NATIONAL RADIO ASTRONOMY OBSERVATORY
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# OBSERVING THE SUN WITH THE VLA

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## 1.0 INTRODUCTION AND BACKGROUND READING

The VLA receivers were designed for observations of galactic and extragalactic radio sources, where the dominant source of noise is the receivers themselves and where the total system noise varies only over a small range. Observations of the Sun are difficult because, first, the Sun dominates the system noise at all bands, raising it above its design value by a factor of 200 to several thousand; and, second, the Sun is highly variable, so that the system noise temperature is hard to predict in advance.

Modifications to the hardware to facilitate solar observations are underway as of this date. These necessarily represent a compromise, in that it was not possible at reasonable cost to optimize the receiver performance for the whole range of expected solar flux at all bands. The final choices resulted from extensive studies and discussions by the technical staff (principally John W. Archer, Peter J. Napier and myself), in consultation with solar astronomers who are users of the VLA.

The hardware modifications are described by Archer [1,2], and the reader is assumed to be familiar with his reports. As background to understanding these, one should have a good, general understanding of the operation of the VLA electronics (see, e.g., [3]).

The present report deals with the use of this equipment for actual observations and with data reduction procedures, with the objective of obtaining accurately calibrated visibility measurements.

Interim procedures for observing with the original hardware (prior to the planned modifications [2]) are also mentioned. Procedures for computing maps, or for any other processing of the calibrated visibilities, will not be covered here. Special software for mapping solar data would be desirable; but since it is not yet available, the user is restricted to mapping techniques identical to those for weak sources.

## 2.0 ASSUMPTIONS REQUIRED IN CALIBRATING THE MEASUREMENTS

In observation of relatively weak sources ($T_A << T_{sys}$, where $T_A$ is the antenna temperature due to the source and $T_{sys}$ is the system temperature), calibration of the interferometers is achieved by observing a calibrator; i.e., a weak source of known position and/or flux density which is also known to be unresolved. From the observed visibilities, the complex gain which each interferometer had during the calibrator observation can be determined. To transfer this information to the unknown source observation, we make use of stable noise sources which are connected to each receivers input; the magnitudes of the visibilities observed for both unknown and calibrator are normalized to the measured signal strength from this noise source. To transfer the phase, we simply assume that the phase of the complex gain is the same for the unknown and the calibrator. The magnitude (or "amplitude") calibration is thus facilitated by referencing both calibrator and unknown to the same noise source, thus accounting for any gain change between the two observations. Note that, for the VLA, a change in system temperature (total noise power referred to the receiver input) leads directly to a change in gain through the action of ALC loops.

This method does not work when observing the Sun because there are no calibrators of strength comparable to the Sun; and the discrepancy is so large that there is no choice of reference noise source strength such that the noise source is detectable when observing the Sun, and the calibrator is detectable when the noise source is on. If two different reference sources are used, then the ratio of their strengths (for each receiving channel of each antenna) must be accurately known and stable.

## 2.1 Amplitude Calibration

Noise sources appropriate to calibrator observations are already available at all antennas. Because the installation of additional high-temperature noise sources and appropriate switching circuitry at all antennas would be very expensive, we have chosen to do so at only one antenna[1]. We can transfer the measured strength of the signal from the noise sources at this antenna to the other antennas by making the following assumptions:

1. the gain of any receiving channel is inversely proportional to the total noise power referred to its input;
2. $T_A >> T_R$ for all receivers, so $T_R$ can be neglected; and
3. all antenna temperatures $T_A$ of the same polarization are equal.

That is, we assume that the Sun dominates the system temperature and that all antennas intercept the same solar flux. The latter requires that the antennas have equal efficiencies and that they be identically pointed.

At 18-21 cm, 6 cm and 2 cm we believe that the efficiencies are the same within about 2%; at 1.3 cm, variations in surface accuracy and focusing make this less certain. However, serious violations of assumption 3 can result from pointing errors, especially when pointing near the limb of the Sun. Of course, the effect gets worse with increasing frequency. Also, assumption 3 can be violated if a strong active region is in a side lobe of the antenna beam, since side lobe aperture efficiency is subject to much wider variation than main beam efficiency.

Assumption 2 is easily satisfied at 18-21 cm and 6 cm, where $T_R < .002T_A$ for the quiet Sun, provided that $T_R$ has its normal value of about 50 K (if the paramps are turned off, $T_R \approx 1000$ K $= .05T_A$ for the quiet Sun). At 2 cm and 1.3 cm, $T_R \approx .05T_A$ at normal $T_R \approx 300$ K, again for the quiet Sun [2].

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[1] For better reliability, a second antenna will probably be so equipped later.

Assumption 1 is violated at any one time only to the extent that the receiving channel is nonlinear. This can happen if some amplifiers are allowed to saturate, and for this reason some means of reducing the gain when pointing at the Sun must be introduced early in the signal processing.

One further piece of data is needed in order to compare the visibilities observed on a calibrator to those observed on the Sun: the ratios of the output powers of the high-temperature noise sources (one for each polarization at the single antenna having them) to the low-temperature noise sources for the corresponding polarizations at all antennas. If the user is not concerned with obtaining an accurate absolute calibration (in Janskys, say) then only the relative values of these ratios are required; but note that this still requires that the relative strengths of the numerous low-temperature noise sources be known. Such knowledge is not needed for weak source observations, since, for every receiving channel, the same noise source can be used for both unknown and calibrator, so that its strength cancels out.

With the above assumptions and data, it is possible to calibrate the magnitudes of the observed solar visibilities in absolute units, e.g., Janskys or sfu. The accuracy with which this can be done depends on various factors, including

a. the extent to which the system temperature at the various antennas are unequal (violations of assumption 2 or 3);

b. the accuracy with which the reference noise source strengths are known;

c. the accuracy with which the signal from the reference noise sources can be measured during the observation;

d. the extent to which the calibrator is partially resolved on some baselines;

e. the extent to which the transfer functions (passbands) of the receiving channels are not identical, so that the interferometer complex gains cannot be accurately expressed with channel complex gains; and others.

Items c, d and e occur similarly for nonsolar observations, and will not be discussed in detail here. Item a has already been discussed. In practice, the largest contributor to the error budget is probably item b. The various low-temperature noise sources are regularly intercompared by pointing at the Moon; this check is done approximately monthly, and the results are maintained by the VLA Telescope Operations staff. These should be accurate to about 10% peak error in the ratios. It should also be possible to measure the ratios of the corresponding high- and low-temperature sources at the same antenna to an accuracy of a few percent, but a regular procedure and schedule for doing this has not yet been worked out. The reference source data maintained by the VLA staff applies to only one observing frequency in each band, normally the frequency resulting from the "default" LO settings; variations of about 35% can be expected across a band, so observers using other frequencies are advised to do their own calibration of the reference sources.

If the high-temperature reference sources are available on no antennas, a rough estimate of the system temperature while observing the Sun can be made by monitoring a total power detector placed ahead of the first ALC loop. (At this writing, such detectors are available for channel C on almost all antennas and for channel A on about half of the antennas; eventually they will all be phased out in order to implement more accurate gain monitoring). This requires assuming that the gain ahead of the detector (about 120 dB) is stable and that the gain reduction inserted for observing the Sun can be separately measured (see 3.2, below).

## 2.2 Phase Calibration

We would like to be able to make the same assumption as is made with weak-source observations, namely that the phase of the complex gains is the same for the unknown (the Sun) and the calibrator. But this may not work, for two reasons: first, steps must be taken to reduce the gain of each receiver when observing the Sun, and this can introduce large and widely varying phase shifts; and second, since the range of solar fluxes of interest is large, part of the gain change must be taken up by an ALC loop which has significant phase variation with gain[2].

There are several ways in which the gain can be reduced by an amount appropriate for observing the Sun: the parametric amplifiers may be turned off, for a net change of about 23 dB; an RF attenuator may be inserted further downstream, for an adjustable change now set at 15 dB but planned to be 8 dB [2, Addendum, p. 5]; and an attenuator may be inserted just after the paramps for a change of 20 dB (planned). This last attenuator is not yet installed, but prototypes have been tested; it is specifically for solar observing, and should introduce negligible phase change ($<0.1°$) when switched in or out. Phase changes for the other methods are large and unpredictable.

With carefully chosen amounts of gain reduction, the operating point of the ALC loop can be kept about the same when observing the calibrator at normal gain and the Sun at reduced gain. For a quantitative discussion, see [2].

However, if it is necessary to use one of the first two methods of gain reduction (as in the interim until the "solar attenuators" are installed), then either the calibrator must also be observed at reduced gain, or a correction must be made for the phase shift. Neither method is very desirable. If the paramps are turned off, then in practice they must be left off for the whole observing session because the pump oscillators require a long warmup time (~30 minutes) for stable operation; thus any calibrator observations except those at the beginning

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[2] The ALC loop was carefully designed to minimize the latter effect, but it could not be made negligible.

must be made with reduced gain, and also with increased receiver temperature ($T_R \approx 1000$ K at the 6-cm band). This means that only a few strong calibrators are usable. Observing calibrators at reduced gain may also result in some channels having insufficient spare gain to bring the correlator input signal up to normal level; baselines involving these channels will record no useful data. The spare gain must come from the ALC loops. The first ALC loop, at the antenna, usually will not have enough spare gain and will operate wide open, introducing an uncalibratable phase shift. The second (and last) loop, at the Control Building, then takes up the slack (if it can), introducing an additional phase shift.

The alternate procedure of observing the calibrator at normal gain and the Sun at reduced gain and later correcting for the phase difference of the two modes requires that this phase difference be measured for each channel. We can make the reasonable assumption that the phase differences are stable over the observing period, so that they need be determined only once. We can then do so by observing one very strong calibrator, not necessarily near the Sun, at both normal and reduced gain; this yields the phase differences by baseline, and these must be reduced to phase differences by receiving channel for compatibility with the available software. Note that the latter reduction can lead to additional errors (known as "closure errors") if the transfer functions of the channels are not identical.

Any method which requires observing a calibrator at reduced gain and assuming that the instrumental phase is then similar to that obtained on the Sun (also at reduced gain) suffers from the fact that the ALC loops will be at vastly different operating points during the two observations, introducing unknown phase errors. These errors are probably between 20 and 50 degrees; they will partially cancel on some baselines by being similar at some antennas, but presently there is a mixture of types of ALC attenuators so that some errors could be of opposite sign. Eventually all ALC loops will be similar and have lower phase shifts, but by then the zero-phase-shift solar attenuators should be installed.

### 2.3 Polarization

Polarization calibration of solar observations is beyond the scope of this report. Those wishing to make maps of polarized solar radiation are advised first to become expert at polarization mapping of weak sources with the VLA, a procedure not without considerable difficulties. Effects more peculiar to solar observations include (1) the fact that most of the polarization is usually circular, whereas for other sources it is usually linear, and therefore the beam-squint phenomenon [4-6] has a more serious effect; (2) the existing software makes some approximations not appropriate for large circular polarization; and (3) at most bands, the Sun produces significant radiation, polarized and unpolarized, from a region large compared with the antenna beam.

## 3.0 OBSERVING PROCEDURES

### 3.1 Planned

After the planned modifications [2] are completed, it will be possible (and recommended) to observe in the following way: observe a calibrator near the Sun every 10 to 60 minutes (depending on the expected instrumental and atmospheric stability) using normal gain and with the reference noise sources at normal level (low temperature) for all channels. Observe the Sun using reduced gain by means of the special attenuators, and with the reference sources at high level for those channels on which this is available.

It will still be necessary to know, as accurately as possible, the relative strengths of all reference sources at the actual frequency of observation. This may require a separate astronomical calibration.

The visibility data will be corrected to standard system temperatures using off-line software. However, on-line software exists which will correct for system temperature variations, but it does not take account of the special conditions of solar observing. Therefore, the user must ensure that the on-line correction is disabled for his entire program, including calibrators. This is accomplished through the on-line control files [7, and revisions thereto]; note that when the correction is disabled, certain scaling factors in the control files must also be changed[3].

Another consideration is the visibility data exponent, known in the software as the "gain code" (although it has nothing to do with gain). This results from the fact that visibilities are stored as fixed-point numbers, and the user must specify, in advance, the size of the numbers to be stored; they are then appropriately shifted to fit the available 16-bit words. Unfortunately, the same shift is used for all baselines and polarizations; and the off-line mapping software will later require that all the data to be used in a particular map be identically shifted. A "gain code" of 0 (zero) stores the 16 least significant bits of the correlator output, and should be used whenever the correlation coefficients on all baselines will be less than .004; larger correlation coefficients will produce overflows. A "gain code" of N > 0 causes the data to be shifted right N bits before storing; N = 8 will store 100% correlation coefficients without overflow, but the 8 least significant bits of correlator output are lost. On the Sun, correlation coefficients above 50% can occur on short baselines.

### 3.2 Interim

Table I(a) gives a typical observing sequence for use when the special attenuators are not available. Provision is made at the beginning (and optionally at the end) for measuring the

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[3] As with nearly all of the on-line software, there is no documentation on this. See Barry Clark, since only he is familiar with the details.

## TABLE I: INTERIM OBSERVING SEQUENCES

### (a) Parametric Amplifiers Left On

| Source | Gain | Duration | |
|---|---|---|---|
| Calibrator | normal | 3 minutes | |
| Calibrator | reduced | 12 | |
| Sun | reduced | 20 | repeat as required |
| Calibrator | normal | 3 | |
| o | | | |
| o | | | |
| o | | | |
| Calibrator | normal | 3 | optional |
| Calibrator | reduced | 12 | |

### (b) Parametric Amplifiers Off

| | | | |
|---|---|---|---|
| Strong calibrator | normal | 3 | |
| Strong calibrator | PA off | 27 | |
| Sun | PA off | 20 | repeat as required |
| Strong calibrator | PA off | 10 | |
| o | | | |
| o | | | |
| o | | | |

phase change introduced by the gain reduction.

However, if the gain reduction is done by turning off the parametric amplifiers, then the sequence of Table I(b) is more appropriate. In this case, a very strong calibrator must be used, since the receiver temperature is significantly increased (to about 1000 K at 2 and 6 cm, and about 3300 K at 2 and 1.3 cm). In addition, relatively long calibration times are needed for good SNR.

Furthermore, only the initial, normal-gain calibrator observation can be used for amplitude calibration; the others are usable for phase calibration only.

If, in addition to not having the special attenuators, the high-temperature reference noise sources are not available on at least one antenna, then the best known procedure for establishing the amplitude scale is the following: choose a channel on which a total power detector is available ahead of the first ALC; calibrate the scale of this detector (detector output/system temperature) at normal gain using the low-temperature reference source; and measure, with laboratory equipment, the gain change when the gain is reduced to the value used for solar observing. The detector scale can then be assumed to increase by the gain reduction factor. The latter measurement must be made before or after the observing period, so it is necessary to assume that the gain reduction factor is the same throughout the observation. One must also assume that the gain ahead of the detector does not vary between times when the detector scale at normal gain can be redetermined. Finally, the measurement of the gain reduction factor can only be expected to be accurate to ±1 dB.

## 4.0 REDUCTION PROCEDURES

Sufficient software exists to carry out the calibration methods discussed in Sections 2 and 3 above, subject to the assumptions and limitations mentioned there. A suggested procedure is given in Table II.

## TABLE II: TYPICAL DATA REDUCTION PROCEDURE

| Step | Description | Program(s) Needed |
|---|---|---|
| 1 | Edit to delete bad measurements. | LISTER, FLAGER |
| 2 | Enter flux densities of calibrators. | SETJY |
| 3 | Correct normal-gain observations to standard $T_{sys}$ (requires table of reference source temperatures). | GTTSYS |
| 4 | Correct solar observations to standard $T_{sys}$, using actual $T_{sys}$ from one antenna. | GTTSYS |
| 5 | Correct all observations for any other known system errors, e.g., antenna position (baseline) errors. | GTBCOR |
| 6 | Correct the solar observations for any known phase difference between solar and calibrator observations. | GTBCOR |
| 7 | For each calibrator observation, solve for the system complex gains by receiving channel. | ANTSOL |
| 8 | Take the complex gains determined from normal-gain calibrator observations and apply only the amplitude part to the solar observations. | GTBCAL |
| 9 | Take the complex gains determined from phase calibration observations (either normal or reduced gain) and apply only the phase part to the solar observations. | GTBCAL |

The details of operating the programs should be obtained from current program documentation and will not be covered here.

In step 4, the $T_{sys}$ correction of the solar observations requires knowledge of the high-temperature reference source strength (if available), or knowledge of the total power detector scale.

Steps 8 and 9 can be combined if the phase calibration observations can be made at normal gain.

# REFERENCES

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