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CDL 4-Year SIS Receiver Development Plan

ARK — January 19, 1997

Driving Forces

SIS receiver development in the CDL over the next few years will continue to be guided jointly by the immediate needs of the 12-m telescope and the longer term requirements of the MMA. The needs of the 12-m telescope mostly coincide with the planned MMA development work, so there is little conflict between the two, except for the substantial production time required for the newer multi-channel 12-m receivers (*i.e.*, the 8-beam 230 GHz receiver and the 8-channel 3-mm receiver).

Frequency Bands and Bandwidths

For a given receiver noise temperature, receivers with very wide RF bandwidths are preferable because fewer receivers are needed to cover a given spectral range. The main arguments against very wide-band receivers are (i) their greater susceptibility to out-of-band interference, (ii) their more limited dynamic range (which could be a problem, especially in solar observations, even if attenuators are inserted ahead of the receivers), and (iii) the greater difficulty of fabricating wideband SIS mixers reproducibly because of the higher critical current density and smaller junction size required. In principle it is possible to make tunerless SIS receivers (i.e., no mechanical tuners) that cover a full waveguide band (~1.5:1 frequency range) with "low noise". Whether this is practical, especially in the production quantities needed for the MMA, has yet to be determined. A conservative assumption, based on experience at SAO, is that receivers will cover at least a 1.3:1 frequency band. The goal of "low noise" means a receiver noise temperature of (2-4)*hf/k across the useful band (*e.g.*, 22-44K for a 230 GHz receiver), which is based on the best reported receiver results to date.

To use the standard waveguide bands, for which components are commercially available, would have obvious advantages. This would require only 8 receivers if 1.5:1 frequency coverage could be obtained. However, some band breaks, at which receiver noise temperatures are likely to be highest, would then fall at astronomically important frequencies where the best sensitivity is desired. To satisfy the constraint of a 1.3:1 bandwidth, the bands can be chosen as shown in Fig. 1. The specified MMA frequency coverage is achieved, with the exception of gaps at 68-70, 116-130 and 170-183 GHz (which we believe are not critical to the MMA community), in ten bands. Furthermore, all bands fall within standard waveguide bands, with the exception of those above 330 GHz for which there are no standard bands. Band breaks occur near 115 and 230 GHz, probably the two most important frequencies for the MMA, so it will be essential to ensure that receiver noise temperatures are low at these frequencies. This should not be difficult if we find that receiver bandwidths of 1.4:1 or 1.5:1 are in fact practical.

Based on the above, we should concentrate our future SIS receiver development on the standard waveguide bands — a change from our current practice of using non-standard bands.

Development of prototype mixers should be done at a frequency important to the 12-m telescope — *e.g.*, the 230 GHz band.

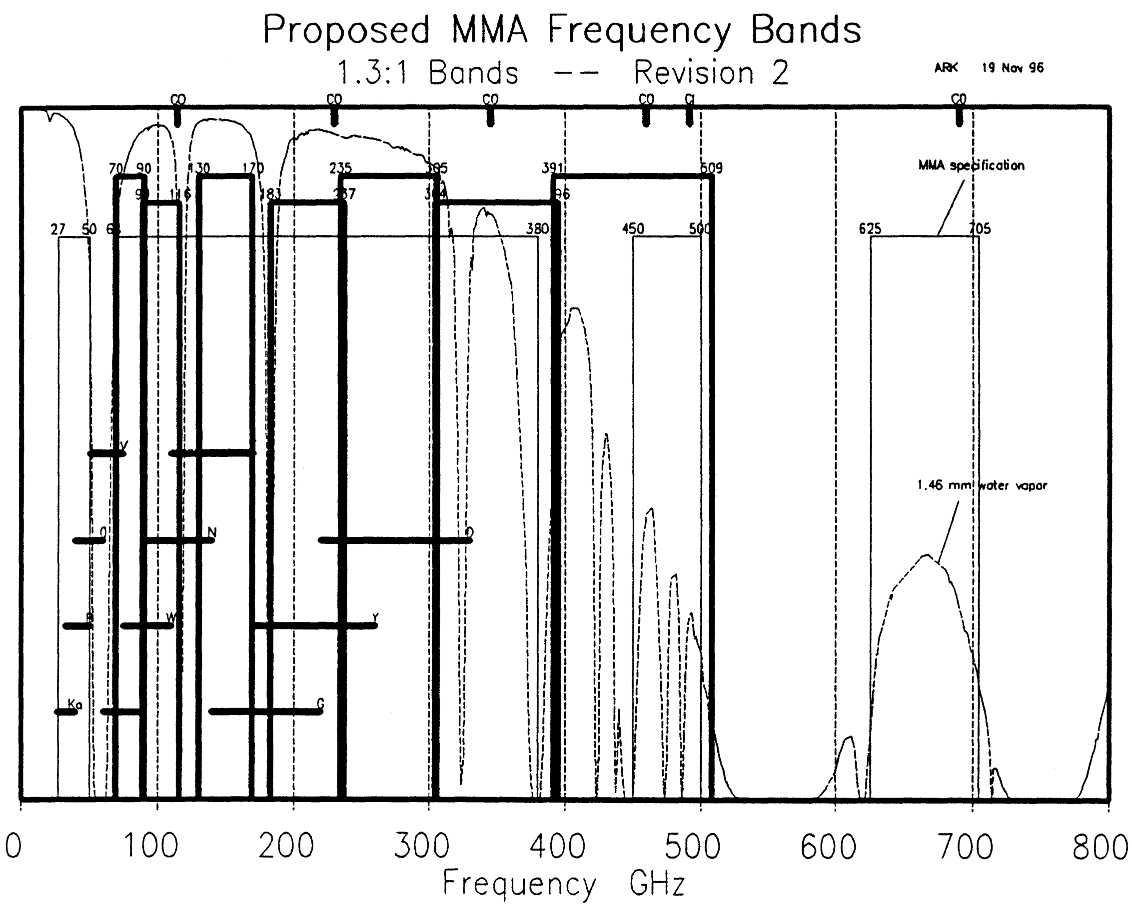

Fig. 1. Ten bands covering 27-700 GHz. Horizontal bars indicate the standard waveguide bands. (Note that the 27-50 GHz band shown is actually two bands.)

SIS Mixer Types

Mechanically tunable SIS mixers usually have two adjustable waveguide short-circuits. The cryogenic drive mechanisms for these tuners, and the associated coupling via high-vacuum rotary feedthroughs to room temperature servo motors, have been the most unreliable components in SIS receivers at NRAO. We believe it is important to avoid all mechanical tuners on the MMA if at all practical. An additional disadvantage of tunable SIS receivers is the difficulty of achieving the desired 8-GHz IF bandwidth (which implies an RF bandwidth of 20 GHz or more, depending on the choice of IF).

Broadband tunerless SIS receivers have demonstrated good performance over frequency bands of ~1.3:1. A factor affecting the design and reproducibility of tunerless SIS mixers is the *number of junctions*. Mixers with one or two junctions have simpler topology and are easier to design, but require smaller junctions with higher critical current densities which can result in poorer junction quality and reproducibility, and lead to dynamic range limitations. Mixers with more than two junctions require more complex embedding circuits, but permit larger junctions with lower critical current density. They have larger dynamic range, but also require more LO power, and are more susceptible to AM sideband noise from the LO circuit. A logical extension of the multi-junction mixer is the *traveling-wave* SIS mixer, which uses an electrically long, very narrow SIS junction. The signal and LO are attenuated as they propagate along the junction. This scheme has wide bandwidth, but, because of the relatively large total junction area, the junction capacitance is high, which can limit the IF bandwidth. Traveling-wave SIS mixers are likely to be advantageous at the highest MMA frequencies where their total junction area is relatively small, and matching circuits for other types of mixer are difficult to realize. Prototype development work should be continued on all three classes of SIS mixer (1 or 2 junction, multi-junction, and traveling-wave) to determine their relative merits in real receiving systems. It is important to develop a means of testing the dynamic range of SIS mixers in the presence of a high-temperature thermal noise background.

All SIS receivers currently in use for radio astronomy use *single-ended* (as opposed to balanced) mixers. Single-ended mixers have a common input port for the RF signal and LO power, which requires some form of LO/signal diplexer in front of the mixer. Such a diplexer in an SIS receiver is usually a directional coupler (waveguide or quasi-optical), but may also be a mechanically tunable device such as a Martin-Puplett interferometer or a resonant-ring four-port filter. To avoid mechanical tuners, the latter two options are rejected for the MMA. The simple directional coupler type of LO diplexer has two shortcomings: (i) For low signal attenuation, the LO attenuation must be substantial — typically 20 dB. And (ii) there is no inherent rejection of AM sideband noise from the LO circuit. These limitations are overcome by a *balanced* mixer, in which the LO is efficiently divided between two SIS mixers, and AM sideband noise is eliminated by appropriate phasing of the RF, LO and IF signals in the two mixers. A balanced SIS mixer would require LO power ~17 dB lower than required by a single-ended mixer. Development of prototype balanced mixers should have a high priority.

When observing a single spectral line through a lossy atmosphere, atmospheric noise in the image sideband can seriously degrade the overall system noise temperature. It is then advantageous to use an *image-separating* SIS mixer, which has separate IF output ports for the upper and lower sidebands. The heart of an image-separating mixer is a matched pair of broadband mixers — single-ended or balanced. The CDL is at present working on a prototype single-chip image-separating mixer for 200-300 GHz, and continuation of this work should have high priority.

A *balanced image-separating* SIS mixer would combine the advantages of the balanced and image-separating designs — *viz*: low LO power, immunity to LO sideband noise, and rejection of image noise. Balanced image-separating mixers should be the ultimate goal of the MMA SIS receiver development effort.

Other Essential Projects

Crucial to successful SIS receiver development is access to a reliable fabricator of high quality niobium circuits. The nature of millimeter-wave receiver work puts it outside the scope of the few remaining commercial Nb foundries — our junctions are too small and critical current densities too high, and there is no expectation of commercial application for these devices to stimulate the interest of commercial sources. The two US laboratories capable of (and interested in) doing our Nb fabrication are at UVA and JPL. Expanded support for the UVA facility, and a contract with JPL are essential to ensure successful receiver development for the MMA.

Based on our experience trying to produce 8 well matched mixers for the 8-beam 230 GHz SIS receiver on the 12-m telescope, much improvement is needed in SIS wafer quality control. We have started work with UVA to design a group of monitor circuits to be included on all wafers which will allow all the important wafer parameters to be measured — J_C, C_S, λ_L, C_{oxide}, and the I-V characteristics.

A major tool for mixer diagnostics would be a means of measuring the embedding impedance seen by the SIS junctions. This can be done by analyzing the pumped I-V curve of a mixer. Pan has started developing a computer program to do this.

With the 8-GHz IF bandwidth desired for the MMA, SIS receivers will no longer be able to use IF isolators. Rather, the first IF transistor (or two) will be mounted in the mixer block, electrically close to the SIS junction. The mixer-to-IF coupling circuit (including mixer bias connections) and IF amplifier must be designed to accommodate the wide range of output impedances (negative in some cases) characteristic of SIS mixers as the LO frequency is adjusted across the band. Good thermal isolation is required between the transistor(s) and the SIS junction. Provision for SIS bias connections should include maximum protection against static discharge.

Development of local oscillator sources for the MMA must be started without delay. In addition to the proposed laser heterodyne scheme, it seems prudent to develop more conventional multiplier-chain sources for immediate use in the laboratory and as a backup in case the laser scheme is impractical. Measurements should be started as soon as possible on the noise and phase stability of sources of both kinds. In addition to developing LO sources for the MMA, a variety of laboratory sources will be needed for use both as LO's and test signal sources.

NRAO has long had a dismal history of millimeter receiver feed design, mainly because no experienced antenna designer has ever been assigned to this job. The MMA will require many quasi-optical components (feed-horns, lenses, IR filters, vacuum windows) whose characteristics will profoundly influence the performance of the MMA. This is an appropriate time to find a PhD level engineer to work on feeds and quasi-optics, and to provide him with a good antenna and material measurement laboratory.

The MMA will need a number of cryogenic IF components. With image-separating or balanced SIS mixers, multi-octave quadrature and 180° IF hybrids are required. Second stage IF amplifiers, following the one- or two-stage amplifiers in the mixer blocks, can probably be commercial MMIC amplifiers. Within the cryostat, it may be cost-effective to use solid-state (or mechanical) switches to connect the receivers in use to a common set of IF amplifiers and vacuum feedthroughs (2 amplifiers and vacuum feedthroughs, vs ~20).

CDL SIS Receiver Development Plan

	1997				1998				1999				2000				2001				2002					
GENERAL DEVELOPMENT																										
200-300 GHz tunerless mixer (SIS373)	X	X																								
260-300 GHz tunable SIS mixer (SIS302a)	X	X	X																							
260-300 GHz tunerless SIS mixer (SIS302b)	X	X	X																							
200-300 GHz image-separating SIS mixer (ISM371)	X	X	X	X																						
200-300 GHz balanced SIS mixer			X	X	X	X																				
200-300 GHz balanced image-separating SIS mixer					X	X	X	X																		
1- or 2-junction SIS mixer 200-300 GHz			X	X	X	X																				
On-wafer process monitor	X	X	X	X																						
Mixer analysis program	X	X																								
IF amplifier for integration into SIS mixer blocks		X	X	X	X	X	X	X																		
Quasi-optical component development																										
Low leakage narrow-band window	X	X	X	X																						
Expanded PTFE IR filter			X	X	X	X																				
Materials measurements -- PTFE and HDPE					X	X	X	X																		
0-12 GHz IF plate			X	X																						
Sideband measurement equipment		X	X	X																						
170-260 GHz extension to 8510				X	X	X																				
IF components for 4K operation																										
IF switch -- mechanical	X	X	X																							
IF switch -- solid-state									X	X	X	X														
Broadband quadrature hybrid					X	X	X	X																		
Broadband 180-degree hybrid					X	X	X	X																		
Second JT SIS test station					X	X	X	X																		
Third JT SIS test station									X	X	X	X														
MMA-SPECIFIC <<< (in MMA receiver bands) >>>																										
90-116 GHz tunerless SIS mixer																			X	X	X	X				
130-170 GHz tunerless SIS mixer															X	X	X	X								
180-240 GHz tunerless SIS mixer					X	X	X	X																		
230-300 GHz tunerless SIS mixer									X	X	X	X														
300-400 GHz tunerless SIS mixer													X	X	X	X										
400-500 GHz tunerless SIS mixer																	X	X	X	X						
600-700 GHz traveling-wave SIS mixer											X	X	X	X												
90-116 GHz balanced image-separating SIS mixer																							X	X	X	X
130-170 GHz balanced image-separating SIS mixer																			X	X	X	X				
180-240 GHz balanced image-separating SIS mixer									X	X	X	X														
230-300 GHz balanced image-separating SIS mixer													X	X	X	X										
300-400 GHz balanced image-separating SIS mixer																	X	X	X	X						
400-500 GHz balanced image-separating SIS mixer																					X	X	X	X		
600-700 GHz bal/im-sep.traveling-wave SIS mixer																			X	X	X	X				
90-116 GHz LO chain																X	X	X	X							
130-170 GHz LO chain												X	X	X	X											
180-240 GHz LO chain		X	X	X	X																					
230-300 GHz LO chain						X	X	X	X																	
300-400 GHz LO chain										X	X	X	X													
400-500 GHz LO chain														X	X	X	X									
600-700 GHz LO chain								X	X	X	X															
Other test equipment to be built as needed: 4K Receiver test stations; LO chain power & noise test equipment																										