A white paper submitted to the RMS and EOS panels of
The Astronomy & Astrophysics Decadal Survey Committee
Astro2010

In Support of Instrument Technology Development for THz Astronomy

Authors:
Scott Barker, UVA
Eric Bryerton, NRAO
Tom Crowe, Virginia Diodes Inc.
Neal Erickson, UMass
Rick Fisher, NRAO
Paul Goldsmith, JPL
Carl Gottlieb, Harvard/CfA
Chris Groppi, ASU
Jeffrey Hesler, Virginia Diodes Inc.
Todd Hunter, NRAO
Tony Kerr, NRAO
Arthur Lichtenberger, UVA
Gopal Narayanan, UMass
Steve Padin, U of Chicago
S.-K. Pan, NRAO
Adrian Russell, NRAO
S. Srikanth, NRAO
Pat Thaddeus, Harvard/CfA
Chris Walker, UAZ
John Webber, NRAO
Bobby Weikle, UVA
Al Wootten, NRAO
Lucy Ziurys, UAZ
Jonas Zmuidzinas, JPL

Communicating author:
A. R. Kerr, NRAO
434-296-0363
akerr@nrao.edu

28 March 2009

In Support of Instrument Technology Development for THz Astronomy

Executive Summary

The electromagnetic spectrum from 1-5 THz is extremely rich in molecular and atomic fine structure lines and is expected to be highly rewarding for astronomy if sensitive wideband heterodyne detectors can be developed. Recent developments in devices, materials, and fabrication technology suggest that nearly quantum-limited sensitivity with ~16 GHz bandwidth on the sky should be possible in the next decade. The new technology will be suitable for focal-plane and beam-forming arrays as well as conventional single element receivers and interferometers. In recent years, due to lack of funding, work on THz radio astronomy instruments in the U.S. has been overtaken by work in Europe and Japan, and we believe this to be a good time to restore U.S. competitiveness.

1. Scope

This white paper considers development of wideband quantum-limited heterodyne receivers for spectral line and continuum observations with single-pixel receivers, beam-forming arrays, and interferometers, in the atmospheric windows at 1.1, 1.3, 1.5, 2, and 2.5 THz, and in space up to ~5 THz, substantially above the limit of current SIS receivers.

2. Technological rationale

With a focused development effort it is likely that quantum-limited heterodyne detectors suitable for single pixel and array operation up to several THz will become practical in the next decade.

(i) The major advances in superconducting device fabrication fostered by HIFI and the high production requirements of ALMA have prepared foundries for development of new material systems capable of making SIS mixers for operation at frequencies beyond the limits of current niobium-based circuits.

(ii) Beyond SIS mixers, new devices such as the recently proposed quantum-well intrasubband photodetector (QWISP) [1] could provide quantum limited sensitivity in the THz range.

(iii) An obstacle to THz instrument development in the past has been the lack of suitable local oscillator sources above a few hundred GHz. Recently, reasonably priced commercial sources have become available to >2 THz [2], and quantum cascade lasers look increasingly promising for the THz bands [3,4,5]. This development can be expected to continue if there is support from the scientific community.

(iv) Improved receiver configurations using balanced and sideband-separating mixers will give improved sensitivity and require an order of magnitude less local oscillator power, thus benefitting array receivers as well single pixel receivers.

3. Political rationale

(i) In the last decade, the US position in sub-mm/THz astronomy instrumentation has declined relative to that of Europe and Japan. Europe is now ahead of the U.S. in THz receivers using HEB mixers, and Japan is overtaking the U.S. in SIS receivers. Examples are the development in Europe of the Herschel HIFI instrument (480-1910 GHz using SIS and HEB mixers), and in Japan of the ALMA Bands 8 (385-500 GHz) and 10 (787-950 GHz) using SIS mixers.

(ii) The two US laboratories capable of fabricating ALMA-quality SIS devices have almost foundered for lack of funding in recent years. If these laboratories lose funding, even briefly, it will take many years to assemble a new team with comparable expertise.

(iii) The U.S. currently leads in THz local oscillator technology, as exemplified by Herschel-HIFI and ALMA which would not have been possible without the frequency multiplier technology developed at UMass, JPL and Virginia Diodes Inc. In the development of quantum cascade lasers

as THz sources, the U.S. and Europe are currently about even.
(iv) Future development of THz technology will have commercial applications such as imaging, non-invasive monitoring/testing, and THz chemical spectroscopy.

4. The astrochemical transformation

In the total electromagnetic spectrum of the Universe, there are three major peaks. The biggest is the peak from the 3 K blackbody radiation relic of the Big Bang, at millimeter wavelengths. The third strongest peak occurs near one micron–this contains the accumulated light from all of the stars in the Universe. The second strongest occurs at about 1.5 THz or 200 microns wavelength. Light of these wavelengths cannot penetrate the atmosphere, as it is absorbed by water and other molecules in the atmosphere–this peak was identified only recently through satellite observations. This spectral feature represents all of the cool (~ 200 K) objects in the Universe–clouds of dust and gas as well as radiation from warmer sources that is absorbed and re-radiated. Radiation at the wavelength of the peak is not accessible from the ground. Fortunately, for local objects emission from its longer-wavelength components may be examined from high dry sites. Furthermore, at a redshift of 1 the wavelength of the peak migrates to wavelengths below 300 microns, providing ground-based telescopes access to this important window on galaxy assembly and evolution. ALMA will image the cool thermal radiation which comprises most of the photons in the Universe, photons emitted by stars and planets during their formation processes, as well as warmer radiation from the distant Universe which is shifted into its range by the expansion of the Universe.

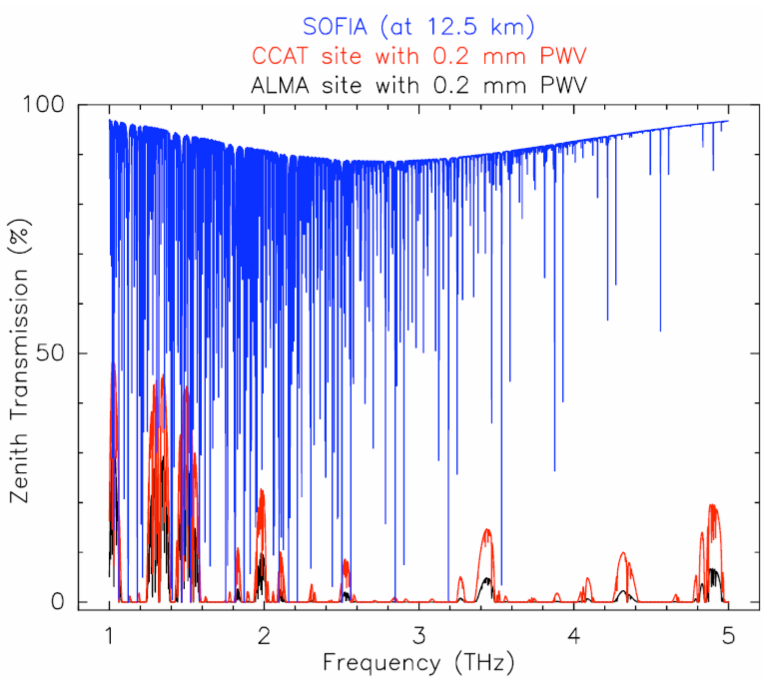

Fig. 1. A comparison of atmospheric transmission in the THz frequency regime from ALMA (black, 5000 m), CCAT (red, 5612 m) and the Stratospheric Observatory for Infrared Astronomy (SOFIA; blue, flying at 12.5km. The amount of precipitable water vapor for the earthbound sites are 0.2 mm.

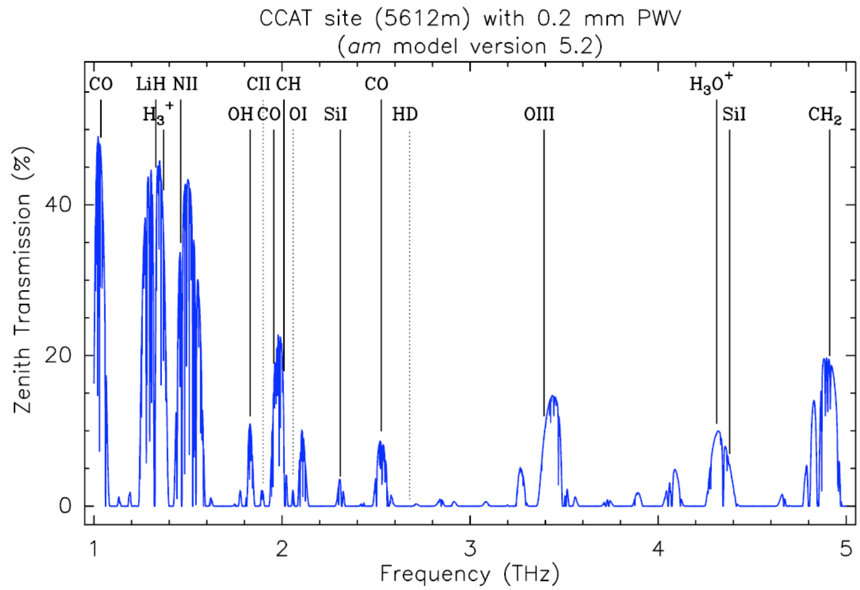

Fig. 2. The atmospheric transmission from the CCAT site plotted to show the location of the lines included in Table 1. Dotted lines denote those transitions which do not fall in an clear window unless they are emitted from a source whose expansion velocity redshifts it there.

In addition to this continuum radiation, the THz spectral regime, covering frequencies from 1 to 5 THz, includes spectral line emission from many important molecules (HD, CO, OH, CH and HeH+, SiH, FeH, and MgH) and atoms (C I, C II, O I, O III, N II, N III, S I and Si I) – Fig. 2 and Table 1. Radiation in these lines may be quite strong. For instance, the C II line at 1.9 THz may radiate 1% of the luminosity in its parent Galaxy in that single line. Unfortunately, this strong dust and line emission is blocked at its rest wavelengths by the atmosphere. Observations are possible from the

Table 1. Summary of Important Atomic and Molecular Transitions at THz Frequencies

Line	Transition	Frequency (THz)[a]	Approximate Co. Chajnantor	Transmission Antarctica[a] (%)
$[OI]$	${}^3P_1 \rightarrow {}^2P_2$	4.74	...	...
$[OI]$	${}^3P_0 \rightarrow {}^2P_1$	2.06	2	18
$[OIII]$	${}^3P_2 \rightarrow {}^2P_1$	5.79	??	38
$[OIII]$	${}^3P_1 \rightarrow {}^2P_0$	3.393	9	60
$[CII]$	${}^2P_{32} \rightarrow {}^2P_{12}$	1.901	1.5	20
$[NII]$	${}^3P_2 \rightarrow {}^2P_1$	2.459	...	...
$[NII]$	${}^3P_1 \rightarrow {}^2P_0$	1.461	32	??
$[SiI]$	${}^3P_2 \rightarrow {}^2P_1$	4.38	5.6	35
$[SiI]$	${}^3P_1 \rightarrow {}^2P_0$	2.31	2.7	27
$[SI]$	${}^3P_0 \rightarrow {}^2P_1$	5.323	...	...
H_3^+	$1_{0,1} \rightarrow 0_{0,0}$	1.37[b]	36	??
HD	$1 \rightarrow 0$	2.68	...	..
LiH	$3 \rightarrow 2$	1.329	30	??
H_3O^+	$4_3 \rightarrow 3_3$	4.31	10	??
OH	${}^2\Pi_{12} J = 3/2^- \rightarrow 1/2^*$	1.83	11	40
CH	${}^2\Pi_{32} J = 3/2^- \rightarrow {}^2\Pi_{12} 1/2^*$	2.01	14	59
CH_2	$2_{2,0} \rightarrow 3_{1,4}$	4.93	18	..
CO	$17 \rightarrow 16$	1.96	15	..
SiH	${}^2\Pi_{1/2} J = 5/2 \rightarrow 3/2$	1.11	...	...
FeH	${}^4\Delta_i, J = 9/2 \rightarrow 7/2$	1.41	...	...
MgH	$N = 3 \rightarrow 2$	1.03	30	...

[a] Cerro Chajnantor (CCAT) transmission for 0.2mm PWV as shown in plot. Antarctic numbers for 0.1mm PWV from Townes and Melnick, PASP 102, 357 (1990). [b] Molecular Frequencies from http://www.splatalogue.net or CDMS

ground for some redshifts. Alternatively, observations may be made from airborne platforms, such as SOFIA (flying at 13km), or from space. Unfortunately, the collecting areas available on flying and space platforms are limited. Ground, airborne and space observations all need sensitive detectors to see faint lines from distant objects.

5. Current instrumentation
The current best laboratory results for THz heterodyne receivers are summarized in Fig. 3 which includes receivers using both SIS and HEB mixers. It is clear that current SIS mixer receivers suffer degraded sensitivity above ~1 THz. While HEB mixer receivers have shown good sensitivity in the

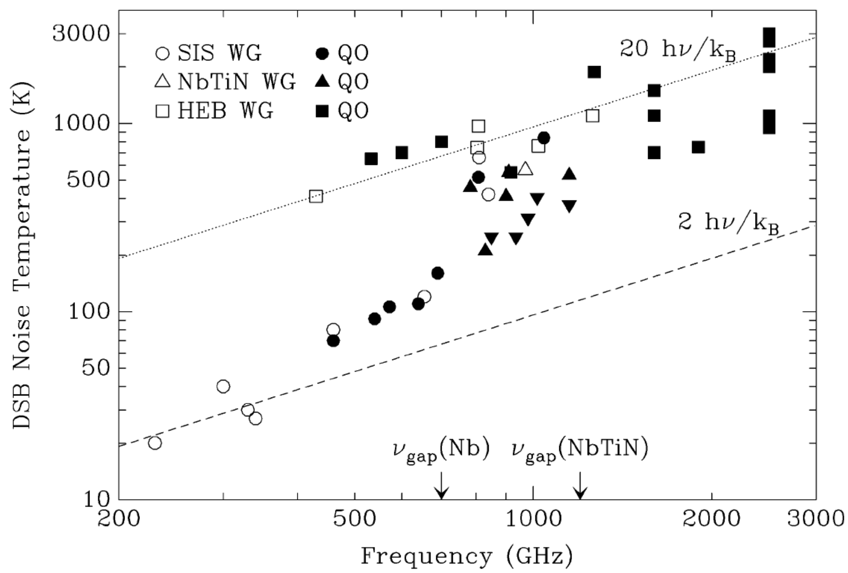

Fig. 3. Heterodyne receiver sensitivity vs frequency, for receivers using SIS and HEB mixers. Inverted triangles are NbN/NbTiN results corrected for the LO injection beam splitter loss [6].

1-3 THz range, their IF bandwidth is limited by the hot electron relaxation time. Also, potential bias instability in HEB mixers [7] makes them problematic for use in multi-element arrays. For these reasons HEB receivers (square markers) are outside the scope of the present document.

6. The next generation of THz heterodyne receivers
Advances in THz heterodyne receivers in the next decade are likely to come from a combination of new technology and improvements in existing technology. The development of new devices such as semiconductor quantum-well detectors should be supported, and also the exploration of new superconducting materials for SIS mixers. Significant improvements will also be accomplished by using receiver configurations which minimize noise from extraneous sources (LO, atmosphere) and, important for array receivers, which make efficient use of LO power. New THz oscillators will make large heterodyne array receivers feasible.

6.1 New mixing devices
While SIS mixer technology can probably be extended to operation substantially above 1 THz with the development of new materials and fabrication techniques, progress will become more difficult at the higher frequencies. Quantum-well detectors appear to hold promise for the THz range [1,8]. They have the potential for wide IF bandwidth, and the low quantum efficiency of early FIR quantum-well detectors may be overcome, for example, by the quantum-well intrasubband

photodetector (QWISP) [1].

6.2 New frequency sources (local oscillators)

Quantum cascade lasers (QCLs) are an emerging technology that has considerable promise above 2 THz as a versatile LO source. At this frequency, multiplier technology is difficult due to the number of multiplier stages that must be cascaded, and output power is minimal. By contrast, QCLs work better with increasing frequency and can produce >1 mW output power above 2 THz. They can be phase locked for extended periods of time [3]. The present difficulties with using QCLs are: (a) multi-mode oscillation, spreading power into several nearby frequencies, (b) very poor output beam pattern and (c) limited tunability. Tunability may be increased with more advanced resonator design, but will always be limited by the quantum-well structure. Improved resonators [4] should also concentrate power into a single mode. The beam pattern is inherently quite divergent, but work is ongoing to convert this to a more desirable mode [5]. In the last four years progress has been very rapid on all of these fronts, and work is proceeding at several institutions.

6.3 New materials for SIS mixers

The great majority of receivers currently in use for mm/sub-mm radio astronomy use niobium SIS mixers. The superconducting energy gap of Nb ($T_C \sim 9$ K) limits its use in low-noise receivers to ~700 GHz, with operation at reduced sensitivity at higher frequencies. The superconductor NbTiN has Tc ~15 K, implying operation to ~1.2 THz if high quality all-NbTiN junctions could be made, but so far NbTiN has only been used in combination with Nb to make SIS mixers with good performance to ~1 THz. All-NbTiN SIS junctions were briefly explored using MgO [9] and AlN [10] barriers with fair initial results (gaps of ~5 mV but Rsg/Rn of only ~6) before researchers realized that the Nb/Al-AlN/NbTiN material stack was easier to optimize. Now that Nb/Al-AlN/NbTiN junctions of very high quality have been obtained [11] there is a good likelihood that all-NbTiN SIS junctions will become practical, opening the way to quantum-limited SIS receivers up to ~1.2 THz (and usable with reduced sensitivity to ~2.4 THz). Additionally, it is reasonable to expect that other A15 superconductors, e.g., Nb_3Ge with $T_C = 23$ K, which have received very little attention to date, could yield high quality SIS junctions capable of operation somewhat beyond 1.2 THz.

Two other superconducting materials, so far unexplored for SIS mixer applications, are BKBO ($Ba_{(1-x)}K_{(x)}BiO_3$, Tc = 34 K) and magnesium diboride (MgB_2, $T_C = 39$ K). SIS mixers based on these materials could permit quantum-limited operation as high as 2.6 THz and 3 THz. BKBO is one of only two high-temperature oxide superconductors which is isotropic, the other being BKFA [12]. Simple BKBO grain-boundary junctions have shown good I(V) characteristics similar to those of Nb junctions, but a method for producing well controlled junctions has not been developed. MgB_2 has dual energy gaps which may complicate its use as a THz mixer, but its potential should be explored. Development of new materials such as BKBO and MgB_2 for THz receiver applications is a high risk, long term project, but success could revolutionize mm/sub-mm receiver technology.

There is currently no funding for work on superconducting materials with medium critical temperatures (15-40 K) which could conceivably permit quantum-limited heterodyne detection to ~2.6 THz (and usable with reduced sensitivity to ~5 THz).

6.4 Configuration

The growing interest in radio cameras – beam-forming arrays and focal plane arrays of receivers – in the millimeter bands will extend into the THz range once the technology can support them. For such multi-element receiver arrays, provision of sufficient LO power in the low THz range is difficult unless balanced mixers are used. With the development of a compact superconducting wideband IF hybrid (Fig. 4), balanced mixers can be developed which will require 30-50 times less LO power than corresponding single-ended mixers.

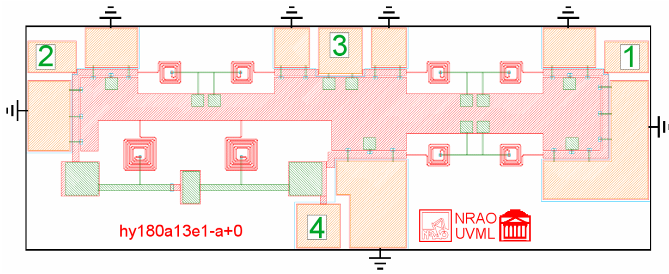

Fig. 4. Superconducting 4-12 GHz 180°-hybrid on a quartz chip. Dimensions: 1.42 mm x 0.51 mm. [13].

Using a balanced mixer also simplifies LO injection. A typical sub-mm radio astronomy receiver uses a beam splitter to couple LO power into the mixer. The loss from the beam splitter in the signal path significantly degrades the receiver sensitivity, as is clear from the erect and inverted triangles in Fig. 3. With a balanced mixer, the LO port is separate from the signal port.

An additional advantage of balanced mixers is their inherent rejection of LO noise. A serious limitation of multiplier-chain LO sources can be their noise in the receiver sidebands [14,15]. With sufficient engineering effort it is possible to minimize the excess noise, as was done in the case of the ALMA LOs. However, making a good LO with a multiplier chain which is broadband and has low noise is difficult and expensive – a better solution is to allow a noisier LO and use a balanced mixer. In addition to the lower LO power requirement, this makes the balanced mixer configuration very attractive for THz operation.

For terrestrial spectral line observations, the opacity of the atmospheric windows significantly degrades system sensitivity, even under the best conditions. To eliminate the atmospheric noise from the image band, sideband-separating mixers should be developed. These have the added advantage of separate upper- and lower-sideband IF outputs, each with the full bandwidth of the receiver, which can be crucial in unraveling complex spectra. Millimeter wave receivers with sideband-separating mixers have given outstanding results [16].

Above ~1 THz there has been considerable success with so-called quasi-optical mixers which use a planar radiating structure on the flat surface of a lens, often silicon [6]. While the quasi-optical configuration avoids very small waveguide structures, it is not well suited to balanced mixers nor to sideband-separating mixers. Although quasioptical balanced and sideband-separating mixers are possible, they require the use of relatively large quasioptical LO couplers and/or interferometers in the signal path which reduce sensitivity and are difficult to incorporate into arrays of any substantial size. It seems likely that the next generation of nearly quantum-limited THz heterodyne receivers will adapt the waveguide technology well established in the sub-THz bands. Approaches to fabricating waveguide receivers up to several THz are discussed below.

6.5 Fabrication

In recent years there has been considerable progress in the fabrication of circuits for millimeter/sub-millimeter wavelengths. Thick quartz substrates have been replaced by silicon membrane and beam lead technology [17], and new micromachining methods allow rectangular waveguides to be used well into the THz range.

Advanced micromachining will play an important role in the development of THz technology for radio astronomy. The best CNC milling machines have a position accuracy of ~1 micron, and with the smallest cutters available (~25 microns diameter) could machine simple waveguides and radiating structures for operation to ~5 THz. However, the essential circuit elements (transducers, hybrids, couplers) have features an order of magnitude smaller and will require microfabrication methods in conjunction with conventional machining.

Several micromachining processes currently under development are applicable to fabrication of THz detectors. Bulk-silicon micromachining via deep reactive-ion etching (DRIE) and surface micromachining of SU-8 photoresist both utilize photolithography to define a pattern with sub-micron resolution. DRIE Si processes are not selective to specific silicon crystal planes (as are many wet etchants) and can therefore realize vertical sidewalls. This process has been used to create waveguide structures including couplers and filters [18]. SU-8 is an epoxy photoresist with extremely low optical absorption which allows layers as thick as several hundred microns to be exposed using standard UV lithography to obtain aspect ratios as high as 10:1. With subsequent metalization, it has been used for components with integrated horn antennas up to 1.6 THz as well as couplers and resonators as low as 300 GHz [19]. Another process under development but not yet demonstrated in the context of THz technology is deep ICP (inductively-coupled plasma) etching into metal and insulator structures.

These fabrication processes are directly applicable to single detectors and to one-dimensional (linear) arrays of detectors, and, with further development, should be applicable to monolithic two-dimensional arrays. In the interim, focal plane array receivers consisting of multiple parallel linear arrays will greatly increase observing speed relative to a single-pixel receiver.

6.6 Radiating structures

Corrugated horns have a circularly symmetric beam, low cross polarization and wide bandwidth and are the best choice for feeding radio telescopes in the millimeter bands. With the development of high precision computer controlled lathes, corrugated horns have been successfully fabricated up to about 1 THz, but at higher frequencies, the dimensions pose manufacturing difficulties. Diagonal horns have been used but have much lower usable bandwidth and higher cross polarization. In recent years, a type of smooth-walled horn possessing most of the desirable characteristics of the corrugated horn has been developed [20]. It has a spline profile optimized to give the desired radiation pattern. With the use of CNC machining, possibly combined with the micromachining processes described above, it should be possible to machine this type of horn directly into a split-block waveguide structure as an integral part of a mixer. Application to monolithic receiver arrays, linear or two-dimensional, should be straightforward.

7. THz array receiver technology

First generation submillimeter arrays [21-24] were constructed using discrete components, stacking individual mixer blocks in a common cryostat. A quasi-optical diplexer in the signal path was used to inject the LO power to the mixer array. With this approach array sizes up to 16 pixels have been made. For larger arrays a greater degree of integration will be required to control the cost. An example is SuperCam, a 64-pixel,

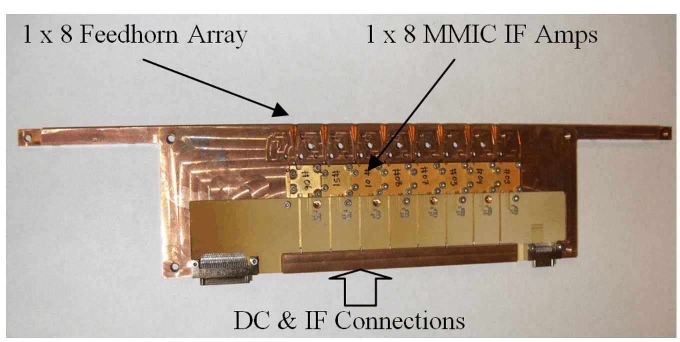

Fig. 6. SuperCam 1 x 8 mixer module.

345 GHz camera nearing completion at the University of Arizona [25]. The focal plane unit is composed of 8 mixer modules, each a 1 x 8 array of mixers machined into a single split block (Fig. 6). The SIS devices are made on 3-µm SOI membranes with self aligning beam leads [17]. Low-noise, low-power MMIC IF amplifiers are integrated into the block and bonded directly to the IF output of the SIS devices. This 1-dimensional level of integration has made the construction of this size array practical, both in terms of packaging and cost.

For future large submillimeter telescopes, such as the planned 25m Cornell-Caltech Atacama Telescope (CCAT), large format cameras are essential to nearly all the science programs. Heterodyne cameras with as many as 1k pixels are already being considered for CCAT, but even

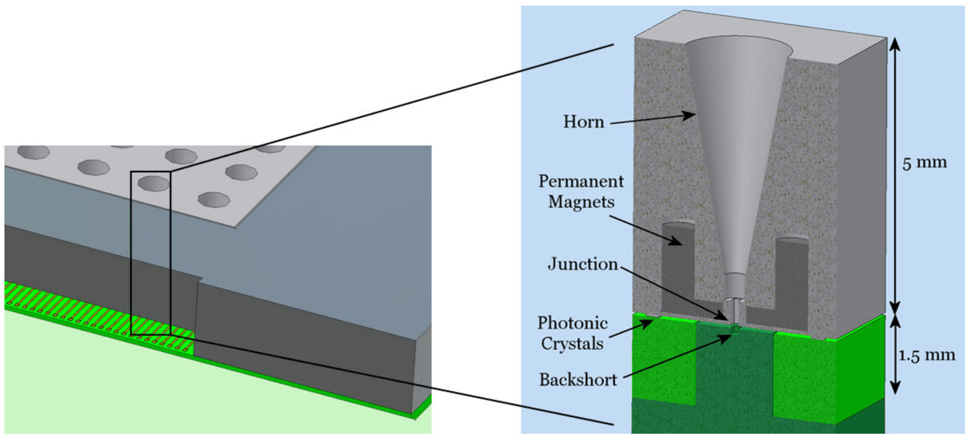

Fig. 7. Section of KCAM 2-D integrated array.

with the underfilled array shown in Figure 7, a 1 k pixel camera at 0.65THz would have a field of view of only ~5'. Nearby star-forming regions are much larger, and CCAT's field of view is ~0.3deg, so there will be a need for even larger cameras.

Kilo-pixel heterodyne cameras (KCAMs) will probably require integrated 2D arrays of horns and mixers (Fig. 7). This same basic architecture is already being used for incoherent, bolometer arrays, but heterodyne cameras are more complex because they require local oscillators, an IF amplifier and a spectrometer for each pixel. The key enabling technologies are micromachining (for arrays of backshorts and horns, e.g., platelet corrugated horns [26]) and packaging (for the individual detectors, arrays of mixers, IF amplifiers and local oscillator distribution).

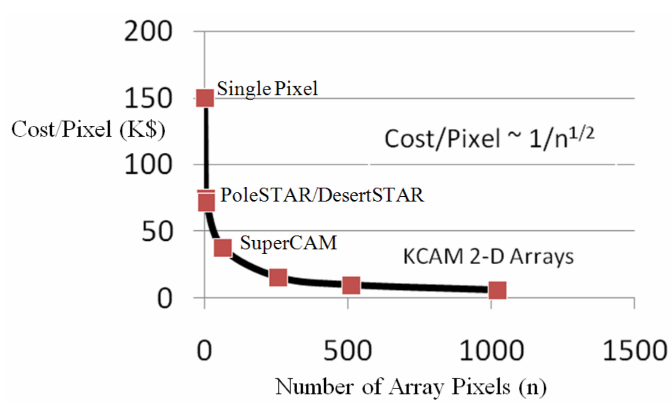

Fig. 8. Cost per pixel for heterodyne arrays built at the University of Arizona. The points for a single pixel receiver, PoleSTAR (multiple mixers in the same cryostat) and SuperCAM (1-d integration) are actual costs.

A higher level of integration often leads to leaps in performance at a reduced price. This already appears to be the case for heterodyne cameras (Fig. 8). The cost of the spectrometers for a large format camera has historically been prohibitive, but developments in computing systems (e.g., arrays of reconfigurable gate arrays) are driving the cost down rapidly. Heterodyne camera spectrometers will certainly benefit from the substantial investment in digital signal processing for the SKA. The associated correlator developments would also allow small heterodyne receiver arrays to be deployed on interferometers (e.g., ALMA) to substantially increase the throughput.

Large coherent arrays are the subject of a separate Astro2010 White Paper lead by Paul Goldsmith of JPL.

8. Level of effort

Assume eight related sub-projects at multiple institutions – *e.g.*, SIS junction development, materials, mixer design, array design, fabrication technology, *etc.* The quantum of funding for this kind of work is currently ~$400k/year. Hence the total funding should be ~$3.2M/year for 10 years.

References

[1] D. Z.-Y. Ting, Y.-C. Chang, S. V. Bandara, and S. D. Gunapala, "Quantum well intrasubband photodetector for far infared and terahertz radiation detection," Applied Physics Letters 91, 073510 2007.

[2] T. W. Crowe, J. L. Hesler, W. L. Bishop, G. S. Schoenthal, and K. Hui, "Terahertz Local Oscillator Sources," 20th International Symposium on Space Terahertz Technology, Charlottesville, 20-22 April 2009, and http://www.vadiodes.com/.

[3] Heinz-Wilhelm Hübers, "Experiences with Quantum Cascade Lasers as Local Oscillator," 19th International Symposium on Space Terahertz Technology, pg 20, Groningen, April 2008.

[4] Jonathan A. Fan, Mikhail A. Belkin, and Federico Capassob, Suraj P. Khanna, Mohamed Lachab, A. Giles Davies, and Edmund H. Linfield, "Wide-ridge metal-metal terahertz quantum cascade lasers with high-order lateral mode suppression," Applied Physics Letters 92, 031106, 2008

[5] Wilfried Maineult, Pierre Gellie, Alessio Andronico, Pascal Filloux, Giuseppe Leo, Carlo Sirtori, Stefano Barbieri, Emilien Peytavit, Tahsin Akalin, Jean-Francois Lampin, Harvey E. Beere and David A. Ritchie, "Metal-metal terahertz quantum cascade laser with micro-transverse-electromagnetic-horn antenna," Applied Physics Letters 93, 183508 2008

[6] J. Zmuidzinas and P. L. Richards, "Superconducting Detectors and Mixers for Millimeter and Submillimeter Astrophysics," Proc IEEE, vol. 92, no. 10, Oct. 2004

[7] J.W. Kooi, J.J.A. Baselmans, A. Baryshev, R. Schieder, M. Hajenius, J.R. Gao, T.M. Klapwijk, B. Voronov, and G. Gol'tsman, "Stabilty of Heterodyne Terahertz Receivers", J. Appl. Phys., Vol. 100, 064904, Sept. 2006.

[8] E. R. Brown, K. A. McIntosh, F. W. Smith, and M. J. Manfra, "Coherent detection with a GaAs/AIGaAs multiple quantum well structure," Appt. Phys. Lett. 62 (13), pp. 1513-1515, 29 March 1993.

[9] J.A. Stern, B. Bumble, H.G. LeDuc, J.W. Kooi, J. Zmuidzinas, "Fabrication and DC-Characterization of NbTiN Based SIS Mixers for the Use between 600 and 1200 GHz," Ninth International Symposium on Space Terahertz Technology, Pasadena, California, March 1998.

[10] Z. Wang, A. Kawakami, and Y.Uzawa, "NbN/AlN/NbN tunnel junctions with high current density up to 54 kA/cm^2, Appl. Phys. Lett. 70, 114, 6 January 1997.

[11] T. W. Cecil, M. E. Cyberey, R. E. Matthews, J. Z. Zhang and A. W. Lichtenberger, "Development of Nb/Al-AlN/NbTiN SIS Junctions with ICP Nitridation," to appear in IEEE Trans. Applied Superconductivity, 2009.

[12] H. Q. Yuan, J. Singleton, F. F. Balakirev, S. A. Baily, G. F. Chen, J. L. Luo and N. L. Wang, "Nearly isotropic superconductivity in (Ba,K)Fe2As2," Nature 457, 565-568, 29 January 2009.

[13] A. R. Kerr, A. W. Lichtenberger, C. M. Lyons, E. F. Lauria, L. M. Ziurys, and M. R. Lambeth, "A Superconducting 180-degree IF Hybrid for Balanced SIS Mixers," Proc. 17 th Int. Symp. on Space THz Tech., Paris, pp. 29-32, May 2006.

[14] V. Vassilev, D. Henke, I. Lapkin, O. Nyström, R. Monje, A. Pavolotsky, and V. Belitsky, "Design and Characterization of a 211–275 GHz Sideband Separating Mixer for the APEX Telescope," IEEE Microwave and Wireless Components Letters, Vol. 18, No. 1, pp. 58-60, January 2008.

[15] E. Bryerton, "AM Noise in Front End Local Oscillators," ALMA document FEND-40.10.00.00-093-A-REP 24 April 2008.

[16] E. F. Lauria, A. R. Kerr, G. Reiland, R. F. Freund, A. W. Lichtenberger, L. M. Ziurys, M. Metcalf and D. Forbes, "First Astronomical Observations with an ALMA Band 6 (211-275 GHz) Sideband-Separating SISMixer-Preamp," Proc. 17th Int. Symp. on Space THz Tech., Paris, May 2006. ALMA Memo 553, http://www.alma.nrao.edu/memos/

[17] R.B. Bass, A.W. Lichtenberger, R.M. Weikle, S.-K. Pan, E. Bryerton, J. Kooi, C.K. Walker, "Ultra-Thin Silicon Chips for Submillimeter-Wave Applications," Proc. Fifteenth International Symp. on Space THz Technology, March 2004.

[18] Kirby, P.L.; Pukala, D.; Manohara, H.; Mehdi, I.; Papapolymerou, J., "A micromachined 400 GHz rectangular waveguide and 3-pole bandpass filter on a silicon substrate,"International Microwave Symposium Digest, 2004 IEEE MTT-S, vol.2, no., pp. 1185-1188 Vol.2, 6-11 June 2004

[19] Smith, C.H., III; Haiyong Xu; Barker, N.S., "Development of a multi-layer SU-8 process for terahertz frequency waveguide blocks,"International Microwave Symposium Digest, 2005 IEEE MTT-S, vol., no., pp. 4 pp.-, 12-17 June 2005

[20] C. Granet, G. L. James, R. Bolton, and G. Moorey, "A Smooth-Walled Spline-Profile Horn as an Alternative to the Corrugated Horn for Wide Band Millimeter-Wave Applications," IEEE Trans. Antennas and Propagation, vol. 52, no. 3, March 2004.

[21] Groppi, C., Walker, C., Kulesa, C., Golish, A., Putz, P., Hedden, A., Weinreb, S., Bardin, J., Jones, G., Mani, H., Kooi, J., and Lichtenberger, A., ``Supercam: A 64 pixel heterodyne imaging spectrometer", in Millimeter and Submillimeter Detectors and Instrumentation for Astronomy, eds. Zimuidzinas and Holland, Proceedings of SPIE, vol. 7020-37, 2008.

[22] Guesten, R., Heyminck, S., Klein, B., Klein T., and Kassemann, K., ``Subillimeter Heterodyne Arrays for APEX", in Millimeter and Submillimeter Detectors and Instrumentation for Astronomy, eds. Zimuidzinas and Holland, Proceedings of SPIE, vol. 7020-36, 2008.

[23] Smith, H., Hills, R., Buckle, J., Curtis, E., Bell, G., Richer, J., Withington, S., Williamson, R., et al., ``HARP: a submillimeter heterodyne array receiver operating on the James Clerk Maxwell Telescope", in Millimeter and Submillimeter Detectors and Instrumentation for Astronomy , Zimuidzinas and Holland, Proceedings of SPIE, vol. 7020-35, 2008.

[24] Walker, C.K., Groppi, C., D. d'Aubigny, C., Kulesa, C., Hungerford, A., Jacobs, K., Graf, U., Schieder, R., and Martin, C. ,`` PoleSTAR: A 4-Pixel 810 GHz Array Receiver for AST/RO", Proceedings of the 12th International Symposium on Space TeraHertz Technology, San Diego, CA, eds. Mehdi & McGrath, JPL, 2001.

[25] Groppi, C., Walker, C., Kulesa, C., Golish, A., Putz, P., Hedden, A., Weinreb, S., Bardin, J., Jones, G., Mani, H., Kooi, J., and Lichtenberger, A., ``Supercam: A 64 pixel heterodyne imaging spectrometer", in Millimeter and Submillimeter Detectors and Instrumentation for Astronomy, eds. Zimuidzinas and Holland, Proceedings of SPIE, vol. 7020-37, 2008.

[26] J. Gundersen and E.J. Wollack, "Millimeter Wave Corrugated Platelet Feeds," 2008. http://www.google.com/url?sa=U&start=4&q=http://cmbpol.uchicago.edu/workshops/technology2008/depot/wollack_plateletfeeds_v1_20080820.doc&ei=5CLEScezMI7unQedsN2MDg&usg=AFQjCNG2tdImlrwO6elyuPzyCEhh9-UtKg.