A CARMA First-light Correlator Plan

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In this document we outline a plan for CARMA correlator development over the next four years, derived from discussions at the f2f meeting in December and subsequent Hardware/Science working group discussions. During these meetings scientific and operational requirements for the correlator were addressed, and the following critical assumption was agreed upon: that the first-light CARMA correlator does not need to be a 23-station system. Including the SZA in CARMA results in 23 antennas on site, however initial analysis by Mel Wright has shown that cross-correlating the eight 3.5m SZA antennas does not generally enhance the imaging capability of the instrument (except in certain circumstances). Therefore, the additional costs of building a 23-station correlator are not warranted. Implementing a 15-stn correlator with user flexibility to select which antennas are routed to the correlator inputs is the preferred approach.

The first-light correlator plan for CARMA depends on two developments taking place outside the project:

COBRA – A new OVRO correlator currently under development. Based on reprogrammable FPGA technology, COBRA will handle 4-GHz BW from 6 antennas. Implementation of COBRA in wideband mode is expected in September 2002.

SZA – A FPGA-based correlator directly based on COBRA to be built for John Carlstrom's Sunyaev-Zeldovich Array. It will handle 8-GHz BW from 8 antennas with limited spectral resolution. Implementation expected sometime late 2003.

The first-light correlator plan for CARMA actually relies on the existence of two correlators – a first-light CARMA correlator and the SZA correlator.

First-light CARMA Correlator

The first-light correlator for CARMA will be a direct hardware expansion of the COBRA system. By reprogramming the existing COBRA hardware, it is believed that a 15-stn 1.5-GHz BW correlator can be produced (although there are technical issues to be resolved). Adding additional bandwidth to this system by building more (identical) hardware costs an estimated \$800k/1.5-GHz, therefore a 15-stn 4-GHz correlator can be produced for ~\$1.5 M (currently, the project plan allocates \$4.2 M for an "interim" 1.5-GHz correlator and "final" 8-GHz system).

Technical Specifications

Wideband - The first-light correlator would process 4-GHz of BW in eight 500-MHz bands from 15 stations. Ideally, each of these bands can be placed anywhere within the receiver tuning range by the spectral-line downconverter (SLD, discussed below). This wideband capability is consistent with the existing receivers and planned IF capabilities for the array.

Spectral-line **-** Within each of these 500-MHz bands, the following configurations are possible:

Band Spectral-line Configurations

Bandwidth (MHz)	Channels	3 mm channel spacing (km/s)	3 mm total velocity width (km/s)	1 mm channel spacing (km/s)	1 mm total velocity width (km/s)
512	16	96	1536	32	512
256	32	24	768	8	128
128	64	6	384	2	128
64	128	1.5	192	0.5	64
32	128	0.75	96	0.25	32
8	128	0.18	24	0.06	8
2	128	0.05	6	0.01	2

Other (intermediate) channelizations are possible (involving FPGA programming efforts at roughly 1 month per configuration, and $5k hardware per band to outfit the whole array). A total of eight 500-MHz bands capable of these configurations will be available, allowing numerous permutations of channel spacing & total frequency coverage.

It is important to note that both upper and lower sidebands are processed by the correlator, and that either or both sidebands can be selected after correlation, meaning that the correlator will actually produce 16 data streams, each of which would be channelized as per the configuration table above. If scientifically-interesting lines can be placed in both upper and lower sidebands simultaneously, they can both be processed by the correlator.

The critical hardware elements of this correlator (the digitizer and correlator boards) are currently undergoing testing as part of the COBRA effort. Expanding the COBRA system using identical hardware should provide a predictable cost/schedule for the first-light correlator. Once COBRA is operational (September 2002) a design revision of the digitizer and correlator boards will commence, allowing the possibility of performance increases and/or cost savings. The kinds of modifications considered at this point would be small hardware changes (parts and layout on the boards) and FPGA reprogramming. The SZA correlator will also require a revision of the COBRA hardware to deal with higher I/O data rates. The options for design revision will be examined in a combined CARMA & SZA Preliminary Design Review in November 2002.

Technical Issues to be Addressed/Milestones

In converting the existing 6-stn 4-GHz COBRA correlator to a 15-stn 1.5-GHz correlator, a number of technical issues need to be addressed. Each of these has associated scientific issues and project milestones.

- *Phase switching*. The use of Walsh phase-switching cycles used to guarantee antenna and baseline orthogonality depends on the number of antennas involved and the minimum data dump rate from the correlator (which in turn depends on number of channels etc.). Preliminary analysis of the COBRA hardware indicates that long (2-5 seconds) integration times might be required to complete phase-switching cycles for 23 antennas.

Issue: What are the acceptable integration times at first-light? – March 2002 (SSC)
Milestone: White paper describing phase switching limitations and first-light solution – March 2002 (Woody)

- *Data fan-out*. The COBRA digitizer cards accept two input analog signals, each of which can be routed to two 32-bit digital output connectors on the front panel (four connectors, total). Each of these connectors can distribute either one antennas digitized output (32 bits at 62.5 MHz, a time demultiplex of 16) or two antennas (16 bits at 125 MHz, time demultiplex of 8). Therefore, the maximum antenna data fan-out per digitizer board is a factor of 4. To implement the 15-station 1.5-GHz system from the COBRA hardware, a fan-out of greater than 4 is required, implying that (a) a special-purpose digital fan-out cards needs to be designed/implemented, (b) a design revision of the existing COBRA digitizer layout is needed, or (c) an analog fan-out solution followed by additional digitizers should be used. This issue will be addressed in the Preliminary Design Review in November 2002.

  Milestone: Data fan-out solution – PDR November 2002 (Hawkins)

Subarraying

To minimize the loss of scientific capabilities of the arrays once they are combined, at least two independent subarrays are required for first-light operations. In this plan, CARMA would have access to two correlators at first-light:

- The first-light correlator described above, capable of 15-station 4-GHz continuum and flexible spectral-line performance.
- An 8-station 8-GHz correlator (the SZA correlator).

Assuming an ability to route any antenna to either correlator (involving an analog switch capable of routing any group of antennas to either correlator), CARMA would then be able to work with two subarrays. The three sets of antennas (OVRO: 6x10m, BIMA: 9x6m, SZA: 8x3.5m) could then be combined into heterogeneous subarrays (occasionally dropping one or two antennas) according to the science requirements. Some examples:

- A 15-stn (OVRO+BIMA) 1mm project + 8-stn SZA survey
- A 15-stn (9 BIMA + 6 SZA) spectral-line mosaic + 6-stn OVRO 4-GHz project
- A 6-stn OVRO or 8-stn SZA continuum project + 8-stn BIMA spectral-line 70-GHz project.

A primary issue for the PDR will be the spectral-line performance of the SZA correlator. As we expect the SZA and first-light correlator to possess identical hardware (and therefore similar real-time code), the spectral-line performance of the SZA correlator is (in principle) as good as the projected abilities of the first-light correlator. However, the SZA project does not require tunable narrow-band downconverters, therefore a decision to use CARMA SLDs for the SZA (or some low-cost implementation of them, e.g. without a full set of narrow-band analog filters) would need to be made by SZA management to implement spectral-line capability.

Any subarray performing a spectral-line experiment would be allocated to the first-light correlator, placing limitations on the subarray directed to the SZA correlator. The third example (above) highlights this issue. If BIMA is observing at 70 GHz in spectral-line mode, then the SZA correlator will (in its currently-planned continuum mode) process 8 antenna inputs, i.e. some grouping of the 6 OVRO or 8 SZA antennas, but not all of them, in wideband continuum mode. Implementation of tunable SLDs for the SZA (with some or all of the analog filters implemented for CARMA) would remove this limitation, as the BIMA experiment could then be correlated on the SZA correlator and the OVRO+SZA antennas can be combined into a 14-stn continuum or spectral-line experiment. Another possibility would be to implement some minimum set of SLDs for the SZA (e.g. 4 tunable SLDs, 14 fixed downconverters), providing a reasonable spectral-line performance for the SZA correlator without significant increase in scope of the SZA project.

Another option is to implement a third LO system across the array, and allow for multiple independent subarrays in the first-light/SZA correlator (i.e. process all three arrays independently). The cost and schedule impact of this approach will be examined during the LO, IF and Correlator PDRs. At the present time a two-LO system is under development, and multiple simultaneous subarrays are not planned for the correlator real-time system.

At first light, idling either the 3.5-m or 10-m antennas during times when BIMA is observing 70-82 GHz in spectral line mode (probably a rare occurrence) is a reasonable compromise.

Issue: Will this subarray/two-correlator plan satisfy first-light science requirements? – February 2002 (SSC)
Milestone: Design of analog switchyard for signal routing – PDR November 2002 (Woody)

Spectral-line Downconverter (SLD)

Each CARMA antenna will produce 4-GHz of IF BW. This needs to be filtered into ≤500 MHz bands for digitization and input into the correlator. In the Table above, there are 7 filtered bandwidths identified – these would be implemented as selectable analog filters in the SLD. Reducing this number to 4 filters would be desirable for simplicity/cost reasons (and under investigation by the Science Steering Committee), i.e. trading the number of channel configurations versus the number of bands positioned contiguously. The SLD would allow placement of these filters anywhere in the 4-GHz IF bandwidth presented to it.

At present a set of fixed-frequency downconverters are under construction for COBRA (spacing the 500 MHz bands contiguously). A design revision of these downconverters to incorporate variable IF tuning and the additional filters is required.

Issue: Acceptable scientific parameters for correlator need to be defined – February 2002 (SSC).
Milestone: Design of CARMA SLD – PDR November 2002 (Woody)

Design reviews

In this plan there would be two design reviews:

- A Preliminary Design Review (PDR) in November 2002 to assess COBRA performance, options for design revision of digitizer and correlator boards, options for data fan-out, SLD design, analog switchyard design, and a plan for production and testing of the CARMA & SZA correlators.
- A Critical Design Review (CDR) 4-6 months later to make final technical & implementation decisions before beginning hardware production.

Next generation correlator development

The first-light 15-station 4-GHz CARMA correlator is a scaled solution from the FPGA COBRA correlator system. This design does not sensibly scale to 8-GHz or a greater number of antennas due to current limitations in data fan-out and routing. In the original CARMA Project Plan an “interim – final” correlator pair was presented. The “final” correlator involved a new switching technology, where digitizers offered their data on a commercial fiber port to a switchyard, where signals from antennas were broadcasted to fiber-capable correlator boards. Commercial data transmission systems and switchyards appear to be capable of the data rates involved (Terabits/sec), but substantial redesign of all correlator systems and prototyping of this new system was required.

We define a next-generation correlator as follows: a 23-station 8-GHz full-polarization (i.e. producing all 4 Stokes parameters) system, incorporating commercial off-the-shelf (COTS) network hardware. Using the COTS network routing approach, the numbers of antennas being correlated in any subarray, the number of subarrays and the polarization processing of any subarray would be completely flexible. The COTS hardware would be a digital equivalent of the analog switchyard proposed for the first-light plan.

In the plan presented above, there is little new design effort required to produce the first-light correlator, as it builds upon the technology and experience gained from COBRA. Once the first-light correlator is in production, design and prototyping of the next-generation correlator could begin. The $600k to begin design/prototyping work would remain in the budget. An optional deliverable from the construction project would then be the design of the “next-generation CARMA correlator” for which we would then begin seeking funding.

Milestone: (a) Research/prototyping for next-generation correlator – Jan 2004; (b) next-generation correlator preliminary design – June 2004 (Hawkins). (optional)

Schedule

Adopting this plan would lead to the following timeline:

- Implementation of COBRA 4-GHz system (outside CARMA Project) – September 2002
- Engineering evaluation of digitizer/correlator board improvements – September – October 2002
- Combined CARMA & SZA Correlator Preliminary Design Review (including Production & Testing Plan) – November 2002
- Design Revision engineering/prototyping – December 2002 - May 2003
- Combined CARMA & SZA Correlator Critical Design Review – May 2003
- SZA correlator production – June 2003 – December 2003
- CARMA correlator production – June 2003 – June 2004
- Proposal for next-generation correlator research – May 2004
- Begin design/test prototype of next-generation correlator – Jun 2004
- Deliverables: (a) first-light CARMA correlator & (b) next-generation correlator design/prototyping – June 2004

Summary

There are numerous advantages to adopting this first light plan:

- It involves building a single highly-flexible correlator based on proven hardware.
- It involves additional manufacturing of existing hardware with incremental design work, and therefore can be more readily costed/scheduled
- The software to support the correlator can begin with COBRA systems
- It expands upon the COBRA experience gained over the last two years. The PDR in November 2002 will allow a clear decision point on how to proceed with correlator development based on the COBRA experience and gains in technology/cost over the next 9-12 months. The CDR in May 2003 will complete final technical & implementation considerations before beginning hardware production.
- It is a cheaper and more focused plan than the existing two-correlator proposal

A critical assumption of this plan (and the SZA plan) is the successful execution of COBRA project over the next nine months; any delays or problems in COBRA will directly impact the CARMA schedule/budget. The PDR in November will also provide a decision point for the project to follow this COBRA-based first-light plan or (if necessary) examine alternatives.