National Radio Astronomy Observatory
520 Edgemont Road
Charlottesville, VA 22903 USA
434.296.0211 Fax 434.296.0278
www.nrao.edu

MEMORANDUM

To: ANASAC

From: Eric W. Bryerton and Mark McKinnon

Date: 16 October 2012

Subject: Proposal for Support of UVML SIS Foundry

As requested by the ANASAC at the September 20-21 face-to-face meeting, we are distributing the UVML proposal for maintaining SIS foundry support over the next 2 ¼ years. We are pleased that the ANASAC expressed unanimous agreement about the importance of maintaining this critically important capability.

We understand and share the committee's concern about the process for approval of development projects. It should be noted that since the European development budget is fully committed over the next few years (for construction of band 5 cartridges) and the East Asian development budget is also anticipated to be committed over this span (for construction of band 1 cartridges), there is little motivation from our partners for global coordination of other development projects until the 2016-2017 timeframe. That being the case, it is currently appropriate for the ANASAC (as representative of the North American community) to take a leading role in vetting and endorsing North American development projects. We also note that SIS foundry support was included in the original strawman plan for the use of ALMA development funds in NRAO's proposal for ALMA-NA operations in 2011-2015. Furthermore, as members of the ANASAC rightly noted at the meeting, development funds not used are at risk of being diverted by the NSF.

We would also like to reiterate that this 2 ¼ year funding for UVML is indeed bridge funding until the renewal of the Cooperative Agreement, at which point it is our intent to transfer SIS foundry support into the ALMA operations budget, reserving the development budget for projects with finite scope and duration. If this bridge funding is not provided, the UVML foundry will need to seek other funding to maintain its SIS capabilities, likely resulting in halting of SIS fabrication and development. This will not only stall North American sub-millimeter receiver development for ALMA in the next few years, but restarting this capability in 2-3 years will likely result in an additional 1-2 years delay in bringing the processes back online before useful devices can again be produced.

Enabling the Full Potential of ALMA

An ALMA Development Proposal for Superconducting Circuits Foundry Support

Eric Bryerton[1], Anthony Kerr[1], Shing-Kuo Pan[1], Mark Lacy[1], Bryan Butler[2], and Arthur Lichtenberger[3]

[1]NRAO, Charlottesville, VA
[2]NRAO, Socorro, NM
[3]University of Virginia Microfabrication Laboratory

Abstract

ALMA has already begun to produce outstanding images and scientific results. To maintain this capability over its lifetime and to enable the improvement of ALMA to its full potential requires continuing development of the fundamental enabling technology for ALMA receivers, SIS mixers. While all science with ALMA will clearly benefit from receiver improvements, particularly noise temperature and bandwidth, it is clear that the high-profile science areas of high-redshift galaxies and planetary system formation will benefit to the greatest degree. The early days of SIS research and development benefitted from investment in several U.S. foundries. However, there is now only one operating SIS foundry in North America. Without continued support by ALMA, it will also cease SIS operations. Reviving such a capability would cost many millions of dollars and take several years to produce useful devices.

The ALMA development program solicits calls for one-year design studies, some of which require access to a superconducting device foundry, with a maximum cost of $100,000. This amount is insufficient to support a foundry for even a single year. However, with the base support proposed here, there will be a U.S. foundry which can be used for these design studies, by anyone, at a small marginal cost, to prototype new mixer circuits and other experimental superconducting circuits, eventually leading to a new suite of improved ALMA receivers. This capability will also be used to spur innovation at other North American sub-millimeter facilities, such as CARMA, ARO, and the SMA. This support will also keep in place emergency backup capability for band 3, 6, and 7 SIS mixers should there be a severe electrical event at the site destroying a significant number of mixers.

In this proposal, we first look at the science that will benefit the most from more sensitive and wider band SIS receivers. From these cases, we determine the most critical developments needed for SIS technology and focus the development program on these key areas. These include maintenance of current generation Nb/Al_2O_3/Nb SIS mixer capability to enable design and prototyping of balanced and balanced sideband-separating mixers for ALMA receivers below 500 GHz, development of high current density AlN barriers to enable lower noise over a broader tuning bandwidth and to enable deposition of NbTiN for higher frequency operation, and development of SIS processes for truly quantum-limited SIS mixers for bands 9, 10, and beyond.

A 2.25-year program of support to the University of Virginia Microfabrication Laboratory (UVML) is proposed here. Three SIS mixer processes will be made available to the North American astronomy community. The total cost is approximately $300,000 per year and reflects a significant cost sharing due to a Memorandum of Agreement (MOA) between the NRAO and the University of Virginia. This total cost represents a small fraction of the capital equipment involved in SIS mixer fabrication at this facility.

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I. Science Case and Significance for ALMA

Even in early science, with only a fraction of the antennas in use over the shorter baselines, ALMA has already begun to produce significant scientific results. When ALMA is in full operations in late 2013, it will still not be operating at its full potential. Superconducting SIS mixer receivers are used for all of the eight high-frequency bands (from 84 to 950 GHz), and receiver improvements in these bands are likely to stem primarily from SIS mixer development. While improvements to the mixers clearly benefit all science done using ALMA, we concentrate on two high-priority science areas where improved SIS mixers will have a clear and immediate impact: high-redshift galaxies and planetary system formation.

A. Galaxies at High Redshift

ALMA is expected to provide answers to questions about when and how the first stars and galaxies formed. To probe star formation, and hence galaxy formation, ALMA will study molecular gas, the fuel for star formation. Emission from the rotational transitions of CO will be a key tracer of molecular gas, with their relative strengths informing on the physical conditions within this gas via excitation studies (Solomon & Vanden Bout 2007, ARRA, 43, 677). Fig. I-1 shows the CO rotational transitions visible in the ALMA bands as a function of redshift. In early science, molecular studies will be difficult except for the brightest or lensed targets. In full operations, ALMA will have the potential to image these CO transitions as well as dense gas tracers, such as HCN and HCO+, which will be used to study the different phases of the ISM in these galaxies.

In addition to probing star formation through molecular gas observations, ALMA will be able to observe fine structure lines, which provide critical diagnostics of ISM physics and energetics (Stacey et al 1991 ApJ 373, 423). Far-infrared (FIR) fine structure lines which redshift into the ALMA bands are shown in Fig. I-2. Emission lines from lower ionization species such as CII (158 μm) and OI (63 μm, 145 μm) are the dominant coolant in the neutral ISM. Higher ionization species such as OIII (52, 88 μm) and NIII (57 μm) trace the ionized ISM (Malhotra et al 2001, ApJ 561, 766; Brauher et al 2008 ApJS, 178, 280). ALMA has already shown its potential to detect these highly redshifted lines in Science Verification and Cycle 0 observations. In Cycle 0 observations, Nagao observed the [NII] 205 μm emission from Sub Millimeter Galaxy (SMG) LESS J033229 at a redshift of 4.76 using the Band 6 receiver (Nagao et al 2012 A&A 542L 34N. Nagao also attempted to detect the redshifted CO (J=12→11) tranisition in the other sideband, but the SNR was insufficient. In science verification, Wagg detected the BR1201-0725 system at a redshift of 4.7 using band 7 at 335 GHz (Wagg et al 2012 ApJ 752L 30W).

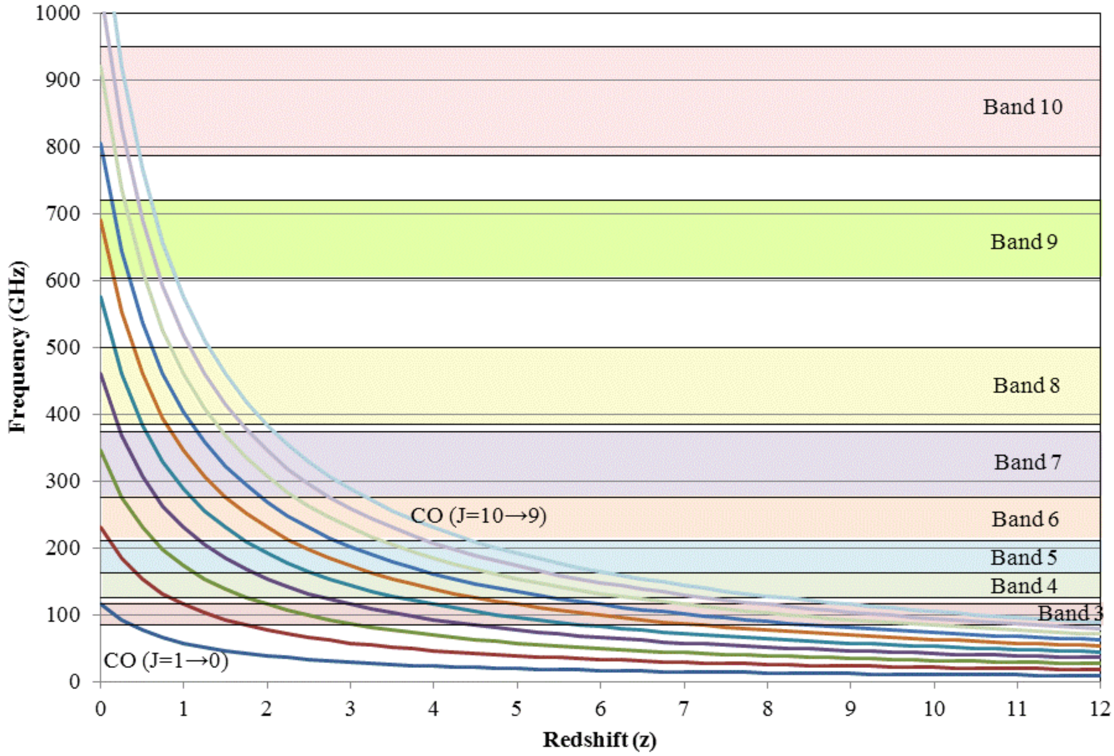

Figure I-1: The first ten rotational transitions of CO as a function of redshift visible in the ALMA SIS bands (bands 3-10).

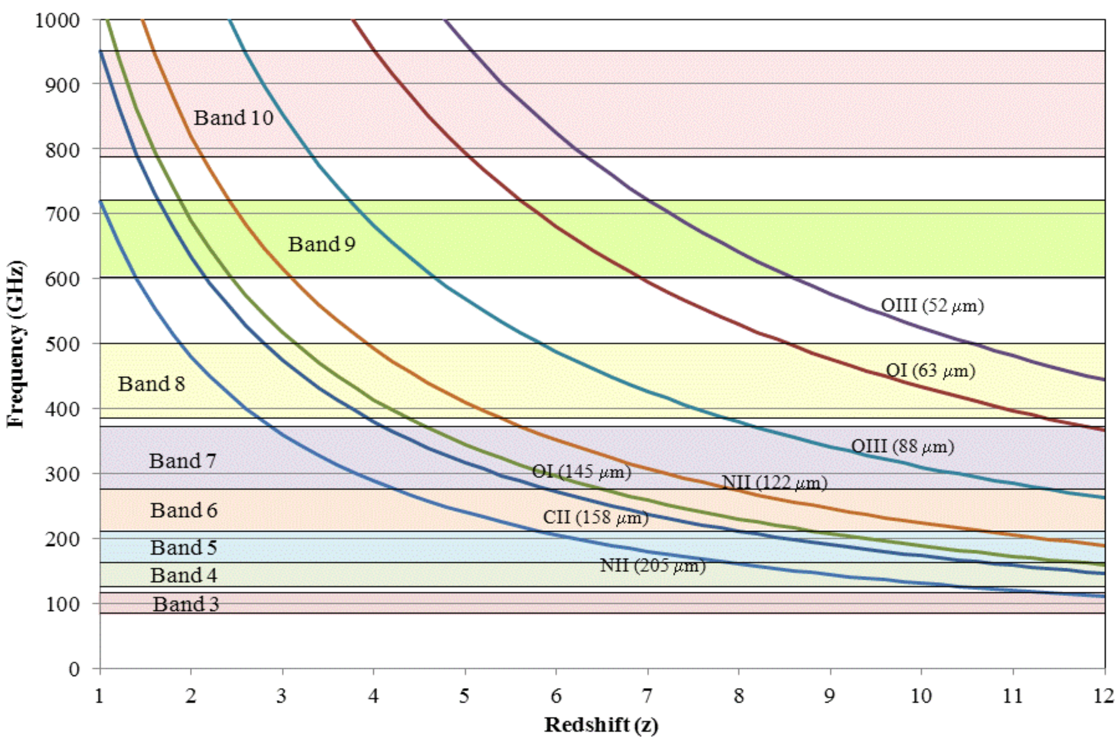

Figure I-2: Far infrared (FIR) cooling lines observable by ALMA as a function of redshift.

Even in full operations, redshift searches will be limited by the 8 GHz instantaneous bandwidth and there will be strong motivation to double this to 16 GHz (there is in fact already an ESO led design study investigating the backend costs of this). This is particularly important for "blank field" redshift surveys designed to obtain an unbiased view of the gas content of high redshift galaxies, where the extra bandwidth will double the chances of detecting a random field object. This extra bandwidth will also be important for objects with known redshifts, where multiple lines could be imaged simultaneously. A 16GHz bandwidth will also increase the sensitivity of continuum surveys for dust emission, halving the telescope time needed to detect, for example, the star forming dwarf galaxies responsible for reionization at z~6-10. To achieve 16 GHz per polarization instantaneous bandwidth will require 4-12 GHz IF 2SB SIS mixers in every band. This will require SIS mixer development for every band from band 3 upward.

Not shown in Fig. I-2, but an intriguing possibility, is the detection of the lowest order rotational transition from molecular hydrogen (28 μm), which enters the upper edge of band 10 at z=10.3. In the absence of heavy elements in the early Universe, H_2 is the primary coolant needed to collapse gas to form the first stars (e.g. Tegmark et al. 1997, ApJ 474, 1). Detection of this line requires development of a more sensitive receiver for the upper edges of band 10. Band 10 will also be critical for observing these fine structure lines during the peak of star formation ($1 < z < 3$).

In addition to increased instantaneous bandwidth, it will be critical to have the most sensitive receivers possible, in all bands, to detect and study these very early galaxies. Fig. I-3 shows the typical receiver noise temperatures for the SIS receiver bands (bands 3 and above) currently being installed on ALMA. The receiver noise temperatures are all given as SSB noise temperatures—for the DSB receiver bands (bands 9 and 10), twice the typical DSB noise temperature is shown. Clearly seen on this plot is the dramatic rise in noise temperature at the Nb gap frequency of ~660 GHz. Above this frequency, the photons have enough energy to break the Cooper pairs in a SIS mixer, increasing the loss and noise. Below this frequency, the SIS receivers are essentially at the practical limit of ~4 hf/k SSB noise temperature. (Bands 3 and 4 are a little above this line since noise originating elsewhere from the SIS mixer dominates at these lower frequencies.) From this plot, it is clear that there is much room for improvement in the bands 9 and 10 receivers. This improvement must come from the SIS junction itself. A higher gap frequency material than Nb is needed for the SIS junction. NbTiN is one such material that has been demonstrated and it will be the subject of the high-frequency development work in this proposal.

Improving the sensitivity of the band 10 SIS mixer, using a 2SB balanced NbTiN SIS mixer, could yield a band 10 receiver much closer to the 4 hf/k SSB practical limit currently achievable below 500 GHz. The choice of the DSB receiver configuration for bands 9 and 10 is a reflection of SIS mixer technology when the initial ALMA design parameters were frozen. Because there is significant atmospheric noise in the image band, the penalty for using a DSB receiver at the higher frequencies is even greater than it appears to be from the comparison of SSB noise temperatures in Fig. I-3.

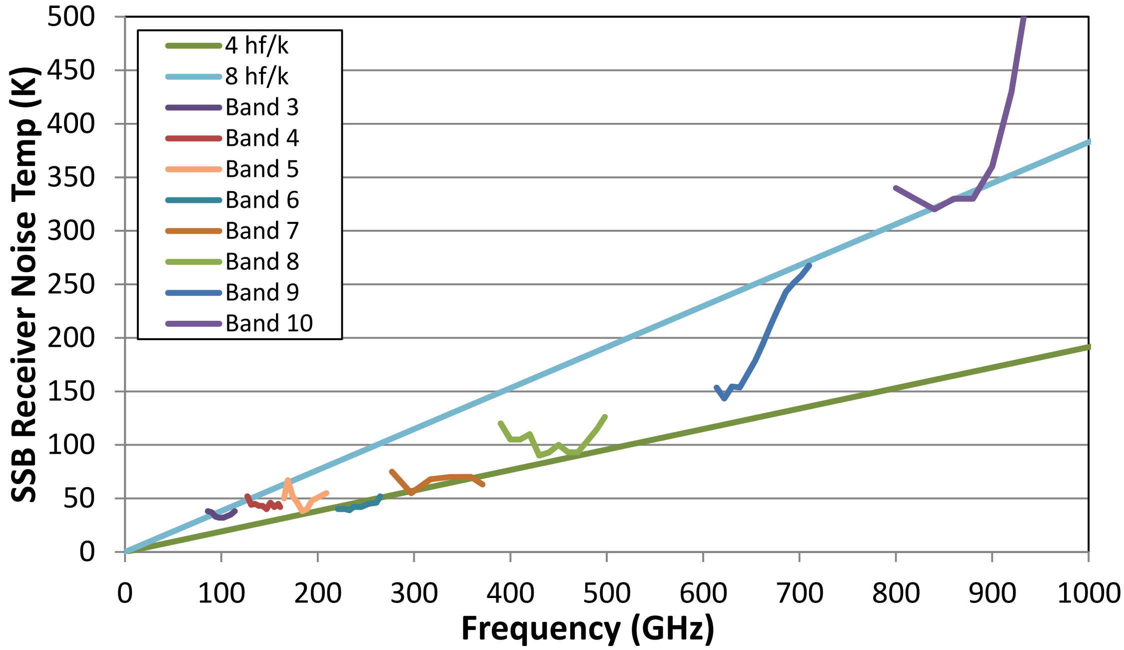

Figure I-3: Typical SSB receiver noise temperature for the ALMA SIS receiver bands (bands 3-10). Twice the DSB receiver temperature is shown for bands 9 and 10. Because of atmospheric noise in the image band, the effective SSB *system* noise temperature for bands 9 and 10 will be worse than shown here.

B. Planetary System Formation and Exoplanets

ALMA will be capable of imaging planetary systems in the earliest stages of their formation, as well as studying the properties of these forming disks in detail—properties such as size, temperature, dust density, and chemistry. In addition, ALMA offers significant advantages in the survey and study of mature planetary systems, i.e. exoplanets. ALMA will provide much higher angular resolution, down to 0.006" at the highest frequency in its most extended configuration, than current optical or infrared telescopes.

Initial results from Cycle 0 observations already hint at the images of disks that will soon be possible (Boley et al 2012 ApJ 750L 21B). Two of the most important technical requirements for study of disks are continuum sensitivity and angular resolution. The highest angular resolutions may be critical to seeing gaps in proto-planetary disks, driving the need for maximum possible sensitivity in the highest frequency bands. To maximize continuum sensitivity for imaging, total bandwidth is also critical. Doubling the total IF bandwidth per polarization would improve sensitivity a factor of sqrt(2) – thereby decreasing observing time to reach a given signal-to-ratio by a factor of two. Further improvements in imaging sensitivity can be gained from reducing the receiver noise temperature. As seen in Fig. 3, there is still lots of room for noise improvement in the band 9 and band 10 receivers, crucial for highest angular resolution. Eventually installing a supra-THz "band 11" receiver would increase the angular resolution further. Based on site testing data, it is estimated that the supra-THz windows (1020, 1350, and 1500 GHz) would be available approximately 5% of the time

In ALMA Memo 475, Butler, Wooten, and Brown explore the possibility of direct detection (direct measurement of thermal emission) of planets around other stars. The figure of merit relevant to direct detection of exoplanets is that for thermal blackbody observations:

$$X_{\nu} = \frac{\nu^2}{\Delta S}$$

where ΔS is the sensitivity at frequency ν. (Note this is a simplified expression and does not include the decrease in coherence at higher frequencies due to phase fluctuations). In ALMA Memo 475, this figure is predicted to be maximized for ALMA at 345 GHz, due to the poor predicted sensitivity at higher frequencies (even in the very best weather). However, with a new 2SB Band 10 SIS mixer closer to the 4 hν/k practical noise temperature limit, this figure would be maximized at the highest frequency, also coincident with the highest angular resolution. By doubling the total IF bandwidth being processed (going from 4-12 GHz DSB to 4-12 GHz 2SB), this figure is increased by a further $\sqrt{2}$. Not only would the increased sensitivity allow one to survey systems further away, but the increased angular resolution would also allow discrimination between planet and star in more of the cases within a certain survey distance. Until the optimized band 10 receiver is available, doubling the total IF bandwidth of the band 7 receiver (going from 4-8 GHz 2SB to 4-12 GHz 2SB) gives the largest benefit. It is also clear from ALMA Memo 475 that improved sensitivity at band 10 would also greatly benefit indirect exoplanet detection using astrometry, since the astrometric resolution of ALMA is proportional to intrinsic resolution divided by the signal-to-noise ratio with which the stellar flux density is detected. Using the highest possible frequency (band 10) not only gives the best intrinsic resolution, but it also provides the highest stellar thermal flux density, increasing the astrometric resolution. The optimum receiver for exoplanet detection using ALMA, both direct and indirect, would be a 2SB 4-12 GHz IF band 10 receiver with SSB receiver noise approaching the 4 hf/k practical limit.

C. Summary

Table I-1 summarizes the key science drivers outlined in the previous section. For each science driver are listed a set of technical requirements needed to achieve these goals followed by the required development at the detector (SIS mixer) level to meet these requirements. From this table, it is deduced that the SIS mixer developments with the highest payoff are those that enable larger IF bandwidths and lower noise over broader tuning ranges, especially bands 9 and 10 where SIS technology development still promises significant advancements in raw noise temperature. Also, balanced and sideband-separating operation are needed advancements for ALMA to meet its full potential. Balanced mixers reject local oscillator (LO) noise, which adds significantly to current ALMA receiver noise at certain combinations of LO frequency and IF. While upgrading to balanced sideband-separating mixer doesn't necessarily require next generation SIS mixer chips, they certainly require a working source of current generation SIS mixers, which this proposed development will also make available. Without a funded SIS foundry, even current generation SIS mixer chips will not be available for developing balanced or balanced 2SB mixers.

This table lists only the highest-profile potential benefits of future SIS mixer development. Of course, almost every other type of observation and science done with ALMA will benefit from higher sensitivity and broader band receivers. For example, the highest ranked 2012 ALMA development proposal was a design study for a second-generation band 6 receiver. This will upgrade band 6 to a balanced, 2SB, receiver with 4-12 GHz IF. The review committee emphasized the importance of wide instantaneous bandwidth for simultaneous observations of multiple CO isotope transitions, e.g. ^{12}CO (J=2→1) and ^{13}CO (J=2→1) at 230.538 and 220.399 GHz respectively.

Table I-1: Science traceability matrix for ALMA SIS mixer development.

Key Science Drivers	Receiver Technical Requirements	Required SIS Mixer Developments
• Trace star formation rates through the early history of galaxy formation via imaging of the continuum and far-infrared fine structure lines from the earliest galaxies. • Study the physics and energetics of the ISM in the earliest galaxies via imaging and kinematic studies of redshifted CO and far-infrared fine structure lines .	In all frequency bands, larger instantaneous bandwidth with moderate spectral resolution.	Balanced sideband-separating mixers with 4-12 GHz IF for all bands.
	In all frequency bands, lower system noise temperature over widest possible tuning bandwidth.	For all bands, higher current density SIS mixers (e.g. using AlN barriers) for increased tuning bandwidth and lower loss tuning circuits. For band 10, requires development of SIS mixer with higher gap frequency, such as NbTiN; also developing sideband-separating mixer for band 10 to reject atmospheric noise from unwanted sideband.
	SSB or 2SB operation at bands 9 and 10 for improved kinematic studies in these bands.	Sideband-separating mixers for bands 9 and 10.
• Imaging of planetary disks at the highest possible angular resolution. • Directly image a protoJupiter exoplanet separate from its star out to distances of 100 pcs at 0.005 arcsecond resolution in less than 100 hours integration time (integration time proportional to D^4, so much less for closer distances, i.e. 10 minutes for 20 pcs). • Improve 850 GHz astrometric resolution a factor of 10 for indirect detection of exoplanets over 345 GHz astrometry.	Lower system noise temperature in band 10.	Quantum-limited SIS mixers for band 10 using NbTiN for one or both junction electrodes. Sideband-separating SIS mixer topology to reject atmospheric noise in unwanted sideband.
	Double integration bandwidth (IF) in Band 10 receiver.	Sideband-separating mixers with 4-12 GHz IF for band 10.
	Supra-THz “Band 11” receiver.	Supra-THz SIS mixer development using hot-deposited NbTiN for one or both junction electrodes.
• Maximize imaging sensitivity at moderate angular resolutions (0.012-0.018”).	Increase integration bandwidth (IF) for Band 6 and 7 receivers.	Sideband-separating mixers with 4-12 GHz IF for bands 6 and 7

II. The Need for a North American SIS Foundry

As shown in Table I-1, maximizing the science in the key areas of highly redshifted galaxies and planetary system formation and exoplanets depends upon continuing SIS mixer development. We propose to fund the UVML as a North American community resource for ALMA superconducting detector development, enabling the advances needed for these improvements. With the foundry funded at a base level, it will be possible for anyone in the North American community to propose, at the Design Study level, design and prototyping of new SIS mixers and other superconducting detectors. This will not be possible without a base level of foundry support; an ALMA design study (maximum 12 months, $100,000) is insufficient to maintain an SIS foundry for more than a few months.

There is currently only one operational SIS foundry in North America, the University of Virginia Microfabrication Laboratory (UVML). Most recently, JPL was developing and producing SIS mixers for the Herschel HIFI mission, but they ceased SIS mixer fabrication following completion of the HIFI instrument. Starting a new SIS foundry, or restarting a defunct one, would be very expensive and it would take several years to become productive. The capital equipment at the UVML directly involved in producing SIS mixers is over $5M, which includes equipment used exclusively for SIS fabrication (~$2M) and equipment essential to SIS fabrication but shared with other non-SIS fabrication projects at UVA (~$3M). These equipment numbers don't include the cost of the cleanroom and its infrastructure (collectively several additional million dollars) or its operation. If North American instrumentalists are to be involved in ALMA sub-millimeter development, then it is imperative that UVML continue to be funded. This is critical not only to ALMA, but also to all other North American sub-millimeter facilities, including CARMA, ARO, and SMA.

SIS foundries in Europe and East Asia continue to operate and will be used by ALMA partners in those regions for mixer development. These include IRAM, where the band 7 SIS mixers were produced; the Technical University of Delft, which produced the band 9 SIS mixers as well as SIS and HEB mixers for the HIFI instrument, Chalmers University of Technology, where the ALMA band 5 mixers are being produced; and the University of Cologne, where SIS and HEB mixers were developed for HIFI and SOFIA. In East Asia, the SIS foundry at NAOJ is producing SIS mixers for bands 4, 8, and 10. ASIAA runs an SIS foundry in Taiwan. Research engineers in these regions will have close access to these facilities, enabling them to work most efficiently. North American instrumentalists will be at a distinct disadvantage if they need to rely on remote foundries. It should be noted that SIS mixers designs are generally not movable between foundries. Fabrication processes and mask specifications vary widely, and converting a design for production at another foundry is tantamount to designing a new circuit.

As detailed in Section V, the proposed cost of keeping the UVML facility operational and making it available to the North American community is only ~$300,000 per year, a small percentage of the capital cost of starting up such a facility.

III. Technical Description

From the science case in Section I, we deduce there are three critical capabilities needed to enable the SIS mixer developments most helpful to ALMA key science over the coming years: (i) maintenance of the capability to produce the current generation of $Nb/Al_2O_3/Nb$ SIS mixers both for the development of balanced and balanced 2SB mixers for frequency bands below 500 GHz and as an emergency back-up source of existing mixers; (ii) development of high-quality SIS junctions using AlN barriers to enable lower noise over wider tuning bandwidths for all bands and to enable the deposition of higher gap frequency NbTiN electrodes; (iii) development of high-quality SIS junctions using higher gap frequency for one or both junction electrodes to enable quantum-limited SIS mixers at band 10 and higher frequencies. In addition to the three primary technical areas described below, the base support of a superconducting foundry will allow for prototyping of other sub-millimeter devices, such as hot-electron bolometer (HEB) mixers, kinetic inductance detectors (KIDs), or entirely new and innovative concepts.

A. Maintenance of $Nb/Al_2O_3/Nb$ SIS Mixer Capability

The UVML SIS foundry has the demonstrated ability to fabricate SIS mixers meeting ALMA specifications for frequencies below 500 GHz. The UVML produced all the SIS mixer chips used in the band 3 and 6 receivers. They also produced a band 7 mixer chip meeting ALMA specifications while the IRAM foundry was having technical trouble. Most recently, they have produced Wafer/Nb/Al-AlN/Nb SIS mixer chips meeting the ALMA band 8 (385-500 GHz) specifications. The requested funding will allow UVML to maintain their current capability both for new receiver developments, such as balanced or balanced 2SB mixers, which do not necessarily require new junction technologies, and as an emergency backup source for SIS mixers for all these bands should there be a catastrophic loss of large numbers of SIS mixers on site.

B. Development of High Current Density Barriers (AlN)

There are two fundamental reasons to develop AlN tunnel barriers. First of all, compared with Al_2O_3 barriers, AlN barrier devices can be utilized to realize small junction areas with higher current densities, which require a lower Q tuning circuit, and therefore enable higher overall tuning bandwidth. In band 6 for example, which covers the 211-275 GHz band, a band 6 SIS mixer using a AlN barrier could have improved noise temperature at the edges of the band. This approach has already been used for Band 9, where AlN barriers were introduced in mid-production with resulting lower temperatures at the lower part of the band. As mentioned, this is the topic of a current ALMA design study for second-generation band 6 receivers. A second reason to develop high-quality AlN barriers is that they also present a successful material path to realize junctions with a NbTiN counter electrode for higher-frequency operation. (This is because a NbTiN counter electrode deposition damages the traditional Al_2O_3 barrier.) AlN barrier growth can be realized using a plasma (e.g., inductively coupled plasma (ICP)) nitridation of an Al overlayer on a Nb base electrode. Precise control of the AlN barrier thickness is critical to fabricating repeatable junctions with the desired current density. It is important to note that Al overlayers are not compatible with a NbTiN base electrode and hence not compatible with an all NbTiN SIS device (which would further increase the energy gap frequency another ~30% over a junction with "only" a NbTiN counter electrode) must be realized with an alternative barrier process (see Section III-C).

UVML was the first to propose and demonstrate the plasma growth of AlN using a low energy nitrogen-based inductively coupled plasma (ICP) process which yields junctions of very high quality and high current density. The ICP plasma growth technology offers excellent uniformity across the wafer. UVML's SIS trilayer deposition system is equipped with an ellipsometer for in-situ monitoring of AlN film growth (whose thickness determines J_C). Junctions will be fabricated using the newly established pentalevel self-aligned junction process that produces an on-wafer junction etch mask with a hard Cr top and an organic bottom with a desirable undercut. The pentalevel resist has recently been shown to be compatible with sputtered SiO_2 insulation which has two orders of magnitude lower pinhole (short-circuit) density than the current evaporated SiO_x layers. The fabrication process is highly repeatable and gives high quality, low-leakage junctions of diameter as small as 0.6 µm. For a 385-500 GHz SIS mixer, the UVML recently fabricated high-quality Nb/Al-AlN/Nb SIS junctions with $J_C = 30,000\ A/cm^2$.

C. Development of High Frequency SIS Mixers

To produce quantum-limited SIS mixers above 700 GHz, i.e. band 10 and beyond, requires development of SIS mixers with new materials. The most successful SIS receivers below ~700 GHz currently use Nb superconductors. This frequency limit is imposed by the energy gap of Nb. At higher frequencies, Nb becomes lossy as superconducting Cooper pairs are broken by the RF photons. The superconductor NbTiN has a larger energy gap than Nb and can be used to advantage at higher frequencies. There has been some success with low-noise THz mixers using NbTiN as one electrode of Nb/Al-AlN/NbTiN SIS junctions (Karpov et al 2007 IEEE Trans. Appl Supercond. 17). The UVML has also demonstrated high quality Nb/Al-AlN/NbTiN junctions, though optimization of the process for mixers has not yet begun. Development of a suitable Nb/Al-AlN/NbTiN process and its availability to the community will spur design studies looking at SIS mixer designs targeted for lower noise and broader bandwidths in Bands 9 and 10, and possibly a future Band 11.

The first generation ALMA SIS receivers use standard millimeter-wave technology with the SIS junctions and associated tuning circuits on a thick quartz substrate suspended across a waveguide. The thickness and width of the substrate are limited by the onset of higher mode propagation in the substrate channel; simply scaling the Band 3 or Band 6 designs to 1 THz requires a substrate 20 μm thick x 60 μm wide which presents enormous fabrication and assembly difficulties and is not appropriate for production in ALMA quantities.

The limitations of thick substrates can largely be overcome using thin dielectric membranes supported by gold beam leads. The UVML was first to develop a process that allows mixer chips to be made as free-standing silicon membranes (e.g, 3-μm thick), with Au beam leads. This configuration is being used at NRAO for experimental SIS mixers at 440 GHz and 860 GHz, and at the University of Arizona for the mixers in the 64-pixel Supercam receiver. Despite their extreme thinness, Si membranes are very robust, flexible, and easily manipulated. NRAO, with the UVML, has previously used them in HEB mixers, and they have recently been used by UVML in 550, 700 and 850-GHz wafer probers in which the metalized Si membrane forms the flexible probe tip. Processes for improved band 9, 10, and 11 SIS mixers will use this silicon membrane technology with gold beam leads.

Nb/Al-AlN/NbTiN SIS mixers will enable quantum-limited noise performance up to nearly 900 GHz, essentially covering band 10. A NbTiN base electrode, replacing the Nb, would increase this upper frequency even further, however an Al overlayer is not compatible with a NbTiN base electrode and hence not compatible with an all NbTiN, larger gap SIS device. All NbTiN junctions must therefore be realized with an alternative barrier process (this has not yet been realized). Direct sputtering of a thin AlN barrier is one possible process that could allow both the bottom and top electrodes to be NbTiN. This may require the use of a heated deposition of the NbTiN base electrode, and the use of a seed layer to enhance the local crystallinity of the NbTiN and AlN layers, to improve the AlN coverage, where there is an expected FCC lattice mismatch of only 1% between the two layers. Another possible route is the use of sputtered amorphous Si barriers with a hydrogenated Si middle spike, which were preliminarily investigated successfully for NbN SIS junctions (Kroger et al 1983 IEEE Trans. Magn. MAG-19), but which gave way to the simpler and now traditional Nb/Al-Al_2O_3/Nb material system that was being simultaneously developed (Kwo et al 1983 IEEE Trans. Magn. MAG-19). These

Si/Si:H/Si barriers were significantly thicker than the Al_2O_3 barriers for similar current density, with low specific capacitance and excellent junction quality.

UVML has begun investigating direct sputtering of cold AlN barriers- one potential process route to realize an all NbTiN/AlN/NbTiN SIS mixer. The UVML has also recently acquired a ten gun superconducting deposition system, five of the guns with a heated stage capable up to 900C. This system will allow the UVML to purse the proposed sputtered AlN with a buffer layer (hot), the Si/Si:H/Si, and other barrier systems for all NbTiN SIS devices. The use of a hot deposited NbTiN base electrode would also increase the gap voltage even further since these films have an ever higher Tc. This research is ongoing and may eventually be incorporated into a THz SIS mixer process (e.g. for bands 10 and 11).allowing quantum-limited operation up to 1.2 THz and degraded performance above that (similar to current Nb SIS performance above ~700 GHz).

IV. Statement of Work

A. Scope and Specifications

The UVML will maintain the ability to supply, as needed, drop-in replacement SIS mixer chips for the present ALMA bands 3, 6, and 7 receivers. The mixer chips must be compatible with the existing ALMA mixer blocks and electronic interfaces (RF, IF, DC). The UVML will also maintain the ability to produce band 8 SIS mixers meeting ALMA specifications.

The UVML will also work to develop a highly reproducible fabrication process for high-quality SIS mixer circuits for quantum-limited operation up to 1 THz and slightly degraded operation to 1.5 THz. Mixers for these higher frequencies will be on silicon membrane substrates with gold beam leads. The basic layers are as follows (additional layers can be used to facilitate processing):

Table III-1: SIS Process Layer Definitions and Specifications

Layer		Thickness	Resolution
M1	Base electrode	165 nm	0.10 μm
J	Junction definition	---	0.05 μm
I1	Insulator	225 nm	0.25 μm
Via	Via definition	---	0.25 μm
M3	Wiring layer	425 nm	0.10 μm
BL	Beam leads	2 mm	0.10 μm
C	Chip outline	3 mm	0.10 μm

To meet these requirements, the UVML will offer three SIS processes for fabrication:

- $Nb/Al_2O_3/Nb$ trilayer with J_C up to 8 kA/cm^2 and junction diameters down to 1.2 μm
- Nb/Al-AlN/Nb trilayer with J_C up to 30 kA/cm^2 and junction diameters down to 0.8 μm
- Nb/Al-AlN/NbTiN trilayer with J_C up to 30 kA/cm^2 and junction diameters down to 0.5 μm

The latter process (Nb/Al-AlN/NbTiN) will not be available at the beginning of the project, but will be developed and become available 1-2 years in. The UVML will also investigate the possibility of NbTiN/barrier/NbTiN trilayer processes (as described above), as well as depositing NbTiN at elevated temperatures, to increase further the upper end of the operating frequency for SIS mixers.

An essential part of the work is the characterization of all materials and devices fabricated, including:

- I(V) characteristics of SIS junctions
- Specific capacitance of representative SIS junctions
- London penetration depth of superconductors employed
- Surface resistance (at RF) of the superconductors or normal metals employed
- Specific capacitance of the SiO_2 insulator
- Consistency of the above parameters from wafer to wafer

B. List of Deliverables

Table III-2 lists the deliverables for the duration of this development project.

Table III-2: List of Deliverables

Item	Qty.	Delivery Location	Notes
Design Rules for Nb/Al_2O_3/Nb SIS process	1	NRAO	A set of current design rules will be maintained by UVML and made available to NRAO upon request. The design kit will contain the design rules for the process, as well as the process characterization parameters listed in Section IV-A.
Design Rules for Nb/Al-AlN/Nb SIS process	1	NRAO	A set of current design rules will be maintained by UVML and made available to NRAO upon request. The design kit will contain the design rules for the process, as well as the process characterization parameters listed in Section IV-A.
Design Rules for Nb/Al-AlN/NbTiN SIS process	1	NRAO	A set of current design rules will be maintained by UVML and made available to NRAO upon request. The design kit will contain the design rules for the process, as well as the process characterization parameters listed in Section IV-A.
Quarterly Progress Reports	Quarterly	NRAO	UVML will provide NRAO with quarterly progress reports containing metrics on number of wafers processed and state of each wafer processed during the previous quarter, for all processes. The report will also contain description of progress made toward development goals, such as sputtered AlN barriers, hot-deposited NbTiN junctions, general process improvements, etc.
SIS Wafers	3 per year	Customer	UVML will produce SIS wafers using one of the three specified processes on demand up to the rate of 3 per year. Increases to specified rate of 3 per year may be possible with increased funding to UVML.

C. Schedule

Table III-3 lists the proposed milestones and dates for the duration of the proposed development project. Not shown in the table are fortnightly meetings between the UVML and CDL teams. In addition to the milestones listed, the UVML will produce SIS wafers at a minimum rate of three per year for the duration of the project.

Table III-3: Milestone list for project duration.

Milestone	Date
Project kickoff	07/01/2013
$Nb/Al_2O_3/Nb$ SIS Design Rules Available	08/15/2013
FY13Q4 Progress Report	10/15/2013
FY14Q1 Progress Report	01/15/2014
Nb/Al-AlN/Nb SIS Design Rules Available	02/15/2014
FY14Q2 Progress Report	04/15/2014
FY14Q3 Progress Report	07/15/2014
Nb/Al-AlN/NbTiN SIS Design Rules Available	08/15/2014
FY14Q4 Progress Report	10/15/2014
FY15Q1 Progress Report	01/15/2015
FY15Q2 Progress Report	04/15/2015
FY15Q3 Progress Report	07/15/2015
FY15Q4 Progress Report	10/15/2015

D. Project Management

This development project will be managed by the P.I., Prof. Arthur Lichtenberger, director of the University of Virginia Microfabrication Laboratory (UVML). The primary technical contact with the NRAO Central Development Laboratory (CDL) will be Dr. Eric Bryerton. The P.I. will ensure that the process design kits are available as needed to the North American ALMA project for Design Study Calls. The CDL will also help to ensure SIS process quality by designing and testing SIS test circuits on a regular basis. Biweekly meetings will be held between the CDL Millimeter/Submillimeter group and the P.I.

V. Project Cost

A. Cost Sharing

Through a Memorandum of Agreement (MOA) between the NRAO and the University of Virginia, the 58% UVA overhead rate is applied only to insurance and cleanroom user fees. This agreement saves $360,000 in indirect costs over the project duration. In addition, by the same MOA, the NRAO has agreed to fund two graduate students through NRAO's Reber Fellowship program.

B. Costs Borne by Proposal

Table IV-1 shows the proposed budget for this development project. The funds will be used entirely to support the UVML superconducting circuits foundry. The proposal supports UVML labor costs as follows: 40% of the UVML director, Prof. Arthur W. Lichtenberger, 100% of a research scientist, and 50% of a research technician for the duration of the project. Also supported by the proposal are UVML costs of $3,600 per month in lab supplies (targets, wafers, chemicals, resists, and gases), $650 per month in cleanroom facility user fees, and $45,000 per year in equipment maintenance (approximately 1% of $4,000,000 total specialized capital processing equipment).

Table IV-1: Cost summary for development project (TBC)

Item	FY2013	FY2014	FY2015	Total
UVML Labor	46,020 / 0.48 FTE	185,002 / 1.9 FTE	188,721 / 1.9 FTE	419,743 / 4.28 FTE
UVML Materials	24,975	99,973	100,267	225,215
UVML Overhead	1,697	6,828	6,999	15,524
Total	72,691	291,804	295,987	660,482

VI. Institutes and Key Personnel

The current generation of mm/sub-mm SIS receivers, as used on ALMA, was the result of a long period of development, largely by the CDL in collaboration with the University of Virginia Microfabrication Laboratory (UVML). This includes the introduction of niobium-based superconducting circuits for radio astronomy, development of wideband SIS mixer chips, and the use of sideband-separating SIS mixers which were pioneered at the CDL. NRAO and UVML have an established record of successful instrument development. The SIS mixers for ALMA bands 3 and 6 were developed by NRAO and UVML, and, before that, all the Nb SIS receivers for the 12-m telescope. Professor Arthur W. Lichtenberger is the director of the UVML. Prof. Lichtenberger has collaborated with a number of astronomical groups for the past 20 years to develop state of the art millimeter and submillimeter receivers for use on radio telescopes throughout the world.

The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation (NSF) operated under cooperative agreement by Associated Universities, Inc. (AUI). This primary contact with the UVML at the NRAO CDL (Central Development Laboratory) in Charlottesville, VA will be Dr. Eric W. Bryerton. Dr. Anthony R. Kerr and Dr. Shing-Kuo Pan will also assist with SIS process characterization, mixer design, and testing. Dr. Kerr and Dr. Pan designed both the ALMA band 3 and 6 SIS mixers currently in use. The CDL produced the full suite of 73 ALMA band 6 receiver cartridges. The CDL SIS mixer group is also currently working on a funded ALMA design study for second generation band 6 receivers.

Arthur W. Lichtenberger

Director University of Virginia Microfabrication Laboratories
Research Professor
Department of Electrical and Computer Engineering
University of Virginia, Charlottesville, VA 22904
Tel: (434) 989-2000, Email: arthurW@virginia.edu

a. Professional Preparation

Amherst College, Amherst, MA	Bachelor of Arts-Physics BA,	1980
University of MA Technician,	Dept. of Radio Astronomy,	9/80-7/81
Amherst College	Summer NSF Research Grant,	5/80-9/80
University of Virginia, Charlottesville, VA	Electrical Engineering M.S.,	1985
University of Virginia, Charlottesville, VA	Electrical Engineering Ph.D.,	1987

b. Appointments

Full Professor of Electrical Engineering, University of Virginia,	7/08-present
Director, University of Virginia Microfabrication Laboratories	3/03-present
Associate Professor of Electrical Engineering, University of Virginia,	8/93-7/08
Assistant Professor of Electrical Engineering, University of Virginia,	7/87-8/93

c. Select Publications

1. *"The Kilopixel Array Pathfinder Project (KAPPa), a 16 pixel integrated heterodyne focal plane array,"* Christopher E. Groppi, Caleb H. Wheeler, Hamdi Mani, Patrick McGarey, Todd Veach, Sander Weinreb, Damon Russell, Jacob W. Kooi, Arthur W. Lichtenberger, Christopher K. Walker, Craig Kulesa, Proc. SPIE 8452, 2012.
2. *"Micromachined Probes for Submillimeter-Wave On-Wafer Measurements:* ***Part I*** *- Mechanical Design and Characterization,"* IEEE Transactions on Terahertz Science and Technology, vol. 1, no. 2, pp. 357–363, November 2011; ***Part II*** – "*RF Design and Characterization,"* pp. 349–356, T. J. Reck, J. Chen, C. Zhang, A. Arsenovic, C. Groppi, A. Lictenberger, R. M. Weikle, N. S. Barker, IEEE Transactions on Terahertz Science and Technology, November 2011.
3. *"On Wafer Penetration Depth Measurements of Superconducting Films,"* M. Cybery, R. Weikle, A. Lichtenberger, Proceedings of the 20th International Symposium on Space Terahertz Technology, August 2010.
4. *"Integrated 585 GHz hot electron mixer focal-plane arrays based on annular slot antennas for imaging applications,"* L. Liu, H. Xu, A.W. Lichtenberger, and R.M. Weikle, II, IEEE Trans. Microwave Theory and Tech., Special Issue on THz Technology: Bridging the Microwave-to-Photonics Gap, vol. 58, no. 7, pp. 1943–1951, July 2010.
5. *"Development of Nb/Al-AlN/NbTiN SIS Junctions with ICP Nitridation"*, Thomas W. Cecil, Michael E. Cyberey, Roy E. Matthews, Jian Z. Zhang and Arthur W. Lichtenberger, accepted to the IEEE Transactions on Applied Superconductivity, 2009.
6. *"Pentalevel Resist Process for the Precise Fabrication of Small Area SIS Junctions"*, Arthur W. Lichtenberger, Gregory Stronko, Jie Wang, Thomas W. Cecil, and Jian Z. Zhang, accepted to the IEEE Transactions on Applied Superconductivity, 2009.
7. *"Supercam: A 64 pixel heterodyne array receiver for the 350 GHz Atmospheric Window*" C. Groppi, C. Walker, C. Kulesa, D. Golish, J. Kloosterman, S. Weinreb, G. Jones, J. Barden, H. Mandi, T. Kuiper, J. Kooi, A. Lichtenberger, T. Cecil, G. Narayanan, P. Pütz, A. Hedden, International Symposium On Space THz Technology, August 2009.
8. *"Formation of High Quality AlN Tunnel Barriers via an Inductively Coupled Plasma",* T. Cecil, Gregory Stronko, Jie Wang, J. Zhang, A. Kerr and A. Lichtenberger, Nineteenth International Symposium On Space THz Technology, SRON Sweden, May 2008.

9. *"Investigation of NbTiN Thin Films and AlN Tunnel Barriers with Ellipsometry for Superconducting Device Applications"*, Thomas W. Cecil, Robert M. Weikle, Anthony R. Kerr and Arthur W. Lichtenberger, IEEE Transactions on Applied Superconductivity, Vol 17 (2) 3, 3525-3528, 2007.
10. *"A Nb-Based 180-Degree IF Hybrid for Balanced SIS Mixers,"* Christine M. Lyons, Arthur W. Lichtenberger, Anthony R. Kerr, Eugene F. Lauria, and Lucy M. Ziurys, IEEE Transactions on Applied Superconductivity, Vol 17 (2) 1, 194-197, June 2007.
11. "Receiver Measurements of pHEB Beam Lead Mixers on 3-μm Silicon", E. Bryerton, R. Percy, R. Bass, J. Schultz, O. Oluleye, A. Lichtenberger, G. Ediss, S. K. Pan, and G. N. Goltsman, The Joint 30th International Conference on Infrared and Millimeter Waves and the 13th International Conference on Terahertz Electronics, Williamsburg, Virginia USA, pg 271-272 , Sep. 2005
12. *"Ultra-Thin SOI Beam Lead Chips for Superconducting Terahertz Circuits"*, R.B. Bass, A.W. Lichtenberger, R. Weikle, J.W. Kooi, C.K. Walker, and S.-K. Pan, 6th European Conference on Applied Superconductivity, September, 2003.

d. Professional Activities:

1. International Symposium on Space THz Technology: program chair 2009, board 2008-present.
2. IEEE Applied Superconductivity Conference: Electronics Program Committee 1998-present
3. IEEE Applied Superconductivity Conference: Elected to ASC Board 2012
4. IEEE International Superconductor Electronics Conference: Program Committee 2012-present
5. Consultant to Virginia Diodes, Inc & Vibratess, LLC in the area of microfabrication technology.

e. Synergistic Activities

1. Infrastructure of Radio Astronomy: Have collaborated with a number of astronomical receiver groups for the past 20 years to develop state of the art millimeter and submm wavelength receivers for use on radio telescopes throughout the world.
2. Present & past member of Organizing, Program and Local committees for the International Symposium Space Terahertz Technology (ISSTT) and the Applied Superconductivity Conference. Co-chaired the 20th ISSTT in Charlottesville VA, 2009.
3. The PI's research group provides opportunities including mentoring, assistance with senior Science Fair projects and interactions in our lab for students in the Charlottesville Public Schools Talent Development Program which is targeted for minority students.
4. Additional summer partnerships with the State of Virginia's Summer Governor School, which is comprised of the best and brightest science high school students in Virginia, and also with the NRAO Undergraduate Summer Student Research Assistantships (NSF's REU program).

f. Collaborators and Other affiliations

Collaborators (outside UVa, alphabetical by institution): Chris Groppi, Arizona State University; Christopher Walker, Lucy M. Ziurys, University of Arizona; Jacob Kooi Sander Weinreb Hamdi Mani, Cal Tech; Charles Cunningham, Stephane Claude HIA-NRC Canada; Karl Jacobs Patrick Puetz, University of Cologne; Abby Hedden, Harvard-Smithsonian Center for Astrophysics; Ville Mottonen, Helsinki, Univ. of Techn; Benard Lazareff, IRAM; Tom Kuiper, Jet Propulsion Laboratory; Gopal Narayana, Sigfrid Yngvesson, U-Mass, Amherst; Gregory Goltsman, Moscow State; Anthony Kerr, S. –K. Pan, E Bryerton, M Pospieszalski, NRAO; Christopher Martin, Oberlin College; Mark Boko, Univ. of Rochester; Seog-Tae Han, TRAO Korea; Stephen Jones, Tom Crowe Jeffrey Hesler Virginia Diodes; Daniel Prober, Yale University.

Graduate Advisor: Robert J Mattauch, Dean and Commonwealth Professor Emeritus School of Engineering, Virginia Commonwealth University (retired)

Thesis Advisor(last 5 years): Dr Robert Bass, Will Clark, Christopher Ellis, Dr. Aaron Datesman, Dr Jon Schultz, Dr Tom Cecil, Christine Llyons, Michael Cybery, Delbert Herald, Roy Matthews, Chunhu Zhang, Greg Stronko.