MMA Memo 165: System Design Considerations for the Atacama Array

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The MMA System Group has discussed some aspects of the Atacama Array, which is an array that would be formed by combining the Large Millimeter and Submillimeter Array (LMSA) that Japan proposes to build and the MMA proposed by NRAO.

The Large Millimeter and Submillimeter Array

Before discussing the Atacama Array it is necessary to review some basic information on the LMSA. It is expected that it will be located in the Atacama desert about 10 km from the MMA. The following data on the LMSA is taken from an information brochure on plans for the array.

Antennas:

- Number, 50
- Diameter, 10 m
- Surface, <20 micrometers rms
- Design, symmetrical paraboloid with quadrupod legs attached at outer rim of dish. Naysmith focus and beam waveguide system.

Receivers:

- Frequency coverage, 35 to 800 GHz in eight bands. SIS mixers cover 80 to 800 GHz with an IF band of 4-8 GHz, i.e. IF Bandwidth is 4 GHz. Dual polarization. Fringe rotation on first LO.

IF Transmission:

- Two fibers from each antenna. Analog transmission with digitization at correlator.

Correlator:

- Sampling at 8 Gs/s. FX type. Bandwidth 4 GHz, 10,000 channels per baseline. Sideband separation at correlator.

The total surface area of the antennas is 1.95 times that of the MMA. The proposed IF bandwidth of 4 GHz is half that of the MMA, for which 8 GHz IF bandwidth is proposed (see MMA Memo 142). The information that we have does not say whether the correlator provides two or four cross products per baseline at full bandwidth.

The Atacama Array

The combination of the MMA and LMSA would provide 90 antennas. As a model for discussion we consider a configuration in the form of a circle of approximately 10 km diameter. The Atacama Array would thus have an angular resolution 4 to 5 times that of the MMA alone. The total collecting area would be approximately three times that of the MMA. The array is envisaged as useful for a wide array of astronomical problems from asteroids to galactic nuclei, and it would be used in both continuum and spectral line modes. The antennas will probably be grouped in clusters of three to six antennas, and the clusters spread around the circle. To fit such an array onto the proposed site it may be necessary to build it around a mountain peak (Cerro el Chason), so connections to the antennas may have to runs around the circumference of the array circle.

There are two reasons for using clusters of antennas. First, within each cluster the antenna spacings will be small enough that atmospheric effects will be closely equal for each antenna. Thus one antenna in each cluster can observe a calibrator continuously to calibrate atmospheric effects. Second, connecting the antennas in a cluster as a phased array is a possibility that would reduce the number of required inputs to the correlator, so the array bandwidth would not be limited by the correlator capacity. As a model for discussion at this point, the System Group considered 18 clusters of five antennas each, spaced at equal intervals around the 10 km diameter circle. This is probably about the smallest number of clusters that would give adequate (u,v) coverage. In the MMA, rapid switching of the pointing between a calibrator and the target source is a proposed mode of operation, but it is supposed that the LMSA antennas may not be able to move as rapidly between pointings as the lighter MMA antennas. Also, with rapid switching the loss in observing time on the target source results in a greater loss in sensitivity than devoting one antenna in five to calibration. The large number of antennas in the combined array makes clustering an attractive possibility.

Interconnection of the Antennas to the Correlators

Both the MMA and the LMSA will require very large correlators for stand-alone operation, and it is assumed that these two correlators together would provide the total correlator capacity for the combined array. The MMA correlator will provide for 780 baselines with an IF bandwidth of 8 GHz for each of two polarizations. As the correlator is envisaged at this time, for the 8 GHz bandwidth only two polarization products are generated (i.e. only the parallel-hand products, not the crossed-hand ones). The LMSA correlator will provide for 1,225 baselines with an IF bandwidth of 4 GHz, and we will assume that this is also for two polarization cross products. If the operating bandwidth for the array is 4 GHz, as currently planned for the LMSA system, then the total capacity of the two correlators should correspond to 2 x 780 + 1225 = 2785 baselines with two polarization products each. The requirement that the MMA correlator could operate as 780 baselines at 8 GHz bandwidth or 1560 baselines at 4 GHz would not impose unacceptable constraints on the correlator architecture. Note that in discussing baseline requirements for the correlator, one baseline represents cross correlation of two 4 GHz wide IF signals from each antenna, resulting in two polarization cross products.

There are two main possibilities in the connection of the antennas to the correlator. Cross correlations can be made between individual antennas only, or the antenna clusters can be connected as phased arrays and the cross correlations made between pairs of clusters.

Correlation of individual antennas

Let us suppose that one antenna in each of the 18 clusters is used to observe the calibrator. There are 40 + 50 - 18 = 72 antennas that observe the target source, with which the number of baselines is 2556. An effect of the clustering is that if all possible pairs are cross correlated there will be too many short spacing measurements as a result of intra-cluster baselines (baselines between pairs in the same cluster). There will be 18 x (4x3/2) = 108 such short baselines, and if we omit these the total number of baselines to be correlated for the target source is 2556 - 108 = 2448. We assume that at the full 4 GHz bandwidth the array would be used mostly for continuum observations and that polarization measurement would not be necessary. It is believed that the different antenna geometries for the two arrays (Cassegrain focus of the MMA and Naysmith focus of the LMSA) will result in different rates of rotation of the feeds on the sky in the two cases. This will not be a problem when the arrays use circularly polarized feeds, but when linear polarization is used it will be necessary to form four cross products at each correlator for those baselines that involve one MMA antenna and one LMSA antenna. If we assume that the 18 calibrator-observing antennas all come from the MMA, then the number of MMA-LMSA antenna pairs observing the target source is 50 x 22 = 1100. This effectively this adds 1100 to the number of baseline cross correlations required, so the number becomes 3548. Since 153 baselines are required for calibration, the number left for the target source is 2785 - 153 = 2632. If the polarization incompatibility between the two antenna types is not resolved, and 3548 baselines are required for the target source, the limit of 2632 baselines that can be accommodated by the correlators results in a loss in sensitivity by a factor of $(2632/3548)^{½}$ = 0.86. Although this arrangement would not be ideal, it would still provide useful capability for many observations.

The lack of compatibility of linear polarization for the two arrays is unfortunate, and if there is to be much joint operation of the arrays it is very desirable that there should be some way to overcome it. Receivers with circular polarization would be a solution, but linear feeds are preferred because of their greater bandwidth. Conversion from circular to linear polarization at IF is a possibility and for the 4-8 GHz IF band, where the width is only one octave, quadrature hybrids of sufficient accuracy should be easily obtainable. This possibility should be explored further.

Cross correlating individual antennas rather than arrayed clusters has two advantages. One advantage is that when correlating individual antennas the field of view would be the beam of a single antenna, not of the phased sub-array. The other advantage is that the effort in on-line software development required to adjust the phase of the antennas in forming phased arrays would be avoided. It is estimated that the phasing software would be a significant fraction of the total MMA on-line software effort. This estimate is based on experience with the VLA, both as a synthesis array and as a phased array. Bringing the MMA into operation in a stand-alone mode will require a very large software effort, and the MMA schedule could be jeopardized by additional tasks. Also, if phased arraying is avoided the required electronic hardware remains essentially the same as for stand-alone operation, except that larger ranges are required for the fringe frequencies and the compensating delays.

Operating with Phased Antenna Clusters

In this arrangement the antennas in each cluster (other than the one that is used for the calibrator) are connected as a phased sub-array, as discussed in some detail in MMA Memo 157. At the correlator the combined signals can be treated in the same way as a signal from a single antenna, and thus the required correlator capacity is reduced. For 18 subarrays the number of baselines is 153. However, if there is polarization incompatibility between the LMSA and MMA antennas it may be necessary to form separate subarrays for the two antenna types which would increase the correlator capacity required, but not beyond that available. Thus the main advantage of the phased-array connections is that correlator inputs can be set free so that there is no loss in sensitivity resulting from the capacity of the correlator. Also, it may be possible to increase the bandwidth for the same total correlator capacity. With regard to increased bandwidth, the limit that may eventually be set by the receivers is about 32 GHz for SIS front ends. Present IF bandwidths for NRAO SIS receivers are approximately 2 GHz. It has been demonstrated at Caltech that by integrating the first IF stage onto the mixer substrate a bandwidth of 4 GHz is obtainable. The front end group at NRAO have proposed a goal of developing mixers with 8 GHz bandwidth without serious increase in system temperature over present mixers. Further, there is an effort in progress to develop sideband separating mixers at NRAO which would provide separate outputs for upper and lower sidebands. If all these efforts are fully successful the bandwidth available at the front end output could be as high as 16 GHz per polarization.

In connecting antennas in sub-arrays, the signals from each antenna of a cluster must have adjustments in both phase and delay before they are combined. The phase adjustment can be applied through the fringe rotation on the first LO which is required for the stand-alone operation of the array. For the delay adjustment several schemes can be envisaged and these were briefly considered by the System Group. They are as follows.

(a) Develop variable analog delay lines that can handle the IF signal band and apply them to the IF signals at the antennas. These delays are needed to compensate only for the differences in signal paths within a cluster, and the main delays to compensate for the inter-cluster path differences would be applied digitally. After analog delaying at the cluster location, the IF signals would be combined and transmitted to the correlator building for channelization, digitization and digital delaying. To cover the large IF bandwidth the analog delays would have to be implemented in optical fiber. They would need an accuracy of approximately 1/32 of the reciprocal bandwidth which corresponds to 1 mm of air path. Most of the variation could be implemented by switching lengths of fiber in and out of the path, but for fine adjustment some kind of moving-mirror system might be required. Use of analog delays would require some additional optical transmitters and receivers since the delayed signals would have to be demodulated before being combined, and then modulated onto a light beam again for transmission to the correlator location. This scheme would be more expensive than equivalent digital delays, would almost certainly be less reliable, and could result in variability in the bandpass characteristic. It received no support in discussions in the group.

(b) Digital implementation of delays at the antennas would require moving the channelization and digitization from the correlator location, where they would be located as currently planned, to the antennas. Digital delays to compensate for the intra-cluster delay differences could then be inserted and the signals from the antennas combined digitally. Digital transmission of the combined signal to the correlator would require more fiber than analog transmission, since bandwidth B would be represented by a baud rate 4B for four-level sampling. The necessity to change the planned location of a considerable amount of electronic equipment, and remove it from within the controlled environment of the building, is a significant disadvantage.

(c) Another option is to bring all IF signals from each cluster to the nearest correlator building in analog form and then perform channelizing, digitizing and delaying at that point. Combining of signals could then be performed digitally just before the correlator inputs. This has the advantage that hardware remains essentially the same as for stand-alone operation of the arrays and as much as possible of it is located within the building. A little more fiber is required than for interconnecting the antennas at the cluster location. Also, in any scheme in which delaying is done digitally before combining the signals, the quantization loss occurs twice. Quantization loss occurs at digitization and again when N signals are combined and it is necessary to reduce the 4N levels back to 4. (For an FX correlator it is not so difficult to accept more bits for the input signals.) The loss factor for the assumed 4 levels is 0.88. Signal combination at the correlator location also offers the greatest flexibility. For example, if it were decided to use two antennas per cluster for the calibrator observation, the hardware changes would involve only the interconnection of the signals at the correlator inputs. Overall, this scheme is judged to be preferable to (a) or (b) above.

Suggested Plan

It is suggested that a desirable plan would be to bring all of the IF signals in analog form to the correlator buildings and to channelize, digitize and delay at those locations. The combined array could initially be brought into operation by cross correlating single antennas, using essentially the same on-line software as developed for stand-alone operation of the arrays. Operation of the combined array is likely to be about ten years into the future. As that time approaches, it will be possible to assess more accurately the increase in sensitivity that could be achieved by phased arraying and increasing the bandwidth. For example, it would be known whether SIS mixers with sideband separation and full 8 GHz bandwidth are achievable. Minimal additional hardware would be required to change to the arraying scheme (c) described above, in which the phased-array interconnections are made just ahead of the correlator input. Delaying development of the arraying software until that time would avoid impact on the main phase of construction of the MMA.

Rough Estimate of Cost of Optical transmission Components

An estimate of the fiber and Tx/Rx component cost, additional to that for stand-alone operation of the two arrays, can be made as follows. Assume that there are 18 clusters spaced uniformly around a circle of 10 km diameter. Also assume that the fiber cables run around the circumference of the circle, and that the two correlator buildings are also on the circle and spaced apart by about 10 km. The mean distance from each cluster to a correlator building on the circle is 8 km. To allow for future bandwidth enhancement, let us assign seven fibers to each antenna: 4 for IFs, 2 for LO references and one for monitor and control. Overall, that is 35 fibers per cluster. The price of a 36-fiber (single mode) cable from Optical Cable Corp. is $13.05 per meter. Thus the cost of cables around the circle would be about $1.9M. Assume that all LMSA antenna signals go to the LMSA correlator building and all MMA antenna signals to the MMA correlator building. Each signal would be channelized, digitized and delayed at a correlator building. If all of the 18 calibration antennas are MMA antennas, and all signals from target-source antennas are required at both correlators, then it is necessary to transmit signals from 50 + (40-18) = 72 antennas between the two correlator buildings. For one IF with bandwidth B and four-level quantization the baud rate is 4B, and if we allow two fibers per (digitized) IF, and two IFs per antenna, then the total number of fibers between the buildings is 72x2x2 =288. This would require eight 36-fiber cables each 10 km long, costing approximately $1M. Also required are 288 Tx/Rx pairs which would not be part of the stand-alone electronics. At $10k per pair, they would be $2.9M. If in the future it is decided to go to phased subarrays, combining the IFs of four antennas in each cluster (i.e. all except the one observing the calibrator) should, in principle, allow a substantial reduction in the number of transmitted IFs between the correlators, and a possible increase in the IF bandwidths. Note that, with the rough figures used, the Tx/Rx pairs for the inter-correlator link cost approximately three times as much as the fiber. The relative cost savings of locating the correlators closer together would only be small. (For fiber at $0.36 per meter and one Tx/Rx set at about $10k, the fiber and Tx/Rx costs are roughly equal for distances of 30 km.) The total of the additional cost figures above is $5.8M.

Further considerations

Some further study is required on the feasibility of the figures assumed above for the fiber links. Specifications for currently available DFB laser transmitters (Ortel Corp) indicate that it should easily be possible to transmit 8 GHz of analog bandwidth over the distances of up to three km required for the stand-alone MMA configuration and keep the degradation of signal-to-noise ratio resulting from the laser noise to 0.3%. For the distances up to 16 km required for the Atacama array the performance of the fiber may be more marginal. Higher power lasers are available that can be used with external modulators, but testing of possible systems will be necessary when development funds are available.

Another bandwidth consideration is the magnitude of the baud rate involved in processing the signals. 32 GHz of bandwidth per antenna would be possible if all proposed SIS developments are successful. If all of this bandwidth were digitized the total rate for 90 antennas and four-bit quantization is 11.5 terabaud. It should not be taken for granted that it is practicable to build a digital system capable of handling such a rate. The required number of parallel bit streams reduced to, say, 200 Mb/s is 57,500. It would not be easy to handle all the interconnecting cables and all the clock waveforms that need to be kept in phase.

Requirements in the Near Future

As suggested above, we need to develop a broad general specification of the Atacama array, but details of the engineering will be greatly influenced by the experience gained in development of the MMA and LMSA. Thus it may not be useful to pursue the design at a detailed level at this time. However, it is very important to keep in mind the general requirements of the Atacama array as the two stand-alone arrays are being developed, to make sure that the designs are maximally compatible with combined operation. In particular, compatibility of the following features of the arrays is important for combined operation.

(1) Local Oscillator system. Any frequency received from a source and processed through the electronics should be able to arrive at the correlator input at the same baseband frequency in the two arrays. That is, the sum of the various local oscillators (taken with appropriate signs) should be able to tune to identical values in the two instruments. The LO systems for the two instruments should be capable of being locked to the same standard.

(2) Clock Rates. The same clock rates must be used for the samplers and correlators of the two systems if the correlators designed for stand-alone operation are to be used in a combined mode. Correlator integration and dump times should be compatible.

(3) Phase Switching. Local oscillator phase switching sequences should be chosen so that it is possible to provide a unified Walsh function system for the whole array. Note that the time base for switching sequences is usually chosen to be an integral submultiple of the correlator dump time.

(4) Frequency bands. Any range of frequencies to be observed simultaneously must fall within one front-end tuning band of each array. It is therefore highly desirable that the frequency bands over which the front ends are tunable should be as similar as possible for the two arrays.

(5) It is desirable that IF bandwidths should be similar for the two arrays so that the correlator can be used efficiently.

(6) Polarization. It is highly desirable to develop some scheme by which cross correlations between antennas of the two arrays can be made without requiring generation of all four polarization cross products. Generation of circular polarization in the IF could be a possible solution if it proves to be practicable.

(7) It is highly desirable that both designs of antennas can operate from the same voltages for electric power to minimize costs in power distribution around the array.

(8) There are a number of items that would be convenient, but are not essential to combined operation. These include use of the same types of plugs and sockets for fiber and other interconnections at the antennas. The possibility that antenna transporters could be used with either type of antenna could increase the efficiency of relocation of antennas when setting up the combined array or returning to stand-alone operation.

An Idea to Keep in Mind

Suppose that for the Atacama Array all 40 of the MMA antennas were used for atmospheric calibration instead of just about half of them. The two sets of antennas would then operate independently so far as the system is concerned. Compatibility of the polarization, the precise operating frequency, the correlator clocks and almost everything else would not be needed. The antennas could be in clusters of two MMA and two or three LMSA antennas, or more widely dispersed with one MMA and one or two LMSA. There would be some loss of sensitivity compared with the system that has been discussed which uses only 18 MMA antennas for atmospheric calibration. The total collecting area of 50 LMSA antennas is 78% of that of 50 LMSA antennas and 22 MMA antennas. To compensate for the reduced sensitivity an increase in observing time by a factor of 1.6 would be required, so simplicity of the system is unlikely to be judged to be sufficient compensation for the sensitivity loss. However, the ability to use weaker calibrators as a result of doubling the calibrator collecting area should allow the possibility of finding calibrators closer to the target source. This might be beneficial if atmosphere instability proves to be a difficult at the longer spacings. Note that, as yet, the baselines used for atmospheric testing at the Chajnantor site have not exceeded 300 m, and judgement of the atmospheric stability over 10 km baselines requires considerable extrapolation, even if the general power law of fluctuations with distance is known.