CARMA LO system

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LO system requirements

- Allow for at least 2 subarrays operating at different frequencies.
- Accommodate mix of SIS receivers (2 GHz I.F.) and MMIC receivers (20 GHz I.F.).
- RMS phase noise on each baseline should be < 8° at 230 GHz (< 1% decorrelation).
- Send LO reference signals from lab to antennas on singlemode optical fiber.
- Linelength system monitors electrical phase delay through fiber to an accuracy of 0.05 picoseconds (approximately 5° at 230 GHz).
- 4-state phase switch (0°, 90°, 180°, 270°) on LO1 allows sideband separation and removes correlator offsets.
- Fastest phase switch time is 1 msec, with 30 μsec blanking time in correlator for for phaselocks to settle to new state.
- Should build upon existing hardware where possible.

Proposed LO chain

The proposed LO chain is based on the BIMA phaselock system, shown in Figure 1. Two reference frequencies are sent from the lab:

- 1100 1260 MHz, tunable, from an HP8662 synthesizer
- 10 MHz, fixed

The 8662 synthesizer was chosen because of its exceptionally low phase noise a few Hz from carrier, which is desirable if the array is used for VLBI.

It would be difficult to phaselock a mm-wave Gunn oscillator directly to a harmonic of the ~1.2 GHz reference, so an Xband oscillator, tunable from 8 – 12.5 GHz, is used as an intermediate oscillator in the phaselock chain. The Xband oscillator also serves as a cleanup oscillator, filtering out noise which lies outside the ~100 kHz phaselock loop bandwidth.



Figure 1. The current BIMA LO system

Harmonics of 10 MHz are used as the offset frequencies for the Xband and mm phaselocks; currently BIMA uses 20 MHz and 70 MHz:

- $v_x = nv_{synth} + 20 \text{ MHz}$
- $v_{mm} = mv_{\chi} + 70 \text{ MHz} + foff1$

Here *m* and *n* are integers, *foff1* is the small frequency offset needed for lobe rotation and phase switching. For CARMA, it may be preferable to change the offset frequencies to 10 MHz for the Xband lock and to 40 or 50 MHz for the mm lock. The mm lock box input and output are given in the table below:

	input	output		
SMA	phaselock I.F. from mixer70 MHz reference	mm osc operating voltagephaselock I.F. monitor		
TTL	 mm osc on/off sweep on/off IF monitor on/off 	locked/unlocked70 MHz ref level OK		
analog	 loop gain 	 phaselock error volts phaselock I.F. level phase noise monitor 		



Figure 2. Phasenoise monitor example. The receiver tuning software increases the loop gain until the phase noise monitor output jumps upward, then backs off slightly.

The phasenoise monitor output from the mm lock box is proportional to the AC component of the phaselock correction voltage. If the loop begins to oscillate, the phasenoise monitor voltage increases sharply. By checking this output, the computer can optimize the phaselock loop gain each time it tunes a receiver: the code increases the loop gain in small steps until the phasenoise monitor voltage jumps up, then backs off slightly.

Two mm Gunn oscillators are present on each antenna: a low power unit tunable from 70-115 GHz for the 3mm receiver, and a higher power unit tunable from 67-90 GHz which feeds the tripler for the 1mm receiver. The mm phaselock box supplies the operating voltage to one of these two oscillators; the other oscillator is turned off. A computer-controlled transistor switch selects which oscillator is powered up; simultaneously, an RF switch connects the Xband reference signal and phaselock I.F. input of the lock box to the appropriate mm phaselock mixer.

Currently BIMA uses another output of the 4-way RF switch for test observations at 22 GHz. The Xband oscillator serves as the LO for a harmonic mixer. The mixer downconverts a sample of the water vapor radiometer I.F. from ~22 GHz to ~1.5 GHz. The downconverted signal is switched into the regular receiver I.F. so it can be crosscorrelated with other antennas. Thus, it is possible to test the performance of the WVR by monitoring atmospheric phase fluctuations while simultaneously observing cosmic water masers with the same 22 GHz receivers. Note that for these tests all lobe rotation and phase switching are done with the 1.27 GHz 2nd LO on each receiver, which will not be part of the CARMA system.

Accommodating 3mm MMIC receivers

At first light, CARMA will use a mix of SIS and MMIC receivers for the 3mm band (80-115 GHz). Currently the OVRO SIS receivers use a 0.5 - 4.5 GHz I.F. band, while the BIMA SIS receivers use 1.3 - 2.2 GHz. To achieve single sideband operation, the SZA MMIC receivers will utilize a double downconversion, first to 18.5 - 26.5 GHz, then to 1 - 9 GHz (see Figure 2). Thus, the LO1 frequency will be much lower for the MMIC receivers than for the SIS receivers – 96.5 GHz vs. 114.0 GHz in the example given in Figure 3.



Figure 3. Proposed LO system for 3mm MMIC receivers. Frequencies in italics are appropriate for correlation of the 12CO line for correlation with SIS receivers with the line at 1.5 GHz in the final I.F.

Of course the SZA could be operated as a subarray with its local oscillators phaselocked to a separate frequency synthesizer. This has the disadvantage that uncorrelated low frequency phase noise on the two synthesizers would lead to some loss of coherence after multiplication to mm wavelengths. In addition, each MMIC receiver would need a separate phaselock for the 17.5 GHz 2nd LO, and a separate reference signal would need to be sent from the lab as an LO reference.

John Carlstrom has suggested a simpler alternative, which is to offset both the mm phaselock I.F. and the receiver I.F. by the 2nd LO frequency on the MMIC receivers. Thus, the sky frequency that is downconverted to the final I.F. frequency is:

- for SIS receivers: $v_{SKY} = (mv_X + v_{REF1}) + v_{IF}$
- for MMIC receivers: $v_{SKY} = (mv_X v_{LO2} + v_{REF1}) + v_{LO2} + v_{IF}$

The quantity in parentheses is the LO1 frequency. Both SIS and MMIC receivers use the same Xband frequency (hence the same synthesizer frequency) multiplied by the same harmonic numbers. Since v_{LO2} cancels in the second equation, frequency or phase errors on the 2nd LO have no effect on the I.F. frequency sent back to the lab. It is unnecessary even to phaselock the 2nd LO; an inexpensive dielectric resonator oscillator (DRO), stable to a few tens of kHz, probably would suffice.

Probably the most significant technical challenge is to obtain a reasonable match at 17.5 GHz on the I.F. port of the mm phaselock mixer; this may require modification of the standard (Pacific Millimeter Products) mixer design. In addition, the tuning software must avoid using an Xband frequency in the range 8.5 - 9.0 GHz, which places the second harmonic of the Xband oscillator close to the 2nd LO frequency of 17.5 GHz. When phaselocking in the range 80 - 115 GHz there are 4 to 6 xband harmonics to select among, so this should cause no problems.

Extending frequency coverage to 70 GHz

If it proves feasible to extend the frequency coverage of the MMIC receivers down to 70 GHz, then the 79 GHz high pass filter in Figure 3 must be replaced by a 69 GHz high pass filter. To maintain single sideband operation the 1st IF frequency must be increased to 23.5 – 31.5 GHz, and the 2nd LO must be increased to 22.5 GHz.

Nothing inherent in the design of the LO system prevents this change. The requirements on the mm phaselock mixers are somewhat more stringent, in that the input port must now provide a reasonable match to 22.5 GHz; the forbidden range of Xband frequencies becomes 11.0 - 11.5 GHz; and the tuning range of the mm Gunn oscillators must be larger. Using a 22.5 GHz 2nd LO has the disadvantage that there is a high probability of interference with the 22 GHz water vapor radiometer, however.

Fiberoptic distribution

At BIMA both the 1100 – 1260 MHz and 10 MHz reference signals are sent from the lab to the antennas over singlemode optical fiber, as shown in Figure 4. As an economy measure, the output of each 3540A laser is split 4 ways in an optical power divider so that only 3 of these lasers are required for the array.

For 10 MHz an inexpensive (~ \$180) LED is used instead of a laser transmitter. The outgoing 10 MHz sine wave is converted to a chain of TTL pulses before it is sent to the LED. At each antenna a 10 MHz crystal oscillator is phaselocked to the pulse stream. Timing information can be transmitted to the antennas by deleting occasional pulses, which are detected by the phaselock circuit. This system can be used, for example, to generate a 1 pps clock tick at each antenna with an accuracy of a few nsec.



Figure 4. BIMA fiberoptic distribution and linelength system.



Figure 5. Physical layout of the optical fiber at Hat Creek, showing path for the LO reference signal from the lab to the receiver.

Until recently 10 MHz was sent to the antennas over multimode fiber. In the current LO system 10 MHz is multiplied up to 1270 MHz to serve as a second local oscillator (this will not be part of the CARMA system), and it was found that flexing the multimode cable introduced noticeable phase shifts on the 2nd LO. Singlemode fiber has much greater phase stability.

Figure 5 is a sketch of the physical layout of the fiber at Hat Creek. Because some antenna pads are far from the nearest underground pit, a 50-foot umbilical cable is used to connect the underground cable to the antenna. The splice tray and connectors for the underground cable are mounted in a watertight box. Normally this box is stored in the pit; it is mounted on a portable stand when in use. Unfortunately, all connections from the umbilical cable to this box must be made outdoors, sometimes under poor weather conditions. For CARMA it would be preferable to store short umbilical cables inside each pit, and to pass the end of the umbilical through a hole in the side of the antenna lower cabin so that all fiber connections can be made inside a protected space.

Linelength measurement system

At BIMA approximately 100 feet of fiber to each antenna is exposed to the ambient air temperature. This is the length of the umbilical cable from the nearest underground pit to the antenna pad, plus the cable run through the azimuth and elevation twisters. As shown in Figure 6, the electrical delay through the fiber closely tracks the outdoor air temperature; the coefficient varies from antenna to antenna, but ranges from 3 picoseconds/C to 6 picoseconds/C. At 230 GHz a variation of 3 picoseconds/C between two antennas leads to a phase shift on that baseline of ~250° per degree C. A linelength measurement system is used to track changes in the electrical delays, so astronomical data can be corrected for these rapid phase variations.



Figure 6. *(top)* Variations in electrical cable length to antenna 2 over a 2.3 day period, measured with the linelength system. *(bottom)* Outdoor air temperature measured over the same period.

The system is simple in concept. On each receiver, a sample of the laser carrying the ~1200 MHz reference signal is extracted with a 10 dB fiberoptic coupler and looped back to the lab on a separate fiber in the same cable. In the lab, the echo signal is converted to RF in a photodiode, then mixed with $f_{synth} + 10 \text{ MHz}$ to produce a 10 MHz I.F. After amplification, this 10 MHz signal is mixed with 9.99995 MHz from another synthesizer to produce 50 Hz. This sine wave is digitized with an a/d board and its phase is fit. The phase $\phi = 4\pi \tan f_{synth}$, modulo 2π , where tau is the one way time delay through the fiber, and the additional factor of 2 arises because this is a roundtrip measurement.

The absolute linelength *tau* cannot be determined from a single phase measurement because of the 2π phase ambiguities; it is determined by measuring ϕ at a series of synthesizer frequencies, extending the phases through 2π , and doing a least squares fit. Errors in the absolute linelength do not, however, affect the phase correction at a single synthesizer frequency. The variations in the mm LO phase are just *m n* $\Delta\phi$, where m and n are the harmonic numbers in equations (1).

Advantages of this linelength system are:

- no active electronics at the antenna only a directional coupler.
- delay is measured continuously, while observations are underway.
- both the outgoing and echo signals are at precisely the same laser wavelength, so
 dispersion in the cable does not affect the measurement accuracy.

A disadvantage is that the echo signal returns to the lab on a separate fiber, which might have different electrical delay if the fiber bundle is heated or cooled rapidly (say, as the sun hits the umbilical cable), or as the fiber is flexed in the azimuth and elevation twisters. Although lab tests suggest that these effects introduce only minor errors, real world experience at BIMA is needed to test this.

The fiber linelength system was installed at Hat Creek in mid-December 2001 and is currently under test.

Phase noise measurements

Lab measurements indicate that the phase noise of the present BIMA system is roughly 7° rms (per baseline) at 223 GHz, which corresponds to a correlation efficiency $exp(-sigma^2/2)$ of > 99%.

The measurements were made by locking a transmitter and receiver with independent phaselock chains to a common reference frequency, 1154 MHz from the HP 8662 synthesizer. The transmitter tone, which appeared at 130 MHz in the final receiver I.F., was examined with an Agilent E4408 spectrum analyzer to measure the noise power relative to the central peak. The noise power was measured within 500 MHz of the peak; increasing the adjacent channel bandwidth beyond this produced no measurable increase in the noise power. The rms phase noise then is given by *phi_rms* = *sqrt(Pnoise/(2.*Psig))*. A summary of the results, with the reference frequency sent to the receiver through coax or 2.2 km of optical fiber, is shown below. The expected optical power level at the photodiode is -1 to -2 dBm.

reference signal sent to	optical power	Psig/Pnoise	phi_rms
receiver through	at photodiode		
coax		16.2 dB	6.30°
2.2 km optical fiber	-1.6 dBm	15.7 dB	6.65°
2.2 km optical fiber	-6 dBm	15.2 dB	7.05°
2.2 km optical fiber	-9 dBm	13.8 dB	8.31°

Phase switching

A 4-state phase switch (0, 90, 180, 270) will be applied to LO1 to separate signals entering the upper and lower receiver sidebands (for SIS receivers), and to eliminate D.C. offsets. The phase state will be updated every 1 msec. The correlator will allow 30 microsec dead time to allow for the phaselocks to settle.

It is clear that the *modulation* functions used on the receivers must all be orthogonal. Otherwise, the demodulation functions on baselines connecting non-orthogonal antennas do not average to zero over the phase switch cycle, and cross talk or instrumental offsets do not fully cancel. For example, receiver noise power leaking from antenna A's I.F. into antenna B's I.F. would correlate with itself, generating a strong spurious signal on baseline AB.

It is less clear that the *demodulation* functions on all baselines need to be mutually orthogonal. Suppose the demodulation functions for baselines AB and CD are not orthogonal. Receiver noise leaking from A and/or B into C and/or D should not cause fake fringes – these are fully removed by the demodulation functions on each baseline, orthogonal or not. Cross talk from A to C and from B to D is a problem only if there is a strong astronomical signal (a rarity!) on AB, which could then leak into CD. Despite these expectations, false fringes do appear at BIMA when the demodulation functions are not orthogonal.

Unfortunately, as the number of antennas increases it becomes difficult to find sets of 4state functions which are mutually orthogonal, and whose products also are mutually orthogonal. The modulation functions used at BIMA - sums of Walsh functions with 256 steps – were carefully selected to yield orthogonal demodulation functions for all 45 baselines. In BIMA memo 76, Urry investigates the maximum number of antennas which can be supported by various phase-switching functions (Walsh, m-sequences, Hadamard-derived Walsh, Rademacher-derived Walsh) if all demodulation functions are orthogonal. The table below, reproduced from his memo, shows that at least 256 steps (0.256 sec minimum integration time) is required for full orthogonality on a 15-element array. Apparently at least 2048 steps (2.048 sec minimum integration time) would be required for a 23-element array.

steps	Wal	m-seq	H-Wal	R-Wal
16	3	х	4	4
32	4	3	6	х
64	6	х	7	8
128	7	5	10	х
256	10	х	12	15
512	13		15	x
1024	17			22

Since the phase-switching cycle will be encoded in software, it is not essential to choose a phase switching function at present.

Lobe rotation server

A small offset frequency must be added to each mm oscillator for lobe rotation – that is, to compensate for the differential Doppler shift of each antenna with respect to the phase center of the array. For an antenna displaced 2 km E or W of the array center, the maximum offset frequency is of order \pm 130 Hz at 270 GHz.

At BIMA lobe rotation is done on both LO1 and LO2 so that both the upper and lower receiver sidebands can be tracked. The LO1 and LO2 offset frequencies are generated locally at each antenna. The DSP chip that generates these signals is synchronized to

the leading edge of the telemetry cycle, every 0.01 sec, so that the phases of the offset frequencies are established unambiguously. The low frequency sine and cosine signals generated by the DSP chip are used to modulate 10 MHz. For LO1 the offset 10 MHz signal is mixed with 80 MHz in a single sideband mixer to generate the 70 MHz reference frequency for the mm phaselock box.

For CARMA, the plan is to fringe track only LO1 at the antenna, and to handle the 2nd LO lobe rotation by phase correcting spectra obtained from the correlator. The ~10 MHz offset frequencies can be generated by direct digital synthesis chips. It seems simplest to locate all the DDS chips in the main control building, and to transmit the ~10 MHz signals to the antennas over optical fiber. At each antenna, the 10 MHz signal can be mixed with 40 MHz to generate a 50 MHz reference for the mm phaselock.

A strawman design using Analog Devices AD9830 DDS chips is sketched in Figure 8. The chips are driven by a 40 MHz clock; the 10 MHz output waveform is filtered by a narrow bandpass filter to generate a clean sine wave. Each chip has four 12-bit phase registers (0.09° phase resolution) and two 32-bit frequency registers (0.0093 Hz resolution for a 40 MHz clock) which can be preset, then loaded on a sync pulse. For the 1mm system, the mm oscillator is tripled, so the phase and frequency resolution are 3 times coarser. We imagine that a separate computer or microcontroller will act as a lobe rotation 'server', updating the lobe rotation frequencies and phases every 1 millisecond.



Figure 7. Strawman design for a lobe rotation server.