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PILOT SIGNALS FOR LARGE ACTIVE RETRO-DIRECTIVE ARRAYS

By Dr. C. H. Chan
Program Development Directorate

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16. ABSTRACT

It has been suggested that for large active retrodirective arrays, as in the solar power system, a two-tone uplink pilot signal with frequencies symmetrically situated around the downlink frequency be used in order to reduce ionospheric biases and to lower the cost since a two-tone receiver is economically much cheaper than a single-tone phase-locked receiver. Unfortunately such a system now faces the following well-known difficulties: (i) the π-ambiguity, (ii) a large phase difference between the downlink and uplink signals.

We show in this report how the π-ambiguity can be easily removed by using a two-tone uplink signal with both frequencies situated at one side of the downlink frequency, and the phase difference can be greatly reduced with a three-tone or a four-tone uplink pilot signal.

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MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

PILOT SIGNALS FOR LARGE ACTIVE RETRODIRECTIVE ARRAYS

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I. Introduction

It has been suggested[1] that active retrodirective arrays[2,3] would be particularly suitable as solar power satellite's antennas[4] because they are inherently failsafe. The active retrodirective array works on the so-called phase-conjugation principle. It electronically points a microwave beam back at the apparent source of an incident pilot signal. Retrodirectivity is achieved by retransmitting from each element of the array a signal whose phase is the conjugation of that received by the element. In the satellite power system, the pilot source on ground may be situated at the center of a large rectenna and the retrodirective array is the space antenna in geosynchronous orbit.

Retrodirectivity can be most easily achieved if the uplink signal and the downlink beam have the same frequency. But due to input-output isolation problems. the uplink frequency is either upshifted or downshifted from the downlink frequency, a phase-locked receiver is used to achieve phase conjugation. When the uplink and downlink frequencies are different and because the ionosphere and transmission lines are dispersive, the conjugated uplink phase is no longer exactly equal to the downlink phase and the beam coherence at the rectenna can be lost. The downlink beam then points to wrong directions and this is known as beam squint.

A two-tone pilot uplink signal with frequencies symmetrically situated around the downlink frequency has subsequently been suggested. The two-tone uplink signal circumvents the beam squint problem. It reduces ionospheric biases and biases due to the dispersion of the transmission line. It also lowers the cost since a two-tone receiver is much cheaper than a single-tone phase-locked receiver. But, it introduces a new problem, known as the π-ambiguity, a: the old problem that the conjugated uplink phase could still differ from the downlink phase by an intolerable amount remains. Raytheon,[5] Boeing[6], and Rockwell[7] have all made further suggestions to remedy the problems. Their solutions not only are complicated and require much extra hardware in the already very complicated phase conjugation circuitry, but certain problems still remain.

In this report new designs of two-tone and multi-tone uplink signals with frequencies situated at one side of the downlink frequency are suggested. This method removes the above mentioned difficulties and does not require extra components in the phase conjugation circuit. We shall review in our next section the basic principle of phase conjugation and where the problems are in a symmetrically situated two-tone uplink signal. In section III we show how these problems can be circumvented with our new designs.

II. Difficulties With Symmetrically Situated Two-Tone Uplink Signal

A retrodirective array electronically transmits a microwave beam back to the apparent source of a coherent pilot signal. The beam radiated by self-phasing antenna may or may not be coherent across the aperture but it is coherent when it arrives back at the source. Retrodirectivity is the result of phase conjugation of the pilot signal received by each element of the array. Let the phase of the pilot signal of angular frequency ω received by the kth element of the array at time t be $\phi_k(t) = \omega(t - r_k/c)$ where r_k is the distance from the kth element to the source. We define the conjugate of ϕ_k to be

$$\phi_k^*(t) = \omega(t + r_k/c) + \phi_o$$

where ϕ_o is an arbitrary phase offset but is constant over the entire array. The phase of the beam received from the kth element by a receiver located at the pilot source $(r = 0)$ is, at time t,

$$\phi_k(t,0) = \omega(t + \frac{r_k}{c} - \frac{r_k}{c}) + \phi_o = \omega t + \phi_o$$

Thus the contributions to the field at $r = 0$ from various elements of the array are all in phase at that point.

In the above simple example the uplink frequency was chosen to be the same as the downlink frequency. This restriction is neither necessary nor desirable and is usually avoided because of input-output isolation problems. When these two frequencies are different, a phase-locked receiver is used. Retrodirectivity can still be achieved - provided that the propagating medium is nondispersive.

Due to the fact that single-tone phase-locked receivers are expensive and the ionosphere and transmission lines are dispersive, a two-tone uplink signal with frequencies symmetrically situated around the down-link frequency was suggested and the average of the phases of the uplink tones be taken as a good estimate of the phase at the downlink frequency. Such a system lowers the cost and removes partially the difference between the uplink and downlink phases but it also introduces a new problem known as the π-ambiguity. We shall review here where these problems are. We shall use the ionosphere as an example to study the effect on the phase conjugation due to the dispersive property of the propagating medium.

The dispersion relation for ionosphere with $\omega \gg \omega_p$ is

$$k = \frac{\omega}{c} \left(1 - \frac{\omega_p^2}{2\omega^2} \right) \tag{1}$$

where c is the speed of light in vacuum, k the wave number, ω the angular frequency and ω_p is the plasma frequency. The plasma frequency ω_p is related to the electron density as

$$\omega_p^2 = \frac{Ne^2}{\varepsilon_o m} \tag{2}$$

where ε_o is the vacuum permittivity, e the charge of the electron, m the mass of the electron and N is the volume electron density. From Eqs. (1) and (2)

$$k = \frac{2\pi f}{c} - \frac{Ne^2}{4\pi\varepsilon_o fcm}$$

where $f = \omega/2\pi$ is the frequency. For a beam to transverse a path length L, the total phase change is

$$\begin{aligned} \phi &= \int k \, ds \\ &= \frac{2\pi fL}{c} - \frac{e^2}{4\pi\varepsilon_o} \frac{1}{fcm} \int N \, ds \\ &= A f - \frac{B}{f} \end{aligned} \tag{3}$$

where $A = \frac{2\pi L}{c}$, $B = \frac{e^2}{4\pi\varepsilon_o} \frac{1}{c\ m} \int N\,ds$, and $\int N\,ds$ is the columnal electron density.

With uplink frequencies situated around the downlink frequencies, we have $f_1 = f_D - \Delta f$ and $f_2 = f_D + \Delta f$ where $f_D = 2.45$ GHz is the downlink frequency. Using the notation of Eq. (3)

$$\phi(f_1) = Af_1 - \frac{B}{f_1} = \phi_1$$

and

$$\phi(f_2) = Af_2 - \frac{B}{f_2} = \phi_2$$

then the average of the two phases is

$$\overline{\phi} = \frac{1}{2}(\phi_1 + \phi_2) \tag{4}$$

$$= A\,f_D - \frac{B}{2}\left(\frac{1}{f_D - \Delta f} + \frac{1}{f_D + \Delta f}\right)$$

$$= A\,f_D - \frac{B}{f_D}\left(1 + \varepsilon^2 + \varepsilon^4 \ldots\right)$$

where $\varepsilon = \Delta f / f_D$ is a small number. We may compare this phase $\overline{\phi}$ with the downlink phase

$$\phi_D = Af_D - \frac{B}{f_D}$$

e.g. their difference is of the order

$$\Delta\phi = |\,\phi_D - \overline{\phi}\,| \simeq \frac{B\varepsilon^2}{f_D}$$

To estimate this difference, we shall assume

$$\int N\,ds = 5 \times 10^{17}\ \text{electrons/m}^2$$

a rather large value for $\int N\,ds$ but taking into account for the possible worst condition. With $\Delta f = 50$ MHz, $\Delta\phi$ is estimated to be about 4°, which is not too small.

When we took the average of phases ϕ_1 and ϕ_2 in Eq. (4), there could introduce an ambiguity known as the π-ambiguity. Let

$$\phi_1 + \phi_2 = K(2\pi) + \Delta$$

where $0 \le \Delta < 2\pi$ and K is a positive, zero or negative integer.

Hence

$$\bar{\phi} = K\pi + \frac{\Delta}{2}$$

In performing the phase average, the $K\pi$ term could get lost. For K even, no damage is done. For K odd a π error is introduced and one would conjugate the wrong phase.

In order to remove these two difficulties, especially the π-ambiguity, Raytheon[5], Boeing[6], and Rockwell[7] have all made suggestions. Their solutions are very complicated and usually require a lot of hardware in the receiving and phase conjugation circuitries with much added cost. Furthermore, their soultions do not solve the problem completely. We shall show in our next section several simple solutions which circumvent the above mentioned difficulties and do not add extra costs.

III. New Designs of Pilot Beam System

In this section, several uplink designs are proposed. The first simple design avoids the π-ambiguity and the rest are improved versions of the first one. They are all free from the π-ambiguity but reduce the phase difference $\Delta \phi$ to various orders.

(i) This is also a two-tone uplink, but the two frequencies are both on one side of the downlink frequency with

$$f_1 = f_D - \Delta f$$

$$\text{and} \quad f_2 = f_D - 2\Delta f \tag{5}$$

where f_D is the downlink frequency. We now let $\overline{\phi} = 2\phi\,(f_1) - \phi\,(f_2)$ to be the estimation of the downlink phase. With the notation of Eq. (3)

$$\overline{\phi} = Af_D - B\left(\frac{2}{f_D - \Delta f} - \frac{1}{f_D - 2\Delta f}\right)$$

$$= Af_D - \frac{B}{f_D}\left(1 - 2\varepsilon^2 + \ldots\ldots\right)$$

where again $\varepsilon = \Delta f / f_D$ is a small number. In this simple design the π-ambiguity is removed since no division of the phase is used anywhere. The combined phase $\overline{\phi}$ is also a good estimate of the downlink phase ϕ_D. Their difference $\Delta\,\phi = \left|\,\phi_D - \overline{\phi}\,\right|$ is

$$\Delta\phi = \frac{2\,B}{f_D}\,\varepsilon^2 \tag{6}$$

which is of the same order as the one with two uplink frequencies situated symmetrically around the downlink frequency and is about 8° when the same values for $\int N\,ds$ and Δf are used as in the last section. We also note that in this simple design no extra components are required in the receiving circuitry.

(ii) This is an improved version of the first design. It requires three uplink tones but it also greatly improves the accuracy in estimating the downlink phase ϕ_D. The three frequencies are

$$f_1 = f_D - \Delta f$$

$$f_2 = f_D - 2\Delta f$$

$$\text{and} \quad f_3 = f_D - 3\Delta f$$

We now let

$$\overline{\phi} = 3\phi\,(f_1) - 3\phi\,(f_2) + \phi\,(f_3) \tag{7}$$

to be the estimation of the downlink phase. With the notation of Eq. (3)

$$\begin{aligned}\overline{\phi} &= Af_D - B\ \left(\frac{3}{f_D-\Delta f} - \frac{3}{f_D-2\Delta f} + \frac{1}{f_D-3\Delta f} \right) \\ &= Af_D - \frac{B}{f_D}\ \left(1 + 6\varepsilon^3 + . . . \right)\end{aligned}$$

where again $\varepsilon = \Delta f/f_D$. In this design, there is no π-ambiguity as before and the difference between ϕ_D and $\overline{\phi}$ is reduced by an extra factor ε, e.g. the difference $\Delta\phi$ is now

$$\Delta\phi = \frac{6B}{f_D}\,\varepsilon^3 \tag{8}$$

With $\Delta f = 50$ MHz and $\int N\,ds = 5 \times 10^{17}$ electrons/m^2, this difference $\Delta\phi$ is only about 0.5°, which is samll.

(iii) This version can be used in the event we would like to have an even smaller $\Delta\phi$ or we would like to use a larger Δf, which would otherwise result in a too large $\Delta\phi$ even with a three-tone uplink design. These new specifications can be achieved at the expense of adding a fourth tone. The four frequencies are

$$f_1 = f_D - \Delta f$$

$$f_2 = f_D - 2\Delta f$$

$$f_3 = f_D - 3\Delta f$$

$$f_4 = f_D - 4\Delta f$$

and we now let

$$\overline{\phi} = 4\ \phi(f_1) - 6\ \phi(f_2) + 4\ \phi(f_3) - \phi\ (f_4) \tag{9}$$

$$= Af_D - B\ \left(\frac{4}{f_D - \Delta f} - \frac{6}{f_D - 2\Delta f} + \frac{4}{f_D - 3\Delta f} - \frac{1}{f_D - 4\Delta f} \right)$$

$$= Af_D - \frac{B}{f_D}\ (1 - 24\ \varepsilon^4 + . . .)$$

In this design, the phase difference is reduced further by a factor ε, e.g. $\Delta\phi$ is only

$$\Delta\phi = \frac{24B}{f_D}\ \varepsilon^4 \tag{10}$$

With Δf = 50 MHz and $\int N\ ds = 5 \times 10^{17}$ electrons/m^2, this difference is only about 0.04°. Even with Δf = 100 MHz, this difference is only 0.66° which is still very small.

In all these three designs the uplink frequencies are all on the lower side of the downlink frequency and they are all equally spaced. These are not the only choices. One can use all frequencies on the upper side of the downlink frequency and they need not be equally spaced either. As a simple example one may very well have a two-tone uplink with

$$
\begin{aligned}
f' &= f_D + 2\Delta f \\
f'' &= f_D + 3\Delta f
\end{aligned}
\qquad (11)
$$

and $\overline{\phi} = 3\,\phi(f') - 2\,\phi(f'')$. It will work just as well.

So far we have used the ionosphere as an example to show how the dispersion of the transmission medium could introduce sizable biases between the uplink and downlink phases. For a two-tone uplink signal, this phase difference is about 8°. We suggested one way to suppress it is to use a three-tone uplink. However, it turns out that if the biases were purely due to the ionosphere, it is really not necessary to use a three-tone uplink. This is because even though the phase difference between $\overline{\phi}$ and ϕ_D in our two-tone uplink design is large, its variation from subarray to subarray will be decimal if not infinitesimal. To corroborate more on this statement, from Eq. (6) and the definition of B, the difference between the uplink and downlink phases from the pilot to the kth subarray for a two-tone uplink is

$$
\Delta\phi_k = \frac{2(\Delta f)^2}{f_D^{\,3}} \; \frac{\varepsilon^2}{4\pi\varepsilon_o} \; \frac{1}{cm} \int N \; ds_k \qquad (12)
$$

where $\int N\,ds_k$ is the columnal electron density along the path from the pilot to the kth subarray. Since the horizontal dimension of the region of the ionosphere that would be transversed by the pilot signal to any subarray is very small, typically of the order less than 100 meters, the transverse variation of the total electron along a path of several hundred kilometers within a tube of diameter less than 100 meters would be very small. Hence even though $\Delta\phi_k$ is estimated to be about 8°, its variation is at least several orders less. Then with the use of the phase from one of the subarrays as the reference phase, this difference $\Delta\phi_k$ can be subtracted out and the remainder be treated as a constant phase offset which has no effect on the retrodirective beam. In this sense, though the ionosphere is dispersive, it does not cause any problem, and a two-tone uplink is sufficient.

On the other hand, with the use of "central phasing" we cannot avoid the extra path length of transmission lines for some subarrays. Since these lines are not dispersionless, they will introduce a sizable phase difference. This phase difference can also be estimated. If we assume that this transmission line is a wave guide, its dispersion relation is well known

$$k = \frac{2\pi}{c} \sqrt{f^2 - f_\lambda^{\,2}} \tag{13}$$

where f_λ is the cut-off frequency. Hence the phase for any link is

$$\phi(f) = \frac{2\pi \ell}{c} \sqrt{f^2 - f_\lambda^{\,2}} \tag{14}$$

where ℓ is length of the transmission line. Just as before the phase differences for various uplinks can be calculated. For a two-tone uplink with $\overline{\phi} = 2\,\phi(f_1) - \phi\,(f_2)$, $\ell = 500$ meters and $f_\lambda = \frac{1}{2} f_D$, where f_1 and f_2 are given as in Eq. (5), $\Delta\phi$ is

$$\Delta\phi = \left| \phi_D - \overline{\phi} \right| = 256°$$

Similarly for a three-tone uplink with $\overline{\phi} = 3\,\phi(f_1) - 3\,\phi(f_2) + \phi\,(f_3)$, one obtains

$$\Delta\phi = 23°$$

For a four-tone uplink with $\overline{\phi} = 4\,\phi(f_1) - 6\,\phi(f_2) + 4\,\phi(f_3) - \phi(f_4)$, $\Delta\phi$ is further reduced to

$$\Delta\phi = 3°$$

As we see in this example, the phase difference for a two-tone uplink is very large but this number is greatly reduced in a three-tone or four-tone uplink. These multi-tone uplink signals can be used as a useful alternative method to suppress biases due to the dispersion of the transmission line and the medium.

IV. Conclusion

In our last section we illustrated how simple designs can be used to eliminate the π-ambiguity and reduce the ionospheric biases and biases from dispersive transmission lines. We also note that none of our designs require extra components in the receiving circuitry. All one is required to do is to obtain $\overline{\phi}$, which can be achieved rather easily, and simply conjugate it and use it as the phase of the downlink signal leaving the space antenna.

It is also important to remember that we are here to design a pilot beam system as simple as possible with the phase received by the array as close to the downlink phase as possible. We are not asked to and it is not necessary to determine the ionospheric electron density as required in some other designs.

Lastly our designs of pilot beam can be implemented easily in any large retrodirective arrays. Their advantages are (i) avoiding using phase-locked receiver (ii) free from phase ambiguity (iii) greatly reducing biases due to dispersion of the transmission line and medium (iv) very simple to be constructed.

It will be extremely interesting to have such a system built and tested in the very near future.

References

1. R. C. Chernoff, "Large Active Retrodirective Array for Space Application", IEEE Transaction on Antennas and Propagation, Vol. 27, PP 489-496, July, 1979.

2. M. I. Skolnik and D. D. King, "Self-Phasing Array Antennas", IEEE Transaction on Antennas and Propagation, Vol. 12, pp 142-149, March, 1964.

3. B. A. Sichelstiel, W. M. Waters and T. A. Wild, "Self-focusing Array Research Model", IEEE Transaction on Antennas and Propagation, Vol. 12, pp 150-154, March, 1964.

4. P. E. Glaser, "Power From the Sun: Its Future", Science, Vol. 162, pp 857-861, Nov. 22, 1968.

5. Raytheon Report No. ER79-4032, "Solar Power Satellite (SPS) Pilot Beam and Communication Link Subsystem Investigation Study - Phase 1", Jan 31, 1979, Contract No. NAS8-33157.

6. Boeing Report No. D180-24635-1, "Microwave Power Transmission System", 1978.

7. A. K. Nandi and C. Y. Tomita, "Ionospheric Effects in Active Retrodirective Array and Mitigating System Design," NASA, Solar Power Satellite, Workshop on Microwave Power Transmission and Reception, Jan. 15 - 18, 1980.

APPROVAL

PILOT SIGNALS FOR LARGE ACTIVE RETRO-DIRECTIVE ARRAYS

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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