The Range Increase of Adaptive Versus Phased Arrays in Mobile Radio Systems

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Abstract

In this paper we compare the increase in range with multiple-antenna base stations using adaptive array combining to that of phased array combining. With adaptive arrays, the received signals at the antennas are combined to maximize signal-to-interference-plus-noise ratio rather than only form a directed beam. Although more complex to implement, adaptive arrays have the advantage of higher diversity gain and antenna gain that is not limited by the scattering angle of the multipath at the mobile. Here, we use computer simulation to illustrate these advantages for range increase in both narrowband and spread spectrum mobile radio systems. For example, our results show that for a 3° scattering angle (typical in urban areas) the range increase of a phased array with 100 elements can be achieved by an adaptive array with only 10 elements.

1. Introduction

Multiple antennas at the base station can provide increased received signal gain and range in mobile radio systems. Two approaches for combining the received signals are the phased array, which creates an antenna beam directed at the mobile, and the adaptive array, which maximizes signal-to-interference-plus-noise ratio. Here, we compare the range increase of phased arrays to that of the more complex adaptive array technique, for both narrowband and spread spectrum systems.

Previous papers have studied the increase in range with phased arrays [1-6]. With phased arrays, the signals received by each antenna are weighted and combined to create a beam in the direction of the mobile. The same performance can also be achieved by sectorized antennas, whereby a different antenna is used to form each beam. As the number of antennas increases, the received signal gain (range) increases proportionally to the number of antennas, but only until the beamwidth of the array is equal to that of the angle of multipath scattering around the mobile. Beyond that point, the increased gain of more antennas is reduced by the loss of power from scatterers outside the beamwidth. The range can even be reduced with narrower beamwidths because the resulting reduction in delay spread can cause a loss of diversity gain in systems using equalization, e.g., in spread spectrum systems using a RAKE receiver.

This limitation in range increase can be overcome by the use of adaptive arrays [5-9]. With adaptive arrays, the signals received by each antenna are weighted and combined to maximize the output signal-to-interference-plus-noise ratio (SINR). Although the most widely studied advantage of adaptive arrays is interference suppression [7-10], maximizing SINR also forms an antenna pattern matched to the wavefront (which is not a plane wave for nonzero scattering angle) and therefore provides a range increase that is not limited by the scattering angle. In addition, adaptive arrays can provide higher diversity gain than phased arrays, since all the receive antennas can be used for diversity combining. Thus, for a given number of antennas, adaptive arrays can provide greater range, or require fewer antennas to achieve a given range.

2. Description of phased and adaptive arrays

2.1 Phased array

For the mobile radio base station, the antenna beam should be narrow in elevation and the antenna characteristics should be independent of azimuth. A narrow elevation angle can be created by using a vertical array of antenna elements for each horizontal element. The azimuth dependence can be reduced by placing the horizontal elements in a cylindrical array, as shown in Figure 1. Each antenna element is typically spaced at $\lambda/2$, since smaller spacing reduces gain by creating a wider beamwidth with increased mutual coupling, while wider spacing can also reduce gain by decreasing the beamwidth and creating grating lobes, i.e., gain in

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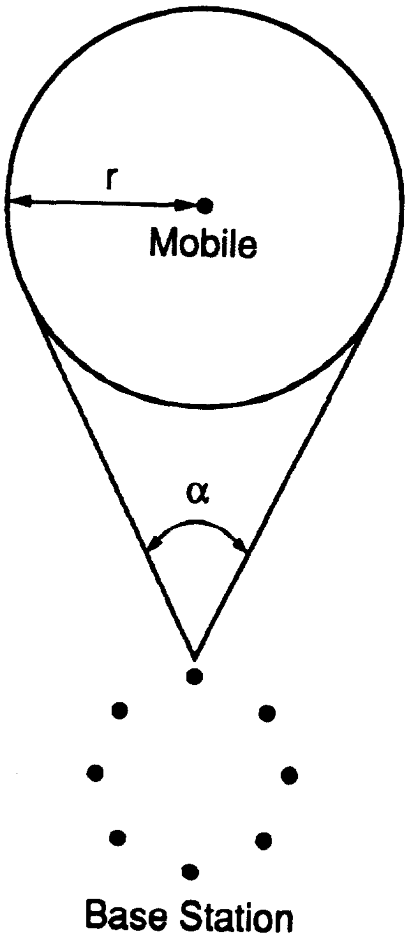

Figure 1 **Mobile radio environment with a cylindrical base station array and scattering around the mobile, where all signals from a mobile arrive within a scattering angle α.**

directions other than the desired angle-of-arrival.

To create a beam in a given direction, the signals from the antenna elements are cophased, based on a plane wave arrival. Since to reduce mutual coupling between elements, each element should have higher gain in the direction pointing away from the center of the cylinder, the signals should also be weighted by the voltage gain in the given direction to maximize signal-to-noise ratio (SNR) in the array output. These weighted signals are summed to generate the array output, with the output SNR for a beam with direction ϕ given by

$$S/N(\phi) = \frac{\left| \sum_{i=1}^{M} s_{rec_i} \cdot s_i^*(\phi) \right|^2}{\sum_{i=1}^{M} \left| s_i(\phi) \right|^2} , \qquad (1)$$

where s_{rec_i} is the complex received signal voltage at antenna i, $s_i(\phi)$ is the expected antenna voltage gain and phase (relative to the other antennas) for a signal arriving from angle ϕ, and the superscript * denotes complex conjugate.

The same performance as the phased array can be achieved by using sectorized antennas, i.e., separate antennas for each beam, as is currently done at many mobile radio base stations. However, to create uniform coverage using sectorized antennas or phased arrays with predetermined (fixed) beams, overlapping beams should be used. This doubles the number of antennas (with sectorized antennas) or the combining hardware (with phased arrays with fixed beams) without increasing the gain.

Arrays increase the range by providing additional received signal gain due to two factors - antenna gain and diversity gain. With an M-element phased array and a point source, the antenna gain is M, neglecting mutual coupling. The range increase is the gain raised to the inverse of the propagation loss exponent, γ, typically a 4th power loss. Thus, with a point source, the range increase due to the antenna gain of an M element array is $M^{1/\gamma}$.

However, signal scattering around the mobile means that the signal received at the base station cannot always be considered as coming from a point source. As shown in Figure 1, with scattering the signal arrives from a range of angles, called the scattering angle. Typically, the mobile signal is scattered mainly by objects within 1000 feet of the mobile, but this distance can vary widely, e.g., with reflections off mountains [11]. Furthermore, this scattering angle increases with decreasing base station height. Here, we don't consider what the likely distribution of scattering angles will be for any given system, but show results obtained for a wide range of scattering angles.

Since receive signal power is lost when the beamwidth, which is approximately $\frac{360°}{M}$, is less than the scattering angle, the signal gain will be less than M in the phased array with large enough M. For example, for a uniform distribution of power within a scattering angle of α degrees, the maximum signal gain is given by an array with $M = 360/\alpha$ elements. Additional elements increase the antenna gain, but the power lost outside the beam reduces the signal gain by the same amount. Thus, with phased arrays the signal gain, and the corresponding range increase, is limited.

The other factor for receive signal gain is the diversity gain. Multipath fading results in a higher average output SNR required to achieve a given average receiver performance (e.g., BER in digital systems) than without fading. The fading in the output signal can be reduced by using multiple receive antennas and combining the received signals. We define diversity gain as the improvement in link margin beyond the factor of M for array gain. For example, for a 10^{-2} BER averaged over Rayleigh fading with coherent detection of PSK, a 9.5 dB higher average output SNR is required than without fading. Two antennas provide up to a 5.4 dB diversity gain, while 3, 4, and 6 antennas provide up to 6.8, 7.6 and 8.3 dB, respectively, with maximal ratio combining. Thus, 6 antennas can provide within 1.2 dB of the maximum diversity gain. However, to achieve the full diversity gain, the fading at the antennas must be nearly independent. This requires that the spacing between antennas is at least the distance such that the beamwidth of an antenna with this aperture is approximately the scattering angle. For example, a spacing of 10 to 20λ is used for the typical scattering angle of a few degrees [11-13].

For a cylindrical phased array, such an antenna spacing between elements is impractical and would create numerous grating lobes without providing the antenna gain commensurate with the diameter of the array (or providing diversity gain). Thus, diversity gain cannot easily be provided by a phased array.

Frequency-selective fading due to delay spread can also be used to provide diversity by using equalization [9], or a RAKE receiver in spread spectrum systems [14]. In this case, the diversity gain of additional antennas is reduced. For example, a 3-finger RAKE is used in QUALCOMM's CDMA system. With received signal energy uniformly distributed over 3 code symbol periods (2.4 μsec), maximal ratio combining of the 3 fingers provides 3-fold diversity, or a 6.8 dB diversity gain at a 10^{-2} BER, and dual antenna diversity provides up to 1.5 dB (the overall combining is equivalent to 6-branch maximal ratio combining) of the remaining 2.7 dB maximum diversity gain. Note, however, that, compared to a narrowband receiver, one finger of this CDMA receiver is 4.8 dB lower in signal power, i.e., the RAKE receiver does not give any increase in average SNR (antenna gain). Finally, note that beamwidths smaller than the scattering angle can reduce the delay spread, and therefore the diversity gain, in systems with phased arrays.

2.2 Adaptive array

With an adaptive array, the received signals are combined to maximize the output signal-to-interference-plus-noise ratio. Thus, the array can null interference, but here we consider only the increase in range due to higher antenna gain. Without interference, the output SNR of an M-element adaptive array is given by

$$S/N = \sum_{i=1}^{M} | s_{rec_i} |^2 \quad . \tag{2}$$

Although (2) is simpler than the SNR equation for the phased array (1), the adaptive array is more complex to implement because the weights are not fixed, but depend on the received signals. Thus, variable gains and phase shifters are needed for each signal on every antenna. These can be implemented in hardware at RF or IF, or in software at baseband. For the software implementation, the signals from each antenna can also be digitized using block processing.

With the adaptive array, though, the array pattern is matched to the multipath wavefront. That is, there is no antenna gain limitation due to multipath scattering angle, as with phased arrays, and an M-fold diversity gain can also be obtained. Achieving this diversity gain requires adequate antenna spacing, however. With a base station array oriented broadside to a small angle, α degrees, of scatterers around the mobile and with power arriving uniformly at the base from within α, the magnitude of the correlation coefficient between two array elements spaced x wavelengths apart is approximately (see also [12], which approximates the envelope correlation $\rho_e(x)$ by the square of the complex phasor correlation $| \rho(x) |^2$)

$$| \rho(x) | \approx \frac{\sin(\pi^2 \alpha x/180)}{(\pi^2 \alpha x/180)} \quad . \tag{3}$$

Thus, an antenna spacing of $\frac{360°}{\pi\alpha}\frac{\lambda}{2}$ is required for independent fading at each antenna, but spacings of about half of this still give low enough fading correlation (<0.7) that nearly the full diversity gain can be achieved. However, even with a spacing of $\frac{360°}{\pi\alpha}\frac{\lambda}{4}$ the required array size can be too large. For example, a 3° scattering angle requires a 10 foot antenna spacing at 900 MHz, and thus, in particular, a 100 element cylindrical array would require a 330 foot diameter. However, since only a few fold diversity is needed to obtain most of the maximum diversity gain, an array with a diameter of a few times the required antenna spacing (20 to 30 feet in the above example) should obtain almost all the maximum-possible diversity gain.

3. Results

3.1 Model

To verify and illustrate the above conclusions, we used Monte Carlo simulation with the following model (see Figure 1). We considered transmission from a mobile to a base station. The multipath model consisted of 20 scatterers uniformly distributed in an circular area of radius r around the mobile. These scatterers had equal transmitted power, with a 4th law power loss from each scatterer to the base station. Received power variation due to shadow fading was not considered. The base station array was a cylindrical array of M equally-spaced cardioid antennas [15], with each antenna pointing out from the center of the array, and one element at 0°. The mobile was at 90°. Note that for M=2, the mobile at 90° results in equal gain from the two antennas, while with a mobile at 0° only one antenna has nonzero gain. Thus, for M=2 the results depend strongly on the angle of the mobile (i.e., dual diversity at 90° versus no diversity at 0°). However, for $M \geq 4$, the effect of angle is negligible, and therefore this angle was fixed at 90°. We considered spacings between elements of $\lambda/2$ or greater, and therefore neglected the effect of mutual coupling.

With the phased array, the weights were set to generate a beam that was pointed directly at the mobile. For cardioid elements, these weights are given by

$$s_i^*(90°) = \sqrt{2}\cos\left\{\frac{\pi}{4}\left[\sin(2\pi(i-1)/M)-1\right]\right\}$$
$$\cdot e^{-j\frac{2\pi r}{\lambda}\sin(2\pi(i-1)/M)} \qquad i=1,\cdots,M \quad , \qquad (4)$$

and the SNR is then given by (1). With the adaptive array, the weights are $s_{rec_i}^*$, $i=1,\cdots,M$, and the SNR is given by (2). We consider coherent detection of phase shift keyed (PSK) signals, for which the BER is given by

$$BER = \frac{1}{2}\text{erfc}\left[\sqrt{S/N}\right] \quad . \qquad (5)$$

We used Monte Carlo simulation to determine the BER averaged over 10,000 cases. Note that the BER depends on the ratio of transmit power to receive noise power. This ratio was adjusted to obtain a 10^{-2} average BER for the baseline case of an omnidirectional transmit antenna with the mobile at a given range and scattering radius. With this ratio and the scattering angle fixed, we generated results for the M-element phased and adaptive arrays, increasing the range until the BER exceeded 10^{-2}, thus giving the range increase. All the following results for range increase and diversity gain are referenced to 10^{-2} average BER.

We considered both the low data rate case (no delay spread) and the delay spread case. For the delay spread case, the signal delay for each scattered signal depends on the distance from the mobile to the scatterer plus the distance from the scatterer to each base station antenna.

For the spread spectrum system with delay spread, we studied the use of a 3-finger RAKE receiver for both the phased and adaptive arrays. To simulate the RAKE receiver, the computer program first convolved the delayed impulse of each scatterer with the spread spectrum correlation function given by

$$f(t) = \begin{cases} 1-\dfrac{|t_d-t-0.8|}{0.8} & \text{for } |t_d-t| \leq 0.8\ \mu\text{sec} \\ 0 & \text{elsewhere} \end{cases} \qquad (6)$$

where t_d is the time delay corresponding to the distance from the center of the base station to the mobile. The responses from the 20 scatterers were then summed to obtain the signal at each antenna.

These signals were weighted and combined by phased array weights or the adaptive array weights ($s_{rec_i}^*, i=1,\cdots,M$). Note that the adaptive array weights vary as a function of delay. We then determined the three largest peaks in the output response that were separated by integer multiples of the code rate and combined these three signals to maximize the output SNR. That is, these three peaks were cophased and weighted by their signal amplitudes before combining. For the phased array, we considered two different models. In the first model, to model the QUALCOMM CDMA system with a phased array, we considered a RAKE receiver on each antenna, followed by phased array combining of the RAKE outputs, with the beam direction optimized for each delay (rather than set to 90° as in (4)). Thus, a separate beam was formed for each of the RAKE fingers. Finally, we modified the first model to consider the beam direction optimized over M different, equally-spaced angles, which models sectorized antennas. For the adaptive array, our model corresponds to a RAKE receiver on each antenna branch, with adaptive array combining of the antenna signals followed by adaptive array combining of the three highest output peaks, with the receiver timing optimized to maximize the output SNR.

For the no delay spread case, in our simulations we used a 40,000 foot range as the baseline case, with the scattering radius given by the required scattering angle. However, our results can be generalized to any range, as they depend only on the scattering angle, not the absolute values of the range and scattering radius. Therefore, in the next section, we present our results only in terms of the normalized range. Similarly, although we generated results for a one foot wavelength, our results can be generalized to any wavelength. Therefore, our results on antenna spacings are only in terms of λ. Also, for the delay spread case, our simulations used a 1.25 Mbps data rate (as in the QUALCOMM CDMA system). The scattering radius was set to 1200 feet (which is typical in mobile radio in suburban and urban areas) which results in a delay spread of 3 symbols. This radius was chosen because this is the minimum delay spread for which the maximum diversity gain is achieved with the 3-finger RAKE receiver. Thus, the scattering radius was chosen to maximize the RAKE diversity gain as well as the effect of a narrow beamwidth on the performance. Again, our results do not depend on the absolute values of the range and scattering radius, and are therefore presented in terms of normalized range and scattering angle.

Finally, note that by keeping the scattering radius constant as we increase the range (which would be typical in mobile radio), the scattering angle decreases. For example, a 10° scattering angle with the baseline case is only about 3° with a 3-fold range increase. With fixed scattering radius, the predicted range increase discussed in the previous section must therefore be modified. It was noted before that, for a given scattering angle α, the maximum gain is $360/\alpha$, and therefore the maximum range R, normalized to the omnidirectional-antenna range R_0, is given by

$$\frac{R}{R_0} = \left[\frac{360}{\alpha}\right]^{1/4} . \tag{7}$$

But since the scattering radius is kept constant, the scattering angle at range R is less than the baseline scattering angle α_0 at R_0, specifically,

$$\alpha = \alpha_0 \left[\frac{R_0}{R}\right] . \tag{8}$$

Therefore, from (7) and (8), the maximum range increase is given by

$$\frac{R}{R_0} = \left[\frac{360}{\alpha_0}\right]^{1/3} \tag{9}$$

(with the corresponding $M = (360/\alpha_0)^{1/3}$). This increase is greater than the maximum range increase of $(360/\alpha)^{1/4}$ for the fixed scattering angle case, e.g., the range increase is 4.9 for α_0=3° versus 3.3 for α=3°.

3.2 Results for range increase

Figure 2 shows the normalized maximum range versus the number of antenna elements for phased and adaptive arrays with $\lambda/2$ antenna spacing, neglecting the delay spread. Results are shown for different fixed scattering radii, with the scattering angle for the baseline case of one antenna element given. We also show the theoretical range due to the antenna gain ($M^{1/4}$) without diversity, and due to antenna gain and M-fold diversity. Also the predicted maximum range with phased arrays is shown.

With the phased array, the range is shown to be

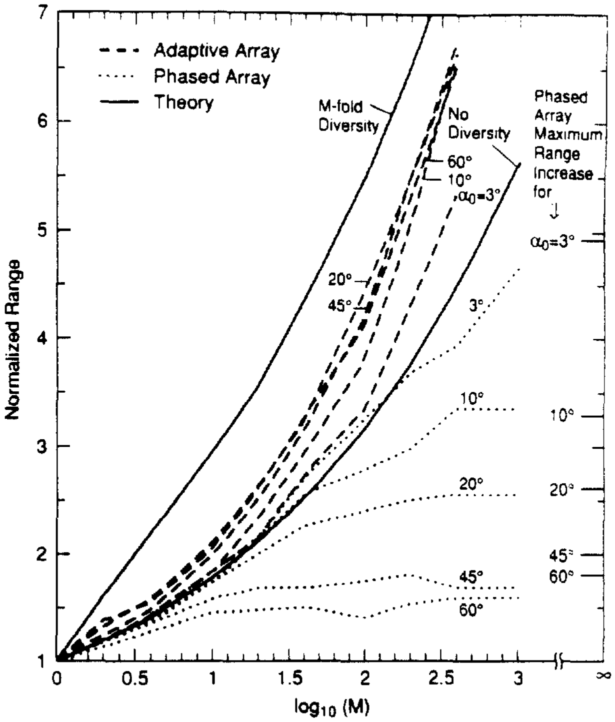

Figure 2 **Normalized maximum range versus the number of antenna elements for phased and adaptive arrays with $\lambda/2$ antenna spacing, neglecting the delay spread.**

limited to the predicted range limitation. However, the range improvement is degraded due to the scattering angle for M less than the theoretical value corresponding to the range limitation, and it requires many times more antennas to actually reach this limitation. For example, with a 20° scattering angle, the predicted range limitation is 2.6, corresponding to 46 antennas, but with 46 antennas the range is only 2.3. Note that at a range of 2.6, the scattering angle is reduced to about 8° for the 20° baseline curve.

For the adaptive array, the range exceeds the no-diversity theoretical range for all scattering angles, due to antenna diversity. The diversity gain increases with scattering angle and M, as expected. However, the diversity gain does not increase for scattering angles greater than about 20°. Thus, because the adaptive array has greater range with increased scattering angle, the difference between the adaptive and phased array increases dramatically with scattering angle.

Our results show that with the phased array, the range does not increase with wider spacing, and, in fact, decreases if the spacing is wide enough. With the adaptive array, the range increases with antenna spacing, up to that corresponding to the maximum diversity gain, which can be achieved with a spacing of about 10λ for scattering angles as low as 2°.

Figure 3 shows the normalized maximum range with delay spread versus the number of antenna elements for phased (with the QUALCOMM CDMA system model) and adaptive arrays with λ/2 antenna spacing and a 3-finger RAKE receiver. As in Figure 2, results are shown for different fixed scattering radii, with the scattering angle for the baseline case of one antenna element given. However, in Figure 3 the baseline case includes a 3-finger RAKE with its 6.8 dB diversity gain. Thus, the actual range in the baseline case is 1.48 ($=10^{6.8/40}$) times greater than in Figure 2. We also show the theoretical range increase due to antenna gain ($M^{1/4}$), and due to antenna gain and $3M$-fold diversity (versus 3-fold diversity due to the RAKE receiver).

With the phased array, Figure 3 shows that the range limitation is negligible for scattering angles less than 20°, but there is degradation in the range increase for scattering angles of 45° and 60° with more than about 40 antennas. This degradation is somewhat larger when fixed sectorized antennas, rather than continuously-adjustable phased array antennas, are used, as Figure 3 shows for the case of a 60° scattering angle.

With the adaptive array, the range exceeds the theoretical range due to antenna gain and 3-fold diversity, showing the additional diversity gain. Thus, there is a significant improvement with adaptive arrays for large scattering angles and large M. Furthermore, in all cases the diversity gain of adaptive arrays increases with larger spacing, as shown in Figure 3 for 5λ spacing with scattering angles of 3° to 60°.

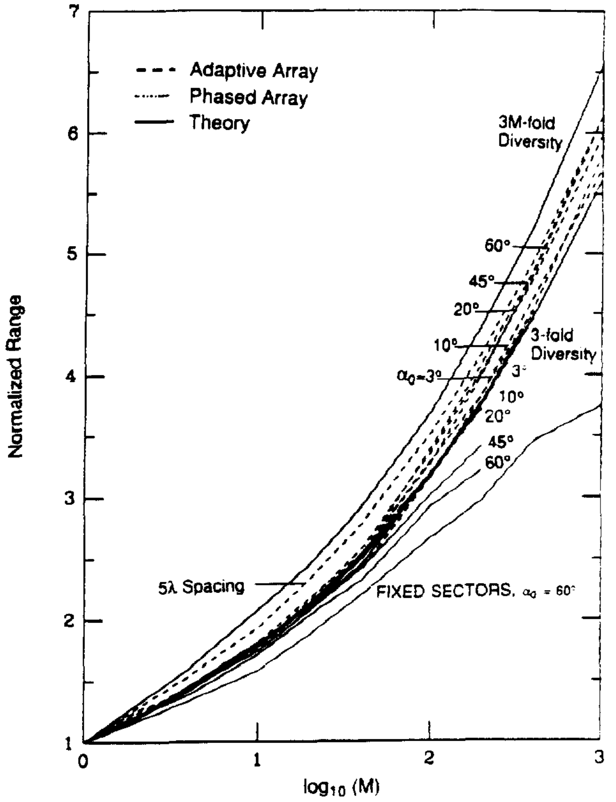

Figure 3 Normalized maximum range versus the number of antenna elements for phased and adaptive arrays with λ/2 antenna spacing and a 3-finger RAKE receiver.

4. Conclusions

In this paper we have compared the increase in range with multiple-antenna base stations using adaptive array combining to that of phased array combining. Our computer simulation considered a multipath model with a uniform distribution of scatterers within a given radius around the mobile, and determined the increase in range with arrays for 10^{-2} average BER with coherent detection of PSK. From our results we make the following conclusions:

- Phased arrays were shown to have a range increase limitation given by the scattering angle. For scattering angles of a few tenths of a degree (typical in rural areas), this limitation is significant only for arrays with more than 100 elements, while with larger scattering angles (typical in suburban and urban areas), the range increase limitation can occur with far fewer elements.

- For spread spectrum systems, using a RAKE receiver with phased arrays, the maximum range increase degradation was much less than that of narrowband systems.
- In both narrowband and spread spectrum systems, adaptive arrays had no range limitation, and could achieve diversity gain with λ/2 antenna spacing with sufficiently many elements. Almost full diversity gain could be achieved with large arrays with antenna spacings of only a few wavelengths for scattering angles as low as 1°.

Acknowledgement

It is a pleasure to acknowledge helpful suggestions by L. J. Greenstein.

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