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Submillimeter Source Needs for NASA Missions

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ABSTRACT

Submillimeter source needs for the NASA astrophysics Submillimeter Intermediate Mission (SMIM) and the Earth Observing System Microwave Limb Sounder (EOS MLS) instrument are presented. Solid state local oscillators using planar devices are planned. State-of-the-art performance for these components is reviewed.

1. INTRODUCTION

Two future NASA missions operate in the submillimeter wavelength range; one astrophysics mission, the Submillimeter Intermediate Mission (SMIM), and one earth remote sensing instrument, the EOS Microwave Limb Sounder (EOS MLS). The SMIM science goals include a complete, submillimeter wave, high resolution, spectral line survey of about 100 astrophysical sources including molecular clouds in the Milky Way, external galaxies, planets, and sources of opportunity such as comets and supernovae. Sensitivity adequate to observe the spectral line confusion limit is desired. The instrument concept consists of heterodyne receivers to cover the frequency range from 400 to 1200 GHz and a scanning Fabry-Perot spectrometer for frequencies from 1000 to 3000 GHz. The focal plane will be cooled to about 4K. A two year lifetime is anticipated. The science objectives of EOS MLS are to study and monitor ozone chemistry in the stratosphere with complete global coverage. Moderate sensitivity with high spectral resolution is required to measure atmospheric thermal emission spectra from critical molecular lines. The field of view of the instrument is scanned through the limb to derive the vertical distribution of molecules. The instrument concept consists of heterodyne radiometers near 215 GHz to measure H_2O, O_3 and pressure, near 440 GHz to measure H_2O, O_3, N_2O, HNO_3 and NO, near 640 GHz to measure HCl, ClO and BrO, and near 2500 GHz to measure OH (1). The focal plane will be radiatively cooled to 80K. A five year lifetime is required.

At submillimeter wavelengths, heterodyne radiometers provide the best sensitivity for high spectral resolution observations. In a heterodyne radiometer a remote submillimeter wave signal from either the astrophysical source or the atmosphere is combined with a submillimeter wave local oscillator source in a non-linear mixer which outputs the convolution of the two signals at the difference or intermediate frequency (IF) usually at microwavelengths. The local oscillator signal has a narrow spectral width so that the remote signal is replicated at the IF. The IF signal is then analyzed at the desired spectral resolution. Key elements of the heterodyne radiometer are the mixer and the local oscillator (LO) source. The needs for local oscillator sources are the subject of this paper.

2. SMIM LOCAL OSCILLATORS

In the SMIM heterodyne instrument the remote signal from the telescope is spatially combined with the local oscillator signal in a quasi-optical frequency diplexer. The combined signal and LO are coupled to a fundamental mixer by a passive quasi-optical frequency multiplexer. The mixers are extremely sensitive SIS (superconductor-insulator-superconductor) tunnel junctions operating at about 4K. To cover the whole submillimeter wave band, ten mixers and local oscillators, each optimized over a 10% bandwidth, are used. Table 1 gives the frequency range for the frequency bands. The IF output from the mixers, centered at 10 GHz with a 4 GHz bandwidth, is preamplified by low-noise, high electron-mobility transistor (HEMT) amplifiers, also cooled to 4K, followed by amplifiers cooled to 40-60K. The IF is then further amplified and downconverted for input into acousto-optical spectrometers. Spectrometer outputs are digitized and passed, with engineering data, to the instrument data system for transmission to the ground.

Table 1: Frequency Bands

10 Bands to Cover Frequency Range				
400-450 GHz	450-510 GHz	510-570 GHz	570-640 GHz	640-710 GHz
710-790 GHz	790-870 GHz	870-970 GHz	970-1080 GHz	1080-1200 GHz

2. . SMIM Local Oscillator Requirements

The SMIM local oscillator requirements are summarized in Table 2. Continuous frequency coverage is required to measure the complete spectrum from 400 to 1200 GHz. The output power is set by the mixer operational needs, losses anticipated in coupling the LO into the mixers, and some added margin for degradation during flight operation. The non-linear mixing element to be used is the superconductor-insulator-superconductor (SIS) tunnel junction. The most sensitive heterodyne receivers in the millimeter wave band employ SIS tunnel junctions as the mixing element. SIS tunnel junction heterodyne mixers were first developed for radio astronomy applications in the late 1970's (2,3). They have been used for radio astronomy observations from 45 to 750 GHz (for example 4,5,6,7).

Table 2: SMIM Local Oscillator Requirements

Frequency Coverage	400 - 1200 GHz
Output Power	50 μW
Fixed Tuned Bandwidth	10%
Electrical Tuning Step Size	2 GHz
Frequency Stability	$1x10^{-7}$
Frequency Knowledge	$1x10^{-8}$
DC Power per LO Source	10 W

The current-voltage (I-V) non-linearity of an SIS tunnel junction, which is responsible for the mixing process, is 100-1000 times sharper than in GaAs Schottky diodes resulting in substantially higher conversion efficiency and much lower local oscillator (LO) drive power requirements. Theoretically, optimum performance of an SIS tunnel junction mixer is achieved with an absorbed LO power of about $(h\nu)^2/R$ where R is the resistance of the junction. This is less than 0.5 μW at 1000 GHz for R = 50 W. Laboratory experience indicates that a few microwatts of power is required at 200 GHz including a factor of 10 loss for LO/signal diplexing. Based on this experience about 50 μW of power is the projected requirement for SIS tunnel junction mixers operating at 1000 GHz. The fixed tuned bandwidth of 10% was chosen as a goal to minimize the number of local oscillators required to cover the entire band. Broader bandwidth is desirable. The electrical step size of 2 GHz allows four measurements of a given frequency in the IF for separation of signals in the upper and lower sidebands. The frequency stability and knowledge requirements are set at 10 and 100 times lower than the highest spectral resolution anticipated (200 KHz spectral resolution is desired for observation of spectral lines in planetary atmospheres). The DC power level is driven by the limited availability of power on the spacecraft.

2.2. SMIM Local Oscillator Baseline Approach

The baseline approach for the SMIM local oscillator employs solid state oscillators to minimize risk and power requirements and to maximize operating lifetimes. Each LO source consists of a fundamental, phase locked millimeter wave oscillator followed by two (or more) multipliers. Each LO chain covers 10% bandwidth. This will be accomplished with electrically tuned millimeter wave oscillators and fixed tuned multipliers.

The SMIM baseline local oscillator design, shown in Figure 1, employs millimeter wave sources operating in the 50 to 100 GHz range multiplied to higher frequencies. Output powers in excess of 50 mW are available from Gunn oscillators. Higher output power may be required. The required electrical tuning over a 10% bandwidth with high power has not been demonstrated. An alternative would be to develop a synthesized millimeter wave source. To date the device of choice for the non-linear element in millimeter and submillimeter wave multipliers have been the whisker contacted GaAs Schottky varactor. Multiplier chains employing these diodes have been demonstrated to about 700 GHz with adequate output power for an SIS tunnel junction mixer. At least twenty multipliers are required for SMIM. Whisker contacted diodes have been space qualified for several missions (UARS MLS, SWAS); however this involves an extremely labor intensive and low yield assembly process. Planar varactor diodes would clearly be a better option.

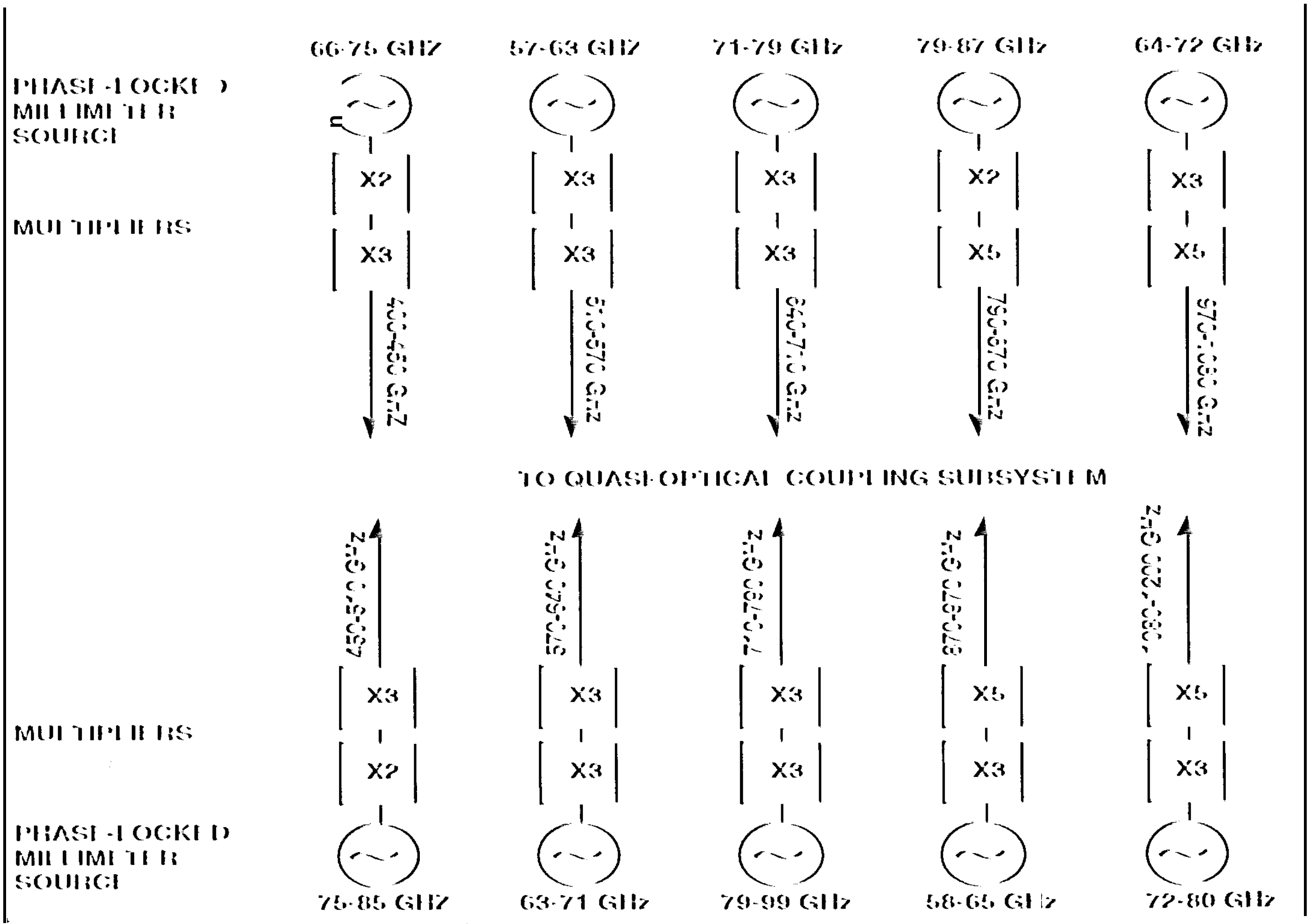

Figure 1: SMIM local oscillator baseline concept.

3. EOS MLS LOCAL OSCILLATOR

In EOS MLS, GaAs Schottky subharmonic mixers are used for 215, 440, and 640 GHz bands requiring local oscillators at about half of the remote signal frequency. A fundamental mixer is used for the 2500 GHz receiver. Hence four local oscillators are required near 110, 220, 320, and 2500 GHz. In contrast to SMIM, the EOS MLS local oscillators are fixed in frequency since very broad band mixer IFs are used to cover the required frequency range. The GaAs Schottky subharmonic mixers operate at about 80K. The IF output from the mixers, in some cases with as much as 20 GHz bandwidth, is amplified and downconverted for input into filter banks and autocorrelator spectrometers. Spectrometer outputs are digitized and passed, with engineering data, to the instrument data system for transmission to the ground.

3.1. EOS MLS Local Oscillator Requirements

The EOS MLS local oscillator requirements are summarized in Table 3. The output power is set by the GaAs Schottky subharmonic mixer operational needs and some added margin for degradation during flight operation. Laboratory experience indicates that a 5 to 10 mW of power is required for back-to-back GaAs Schottky mixer diodes. The frequency stability and knowledge requirements are set at 10 and 100 times lower than the highest spectral resolution anticipated (200 KHz spectral resolution is desired for observation of spectral lines high in the stratosphere). The DC power level is driven by the limited availability of power on the spacecraft.

Table 3: EOS MLS Local Oscillator Requirements

Frequency Coverage	110, 220, 320, 2500 GHz
Output Power	5-10 mW
Fixed Tuned Bandwidth	1%
Frequency Stability	$1x10^{-7}$
Frequency Knowledge	$1x10^{-8}$
DC Power per LO Source	10 W (50W for 2500 GHz)

3.2. EOS MLS Local Oscillator Baseline Approach

The baseline approach for the EOS MLS is summarized in Table 4. The three lower frequency channels employ solid state oscillators to minimize risk and power requirements and to maximize operating lifetimes. Each LO source consists of a fundamental, phase locked Gunn oscillator followed by multipliers. Since the LOs are fixed in frequency, no tuning capability is required. Planar diode, as opposed to whisker contacted diode, based multipliers are planned to reduce risk and enhance lifetime. The local oscillator for the 2500 GHz channel is a FIR gas laser pumped by a CO_2 laser.

Table 4: EOS MLS Local Oscillator Baseline

110 GHz	Gunn oscillator
220 GHz	x2 Multiplier with Gunn Oscillator
340 GHz	x2x2 Multipliers with Gunn Oscillator
2500 GHz	FIR gas laser pumped by CO_2 gas laser

4. MULTIPLIER STATE-OF-THE-ART

The key elements in a multiplier are the non-linear device and its embedding network. Highest multiplication efficiency is achieved using varactor diodes rather than varistor diodes. The most commonly used submillimeter wave varactor is the whisker contacted GaAs Schottky diode varactor. Several novel varactors configurations are currently being studied which use engineered III-V materials, including varactors in the BNN (barrier-n-n^+) family (8,9,10,11,12), single barrier varactors (SBV)

(13,14,15,16), and high electron mobility varactors (HEMV) (17).These may provide better performance, and in some cases exhibit symmetric capacitance-voltage characteristics, generating only odd harmonics, allowing high order multiplication without added circuit complexity. For optimized multiplier performance, the multiplier circuit must provide the appropriate embedding impedance for the multiplier diode at the input frequency, the output frequency, and all the intermediate harmonic frequencies. In addition, for harmonics above the output frequency, the circuit must provide an open or a short. The most successful multiplier mount to date have been the cross waveguide mount (for example 18,19,20,21,22,23,24,25,26,27,28). Alternative approaches using quasi-optical techniques have been demonstrated for single diodes (29,30,31) or with diode grid arrays (32). Figure 7 shows local oscillator power available from frequency multipliers as a function of frequency

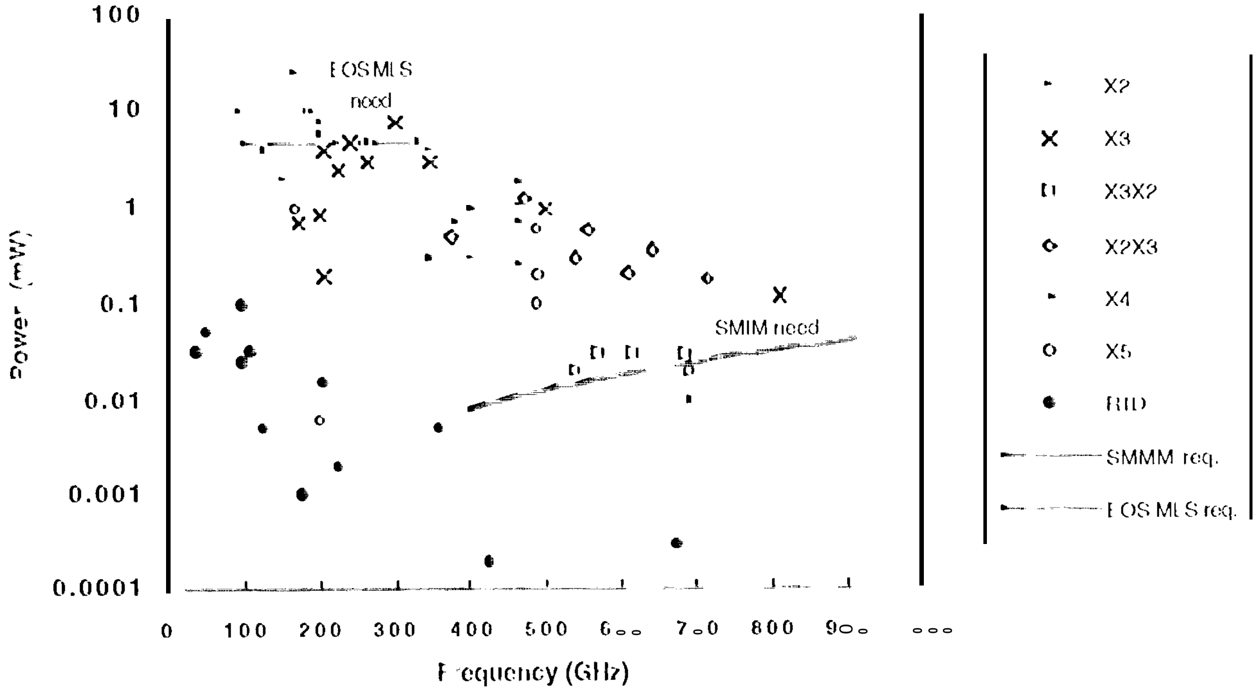

Figure 7: State-of-the-art multiplier performance

Most of the multiplier results to date have been achieved with whisker contacted Schottky diodes. Replacing whisker contacted diodes with planar devices is desirable for space missions to reduce risk and ease assembly. Potential performance advantages of planar diodes include more flexible circuit design and wider bandwidth achieved by integrating tuning elements near the diode. In addition planar diodes can be more easily arrayed to provide higher output power. The challenge for planar diodes is to reduce lead parasitics. Two approaches have demonstrated potential; the air bridge approach used with Schottky varactors (33) and the mesa approach used with BNN varactor (34). The output power from doublers using the air bridge diodes is comparable to that of the whiskered devices up to 270 GHz. In part this is due to the use of multiple diodes in the doublers. The most recent results demonstrate 5.5 mW at 270 GHz (35). The bbBNN tripler at 220 GHz has delivered 0.7 mW (12). These planar diode results are close to meeting the needs of EOS MLS, but considerable more effort is required to reach the higher frequencies required for SMIM.

5. SUMMARY

Technology advances during the last few years have demonstrated the feasibility of local oscillators for SMIM and EOS MLS. However, the instrument requirements continue to pose several technology challenges. In particular, solid state local oscillator sources above 700 GHz need to be developed. The planar diode technology needs to be demonstrated for frequencies above 300” GHz. In addition techniques to increase fixed tuned operating bandwidth of these components, and to make them more reliable and less costly, are needed.

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