VLA Computer Memorandum No. 180

ERRORS IN THE VLA GAIN CALIBRATION WHEN OBSERVING THE SUN

T. S. Bastian

Summary

The online gain calibration of solar visibility data is reviewed. Two serious errors were present in the calibration of solar visibility data beginning in early 1982. One of these errors was recognized and corrected in mid-1985. The other was not recognized until early 1989. Each of these errors is discussed in detail. Implications for published data are discussed elsewhere.

I. INTRODUCTION

The Very Large Array (VLA) is presently the largest and most powerful synthesis radio telescope in the world. While designed for high resolution imaging of cosmic sources, the VLA has also been used with considerable success to observe the Sun. Such observations are fraught with difficulties, not the least of them being an accurate calibration of the antenna gains.

In this memorandum, I discuss two sources of significant error in the gain calibration of solar visibility data. One error existed between the years 1982–1985; once recognized it was corrected, although in my opinion neither the error nor the fact that it had been corrected was widely known, leading to a good deal of confusion. The second error was also present since early 1982 but was not recognized until early 1989. It has also now been corrected. The purpose of this memorandum is to decribe the details of the VLA solar gain calibration system and to discuss the the nature of the errors which arose in the online calibration of solar visibility data. Implications for published data are discussed in Scientific Memorandum No. 160.

II. ONLINE GAIN CALIBRATION OF SOLAR OBSERVATIONS

The online gain calibration of solar observations has been described in considerable detail elsewhere (Archer 1979, D'Addario 1980, Bastian 1989). Here, for the purposes of later discussion, we follow Bastian (1989).

When observing the Sun, the the source dominates the system temperature at all bands, raising the system temperatures by factors of several hundred to several thousand times the design values. In order to observe the Sun, two fundamental hardware modifications are therefore necessary.

First, it is necessary to reduce the effective gain of the receiving system of each antenna. This is accomplished by inserting attenuators into the front end of each antenna. The choice of the most appropriate value for the insertion loss introduced by the switched attenuators was driven by constraints imposed by the "automatic level control" or ALC loops, and by consideration of the microwave emitting properties of the quiet and active Sun. The ALC loops are designed to maintain constant power inputs to the correlator. Since the power level is proportional to the product of the system temperature and the antenna gain, any change in T_{sys} results in a change in the antenna gain; i.e., the antenna gain is deliberately adjusted to ensure constant power inputs to the correlator through the actions of ALC loops.

Since the antenna gain is allowed to vary, some means of monitoring the antenna gain is necessary. Normally, a switched noise signal of known amplitude is injected into each receiver input. Expressed in terms of an equivalent temperature, T_{cal}, the amplitude of the injected signal is typically such that $T_{cal} \approx 0.1 T_{sys}$. Separate noise sources are provided for each band and for each of the two orthogonal senses of polarization. Gain calibration is accomplished through two measurements performed in the front end of each antenna: the *synchronous-detector voltage* and the *total-power voltage*. The synchronous-detector voltage V_{SD} is a measure of the *difference* between the total-power levels when the noise source is on and when it is off. The total-power voltage V_{TP} measures the power level when the noise source is off. The former is, or course, proportional to T_{cal}, the injected noise times the IF gain; the latter is proportional to T_{sys} times the gain. It is then clear that

$$T_{sys} \propto \frac{V_{TP}}{V_{SD}} T_{cal} \qquad (1)$$

Since the gain is inversely proportional to T_{sys} the antenna gains are corrected by multiplying by $T_{sys}{}^{1/2}$, the so-called "T_{sys} correction".

When observing the Sun, the normal T_{cal}'s are of no use because they are orders of magnitude smaller than T_{sys}. Hence, when observing the Sun, special high-temperature noise sources are employed. However, because of the expense of retrofitting all twenty-eight VLA antennas with high-temperature noise sources (*solar CALs*), only four VLA antennas are provided with solar CALs except at 20 cm (five) and 3.6 cm, for which all antennas possess solar CALs. The solar CALs have been adjusted so that T_{cal} is $\approx$10% of the system temperature resulting from quiet Sun conditions.

In practice, several factors limit the accuracy of the solar gain calibration. First, because, in general, only four VLA antennas are outfitted with solar CALs, the gain of the remaining antennas must bootstrapped from those for which T_{sys} is explicitly measured. To do so, one must assume (D'Addario 1979) that i) $T_{ant} \gg T_{rx}$; ii) the gain of each antenna is inversely proportional to T_{sys}(i.e., is linear); and iii) that T_{sys} is the same for all antennas for a given polarization. Assumption (i) is certainly true for all bands. Assumption (ii) is true for quiet Sun observing programs but difficulties are sometimes encountered when observing large, bright solar active regions or large flares. Assumption (iii) is incorrect to the extent that antenna pointing errors result in variations in T_{sys} from one antenna to another, particularly when imaging a source near the solar limb.

A second difficulty involves the accuracy with which the solar CALs are known. Since there is no celestial source of known flux density and sufficient strength to serve as a reference for the solar CALs, they must be measured on an individual basis in the field. The accuracy to which this measurement can be made is of order 20% (P. Lilie, private communication). With four antennas measured the gain calibration should be good to 10%.

The way in which the online T_{sys} correction is actually implemented is somewhat messy, involving many modules and spanning several computers. VLA visibility data are normally written to tape in "D10 units" which correspond roughly to units of Janskys/10. The T_{sys} correction therefore converts a scaled "raw" correlation coefficient into D10 units. To do so, not only are V_{SD} and V_{TP} required for each IF at a particular frequency, two other quantities, the "antenna efficiency" ϵ and T_{cal}, are required for each antenna and IF. The latter two quantities are read from the "IF file" which is maintained on the MODCOMP. Online, a gain factor g_i is formed for each antenna i:

$$g_i = \frac{24.32\epsilon_i}{\mathrm{T}_{\mathrm{cal\ i}}} \tag{2}$$

Every 10 s (the data dump time), for each antenna and each IF a $\mathrm{T}_{\mathrm{sys}}$ correction η_i is computed as

$$\eta_i = \frac{\mathrm{V}_{\mathrm{TP\ i}}}{\mathrm{V}_{\mathrm{SD\ i}}}\frac{1}{g_i} = \frac{3.0\mathrm{T}_{\mathrm{cal\ i}}}{24.32\mathrm{V}_{\mathrm{SD\ i}}\epsilon_{\mathrm{i}}} \tag{3}$$

where V_{TP} has been replaced by its nominal value of 3.0 volts. The quantity η_i is sometimes referred to as the "nominal sensitivity". The gain factors embodied in η_i are applied to the data in the array processor. There, a complex visibility measured on a baseline ij is multiplied by $\sqrt{\eta_i\eta_j}$ before being written to tape. It is seen that division of a visibility V_{ij} by the geometrical mean of the nominal sensitivities of antennas i and j allows one to recover the raw, scaled correlation coefficient for that baseline from the data written on a MODCOMP tape.

During a solar observing run, one typically *turns off* the online $\mathrm{T}_{\mathrm{sys}}$ correction for all antennas except those which have solar CALs. This is done by setting the appropriate flag for a given antenna in the "ROT file", also maintained on the MODCOMP. *Note, however, that all visibility data involving antenna i are nevertheless multiplied by a gain factor $\sqrt{g_i}$.*

III. THE NATURE OF THE ERRORS

A. Interpretation of the Nominal Sensitivity

In the spring of 1982, changes were made to the online software which resulted in two errors in the gain calibration of solar visibility data. One of these errors involved the interpretation of the so-called "nominal sensitivity" recorded on the MODCOMP tape, while the other involved interpretation of quantities written to the IF file. As described above, the nominal sensitivity is an antenna-based quantity that ostensibly allows one to recover the "raw" correlation coefficient. In fact, the correlation coefficient is a scaled quantity such that unity correlation yields 256.0. The nominal sensitivity embodies all antenna-based gain corrections that have been applied to the data to convert the scaled correlation coefficient into D10 flux units, i.e., Janskys/10 (approximately).

Prior to 1982, the nominal sensitivity, η_i' was defined and written to tape as

$$\eta_i' = (\eta_i)^{1/2} \tag{4}$$

with η defined as above in eqn. (3). On 1 April 1982 (honest), a change was made to the online software such that the nominal sensitivity was replaced by η_i, rather than η_i'. Unfortunately, while documented, this change did not propagate to the offline software (specifically, the DEC-10 FILLER). Hence, between April 1982 and July 1985, solar visibility data for those baselines which did not involve a solar CAL antenna were corrected as

$$V_{ij} = \eta_1 \eta_2 v_{ij} \tag{5}$$

rather than

$$V_{ij} = (\eta_1 \eta_2)^{1/2} v_{ij}. \tag{6}$$

Only *solar* visibility data were affected by the error.

B. Interpretation of the IF File

As shown above, computation of the nominal sensitivity involves ϵ, the antenna efficiency, the CAL temperature $T_{\rm cal}$, and a constant factor. Taken together with the $T_{\rm sys}$ correction, these quantities convert a raw visibility to D10 units. The quantities ϵ and $T_{\rm cal}$ are read for each antenna and IF pair from the "IF file", maintained on the MODCOMP. For those antennas not equiped with high-temperature solar CALs, ϵ and $T_{\rm cal}$ were, until recently, assigned the values 0.4 and 2.667, respectively.

I have informally polled both members of the solar radio community who have used the VLA and staff members at the VLA and have found that these default values for ϵ and $T_{\rm cal}$ were assumed to represent either 1) dummy quantities that were not explicitly interpreted by the online system during solar observations or 2) quantities that, while applied to the data in the usual way, were normalized out of the data downstream. It turns out that, prior to 1982, the latter interpretation was correct. If one evaluates $24.32\epsilon/T_{cal}$, one gets 2.0. This factor of 2.0 was later divided out by the online system. Hence, a nominal sensitivity of 1.0 was written to tape for non-solar CAL antennas.

The changes made to the online software on 1 April 1982 no longer took this factor of 2.0 into account – yet the change was not reflected in the procedures used for solar observing. Further, the documentation for the relevant changes to the online software is so inadequate that it was never apparent that such changes were necessary. In order to account for this change, the parameters in the IF file should have been chosen such that $g_i = 24.32\epsilon_i/T_{cal\ i}$ was 1.0 rather than 2.0. This was not done and solar observers were unaware that it should be done.

The net result of this second error was that 1) those baselines involving two non-solar CAL antennas were multiplied by 0.5 when run through the DEC-10 FILLER; 2) those baselines involving one solar CAL antenna and one non-solar CAL antenna were multiplied by $2^{-1/2}$; 3) those baselines involving two solar CAL antennas were unaffected by the error. The problem has now been corrected; all data acquired with the VLA later than 1988 should be free of the error.

IV. DISCUSSION

The difficulties described above were avoidable. Their cause was primarily a problem in internal communication between constituents of the VLA computing division and between the computing division and members of the solar radio-astronomical community who are regular users of the VLA. True, the integrity of the data is ultimately the observers' responsibility. On the other hand, the Sun is a complex and variable source – it is not always possible to establish "what it *should* look like" for reasons described in Scientific Memorandum No. 160. It would therefore be extremely useful for members of the computing staff to alert solar astronomers, in some intelligible way, to software changes that might affect their data. Conversely, solar astronomers who use the VLA must make a conscientious effort to be aware of any such changes and to be alert to their consequences for their solar visibility data.

I thank K. Sowinski and G. Hunt for useful discussions.

REFERENCES

Bastian, T. S. (1989), "Solar Imaging with a Synthesis Telescope" in *Synthesis Imaging in Radio Astronomy*", R. A. Perley, F. R. Schwab, and A. H. Bridle (eds.), ASP Conf. Series, vol. 6, 509 pp.

Archer, J. W. (1979), "Modifications to the VLA front ends for solar observations", NRAO, Addendum to VLA Electronics Memorandum No. 181.

D'Addario, L. R. (1979), "Observing the Sun with the VLA", NRAO, VLA Scientific Memorandum No. 130.