

An SRT Interferometer at MIT Haystack Observatory

Introduction

We made a simple adding interferometer with two SRTs. To copy our configuration, you'll need, in addition to the SRTs, a high-quality coax cable to carry the L-band signal between the two antennas, at least one L-band amplifier to compensate for this cable's losses, a power supply, and various other small parts. To adjust the relative levels, a variable or switchable attenuator is desirable. During setup and testing, you'll need to either turn off each signal separately or disconnect cables and substitute a 75- Ω termination. Most of these additional parts are available at stores that supply DBS television installations. Begin with the SRTs no more than a few-hundred feet apart. The Sun is an ideal first source.

These notes assume that you are already a competent SRT operator.

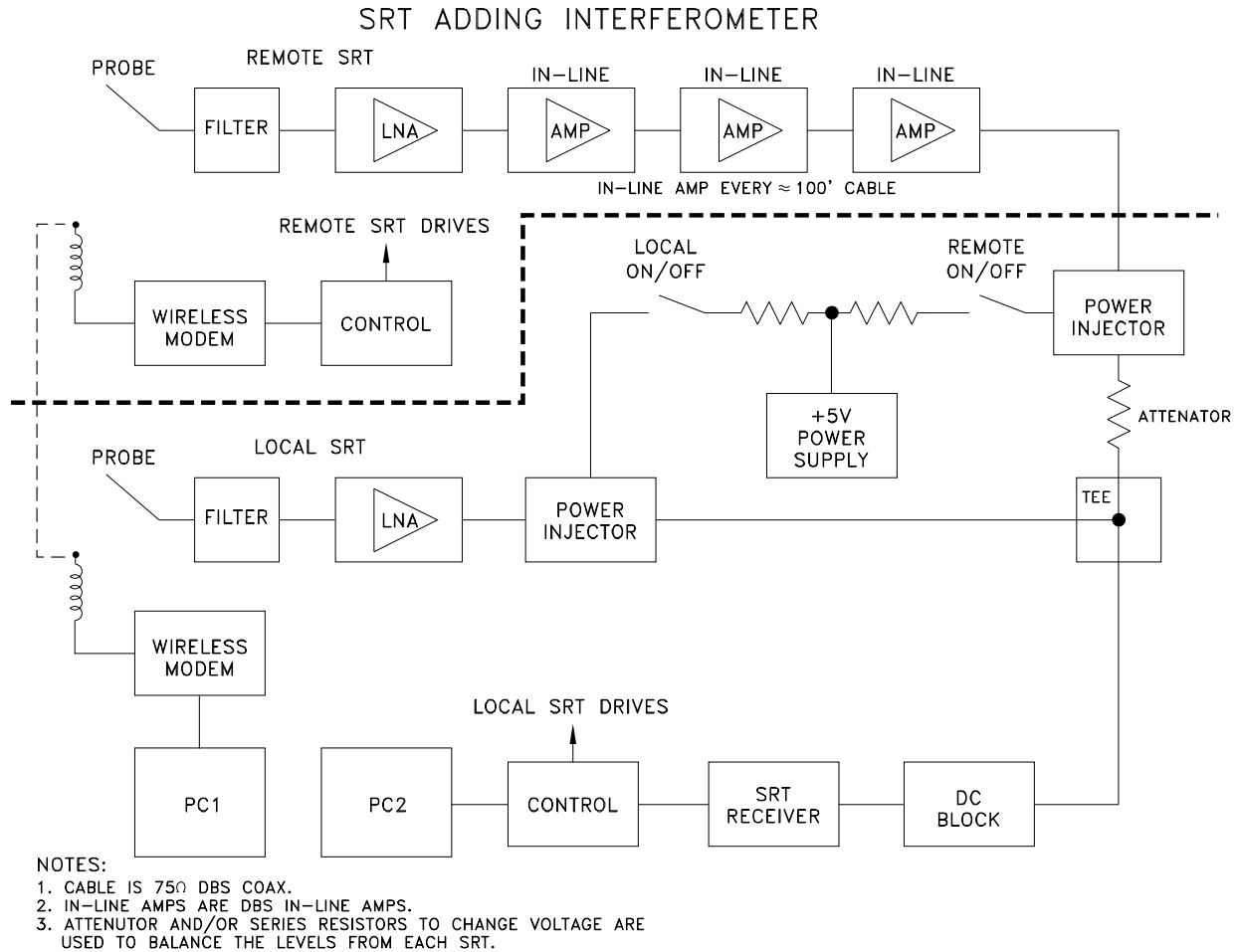


Figure 1

Configuration

Figure 1 is a block diagram of our configuration. We opened the connection between the LNA and the receiver on both SRTs and substituted the additional parts as shown. We recommend an in-line amplifier for each approximately 100 feet of cable from the remote SRT. A separate power supply fed the in-line amplifiers and the LNAs, which would otherwise receive power from their receivers. The remote receiver box is not needed. The two power switches turn off each signal separately and are used for testing and calibration as described below. The power injectors contain DC blocks, and a separate DC block at the input of the receiver prevents the receiver's power supply from being shorted by the attenuator. The tee should be a 75-Ω magic tee (diplexer), which provides an

impedance match on all three ports, but with an ordinary tee, the mismatch is not too serious.

Some simplifications are possible. Provided that you're willing to do setup and calibration by disconnecting cables, one of the power injectors and both power switches can be omitted. In this case, move the DC block to the line to the attenuator so that the local LNA receives power from its receiver.

A wireless-modem pair connected the remote SRT's control box to a PC near the local SRT. We can thus control the pointing of both SRTs from one location.

We obtained these extra parts from vendors such as Radio Shack (<http://www.radioshack.com/>) and Skyvision (<http://www.skyvision.com/>).



Photo 1

Photo 1 shows both antennas of our interferometer from behind the trailer that contains the PCs and some of the electronics equipment. The remote antenna, some 180 feet away, is just visible at the left edge of the picture above the red car. Neither antenna is pointing at the Sun.

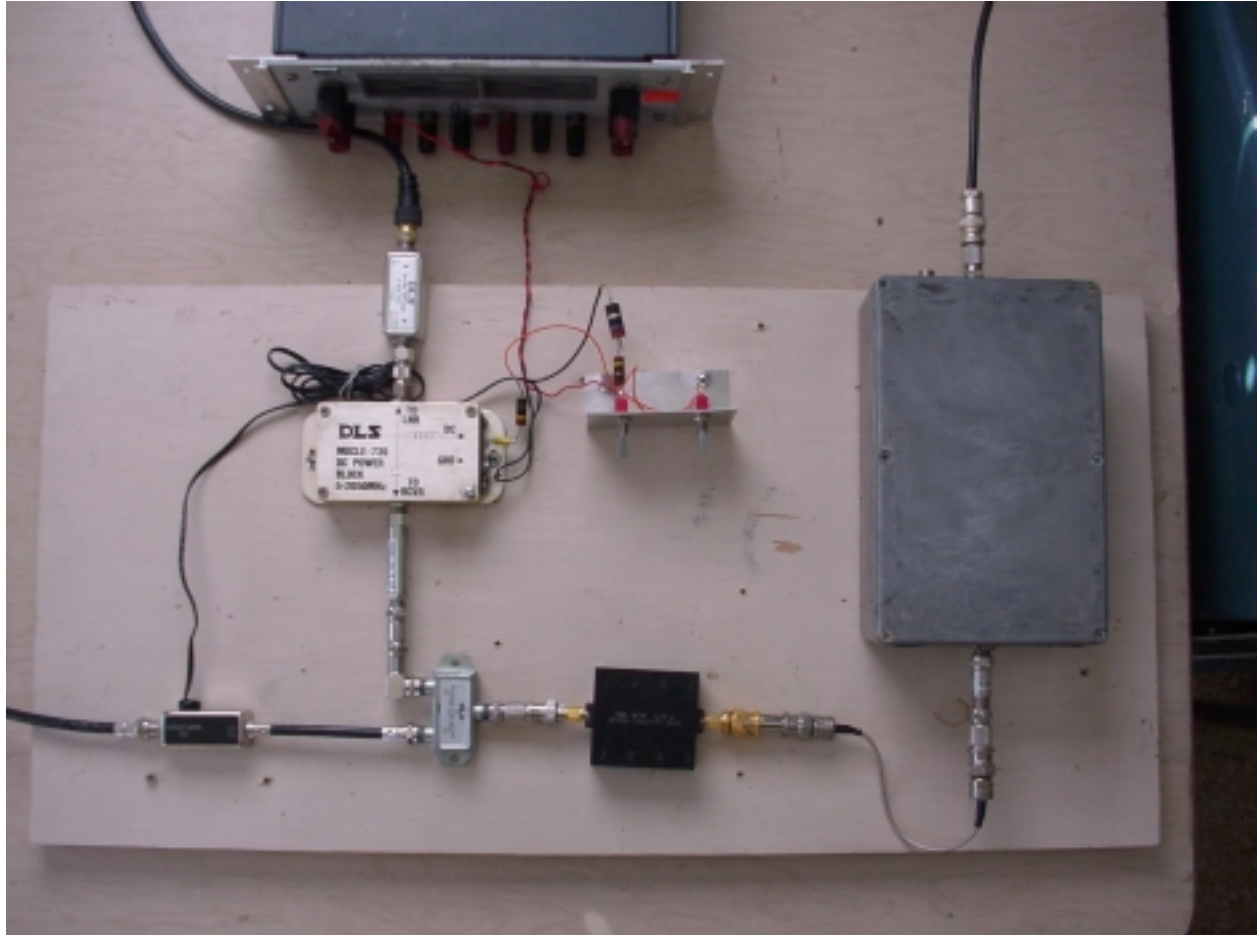


Photo 2

Photo 2 shows our breadboard. The extra power supply is at the top, partly off the picture. The two power switches are near the center. The two power injectors, very different in size, are center left and lower far left. The dark square box lower center is a DC block to the receiver, which is the large box to the right. The signal from the remote antenna comes in from the lower left; the signal from the local antenna comes from the upper left past the power supply and through an additional amplifier not shown in Figure 1.

Setup and Adjustment

1) Either turn off each signal in turn, or, at the tee, temporarily disconnect the cable from each SRT and replace it with a $75\text{-}\Omega$ termination onto the tee. With both antennas pointing away from any strong source, adjust the attenuator so that each antenna alone gives the same power reading in the receiver. With both antennas reconnected, the power level should be 3 dB higher than with either antenna alone. This procedure gives the correct level setting provided that the two SRTs have the same gain and system temperature.

2) Now point each antenna in turn at a strong source such as the Sun. If the gains and system temperatures of the two SRTs are the same, then the change in level from off source to on source should be the same for each antenna (with the other antenna pointing off source). This measurement is a little more difficult than 1) above, but if you're sure that the off-source to on-source power levels are not the same, then you should readjust the attenuator to make them the same.

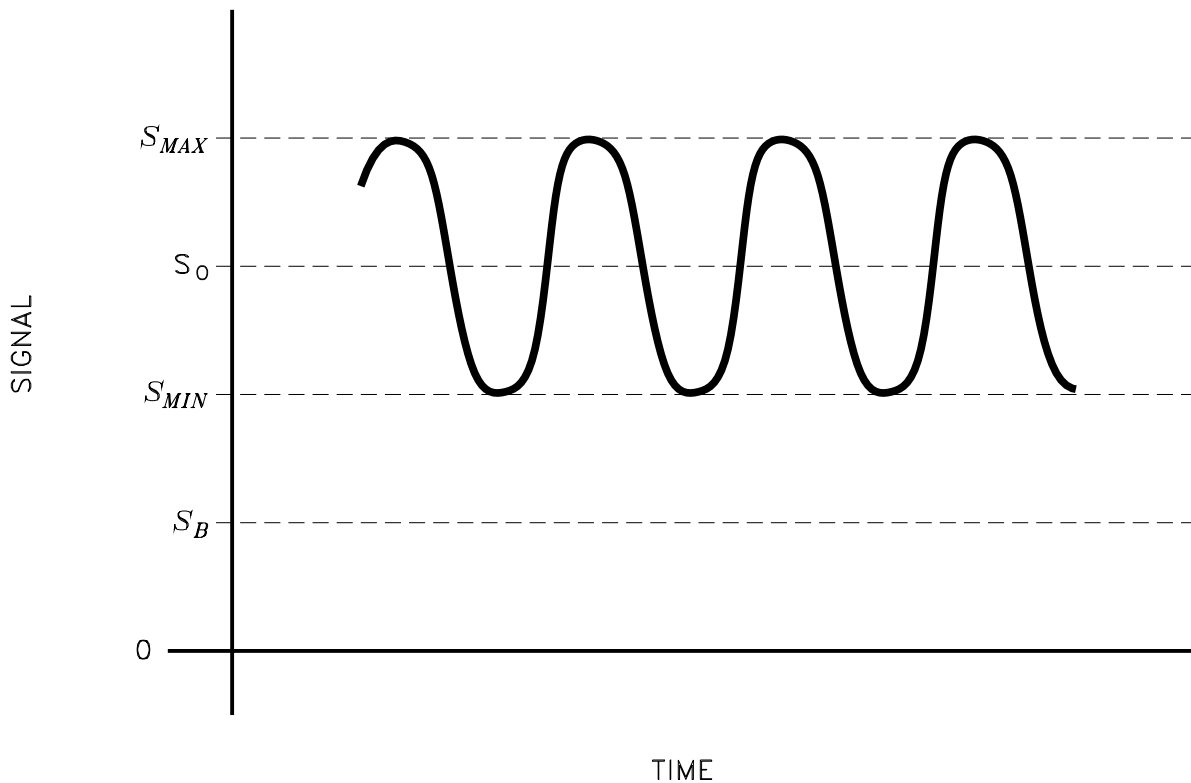


Figure 2

3) With both antennas connected and tracking the source, you should see fringes as in Figure 2.

Analysis

From a plot such as Figure 2, estimate the fringe amplitude by dividing the amplitude of this quasi-sinusoidal variation, $(S_{MAX} - S_{MIN})/2$, by its mean value referred to the base level with no source present in either antenna's beam, that is $S_O - S_B$. The fringe amplitude will range from unity in case the source's angular size is small compared with the interferometer's resolution to zero in case the source's size is large compared with the resolution. Since fringe amplitude is a ratio of power levels, it does not depend on conventional noise calibration.

Estimate the fringe phase at any time by multiplying 360° times the time back to the previous positive-going S_O crossing divided by the period, which is the time between successive positive-going S_O crossings.

The amplitude of these fringes depends on the angular size of the source on the sky compared with the interferometer's resolution as calculated below. Two limiting cases are: (a) The source is large in angle compared with the interferometer's resolution. In this case there are either no fringes or small fringes created by variations in brightness across the face of the source. The chart recorder draws a horizontal line at S_O , a level corresponding to the sum of the powers from the two antennas. If, instead, (b) the source is small in angle compared with the interferometer's resolution, then the fringes will be full size, which means that the bottom of each fringe will touch the base level corresponding to no source in either beam, $S_{MIN} = S_B$; the center of each fringe, S_O , will be at the same level as in case (a); and the top of each fringe, S_{MAX} , will be as high above S_O .

The formula for the angular beamwidth (full width to half power in radians) of an antenna, namely $1.2\lambda/D$, where λ is the wavelength and D is the diameter of the antenna (in the same units), is similar to the formula for a simple interferometer's resolution or fringe spacing (angular period), namely λ/D (in radians), but here D is the spacing between antennas (baseline length) times a

trigonometric factor that accounts for the geometry of the source's location relative to the baseline's orientation. An interferometer's resolution is usually much narrower than a single antenna's resolution. These interferometer fringes in angle translate into fringes in time using the rate of rotation of the Earth times another trigonometric factor. In the simplest possible case, where the baseline is just east-to-west and the source is just at transit, both these trigonometric factors are unity, and the time for a fringe cycle is approximately $(\lambda/D) \times (12 \text{ hours}/\pi)$. For $\lambda=21 \text{ cm}$ and $D=200 \text{ feet}$, get approximately $\lambda/D=0.2$ (the Sun's diameter is about 0.53°) and about 47.4 timesecods per fringe cycle.

Interpretation

Imagine that you are at the source on the sky looking back toward the interferometer on Earth. As the Earth turns, the apparent baseline length as seen from the source will usually be shorter than its actual length as seen face on. When the interferometer is near the edge of the Earth as seen from the source (i.e., the source is just rising or setting as seen from the interferometer), the baseline might appear to be very short indeed. This foreshortened length and its orientation interact with the source to determine the fringe amplitude and phase, which thus change as the Earth turns. In a typical situation, with the baseline more-or-less east-to-west, as the source moves away from transit, the apparent baseline foreshortens, the fringe spacing increases, and the fringe amplitude may also increase. But with a north-to-south baseline, the changes can go the other way.

While still looking back toward Earth from the source, imagine a plane perpendicular to your line of sight on which you plot the projected baseline with the convention that one end of the baseline is always plotted at the origin of coordinates. At each moment of time, plot two points corresponding to having each end of the apparent baseline at the origin. These two points will be, of course, just opposite each other with the origin between. The distance from each point to the origin is the foreshortened baseline length, and the vector angle is that of the projected baseline in source-oriented coordinates, typically right ascension (*RA*) and declination (*Dec*).

As time passes, these points move and trace out two ellipses—either whole ellipses in 24 hours if the source is circumpolar (i.e., never sets) or arcs of ellipses that start when the source rises and end when the source sets. Note that these ellipses depend on the locations of the antennas on Earth (the baseline as a vector) and also depend on the location of the source (specifically its declination) on the sky. With the axes labeled in wavelengths (rather than, say, feet), this is the famous uv plane, much discussed by radio astronomers.

With more than two antennas, there are more than two ellipses at a time. With n antennas, there are $n(n-1)/2$ baselines, each with a pair of ellipses. But the same thing can be achieved with just two antennas by moving one of them each day and observing over many days—*provided* that the source doesn't change over this time. (The Sun does change.) If you can fill in most of the uv plane with ellipses, then you can make a map of the source on the sky by gridding your fringe amplitudes and phases onto the uv plane and calculating the Fourier transform. This is sometimes called *aperture synthesis* because you have thus synthesized a virtual antenna with an aperture (diameter) about as large as the spacing between or among the real antennas.

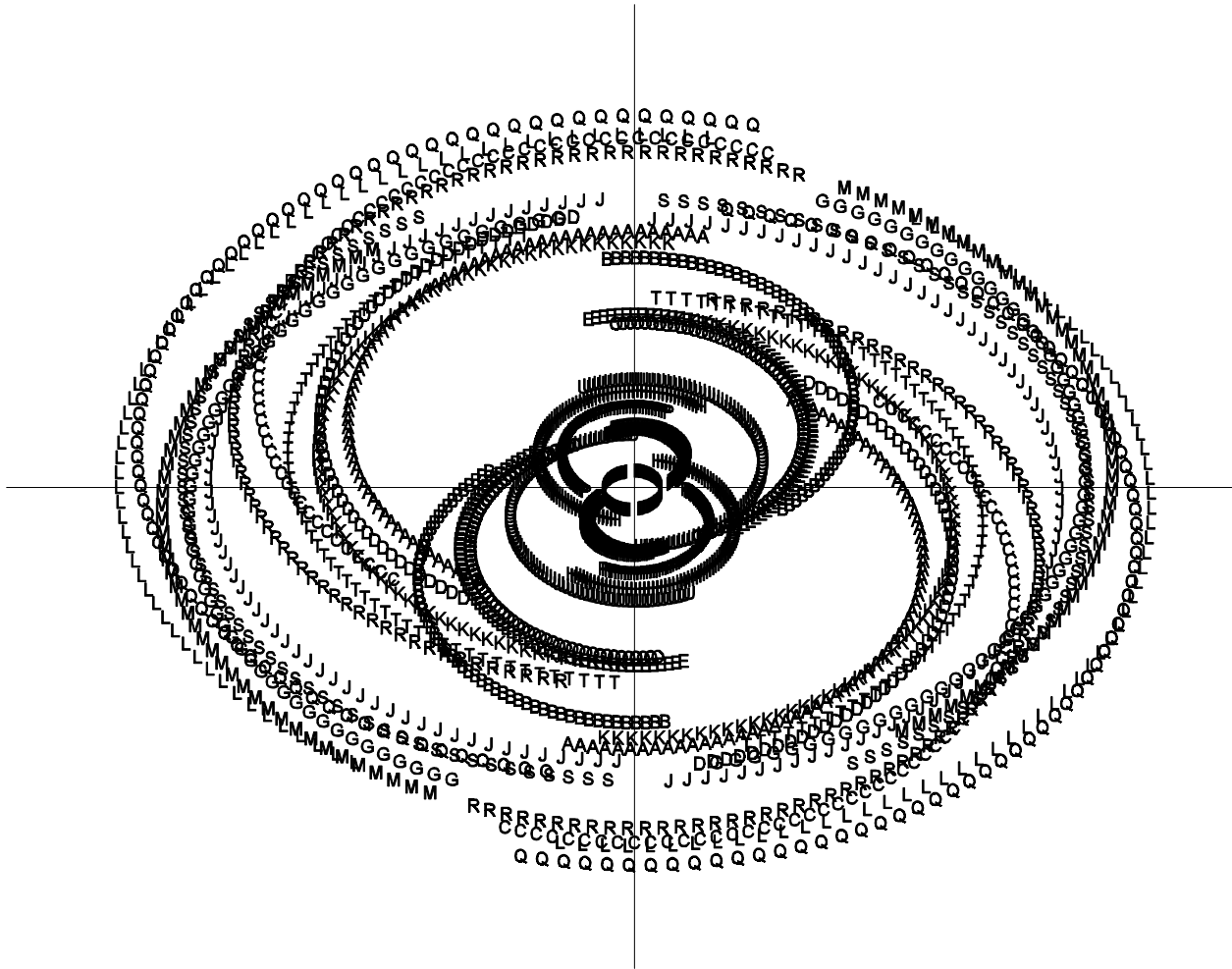


Figure 3

Figure 3 is an example uv plane coverage for a realistic interferometer. Each elliptic arc is plotted with a letter corresponding to a single baseline, that is a single pair of antennas. Each arc starts when the source rises and ends when the source sets at either of the two antennas. Figure 3 is for 7 antennas or 21 baselines. This plot was made using PC-SCHED (see References below) and copied from the PC-SCHED *User's Guide*.

For an SRT interferometer, determine the vector baseline by measuring D (distance), Az (azimuth angle), and El (elevation angle) sighting from one antenna toward the other. Then use COORD(), example II, or ARPNC, section A.7.6

(cites in References below), to calculate the HA (hour angle) and Dec of the two spots on the sky toward which the baseline points. For any source at any time, the foreshortening angle, θ , is the angular separation on the sky from the source to the (nearest) baseline end spot. Given the HA (variable) and Dec of the source and the HA and Dec of the baseline end spot, use `COORD()`, example XII, or ARPNC, section A.7.2, to calculate the angular separation, which is θ . Then the effective baseline length, which is the radius from the origin in the uv plane, is D times the sine of θ . The vector angle from the origin to the points in the uv plane is the initial heading also from `COORD()`, example XII, or ARPNC, section A.7.2.

SRT Interferometer--Sun

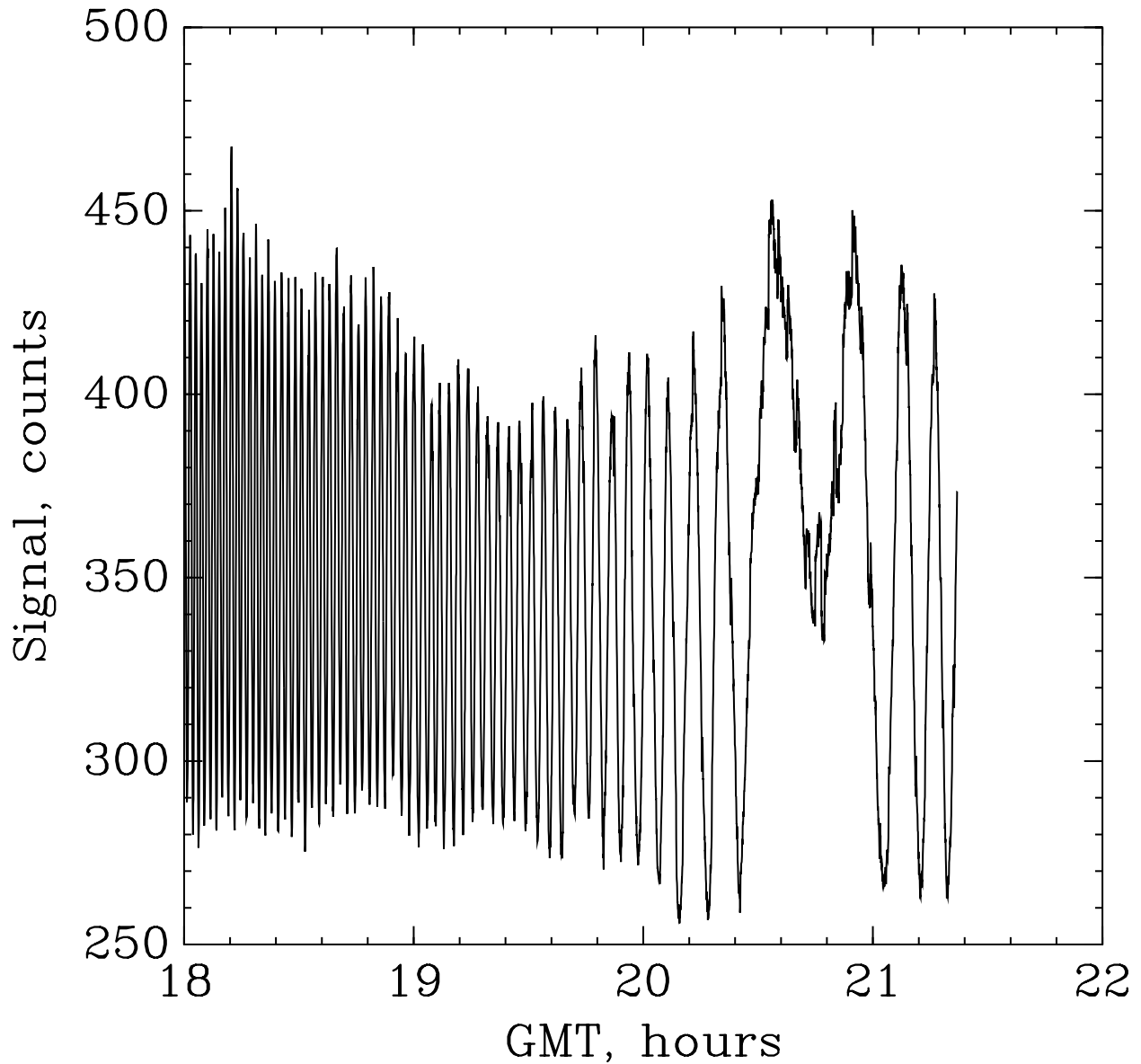


Figure 4

Sample Experiment

Figure 4 shows some of the results of a preliminary interferometer experiment done at Haystack on 2001 September 8. In this plot, Az ranges from about 209° to 260° and El from about 50° down to 19° , which is where an SRT hit

a limit stop. Some of the variations in fringe amplitude in Figure 4 are due to receiver noise or clouds, but some perhaps represent structure on the face of the Sun. At about 20:45 GMT, the Sun's path on the sky reached its closest approach to the end-of-baseline spot, then moved on past and away. This caused the phase-motion reversal at this time in Figure 4. Note that prior to this time, the fringe period was lengthening and the fringe amplitude was increasing a little because the apparent baseline was foreshortening.

Using a hand-held GPS receiver, we measured, rather crudely, the positions of our two SRT antennas and calculated our baseline to be 55 meters long (D) at Az 48°5 and El 2°. From this we calculated its hour angle to be $-7^{\text{h}}57^{\text{m}}50^{\text{s}}$ and declination $+30^{\circ}43'29''$ or, at the other end, $+4^{\text{h}}02^{\text{m}}10^{\text{s}}$ and $-30^{\circ}43'29''$. These calculations can be done using `COORD()`, examples XII and II, or `ARPNC`, sections A.7.2 and A.7.6.

Next we located the Sun on 2001 September 8 using MICA. (The SRT pointing program also knows where the Sun was.) The approximate coordinates were RA $11^{\text{h}}08^{\text{m}}$ and Dec $+5^{\circ}32'$, but the Sun was moving appreciably in this coordinate system, and this motion needs to be taken into account as the afternoon passes.

To compare with Figure 4, we can calculate the fringes that we would see if the Sun were a point source and with some other simplifying approximations. To calculate fringe phases, we need to determine the time delay in arrival of a plane wave from the Sun at one end of the baseline relative to the other. The additional distance is just the baseline length, D , times the cosine of the foreshortening angle, θ . Then multiply this distance times $360^{\circ}/\lambda$, where λ is the wavelength, to get a fringe phase. There is also an additional fixed delay (phase offset) in the cable from the remote antenna.

The overall scheme is as follows: For any date and time, calculate a local sidereal time, LST , and an RA and Dec for the Sun, perhaps from MICA. Then the Sun's HA is $LST-RA$. (For precise work, the Sun's coordinates should be corrected for atmospheric refraction. One way to do this is to convert HA and Dec to Az and El , correct this El for refraction, then convert back to HA and

Dec.) Next calculate the foreshortening angle, θ , and the fringe phase as above. Then with the point-source assumption (i.e., fringe amplitude unity), we can make a plot to compare with Figure 4 above. Figure 5 is such a plot.

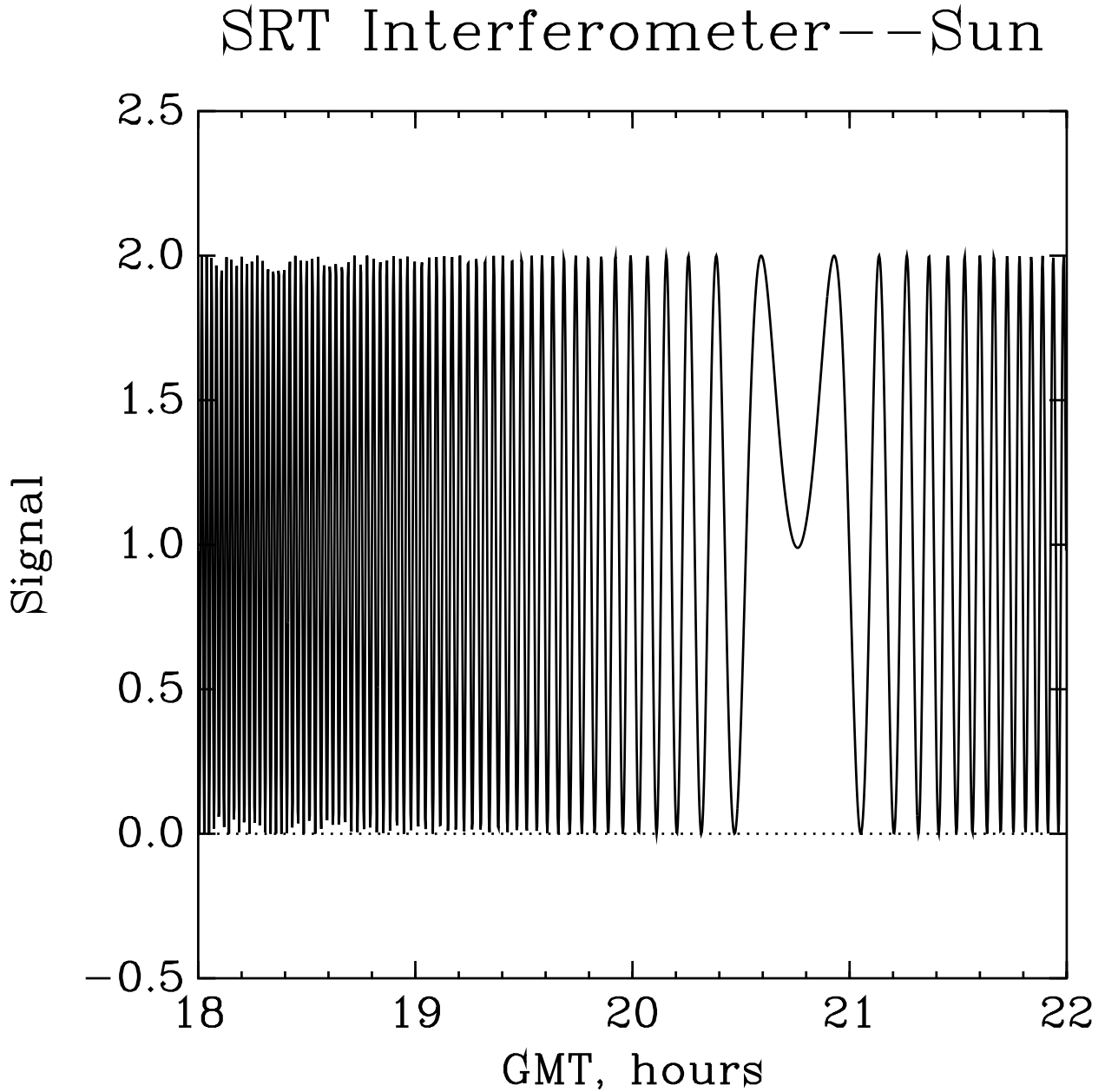


Figure 5

The fringe amplitudes in Figure 5 are not correct, of course, but the phase variations of Figure 4 are quite well reproduced in Figure 5 despite the imprecise baseline parameters and the various approximations.

Future Work

Interferometers can be used to help solve two separate classes of problems: If we know the locations of our antennas on Earth and the various motions of Earth (e.g., rotation and revolution), then we can use interferometers to learn about angular locations, angular sizes, and angular structures of astronomical objects—this is astronomy. If, instead, we already know about such objects on the sky, then we can use interferometers to learn about the locations of our antennas on Earth and about Earth’s motions—this is geodesy. With very-long-baseline interferometry (VLBI), that is tape-recorder interferometry with up to transcontinental baselines, we can measure angular structures on the sky with milliarcsecond precision or locations of antennas on Earth with millimeter precision.

With SRTs, our capabilities are more limited, but we should be able to use well-known information about the Earth and Sun with data such as in Figure 4 above to calculate the relative locations of our SRT antennas (the vector baseline) perhaps to within some fraction of λ (21 cm) and some fraction of the Sun’s diameter (about 0.53). To do this, we would treat the D , Az , and El (or D , HA , and Dec) of the baseline (and a fixed phase offset) as parameters to be determined, calculate a model as in Figure 5 but with these parameters as variables, and use a least-squares fitting procedure to fit the model to our data to determine these baseline parameters. This is left as an exercise for the reader.

References and Notes

The Astronomical Almanac, U.S. Naval Observatory and H.M. Nautical Almanac Office, U.S. Government Printing Office, Washington, and The Stationery Office, London, yearly.

ARPNC = *Algorithms for RPN Calculators* by John A. Ball, Wiley-Interscience, New York, 1978.

COORD() is a FORTRAN subroutine originally in *Some FORTRAN Subprograms Used in Astronomy*, by J. A. Ball, MIT Lincoln Laboratory Technical Note 1969-42, 16 July 1969. A revised version with more examples is in <http://fourier.haystack.edu/coord.f>.

Kraus, John D., *Radio Astronomy*, 2nd edition, Cygnus-Quasar Books, Powell, Ohio, 1986, section 6-10, page 6-20, *et seq.*

MICA = *Multiyear Interactive Computer Almanac 1990-2005*, version 1.5, U.S. Naval Observatory, Willmann-Bell, Richmond, Virginia, 1998. See also <http://aa.usno.navy.mil/software/>.

PC-SCHED, version 3.6, by D. A. Schultz and A. E. E. Rogers, in <http://fourier.haystack.edu/haystack/pc-sched.html>. The *User's Guide* (1989) is out of print, alas.

Rohlfs, K., and Wilson, T. L., *Tools of Radio Astronomy*, 2nd edition, Springer-Verlag, Heidelberg, Germany, 1996, chapter 7, page 160, *et seq.*

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