DOING PASSIVE RADIO ASTRONOMY WITH A MST/ST SYSTEM: A FAST CROSSCORRELATION ALGORITHM

Ronald F. Woodman and
Martin Sarango
Radio Observatorio de Jicamarca, Instituto Geofísico del Perú

There are not too many antennas in the VHF range in the world dedicated to radio astronomy. ST, and specially MST, radars require and have large antenna appertures which could also be used for radio astronomical observations. Definitely, the Jicamarca antenna, the largest in the world (300 m x 300m), has a potential in this field which has not been fully exploited. The present paper was motivated by such application. In addition to the antennas, all radars do their signal processing using digital equipment, which could also be used for this additional application. However, because of the large processing speed required by radio astronomy, some ingenuity and innovation is required.

The simplest astronomical aplication of a VHF antenna is the detection of radio sources or the measurement of their properties. This aplication requires, at least, a power and crosscorrelation processing instrument (interferometer) capable of measuring their position, intensity and size. Jupiter, an importance source, which in fact motivated the present work, is known to be partially polarized. To measure its polarization matrix, a crosscorrelation instrument is required.

The accuracy of power and crosscorretion measurements depend on the number of independent points used in perfoming the statistical averages. The number of independent points, in a given observational (integration) time, is given by the bandwidth of the system. The larger the bandwidth, the larger the number of independent points, and the better the accuracy of the measurements, but at the same time the larger the sampling rate and processing requirements. In the case of Jicamarca the bandwidth is of the order of 1 MHz. It is limited by the bandwidth of the phased array. In a single base line interferometer, or in a polarimeter, we have two complex receiver outputs to process. The power and crosscorrelation estimates require the following operations on the two complex outputs of the receivers, Ai+ jAq and Bi +jBq:

$$Pa=Sum(Ai^2 + Aq^2)$$

$$Pb= Sum(Bi^2 + Bq^2)$$

and $$Re(Pab)= Sum(AiBi + AqBq)$$

$$Im(Pab)= Sum(AiBq- AqBi).$$

There are eight multiply, fetch and sum operations for every sample set used in above estimates, which at the bandwidth mentioned above, they would imply at least 8 million multiplies and sums per second. This is quite a demand for a PC computer, often used in ST and MST radars. The algorithm to be described here reduces the mutiplying demands to only a few per integration period, and to one fetch and add per sample.

The algorithm is based on an alternative way to perform the same average estimates in terms of probability distribution functions (p.d.f.) of the random variables involved. We need to recall the formula for the expectation of a discrete random variable ξ , $E(\xi)$, in terms of its p.d.f., $P(\xi=x) = F(x)$. It is given by $E(\xi)$ =Sum[x F(x)]. The sumation is performed over all possible outcomes of x. The possible outcomes for a random variable which results ---as in the expresions on the right hand side of above equations--- out of the product of two discrete random variables of n bits each, is $2^n \times 2^n= 2^{2n}$. So the expectation can be performed by the sumation of the results of 2^{2n} multiplications, a very small amount when compared with the standard way of obtaining the averages. The burden of the operation is now in evaluating an estimate of the p.d.f., F(x), for all the possible outcomes in above experiment. This, except for a normalizing factor, is simply a count of the number of occurrences of each possible outcome, in a way no different to the way one could evaluate the probabilities for the outcome of the throwing of a die, by actually throwing the die n times and evaluate the distribution by counting. In a corresponding digital implementation, one assigns a computer memory address to each possible outcome of the two factors (2^{2n} addresses), and increments its contents by one, each time the corresponding outcome occurs.

Let us assume for a moment that we need to evaluate only one of the averages of above products, let us say the AiBq product. Let us assume each term is represented by 3 bits (It can be shown that even 1.5 bits, i.e. 3 discrete levels, are sufficiently accurate). Then, there are 64 possible combinations of the two factors in the products and we can assign one memory location to each. Furthermore, a considerable number of computer instructions can be saved if we concatenate the two outcomes corresponding to the two factors into a single number of 6 bits, and use it to control the address of the memory locations were the number of occurrences of that particular pair of numbers is stored. In addition, we pre-store the product corresponding to each of the combinations in a second identical array. The full implementation of the proposed algorithm would then be as follows. The sampled values of each factor are combined (concatenated) to produce a single digital number. For each sample, a 6 bit number is read into the computer. This number is used as a pointer, directly controling the memory address register pointing to the memory location were the count for that particular outcome is stored. For each dual sample a count of one is added to the corresponding address. At the end of the integration period, say a million samples, an estimate of the bivariate probability density distribution function is obtained, except for a normalization factor. To obtain the desired average, we multiply the 64 possible products pre-stored in one of the arrays with the corresponding 64 estimated values and sum the 64 results. In comparison, the classical way would have requiered one million multiply and add operations to do the same. The normalization factor can be factored out at these later stage.

Our algorithm is even more advantageous with our actual requirement since it can perform the eight required averages with no additional real time operations. It would only use more memory . Only once at the end of the integration period the number of operations is increased. But, similarly to the one product case, these operations at the end are a very small fraction of the total number of real time operations. In order to evaluate the eight different averages required to determine the power and the crosscorrelation of the two complex processes we evaluate a four-variate p.d.f. The four random variables correspond to the two in-phase and two quadrature samples of the two complex samples. In this case we concatanate the four 3-bit samples to produce a 12 bit number, which is similarly used as a pointer to the memory location corresponding to the count of the particular outcome. The bivariate distribution functions needed to compute each of the eigth possible averages are obtained by summing over the two variables that are not involved. This opperation require 64 sums of 64 terms each and it is performed once at the end of each integration. Note that the number of real time operations, i.e. the "increment by one" at the location of the pointer address, is the same as in the two variable case, but the memory requirement is 2^{12}= 4096 locations, 64 times larger, still way within the size of an economical memory requirements.

Figure 1 depicts the implementation of the algorith using our Antarctic PC-based radar processing system. These radar has two DSP boards connected in series in two ISA slots of the PC mother board. Figure 1 shows the way the concatanation of the samples has been performed and the operations performed in the first board. The first board evaluates the (unnormalized) p.d.f for a given integration period using a double buffer scheme. Further integrations, and the actual averaging operation, is performed at this time off line. Future plans involve the perfoming of the averaging operation in the second DSP board, with on-line graphics to be performed by the PC.

The integration time should be selected as a compromise between a maximun determined by an overflow of the contents of a 16 bit integer word (64 K occurances of the most probable combination) and a minimum to reduce the data rate to a rate compatible with a digital recording system. The DSP board used is capable of 500, 000 dual complex samples per second, less than the maximum badwidth of the system but comparable to the optimum sample rate for the IF bandwidth of our receivers (~300 KHz). At the serial output of the DSP we have 4096 2-byte words every integration period.

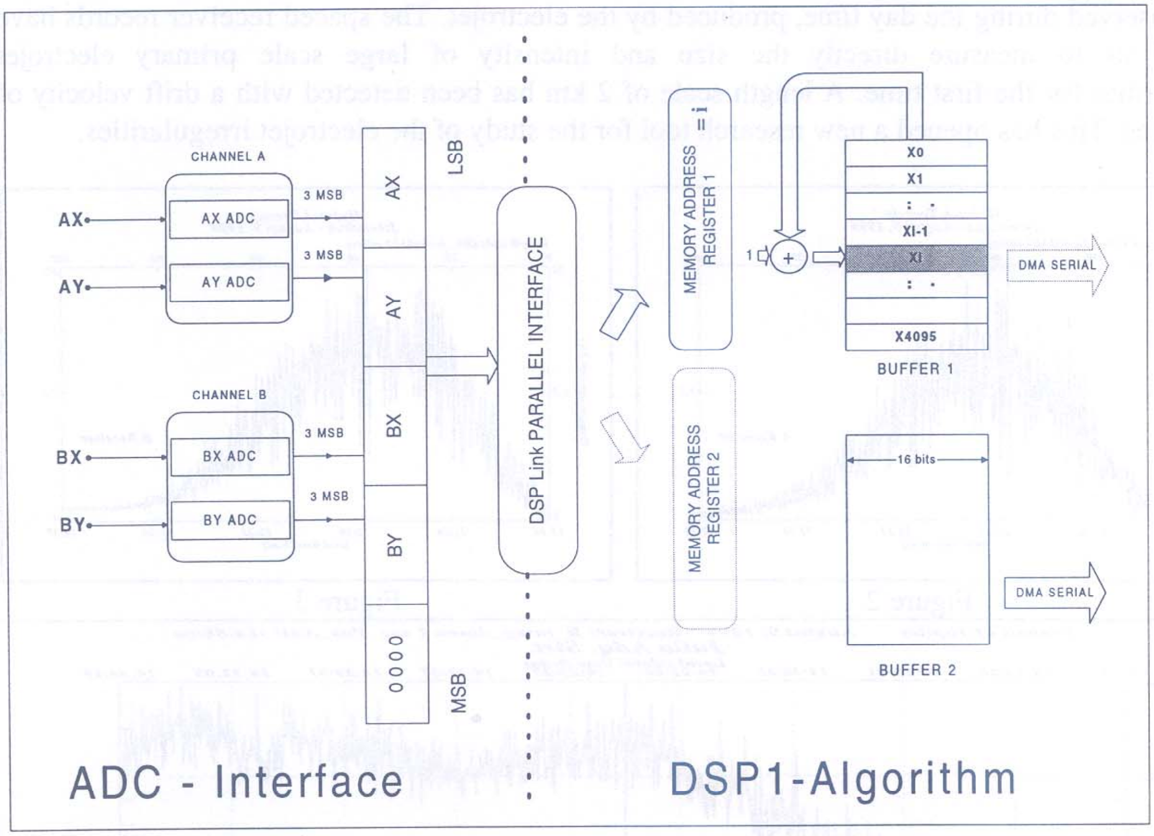

Figure 1

For the first applications presented here, we limited the integration time to a very conservative value: 64 K samples, enough to reduce the output data rate to confortable values for a digital recording system or for outputing it to a ethernet network. We performed further integrations off line. For typical transient times of radio sources of the order of a few minutes or more, desirable integrations would be of the order of several seconds. Having reduced the data output to a few tens of kilowords per second or less, there is no limit in the number of further integrations to be performed on the second DSP board or the PC .

So far, we have used the system for two applications. The first one, which actually motivated the development of the system, was the observation of Jupiter metric synchrotron radiation. This was the first time that such a measurament was made at 50 MHz. The interset in such a masurement is enhanced given the unique sensitivity of the Jicamarca antenna and the fact that during the measurements, the Shoemaker-Levy comet was colliding with Jupiter. The outcome of this measuraments will be the subject of a subsequent paper. Nevertheless, in Figure 2 we show as an illustration the power received by one of the antennas around the transient time. A small bump occurrs at the time of Jupiter transient, but smaller than its expected amplitude. Furthermore, later measurames seem to indicate than the bumb is largely due to a radio source in the same position in the sky background. This apparantly small signal strength at 50 Mhz is a surprising and interesting result. The crosscorrelation possibilities of the instrument were used to implement an interferometer and a polarimeter. Jupiter radiation is partly polarized, but no polarization was observed at the time of the transient.

The other application was the observation of the strongest radio source at Jicamarca latitudes: Hydra A. Its transient by two spaced antennas is shown in Figure 3. Very strong scintillations were observed during the day time, produced by the electrojet. The spaced receiver records have allowed us to measure directly the size and intensity of large scale primary electrojet irregularities for the first time. A length scale of 2 km has been detected with a drift velocity of 132 m/cec. This has opened a new research tool for the study of the electrojet irregularities.

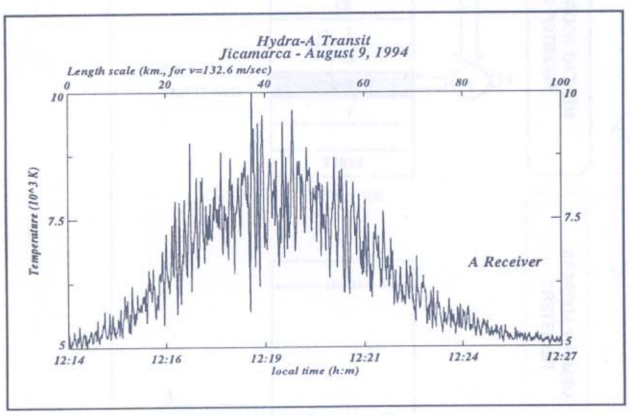

Figure 2

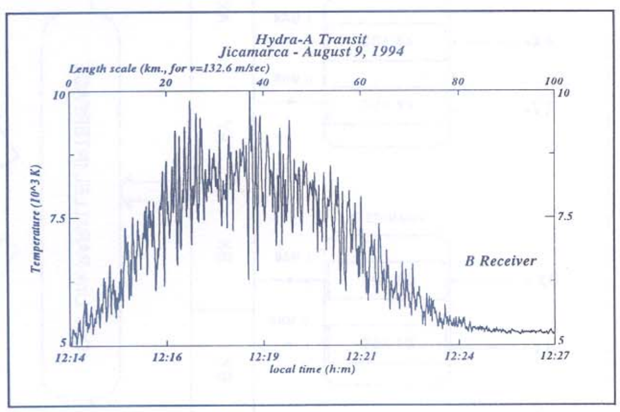

Figure 3

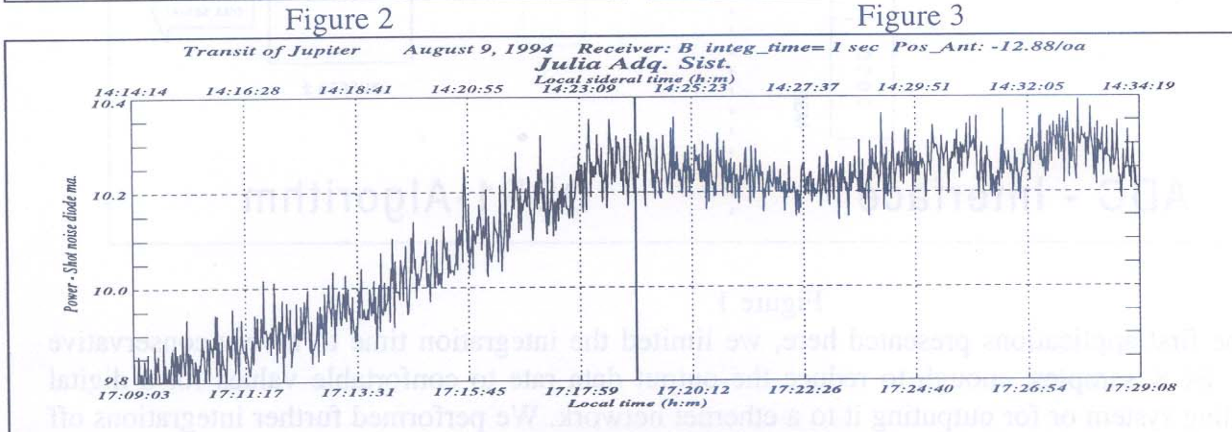

Figure 4