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Some Comments on Instrumental Phase Calibration

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Calibration System for Instrumental Phase and Gain

If we compare the requirements for instrumental stability in the MMA with those for the VLA with which we are familiar, two factors make the MMA case more difficult. (1) The maximum first-LO frequencies are higher by a factor of about 20. (2) Observations will be made with the MMA in which the calibrator measurements are at a different frequency from those of the target source. For example, calibrator observations near 86 GHz for target source imaging at, say, 650 GHz, for which certain phase errors would require a scaling factor of 7.6.

For observations in which the calibrator is observed at a lower frequency than the target source, it is necessary to be able to separate the phase into those parts that scale with frequency and those that do not. The scaling factor would apply to the atmospheric component of the phase and, for a multiplier LO scheme, to the phase of the first LO. That is, the round trip phase measured on a reference frequency that is transmitted to the antenna to be used in generating the first LO would have to be scaled in proportion to the multiplication factor. In a multiplier LO system the highest reference frequency transmitted to the antenna on a fiber is likely to be in the 10-20 GHz range, limited by the frequency response of the modulator. For a round-trip measurement at 15 GHz we assume an accuracy of, say, 0.1 in the phase comparison, which would result in a phase accuracy of 6 at 900 GHz, which should be marginally satisfactory. (MMA Memo 144 specifies 6 for the total instrumental phase stability for median conditions.)

It is possible that in a round-trip system the returned signal could travel on a separate fiber in the same cable as the outgoing signal. This would simplify the separation of the signals. D'Addario and Stennes (1998), have made tests on such a system and found the stability to be as good as 1 ps. This figure is believed to represent the limit of the measurement equipment used, and probably is not the limit set by the matching of the fibers. One ps is short of the stability required for a local oscillator at 900 GHz by one to two orders of magnitude, so some further work is necessary.

Another complication is that for the higher frequency LO a part of the multiplier system would be different from that used at the lower frequency. Thus phase changes in the higher-frequency multiplier might not be corrected by the calibrator observation. Without laboratory measurements on the stability of the multipliers it is not possible to say whether this would be a significant problem. As presently conceived the multipliers would be cryogenically cooled to 15 or 50 K, which would provide some temperature stability. If the stability of the higher frequency LO cannot be corrected by scaling the variation in the lower frequency LO, then a phase calibration system based on a photonic system that delivers a signal of known phase to be injected at the antenna may be a possible solution.

Dispersion in the Optical Fiber

The dispersion coefficient of the optical fiber is a function of the optical wavelength and can be as high a 15 ps/(km.nm). However, if the wavelength is chosen to be near the zero-dispersion point we can assume the dispersion will be no greater than 1 ps/(km.nm). For 20 km of fiber (a 10 km-diameter ring array) and a wavelength of 1550 nm (the zero-dispersion point for dispersion-shifted cable), a shift in wavelength of 1 part in 10^5, which could result from a temperature change in the laser environment, would result in a change in propagation time of 0.3 ps and a consequent phase change of 97 at 900 GHz. In a round-trip phase system applied to the transmission of a reference frequency, it is necessary to know how much of a measured variation to attribute to each direction, in order to be able to calculate the required correction to the LO phase. (Usually it can be assumed that the variations in the two directions are equal.) If some of the variation results from temperature effects in the fiber, and some from a wavelength drift in a laser (if different lasers are used to generate the optical carriers in the two directions), then one would not know how much of the change to attribute to each direction. Such effects would be minimized by working as closely as possible to the zero-dispersion point of the fiber and stabilizing the laser frequencies as well as possible. The best solution would be to avoid using different lasers for the two directions in a round-trip scheme, and instead return some of the outgoing (optical) laser signal. Then even if laser drift causes the round trip phase to vary, the effect will be the same in the two directions and the required correction is known.

Round-Trip Phase with a Photonic LO

In a photonic LO system, one practicable way to implement a round-trip phase measurement would be to return a component of the outgoing laser signal on the same fiber or on a separate one. A second photonic diode would be required at the central building to detect the returned signal. It would then be necessary to compare the phase of the detected signal with that of the difference frequency of the two outgoing laser signals. Although the lasers are phase-locked so that the difference is the required LO signal, in a scheme that is being proposed, only a subharmonic of the LO signal is used to lock the lasers (Payne et al. 1998). Thus to provide a reference with which to compare the phase of the returned round-trip signal, a possible method would be to feed some of the outgoing laser signals into a third photonic diode. The two signals to be compared could be converted to an IF using a common LO, and the phase comparison made at the IF. If 10% of the optical power at the antenna is returned to the central building over 20 km of fiber with attenuation 0.2 dB per km, the strength of the returned optical signal would be 14 dB below the optical signal at the antenna. Since the radio frequency voltage is proportional to the optical power, the returned LO signal would be 28 dB below the LO level, but this should be sufficient for the measurement.

In a photonic LO system the different effects of dispersion on the two laser signals has a significant effect on the LO phase. Two laser signals at a nominal wavelength of 1550 nm, and differing by 650 GHz in frequency, have a wavelength difference of 5.2 nm. If the dispersion is 1 ps/(km.nm), and the fiber length 20 km, then the differential propagation time for the two signals is 100 ps, which corresponds to 65 turns of phase at 650 GHz. However, so long as the differential propagation remains constant to within 1 part in approximately $5x10^3$, any resulting errors would be tolerably small. In any case, such errors would be corrected by a round-trip phase system since the dispersion effects would be the same in both directions.

Photonic Calibration System

It has been suggested that in the event that a photonic system does not prove to be feasible for producing an LO signal, the same type of system could be used to provide calibration signals at the antennas. For such calibration signals the power requirement would be lower than that needed for an LO. It would be necessary to include a round trip phase scheme in this case as the phase would otherwise not be calibrated. In such a system it may be possible to modulate one of the lasers so that the output of the photonic diode is a series of frequencies that provide calibration for all eight channels of the final IF stages of each antenna. When using the narrowest baseband filters, frequencies would have to be generated at intervals of less than 31.25 MHz to ensure that there is always at least one signal within the final IF passband. The phase of the injected signals should be measured in the final IF stages, after they are digitized. It would be necessary to account for the effects of fringe rotation and phase switching in making the phase comparison.

A photonic calibration scheme should also be considered as a means of calibration of amplitude as well as phase. The thermal calibration source would provide the primary amplitude calibration, but the time required to move the mechanical reflectors required to direct the thermal source towards the feed might be a restriction, particularly during observations requiring fast position switching or on-the-fly scanning. The photonic calibration signal could run continuously, or if necessary be turned on and off. However, use of a cw (continuous wave) tone for amplitude calibration is less satisfactory than a broadband signal since with the latter the effect of the inevitable small amplitude ripples in the passband would be averaged out. Also, the amplitude stability of such a photonic signal would depend upon the sensitivity of the output level of the photonic diode to temperature and to the input optical power level, factors that we do not know at this time. Possibly the cw calibration tone could be a useful intermediate standard to use in between less frequent calibration with the thermal noise source, and could provide essentially continuous measurement of variations of the system temperature and gain. Both the total power in the passband and the amplitude of the of the calibration tone would need to be measured. However, in principle the effect that causes the low frequency gain fluctuations in HFETS might also cause fluctuations in the power level generated in the photonic diodes. It is not clear at the present time whether that would be a limitation, or how such fluctuations in the LO power would affect the performance of an SIS mixer.

References

Payne, J. M., L. D'Addario, D. T. Emerson, A. R. Kerr. and B. Shillue, Photonic local oscillator for the Millimeter Array, Proc. SPIE, 3357, 143-151, 1998.

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