrum with no interferer and no delay offset (TM = telemetry, RS = interferer).

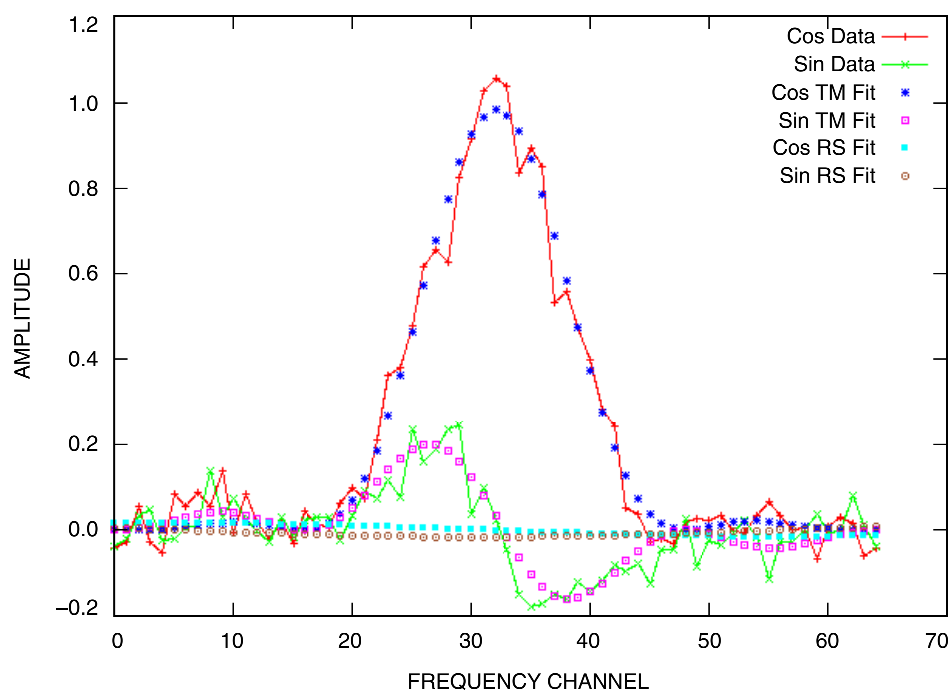

Fig. 2. A fit to the correlation spectrum with delay offset and no interferer.

Figure 3 presents a result when an interferer of equal strength to the peak of the telemetry signal but with no offsets in residual delay is included. While the interferer does not disturb the pointing of the array pencil beam at the telemetry source, it does add to the receiver noise and results in a poorer telemetry SNR. As the interferer is moved off the position of the telemetry, the modified combining algorithms prevent the array pencil beam from moving off the telemetry (as it would do if there were no modification to the algorithms), and the amplitude of the interferer decreases as it moves out of the pencil beam.

Figures 4 and 5 show the spectral fit for the case when the interferer is half-way down (in amplitude) on the array pencil beam, and for the case when it is many beamwidths away. For the case when the interferer is far enough outside the pencil beam that a fit for its position is poor, it is better to change the fitting algorithm so that it does a fit only for the telemetry signal parameters. The effect is to filter out the interferer.

Figure 6 shows a plot of the interferer amplitude as a function of its distance from the telemetry source. In all cases, the modified combining algorithms were able to maintain pointing of the array pencil beam with less than 0.1 dB additional combining loss in the SNR of the telemetry signal. However, as the interferer moved out of the pencil beam, its contribution to the receiver noise became significantly less. As can be seen in Fig. 6, the amplitude drops by as much as a factor of 10, yielding up to 20 dB filtering of the interfering signal when it is outside the array pencil beam.

V. Some Refinements

A. Tilting the Pencil Beam

In the case when the interferer is within the array pencil beam but not immediately on top of the telemetry source, it is possible to obtain a small improvement in the telemetry SNR by tilting the pencil beam slightly off-point in a direction away from the interferer. As this tilting goes from zero to some maximum value, the amplitude drop for the interferer will be greater than that for the telemetry because of their relative positions within the pencil beam.

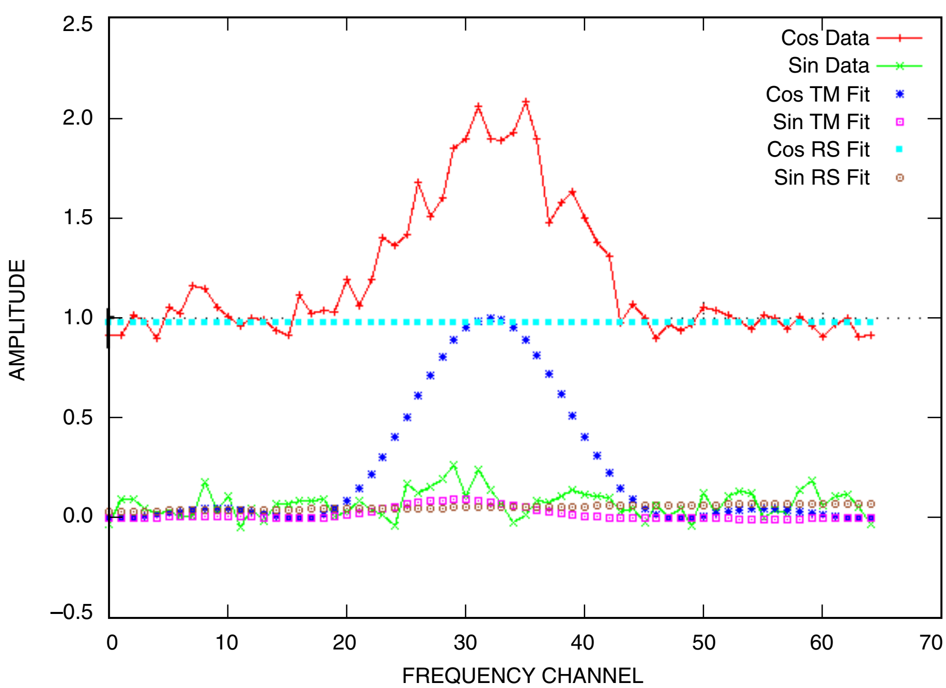

Fig. 3. A fit to the correlation spectrum with both telemetry and an interferer but no offsets.

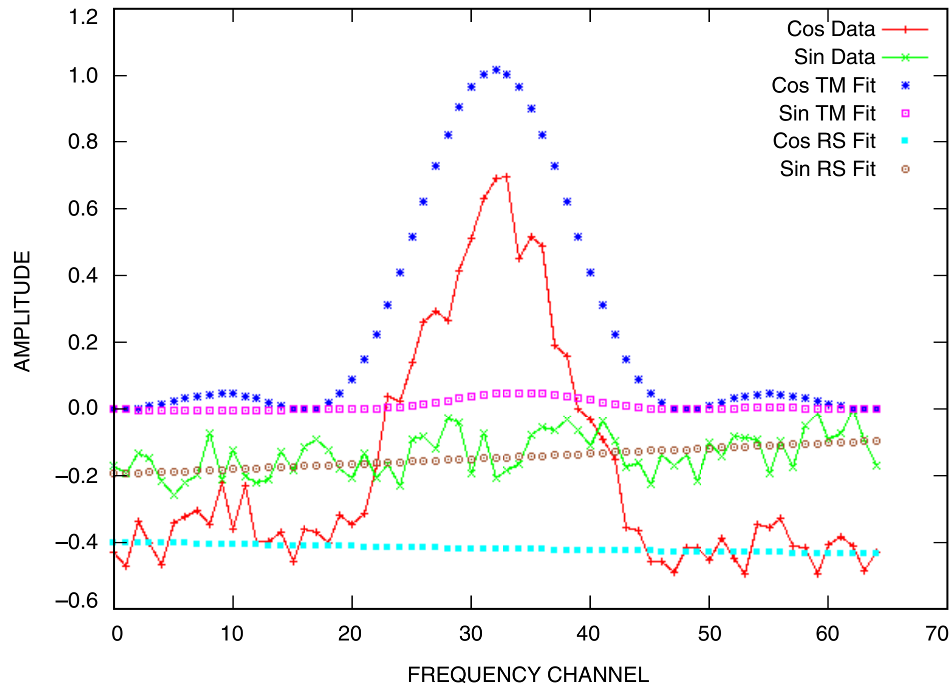

Fig. 4. A fit to the telemetry (no delay offset) and the interferer half-way down the pencil beam.

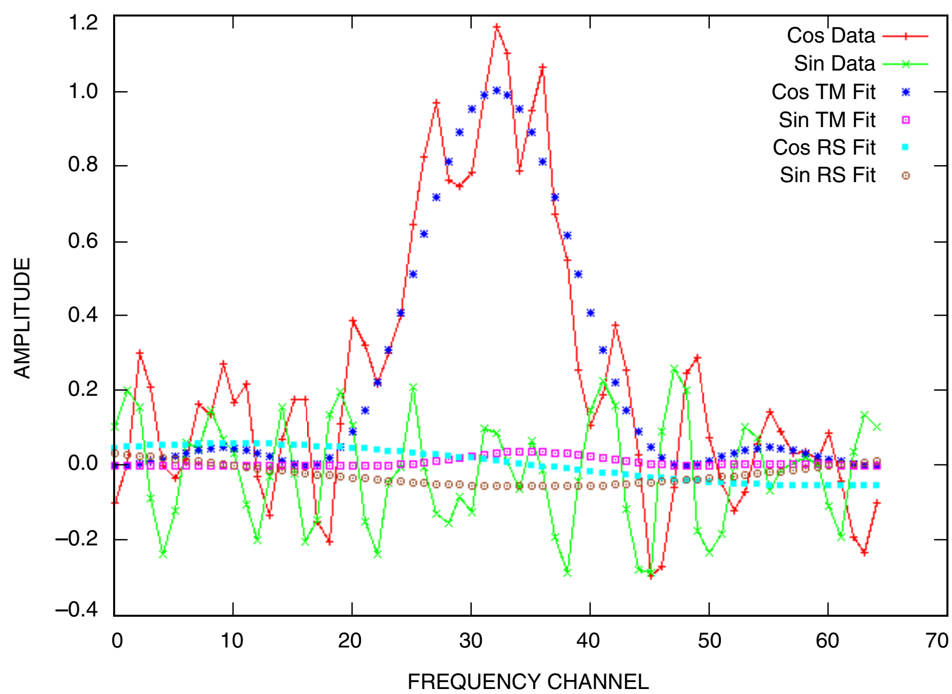

Fig. 5. A fit to the telemetry with the interferer offset by 30 pencil beamwidths.

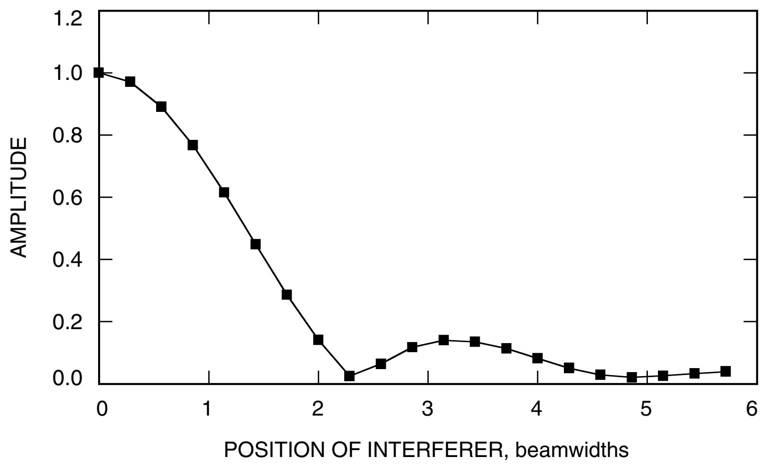

Fig. 6. Amplitude interferer as a function of interferer offset.

If we assume a sinc-squared function shape for the array pencil beam, and both the telemetry and interferer SNRs are 5 dB (i.e., are of equal strength and 5 dB above the receiver noise), then Fig. 7 shows the predicted variation of the telemetry SNR as a function of the tilting of the pencil beam. The improvement in gain is about 1.5 dB when moving from pointing at the telemetry source to pointing about 0.24 beamwidths in a direction away from the interferer. This amount of improvement will vary with the actual shape of the pencil beam and with the relative strengths of the telemetry source, the interferer, and the receiver noise.

Adjustment of the pencil beam tilt (by changing the beam phase and phase slope) was incorporated into the simulation program to accomplish this same effect with a simulated array. Figure 8 shows the variation in gain as a result of tilting the simulated pencil beam. The improvement in gain is about 0.6 dB when moving from pointing at the telemetry source to pointing about 0.3 beamwidths in a direction away from the interferer. Most likely this poorer performance as compared with the above calculation is due to the fact that the simulated array pencil beam does not drop off in amplitude as quickly as the sinc-squared function used in the calculation (note Fig. 6).

B. Reshaping the Pencil Beam

The approach taken above for improving the telemetry SNR in the presence of an interferer was to tilt the pencil beam slightly to reduce the strength of the interferer without significantly reducing the strength of the telemetry source. Another approach is to reshape the pencil beam by giving higher weight to the antennas at the outer edges of the array. This will narrow the width of the pencil beam, reducing the strength of the interferer at the side of the beam, but at the cost of decreasing the telemetry SNR at the beam center (remember that equal weights are optimal for equal-sized antennas with equal receiver noise).

Following the same approach as used for tilting, a beam-narrowing capability was incorporated into the simulation software using a weighting function of the form

$$\text{Weight Factor} = 1 + \text{Narrowing Coefficient} \times \text{Relative Baseline Length} \tag{9}$$

where the narrowing coefficient went from zero up to some maximum value. This form was chosen because it was possible to calculate its effect on a sinc-squared pencil beam in closed form. Figure 9 shows the gain predicted with this weighting function, while Fig. 10 shows the simulation results. The improvement in telemetry SNR is about 0.8 dB in both cases. It is possible that a different weighting function could

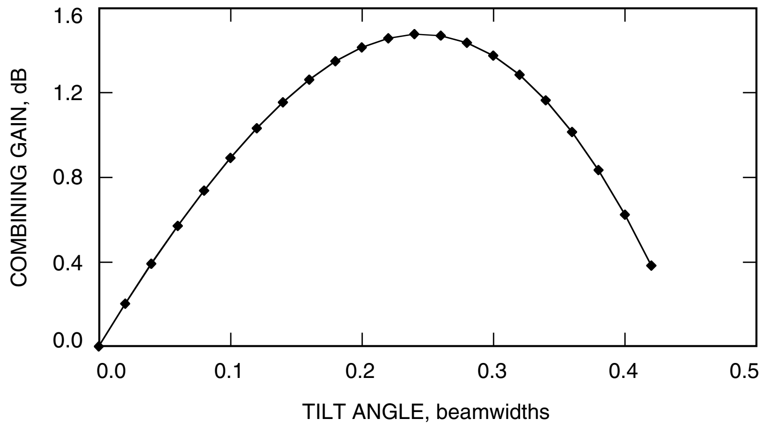

Fig. 7. Predicted gain in telemetry SNR as a function of the tilt angle.

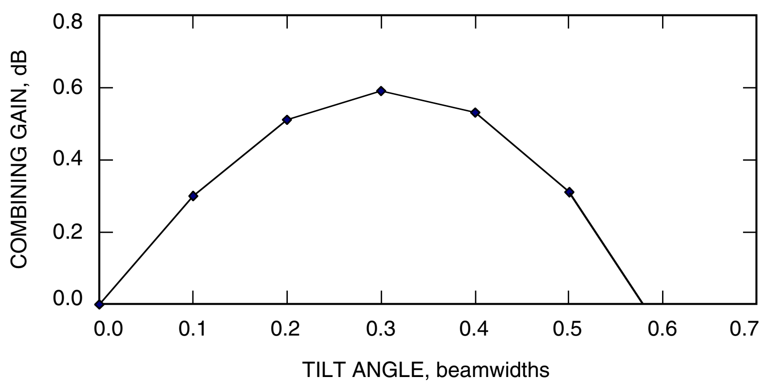

Fig. 8. Simulated gain in telemetry SNR as a function of the tilt angle.

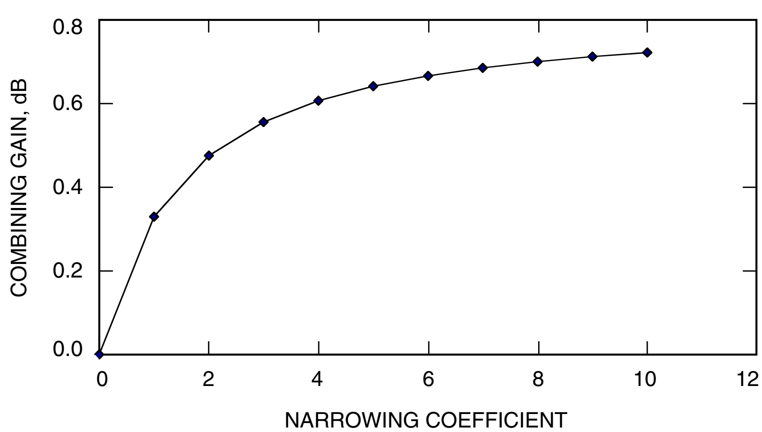

Fig. 9. Predicted gain in telemetry SNR as a function of beam narrowing.

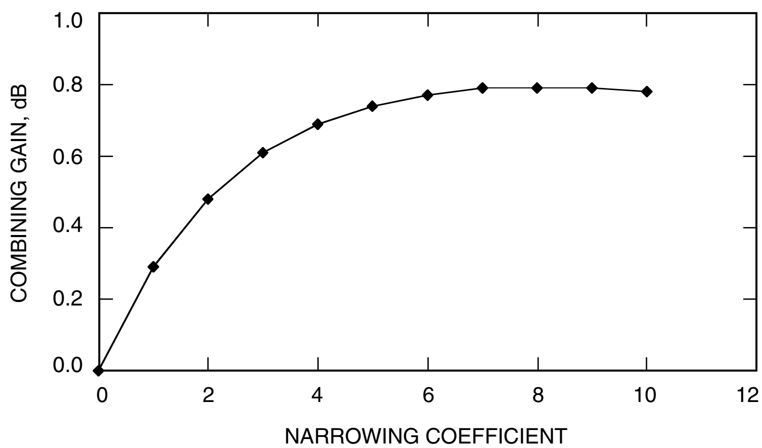

Fig. 10. Simulated gain in telemetry SNR as a function of beam narrowing.

produce better results. However, since these results are for a case when the telemetry and interferer SNRs are 5 dB, and the results are considerably poorer for a case when these SNRs are less (see the next paragraph), it is unlikely that this refinement to the combining algorithms will be as effective as the beam-tilting approach.

Of interest is how these two parameters play off each other. Figure 11 shows the results of the prediction software when both the tilting and narrowing are varied simultaneously. It is apparent that the two improvements do somewhat add together to give a peak gain of about 1.7 dB. An equivalent simulation diagram was not created but is expected to yield similar results.

To see the effect of reducing the telemetry and interferer SNRs down to 0 dB, Fig. 12 was created. Here it is clear that beam tilting provides a gain of about 0.4 dB while beam narrowing gives at best a 0.1 dB improvement.

VI. A Mars-Sized Interferer

A common situation occurring in the DNS is the tracking of a spacecraft transmitting telemetry in the presence of a planet. A planet is typically a source of blackbody radiation, which in the case of Mars has a brightness temperature of about 200 K. If the receiving array pencil beamwidth is smaller than the angular size of the planet (so that the planet "fills the beam"), then the consequence is to raise the effective receiver temperature from a typical 20 K to, for Mars, 220 K. Needless to say, this can be quite damaging in the case of a weak telemetry signal.

To test how well the array performs in the presence of an extended interferer, the simulation program was run using a cluster of seven interfering sources, configured so as to simulate the planet Mars in a typical situation. Figure 13 diagrams how these seven sources were laid out.

In the simulation the amplitudes of the telemetry and the receiver noise were set to be equal. The amplitude of the interferer was set to 1.8 times the receiver noise, corresponding to a Mars brightness temperature of about 200 K. With no interferer, the combining loss was about 0.4 dB. With the interferer present and the telemetry source centered on the interferer, the combining loss was about 10.5 dB, corresponding to the interferer adding a large component to the receiver noise. Moving the telemetry source to a position at the edge of the interferer (about where it would be if it were in orbit around the interferer, and corresponding to the pink dot in Fig. 13) causes the combining loss to drop to

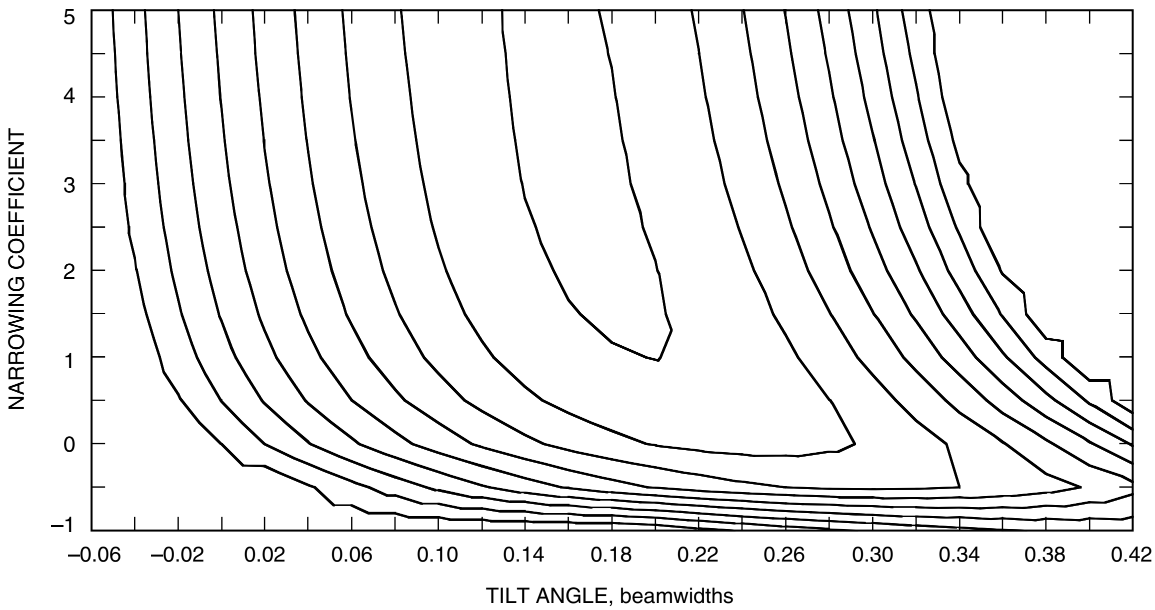

Fig. 11. Predicted gain in combining gain as a function of beam tilt and narrowing when the telemetry and interferer SNRs are 5 dB. Each contour corresponds to a gain of 0.2 dB, and the lowest contour is at a gain of 0 dB.

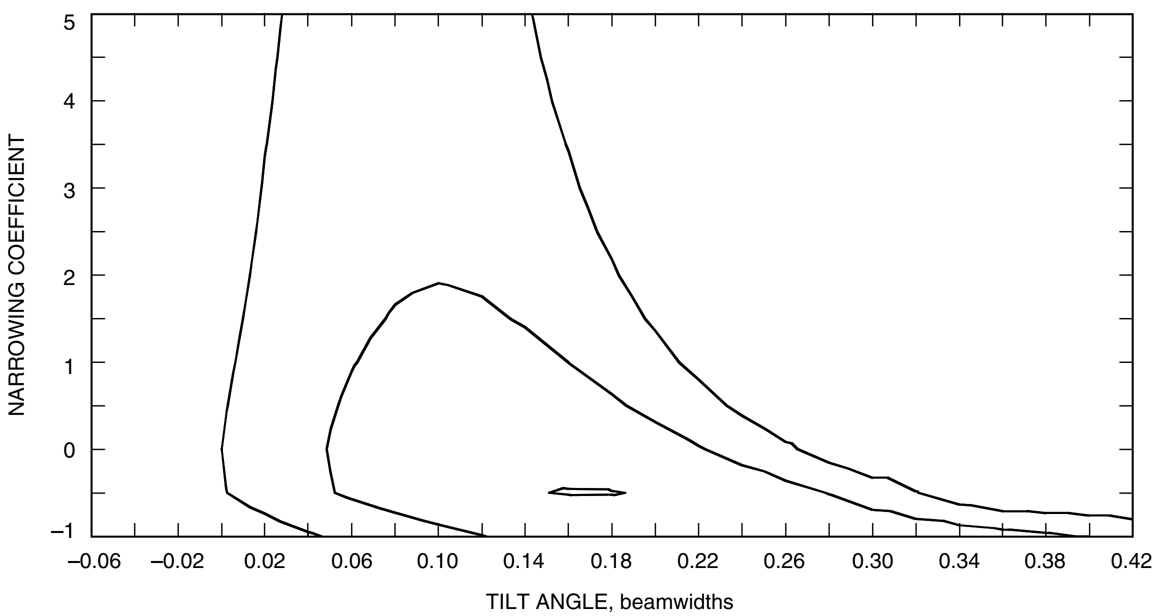

Fig. 12. Predicted gain in telemetry SNR as a function of beam tilt and narrowing when the telemetry and interferer SNRs are 0 dB. Each contour corresponds to a gain of 0.2 dB, and the lowest contour is at a gain of 0 dB.

about 6.7 dB. Tilting or narrowing the pencil beam of the array provides a slight improvement over this loss, shown as a combining gain in Figs. 14 and 15.

All of these improvements grow or diminish depending on the particular values chosen for the strength of the telemetry, interferer, and receiver noise signals. What is clear is that the presence of the interferer does not significantly disturb the pointing of the array pencil beam away from the telemetry source, but it does significantly add to the effective receiver noise.

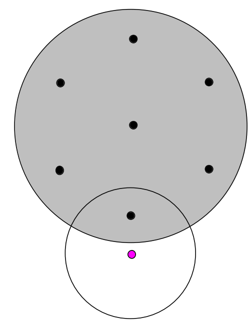

Fig. 13. Diagram of seven point interferers arranged to simulate Mars. The open circle represents the array pencil beam. The shaded circle corresponds to the equivalent size of Mars that yields a shape the same as the seven points. The pink dot represents the spacecraft.

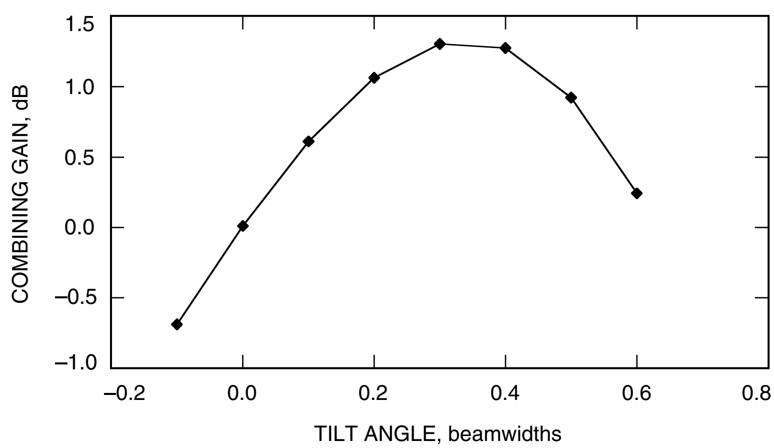

Fig. 14. Simulated combining-loss improvement versus tilt angle for the case in Fig. 13.

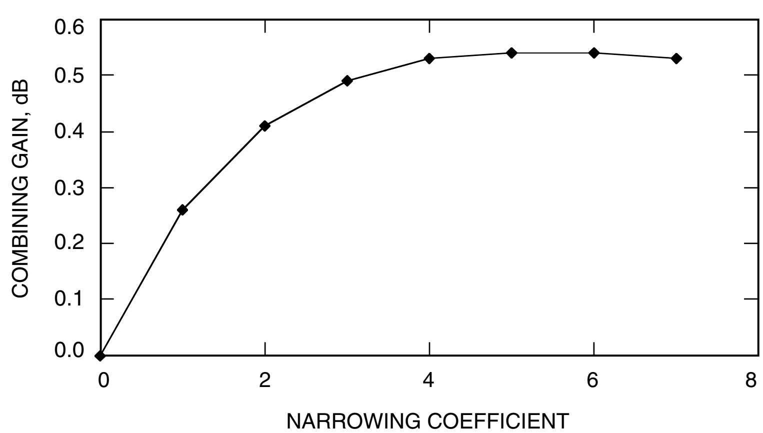

Fig. 15. Simulated combining-loss improvement versus beam narrowing for the case in Fig. 13.

VII. Conclusions

The modifications to the SIMPLE and SUMPLE array combining algorithms discussed in this article to deal with the effects of an interfering radio source appear to be quite effective when the array has spectral capability and the spectra of the two signals are significantly different. The additional combining loss for the telemetry source (not counting the increased receiver noise due to the presence of the interferer) is not more than about 0.1 dB. The approach seems to be quite robust as long as sufficient SNR can be obtained in the correlation process, subject to the limits on time averaging imposed by the troposphere. These results are more easily achieved with SUMPLE. The further refinements of beam tilting and beam shaping to reduce the increase in receiver noise due to the interferer yield on the order of 0.2 to 2 dB improvement in telemetry SNR, depending on the actual angular shapes of the pencil beam and the interferer as well as the relative strengths of the telemetry, interferer, and receiver noise.

Acknowledgments

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Reference

[1] D. H. Rogstad, "The SUMPLE Algorithm for Aligning Arrays of Receiving Radio Antennas: Coherence Achieved with Less Hardware and Lower Combining Loss," *The Interplanetary Network Progress Report*, vol. 42-162, Jet Propulsion Laboratory, Pasadena, California, pp. 1–29, August 15, 2005. http://ipnpr/progress_report/42-162/162B.pdf