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Phasing an Uplink Array Using Radio Source(s)

D. S. Bagri[1]

This article describes a possible approach to phasing an uplink array using radio sources in the sky. The calibration approach requires that each antenna in the array has, in addition to normal transmit electronics, two single-pole, double-throw power switches in the path of the transmit signal just before the feed; (phase) calibrated room-temperature radio-frequency amplifiers and a mixer assembly having stable path delays with time; a directional coupler and a power load; and a cable for carrying baseband signals to a central place for making phase measurements between the baseband signals from various antennas. This approach allows quick calibration of uplink array phasing at any time using a radio source close to any target direction.

It also requires the measuring of the optics path length for each antenna initially (or whenever any change is done in the optics part of an antenna) in one of several possible ways that are described briefly. This is needed for the transmit signals to coherently add at a target without requiring that the optics path lengths be the same on all the array antennas.

I. Introduction

Several schemes have been suggested for phasing uplink arrays, but until now it was felt that using a radio source in the sky is not practical for phasing an uplink array. For downlink arrays, you can use received signals from a radio source for different antennas and compare the received signals from antennas to measure the phase difference between any pair of antennas of the array, and then use that value to phase the array. How to determine phase/delay difference between signals transmitted from a pair of antennas using radio source(s) was not clear because, if you use different receive electronics from the transmit electronics, as is usually thought necessary, then differences between the transmit and receive systems make it difficult to predict the phase difference between transmit signals from the phase measurements of the received signals. In this article, we suggest a simple system that can be used to measure the transmit signal phase/delay between various antennas using radio source(s).

II. Concept

The concept for measuring relative phases for the transmit signals from various antennas of an uplink array is shown in the block diagram of Fig. 1. Here we suggest using the transmit signal, near the input

[1] Tracking Systems and Applications Section.

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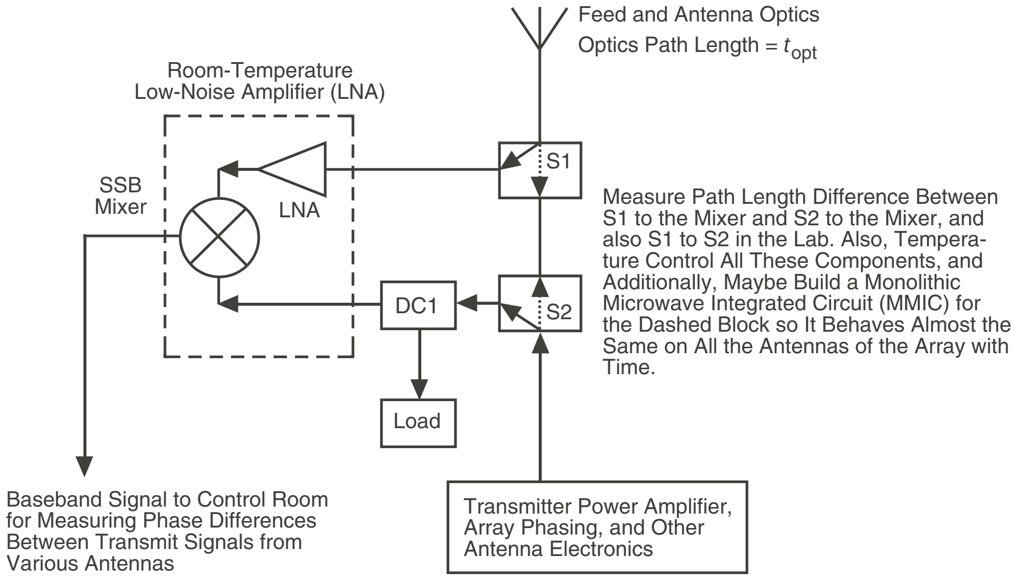


Fig. 1. Block diagram for measuring antenna transmit signal phases between various antennas of an array using a radio source.

of the (transmit) feed point, as a local oscillator (LO) for converting the received signal from a radio source (using the transmit feed) directly to baseband. First, amplify the radio frequency (RF) signal from the radio source using a simple low-noise room-temperature amplifier before giving it to a mixer for downconversion. The LO signal for the mixer is provided as shown in Fig. 1. The baseband signals from various antennas can be brought to a common place (in the central control room) to measure phase differences between different pairs of antennas.

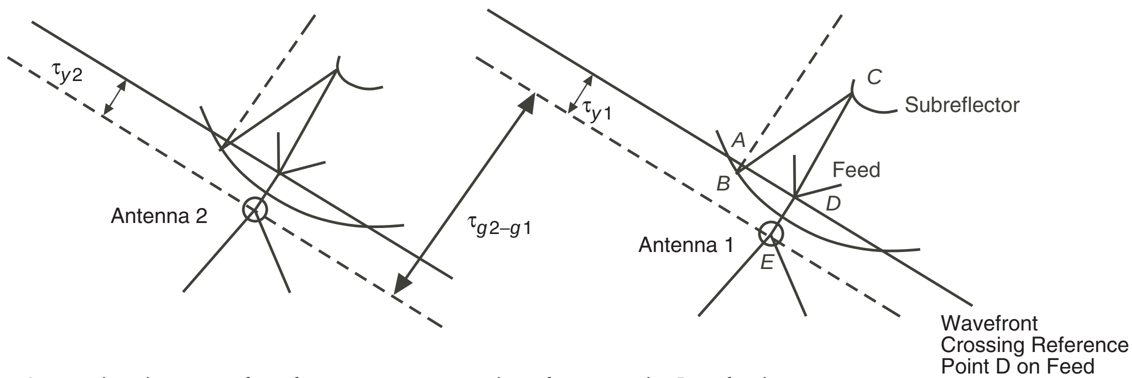
We can achieve this in the following way using two single-pole, double-throw (SPDT) switches (S1 and S2) as shown in Fig. 1. One side of each SPDT switch is connected such that in normal operations the transmit signal goes to the feed for radiating. The other side of the first SPDT switch (S1) connects the RF signal from the radio source through the feed to a room-temperature RF amplifier and to a mixer RF port. The second SPDT switch (S2) connects the transmit signal to be used as the LO signal to a directional coupler whose direct path is terminated in a load (to dissipate a large RF signal outside the dashed block), and the coupled side to the LO port of the mixer. The path lengths for the two paths have an RF amplifier on one side (S1 to the mixer) and the directional coupler (DC1) on the other side (S2 to the mixer), and S1 to S2 can be measured initially in the laboratory.

The measured phase difference between any pair of antennas depends on (1) the geometry of the radio source direction and baseline between the antennas, (2) the phase difference between the transmit signals at the feed input (used as an LO for downconverting the radio source signal to the baseband), and (3) the phase difference at the baseband due to the path length differences between the cables/electronics carrying the baseband signals from the antennas. This assumes that the room-temperature amplifier and baseband conversion process doesn't introduce any phase (or that it can be calibrated and accounted for). This can be expressed (for the upper-sideband case) as

$$\Phi_{ij} = \varpi_{rf}\big\{(\tau_{gi} - \tau_{gj}) - \tau_{(yi} - \tau_{yj}) + (\tau_{ai} - \tau_{aj}) + (\tau_{xi} - \tau_{xj}) - (\tau_{ti} - \tau_{tj})\big\} + \varpi_{bb}(\tau_{bi} - \tau_{bj})$$

Here Φ_{ij} is the measured phase difference between antennas i and j ($I, j = 1, \cdots, N$); $\varpi_{\rm rf}$ is the RF frequency; and τ_g, τ_y, τ_a, and τ_x are, respectively, the geometric delay, the distance between the point where the wavefront crosses the reference point on the feed and the point around which the antenna rotates, the excess path length due to atmosphere over the antenna, and the path length to reach the feed from the place where the wavefront crosses the reference point on the feed, as shown in Fig. 2. Also, τ_t is the delay between the reference point distributing the array transmit signal and the S1 or S2 point on the antenna at the LO/transmit frequency, $\overline{\omega}_{bb}$ is the baseband signal frequency, and τ_b is the baseband signal path length for the antenna. It is assumed that the mixers used for comparing the phases of signals from the radio source and transmitter are upper-sideband (USB) mixers having good rejection of undesired sideband, and that the effect of finite sideband rejection should be accounted for in the errors of phasing the array.

For a calibration radio source, the term due to geometric delay (τ_g) can be determined knowing the geometry of the radio source and baseline between the antennas, and therefore this term can be estimated accurately and removed from the expression for the phase measurements. The value of the phase difference between a pair of antennas due to the τ_b term (at baseband) can be determined from laboratory measurements or calibration on radio sources, and this should be stable to within a degree or two for all practical purposes, if the baseband frequency is kept small (a few megahertz). The variation in signal phase at baseband due to source baseline geometry will be small and can be accounted for in signal processing and therefore can be ignored here for this discussion. Therefore, we can determine the term $\left[\left\{(\overline{\omega}_{\mathrm{rf}}(-\tau_{yi} + \tau_{ai} + \tau_{xi} - \tau_{ti})\right\} - \left\{\overline{\omega}_{\mathrm{rf}}(-\tau_{yj} + \tau_{aj} + \tau_{xj} - \tau_{tj})\right\}\right]$.



A = a point where wavefront from source crosses the reference point *D* on feed

B = point at which signal from *A* reaches the antenna primary reflector surface

C = signal reaching subreflector after reflected from *B*

D = signal reaching feed after reflected from *C*. We can assume this as reference point on the feed for the antenna (corresponding to, say, S1 where the transmitter phase is measured)

E = point around which the antenna rotates, nominally intersection of the axes of rotation of the antenna

$\tau_x = AB + BC + CD$

τ_y = delay for a wavefront from source crossing reference point *D* on feed and point *E* around which the antenna rotates

τ_g = geometric delay for antenna (delay for wavefront from reference plane for the array to time it crosses intersection of antenna optical axes)

τ_{op} = optical path length for antenna = $\tau_y - \tau_x$

Signal path delay for antenna = $\tau_g - \tau_y + \tau_x$

τ_a = excess path length due to atmosphere over the antenna

Excess delay for the signal reaching the feed = $\tau_g + \tau_a - \tau_y + \tau_x$

Fig. 2. Schematic diagram showing signal path delays for a pair of antennas.

If we make such measurements for N antennas ($N-1$ pairs of antennas), we can determine $\{\overline{\omega}_{\rm rf}(-\tau_{yi} + \tau_{ai} + \tau_{xi} - \tau_{ti}\}$ for $N-1$ antennas with respect to a reference antenna or values for each of the N antennas with a common offset.

Now, when we transmit a signal from the ith antenna to a target having geometric delay for the antenna τ'_{gi}, we can add $(-\tau_{yi} + \tau_{ai} + \tau_{xi} - \tau_{ti})$ along with the negative value of the geometric delay in the path of the signal from the transmit reference point and feed of the antenna. Then the phase of such a signal at the feed output (S1) of the antenna can be written as

$$\left[-\overline{\omega}_{\rm rf}\left(- \tau_{yi} + (-\tau_{yi} + \tau_{ai} + \tau_{xi} - \tau_{ti}) - \tau'_{gi}\right)\right]$$

The signal from the feed (S1) output will travel through excess delay given by $(-\tau_{yi} + \tau'_{xi} + \tau'_{ai} + \tau'_{gi})$ before it reaches the target, where τ'_{xi} is the path length from the feed to the aperture plane while looking at the target and τ'_{ai} is the excess path length for the antenna due to atmosphere in the direction of the target. In that case, the net phase for the signal from the ith antenna at the target will be $\overline{\omega}_{\rm rf}(-2\tau_{yi} + \tau_{xi} + \tau'_{xi} + \tau_{ai} + \tau'_{ai})$. The differential values of atmospheric variations from antenna to antenna, i.e., $(\tau_{ai} - \tau_{aj})$ and $(\tau'_{ai} - \tau'_{aj})$, should be negligible most of the time for applications at the 7.2-GHz band (X-band) if the array is not too spread out. It means the signal at the target from the ith antenna will have undesirable delay of $(-2\tau_{yi} + \tau_{xi} + \tau'_{xi})$. It also means that, for the transmitted signals from all the uplink array antennas to add coherently at the target, we should correct signals transmitted from an antenna by this much delay before they leave the antenna. For any calibration to work, it is desirable that $\tau_{xi} = \tau'_{xi}$ (i.e., that the signal path length between points A and D be stable), and this can be achieved by proper design of the antenna structure. Therefore, we need to know $(\tau_{yi} - \tau_{xi})$.

The values of the optics path delay $\tau_{\rm op}(= \tau_y - \tau_{xi})$ may differ from one antenna to another because of variations during construction of the antennas, but if the structure of the antenna is stable, it should be constant with time (unless the antenna optics are changed). Therefore, if we measure it initially, we can account for this along with the geometric delay for the target direction.

The variation of $(\tau_{yi} - \tau_{xi})$ for each antenna with respect to a reference antenna can be estimated by comparing the phases of signals from the antennas in several possible ways:

- Use a receiver at a known location, visible from the antennas, such as a tower, a spaceborne craft, or a building top. Knowing the location of the receiver, one can determine variations of $(\tau_{yi} - \tau_{xi})$ for antennas from the receiver phase measurements between signals transmitted from various antennas. For measurements using a tower-based receiver, the atmospheric terms τ_{ai} may be different for each antenna, but if one knows the distance between the antennas and tower and the meteorological conditions on the ground, it should be possible to estimate these with adequate accuracy[2] and to apply appropriate corrections to the measurements while estimating $(\tau_{yi} - \tau_{xi})$ values.
- If the location of the receiver is not known accurately, then the following alternatives may be possible:
  - Have at least 3 receivers (preferably 4 or more) in widely separated directions, with the positions roughly known, and measure the phase differences between signals transmitted from the various antennas. Using the measured phase differences between transmit signals from various antennas, one can solve for variations of τ_{yi} and the locations of the receivers simultaneously, using at least 4 transmit antennas.
  - Have a receiver in the far field of the antennas in a known direction; then one can determine variations of $(\tau_{yi} - \tau_{xi})$ for antennas from the phase differences, measured at the receiver, between signals transmitted from the antennas.

[2] Thanks to Larry D'Addario for pointing this out.

It is also possible to use a receiver on the ground at a convenient location and transponder(s)/reflector(s) in place of receiver(s) in all of the above cases. Since these measurements are required only in the beginning, or occasionally to check the system, or when something is changed in the optics of an antenna, they can be done carefully and in favorable conditions, such as good weather.

III. Some Numbers for a Practical DSN Case

A practical case of interest for the Deep Space Network (DSN) is an equivalent isotropic radiated power (EIRP) of 85 GW using a 20-kW transmitter on a 34-m antenna. One possible way to achieve this is by using about ten 12-m antennas with 2-kW transmitters. Such an array can be calibrated using a radio source having a flux density of about 1 Jy or more at X-band, and we should have such a calibration source within 5 deg of any target direction in the sky (see [1]). With a 1-Jy radio source, ten 12-m-diameter antennas, having about 70 percent efficiency, 4-MHz baseband signal bandwidth, and 70-K system temperature (assuming ~60 K room-temperature amplifier noise temperature and antenna noise temperature of ~10 K, giving $T_{\text{sys}} = 70$ K), should give a signal-to-noise ratio (SNR) of 18 for a 30-s integration for one antenna against the other 9 antennas. (Actually, initial phasing of the array can be done on a much stronger source that may not be very close to the spacecraft direction, and only final phasing needs to be done using a nearby calibration source.) This will have a root-mean-square (rms) phase error of ~3 deg, which should have a negligible effect on combining losses. Here we have used 12-m antennas as an example, but calibration of smaller antennas (of only a few meters diameter) is possible without problems. If necessary, the integration time can easily be increased to several minutes and the baseband bandwidth to, say, 10 MHz, and one can use calibration sources that are somewhat stronger without affecting phasing at X-band most of the time.

IV. Advantages and Limitations of this Scheme and Some Related Comments

One of the advantages of the scheme described here is that we need to measure optics path length for each antenna in the array only once, or when something is changed in the optics of any antenna. During normal operations, radio sources close to the direction of the desired target can be used for phasing the uplink array antennas. Therefore, a routine calibration can be done very rapidly for all antennas simultaneously as the antenna slew time from the calibrator and target can be small.

Another advantage of the scheme is that baselines for the transmit antennas of the array can be determined by making calibration measurements on a number of radio sources with known positions in the sky and solving for the baseline values. This is an important point because otherwise it will be hard to know the exact values of the baselines between the antennas to the desired accuracy. This is because even if we survey antenna locations (foundations or some such points on or near the structures) accurately, the effective points around which antennas rotate may be displaced differently for various antennas due to construction errors (unless great care is taken, and that may be hard). In the event that the antenna baseline is referred using survey-based measurements and the actual rotation points for the antennas are differently displaced with respect to the survey points, then this will cause error in estimating the value of geometrical delay for each direction, depending on the offsets. This will introduce phasing errors for the array between calibration and looking at a target source.

This calibration scheme requires, like most other schemes (e.g., the scheme currently under test by Larry D'Addario for phasing uplink array antennas using receivers on ground or near ground), that $(\tau_{yi} - \tau_{xi})$ be stable with time; τ_{yi} should be stable because it's a rigid piece of metal, and it shouldn't be hard to keep τ_{xi} stable, but we need to be aware of this while designing the system. Also, any dependence of τ_{xi} on elevation and/or azimuth can be determined using calibration on radio sources.

It has been assumed that the path length differences between the cables/electronics carrying signals from various antennas to the control room are known a priori. This should not be a serious problem because we are considering baseband signals of up to about 5 MHz or so and, if we say that a phase error of a couple degrees will not be a problem, then we can easily tolerate variations of up to several tens of centimeters in the cables that are outdoors (the rest of the electronics are indoors and at low frequencies, so it should not be hard to keep their variations to less than a degree or two). We should be able to do this easily. The effect on phase of the baseband signal for each antenna due to path-length variations because of the source baseline geometry (τ_{gi}, the geometric term) can easily be estimated knowing the positions of the source and antennas and can be accounted for/corrected in signals generated for transmission from each antenna.

Also, we are assuming that the relative phases of the RF amplifiers, used for calibration, on different antennas are not changing or that somehow we measure the changes. We may be able to measure the phase variations by coupling a small part of the LO signal into the input of the RF amplifier and measuring the DC output of the mixer. Alternatively, we may be able to keep the phase variations small by keeping the gain for the RF amplifiers low (say, $<\sim$25 to 30 dB), controlling the temperature of the amplifier mixer electronics, and regulating the supply voltages to the RF amplifiers, etc.

To minimize the effects of strong-transmit-signal sideband noise on signal-to-noise ratio for calibration measurements on radio sources, it may be desirable to avoid baseband signals at very low frequencies (near DC). For this reason, it may be desirable to use baseband signals of 1 to 5 MHz, instead of 0 to 4 MHz.

If there are systematic variations in the values of τ_x (e.g., due to gravity; we don't expect τ_y to change with time), and they are different from one antenna to another, then it may be possible to determine the variations using calibration observations on multiple widely separated radio sources.

If smaller antennas are used instead of 12-m antennas for the transmit array, it may be necessary to use a somewhat stronger calibration source farther away from the target direction, but that only affects slew time and should not affect the uplink phasing.

V. Conclusion

This article describes a scheme for phasing uplink arrays using radio sources in the sky. The variations of optics path length between antennas can be determined in one of various suggested ways. Using this approach, the array can be calibrated to remove almost all phase changes due to instrumental variations, and it should be possible to keep phasing losses to less than a few tenths of a decibel for practical arrays most of the time, especially if calibration is done on a radio source just before using the array for transmitting the signals.

Acknowledgment

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Reference

[1] W. Majid and D. Bagri, "Availability of Calibration Sources for Measuring Spacecraft Angular Position with Sub-Nanoradian Accuracy," *The Interplanetary Network Progress Report*, vol. 42-165, Jet Propulsion Laboratory, Pasadena, California, pp. 1–8, May 15, 2006. http://ipnpr/progress_report/42-165/165D.pdf