NATIONAL RADIO ASTRONOMY OBSERVATORY

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M E M O R A N D U M

To: John Webber

From: Skip Thacker

Subject: Conventional optical reference LO

Abstract

This memo reexamines the conventional optical reference scheme for LO reference distribution in light of the low drift performance of the LO Sources and the recent availability of low-noise off-the-shelf fiber links. A design for the conventional optical reference scheme is described as well as an experimental plan to validate the design.

Background

Three different schemes for distributing the LO reference to the ALMA antennas were originally discussed early in MMA development. They were (1) conventional optical reference in which one or more microwave reference frequencies (in the range of a few GHz) are distributed over fiber by amplitude modulating an optical carrier and then generating the LO from this reference using conventional synthesizer and multiplier techniques, (2) a photonic reference system in which a slave laser would be locked to a master laser at an offset equal to a submultiple of the final LO frequency, then cleaned up and multiplied to the final frequency, and (3) a photonic direct scheme in which a slave laser would be locked to a master laser at an offset equal to the actual LO required at the SIS mixer and the beat note generated between these lasers in a photo mixer would be coupled directly to the LO port of the SIS mixer.

While the conventional optical reference approach was based on existing technology, it still had several areas requiring development: high power MMIC power amplifiers in the frequency range 80 to 120 GHz[1] and the high power varactor multiplier chain to multiply the output of the power amplifiers to the final LO frequency. In addition, the LO synthesizer[2] that would drive the power amplifiers was viewed as costly and complicated. The photonic direct system held the promise of being the silver bullet that would provide an inexpensive simple way to generate LO power at the

[1] The frequency range for the photonic reference system has recently been extended to 73 to 143 GHz.

[2] The LO synthesizer is now called the LO source.

antenna. Unfortunately, as was recognized at that time, the photonic direct scheme was several years in the future because photomixers that could be used at the highest ALMA frequency did not exist. There were photomixers available up to about 40 GHz at that time and it was felt that only a small amount of development would be needed to extend these to the 80 to 120 GHz range. Consequently, the photonic reference system was adopted as the ALMA baseline plan; it was believed to be a good choice because of the minimal amount of change needed to upgrade to a direct photonic LO in the future.

The photonic reference system distributes the reference at a much higher frequency than the conventional optical reference system; this is viewed as an advantage since the conventional wisdom is that the multiplication in the antenna would generate additional drift. While this is in general true, our measurements of the active multiplier chain (AMC) show that this additional drift is well within the ALMA error budget for the LO source and there is no significant penalty for distributing the LO reference at frequencies within the range of commercial off the shelf (COTS) microwave modulators/demodulators. *This is the motivation for this memo.* The drift of the AMC will be discussed in detail in later sections.

The photonic reference system has an advantage over the proposed photonic direct system in that, in principle, it requires only one slave laser and slave laser lock loop per sub-array instead of one per antenna. Not only does this affect the cost, but the photonic reference system preserves one of the advantages the conventional optical reference system has over the direct photonic system in that both distribute a common signal to all antennas of a sub-array. As a consequence, the drift on this common signal cancels and does not adversely affect the performance of the array (except for VLBI). This is significant in that the drift of the slave laser lock loop and the comb generator system has not to my knowledge been quantified and could be a significant source of error for ALMA for the direct photonic system. I note that L. D'Addario has proposed to change the baseline system so that there is one slave laser per antenna, which would negate this advantage.

The Conventional Optical Reference

I will describe a proposed conventional optical reference scheme using commercial off-the-shelf components that requires minimum modification to the ALMA baseline plan. I will describe the measured drift and noise properties of parts of this system that have been measured and describe a plan to measure and optimize the unknown elements. The proposed system is based on the Miteq MDD analog fiber optic link[3], which is a direct modulation link with nominally 11 GHz bandwidth (useable to 12 GHz). List price for a transmitter/receiver pair is $12,300 in small quantities. Costs in Table 1 are given based on recent manufacturers' quotes for the COTS elements and estimates for the NRAO supplied elements. These estimates imply a parts cost for an ALMA array (64 antennas and 5 subarrays) of approximately $2.2M, exclusive of labor. Since these are mainly COTS parts, I would estimate that one technician and one half of an engineer could assemble and test the optical reference and microwave corrector at the rate needed for ALMA plus 6 to 12 man months effort after the proposed proof of concept experiment to optimize and finalize the design and packaging.

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[3] The web link to the data sheet for this device is http://www.miteq.com/micro/pdfs/d279.pdf

Referring to the block diagram at the end of this memo, the outputs from the Central Reference Generator (CRG) and the output of the 8.6 to 11 GHz synthesizer, which must be extended to 6 to 12 GHz, are combined and fed into the laser transmitter. The output of the laser transmitter goes through a diplexer (WDM) to the fiber length corrector ($2400) and then through the fiber to the telescope. At the telescope the signal goes through another diplexer and to the receiver/demodulator where the reference signals are recovered and routed to the front end equipment. The 6 to 12 GHz signal is doubled and used to lock the YTO of the baseline LO source which is followed by the AMC, Power Amp, and cryogenic multiplier. The other port of the WDM goes to the input of another laser transmitter which sends the microwave reference back down the cable where it is phase compared to the original microwave reference and used to servo the fiber length corrector.

The YTO, AMC, power amplifier and cryogenic multiplier are the same design as the present LO source except the loop is closed at the YTO fundamental frequency instead of the W-Band port. Note that the current ALMA design has the power amp and the cryogenic multipliers outside of the lock loop; so the only additional thing that we need to move outside of the lock loop in order to lock at the fundamental YTO frequency is the AMC. We have already measured the performance of the LO source in this configuration (see appendix 2).

Fiber Length Corrector

While it is certainly possible to use the same fiber length corrector with the conventional optical reference scheme as is proposed for the photonic reference or photonic direct cases, considerable cost savings can be realized with little degradation in performance with the scheme shown in the block diagram. The fundamental difference between the laser scheme and microwave scheme is that the laser scheme servos the line length to hold the optical phase of the master laser constant while the microwave scheme holds the phase of the 2 GHz reference signal constant (for a slight increase in cost we could make this signal 4 GHz and improve the phase performance of the corrector). These two alternatives will be referred to as the laser corrector and the microwave corrector respectfully. The cost advantage comes from several sources: (1) The microwave corrector needs only a slow-response line stretcher. The laser corrector needs to cascade a fast piezoelectric line stretcher with the slow stretcher and have a more complex loop to control these two stretchers; otherwise, fast fluctuations in the phase of the laser signal will cause the loop to skip cycles. (2) The laser corrector needs a very stable (very expensive) laser, as its optical frequency directly controls the fiber length. Ideally this laser should be locked to the hydrogen maser as is the microwave signal. (3) The return link for the microwave corrector should be identical to the up link except it will only have the one reference signal being returned. This link could carry other signals back to the central location. This link could replace the simpler link that carries the high speed ethernet data and therefore achieves some cost reduction by eliminating that separate link or providing some redundancy, thereby further improving the cost-benefit ratio of the microwave corrector.

The microwave corrector will never be as precise as the laser corrector by as much as an order of magnitude. Does this matter? Probably not. The allocation for the laser corrector (Project Book Ch 7) is 2.2 femtosec or 0.7 microns and the laser will probably be a factor of 3 better than that with 0.2 micron rms precision[4]. The phase drift budget for all of the electronics is 2.1 microns and the total drift for electronics, corrected atmosphere, and structure is 3.6 microns (note that these add in an rms

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[4] The frequency drift of the laser must be added to this unless it is locked to the hydrogen maser.

sense). Even if the microwave corrector added another 2 micron component this would only slightly degrade the visibility amplitude at the highest frequency of the array.

In ALMA memo 335, I said with respect to the microwave corrector, "For the case of using the 2 GHz reference signal, a half micron is 1.2 millidegree which is a very precise and difficult loop. We agree with John Payne (John Payne, private communication) that this scheme is not really practical." The two things that are different now are: (1) the analog links available now have about 20 dB better noise performance than links that I have used previously and (2) the specification for the corrector could be relaxed to as much as 2 microns; consequently, I think the microwave corrector is now feasible.

Proposal for Lab Experiment

I propose to do an experiment with a prototype conventional optical reference system with a microwave corrector by the end of summer 2002. Dan Sundberg of Miteq has verbally agreed to supply two of the Miteq MDD links and two optical circulators for a few days loan and has agreed to come to CV to help with the experiment. Miteq would have full access to any data produced by this collaboration. In addition to the existing phase noise and phase drift equipment and software we would need to buy or borrow from other NRAO sites the equipment listed in the appendix which has an estimated cost of $9K.

The basic experiment would be to measure the phase noise of our YTO source when locked to a doubled reference provided from the MDD (6 to 12 GHz) link. A secondary experiment would be to measure the phase noise of the YTO source when locked to a reference provided by a link that Miteq has under development that operates in the range of 12 to 24 GHz. This prototype link would eliminate the need for a doubler and may provide some reduction in drift. This link might be as much as 30 to 40% more expensive than the MDD link. I believe that measuring the phase noise performance of this link at the high frequencies is Dan's chief interest. These two measurement are very straightforward and require little in the way of extra hardware or software other than the fiber and some fiber patch cords and adapters for an approximate cost of $3K.

In addition to the phase noise measurements of the conventional optical reference distribution, I would like to make some measurements of the microwave corrector concept. This will require a little more effort and money. We will need two optical diplexers in addition to the optical circulators that Miteq will provide, several more patch cables, and a servo controlled optical delay line for an additional cost of approximately $6K. We could get some meaningful data by only measuring the phase of the return link, without implementing the optical delay line, but this may turn out to not only be less intellectually satisfying but also technically more difficult to implement.

Since we will have the Miteq links for only a short time, we must carefully prepare in order to be successful. Fortunately the interface to these links is microwave SMA connectors; therefore, we can trouble shoot our measurement system by substituting a short cable run for the link. My initial thoughts is to make the measurements of both the Optical Reference and the Microwave corrector on a Thursday and Friday and then do a long term stability run over the weekend and then return the equipment on Monday or Tuesday. Of course if we have difficulty, I will work the weekend and cut the stability run down to only one night.

Miscellaneous Calculations:

The project book chapter 7 generates the phase drift and coherence specifications from the following overall goals:

> The goals for phase accuracy and stability include:
> Greater than 90% interferometric coherence at 950 GHz (77 fsec rms), after all calibrations and corrections, on all time scales from 1s to 1e4 sec.
> Absolute visibility calibration to 0.1 radian at 950 GHz (16.8 fsec).

This is 11.9 fsec per antenna or 3.6 microns, which according to Thompson table 7.1 produces a 0.5% error (error = 1-0.5*p*p, where p is rms phase noise in radians). Adding another 2 microns for the microwave length calibrator gives 4.1 microns or 13.6 fsec per antenna or 19.3 fsec => 0.115 radian or 0.66% error. If the total calibration budget for ALMA is 1.0%, then changing one component of this budget from 0.5% to 0.66% changes the total error to 1.089% which I argue is not significant compared to the large savings in time and money that could be realized from implementing the conventional optical reference system.

The MDD link has a published maximum Noise Figure of 20 dB or -120 dBm in 1 kHz and a max input power of -14 dBm. With 10 dB fiber loss, 6 dB multiplexer loss, and 3 dB dispersion loss we have 86 dB S/N at the input of the phase detector which corresponds to 50 microradian or 1.2 micron for a link at 2 GHz. Note that this error scales inversely with frequency–a link at 4 GHz would have 0.6 micron error assuming the noise figure remains constant. The computer controlled version of the ODL-300 optical delay line has a resolution limit set by its encoder of 1.4 micron, presumably its setability will be better than this when its servo is driven directly as I propose to do for this proof of concept experiment.

The temperature coefficient of a typical fiber cable is approx 6.8 e-6/K which gives a total round trip change of 10.2 cm/K for a 15 km cable. The corrector is also round trip, which means we need a corrector with a 5.1 cm/K range (I don't understand the claim that Bill Shillue has found a piezoelectric line stretcher that covers the required range, unless he is assuming much less than a K temperature variation between epochs of relocking the corrector.) Indeed as John Webber points out, the microwave corrector does not even need a line stretcher at all, as the correction can be done in software if we can measure the phase of the output of the returned signal with respect to the transmitted reference to the required precision. For the initial tests, I prefer to have a null seeking servo rather than worry about the linearity of a 360 degree phase detector with a 50 dB dynamic range, but in principle we could eliminate the line stretcher which is, after all, a motor driven mechanical component.

Appendix I

In ALMA memo 335 we presented some data on W-Band power amplifier drift (see below) that showed that the power amplifier drift was sufficiently small that it could be placed outside the loop. This data was taken with the AMC also outside the loop. This was done because the isolation provided by the AMC generated better stability than the drift of the AMC itself. I propose to use the LO plate that we provided the CDL SIS group, which is configured to lock the YTO directly, and remeasure the drift of this LO chain to obtain further data. While this LO plate is not identical to the final LO source, the pre-prototype LOs that we will be providing to the cartridge designers this fall will also have the AMC outside the loop and they have very similar components to the final design. We will have an opportunity to measure these drifts before they are shipped.

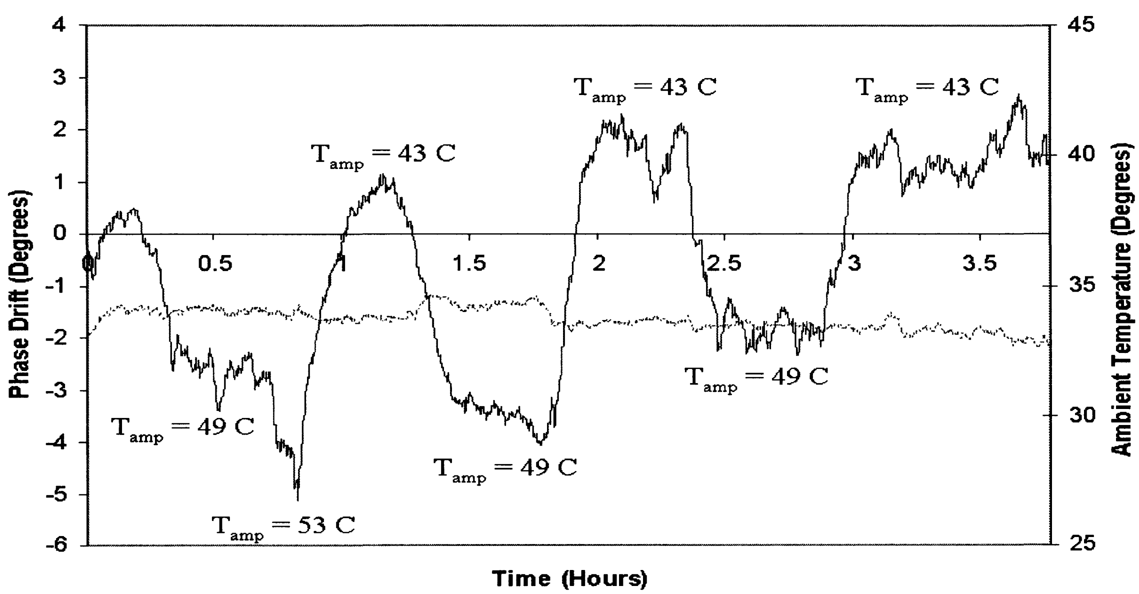

Figure 1 (figure 5 from memo 335)
Power Amplifier #6 (0.6 degree phase per degree Celsius)

Appendix II

Table 1 Estimated Costs for Components for Conventional Optical Reference

ITEM	Number Required	Cost
Fiber Optic Transmitter	1 per antenna + 1per subarray	9600
Fiber Optic Receiver	2 per antenna	2800
WDM assembly (circulator and filters)	2 per antenna	2500 estimate
Optical Delay Line	1 per antenna	2540
Servo Loop for ODL	1 per antenna	300
Optical Patch Cords	1 lot per antenna	1500
EDFA amps	8 per subarray	4000
Subarray Switch	1 per antenna	1500
Optical power splitters 8-way	2 per subarray plus 1	400
Monitor and Control	2 per antenna	1000
Mechanical Packaging	2 per antenna plus 1	1000
Microwave components	1 lot per antenna	1000

parts list and costs for a demonstration and proof of concept experiment

2 each MDD fiber links on loan from Miteq ($normally 12,300 each)	n/a
1 each Optical Delay Line	$2540
2 each optical circulators on loan from Miteq	n/a
2 each optical filters (Estimate $1000 to $2000 each)	$2000
8 each optical patch cords and "splices" (Estimate)	$1500
1 lot misc parts for lock loop chassis	$300
2 Mixer MiniCircuits ZAM-42	$110
2 Power Splitter MiniCircuits ZFSC-2-10G, ZAPDQ-2-50	$150
15 kilometer single mode fiber with connectors (SMF-28)	$2000
2 Amplifiers MiniCircuits ZJL-7G	$200

Total $ 8,800

Table 2 Costs for Array with 64 Antennas and 5 sub arrays

Sub Arrays	5		
Antenna	64		
Item	Number	cost each	cost exten
Fiber Optic Tx	69	9600	662400
Fiber Optic Rx	128	2800	358400
Circulator/Filter	128	2500	320000
Optical Delay Line	64	2540	162560
Servo Loop ODL	64	300	19200
PatchCordsSplices	64	1500	96000
EDFA Amps	40	4000	160000
Subarray Switch	64	1500	96000
Optical power	11	400	4400
Mechanical Pkg	129	1000	129000
Microwave	64	1000	64000
Monitor and Control	128	1000	128000
		Total	2199960

Test plan and block diagram

Figure 2 shows the block diagrams of the tests to be performed on the link. First we would do a basic phase noise test using the low frequency (3.0 GHz) high purity signals out of the E5500. This would characterize the link with the cleanest signal that we have. Next we would test the link at the proposed frequency of operation with signals from an HP synthesizer. At this time we would also test locking the YTO to the doubled reference. After the tests of the phase noise, I propose to measure phase performance of the line corrector by monitoring the signals V3 and V4 with either (both) a vector voltmeter and the E5500 followed with a LabView data monitoring package. Then after verifying that the line length corrector was holding the phase between V3 and V4 constant , we would measure the phase at V5 with respect to V3. Then we would measure the output of the YTO, V2 with respect to the reference in order to get an overall measure of the system performance. If time permits, this could also be done at the output of the AMC in W-Band, V6.

schedule TBD

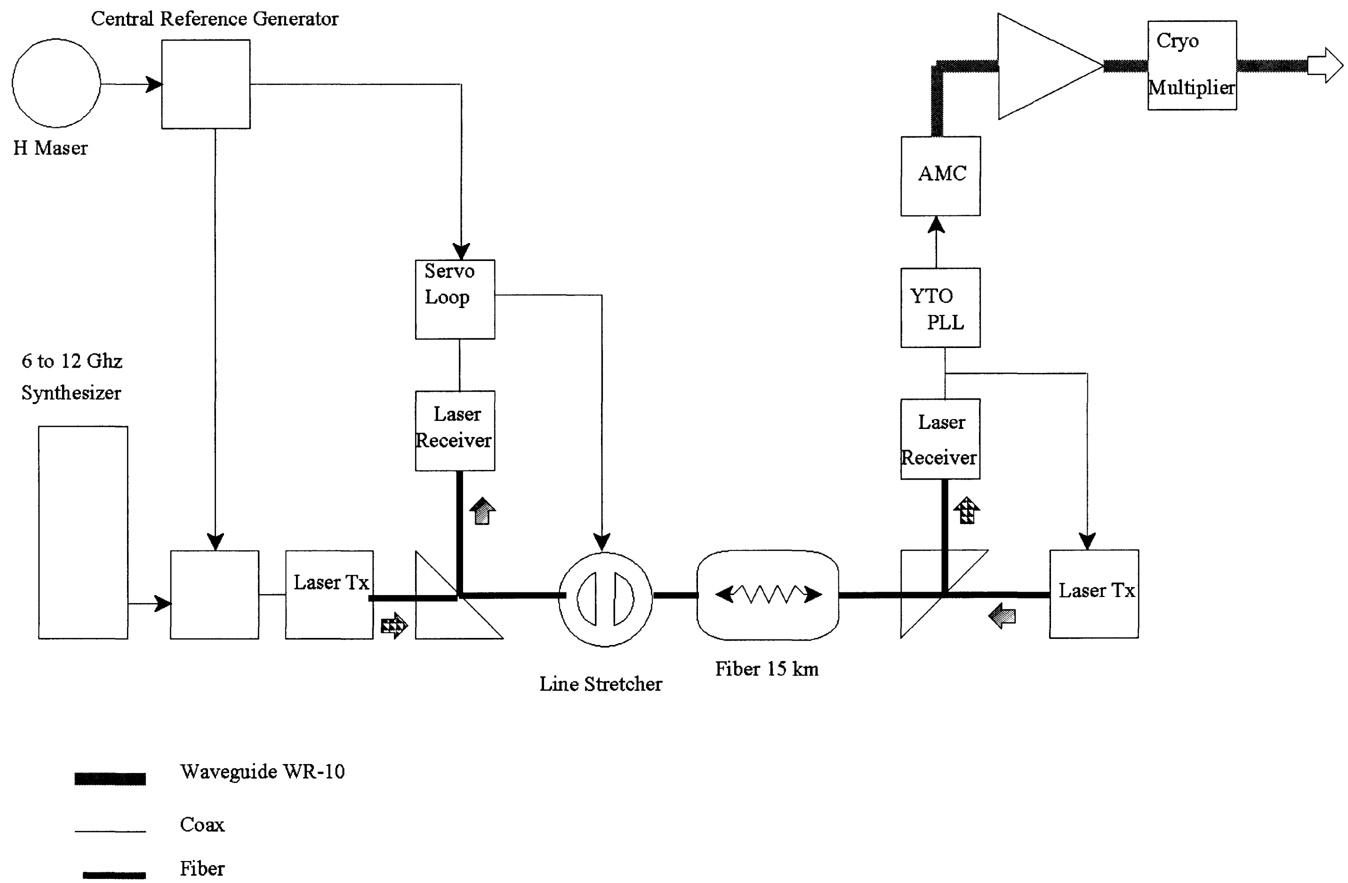

Figure 2 BLOCK DIAGRAM of proposed Conventional Optical Reference

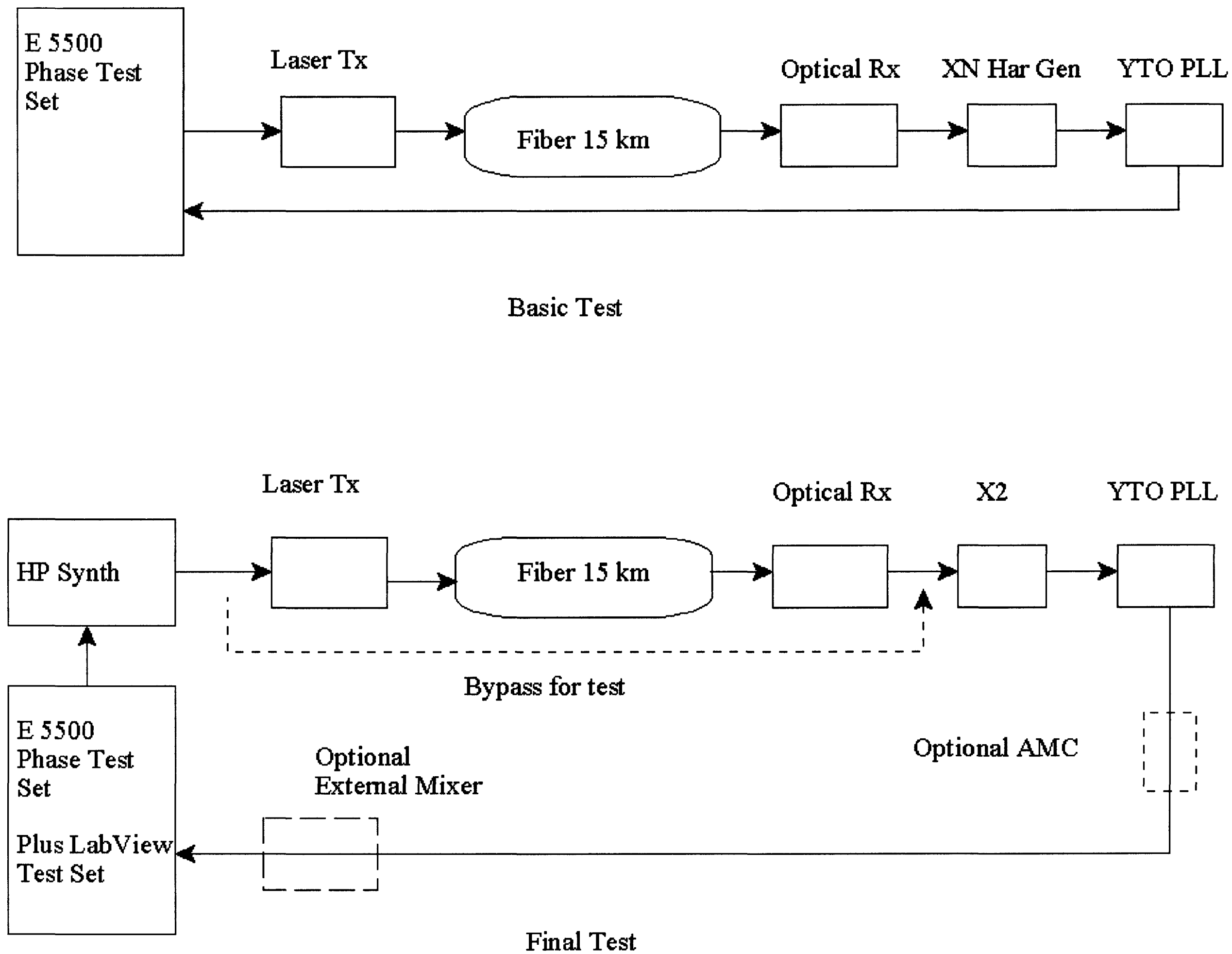

Figure 3 Basic Test Diagrams for Conventional Reference

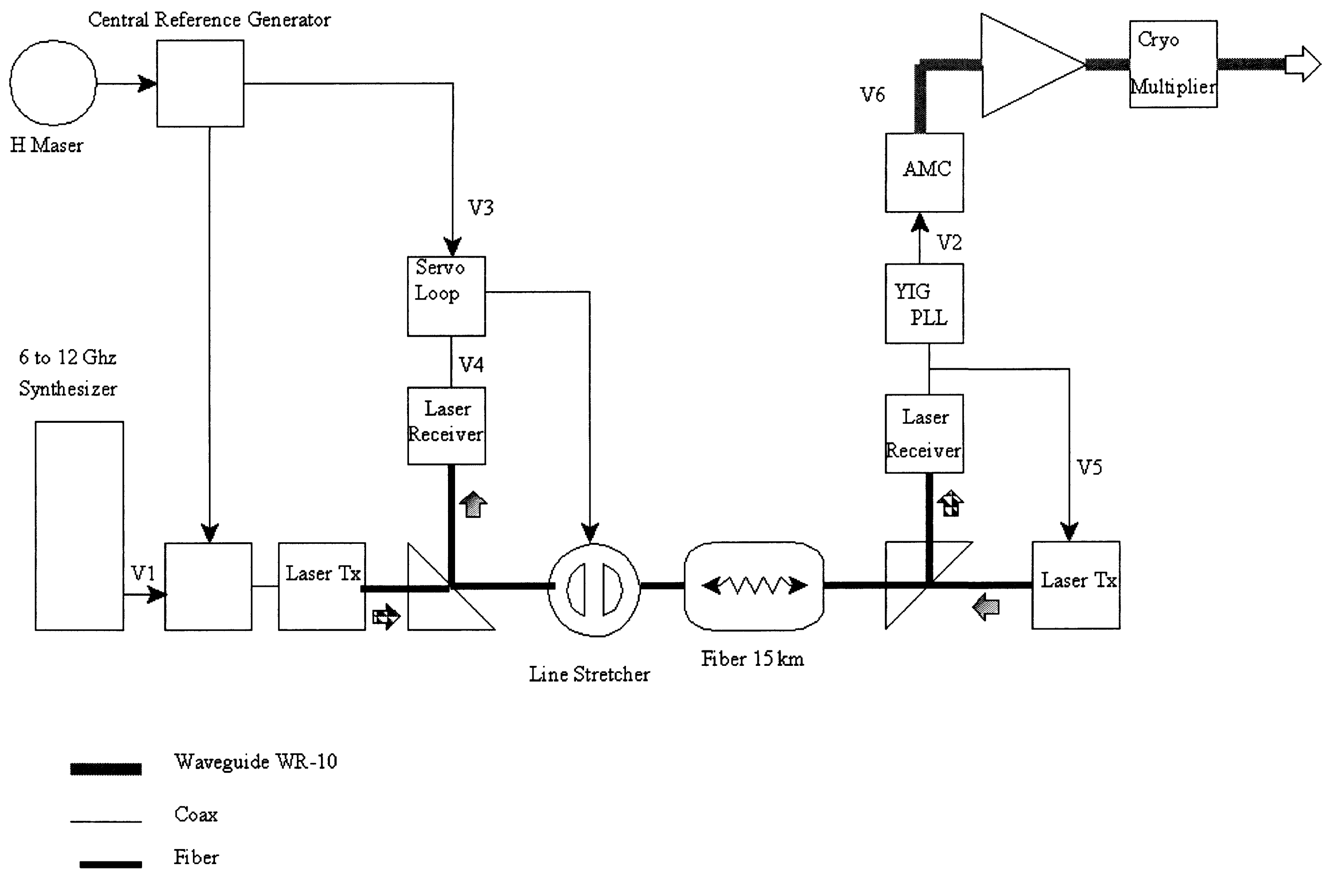

Figure 4 Test Diagram for Microwave Corrector showing test voltages