GUBBINS: A novel millimeter-wave heterodyne interferometer

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***Abstract*—GUBBINS is a prototype heterodyne interferometer currently under construction at Oxford with the aim of demonstrating high surface brightness mm-wave interferometery at modest spatial and spectral resolutions [1]. Once built and tested, the instrument will be used to carry out demonstration observations of the Sunyeav-Zeldovich effect in bright galaxy clusters and measurements of atmospheric phase stability, as well as other tests of ground based interferometery. In this paper we give an update on the progress of the GUBBINS project, in particular, the development of the new technologies employed in this novel instrument.**

***Index Terms*—interferometery, heterodyne, SIS mixer, analogue correlator.**

I. Introduction

We are currently designing and building a prototype single-baseline 220 GHz tracking heterodyne interferometer for high brightness sensitivity astronomical observations. This instrument, GUBBINS (220-GHz Ultra-BroadBand INterferometer for S-Z), will use two small antennas on a short baseline with ultra-wide IF bandwidth SIS mixers developed in collaboration with Cologne University and an ultra-wideband analogue correlator developed in collaboration with the University of Maryland. After extensive laboratory testing the instrument will be deployed for test astronomical observations at the Chajnantor Observatory, Chile, adjacent to ALMA. Although the instrument will make useful astronomical measurements, it will be used primarily for the development of new technologies for mm-wave interferometry.

The technology developed for this instrument will also have applications in other areas of astronomy, particularly in the design of very wide IF bandwidth SIS receiver arrays.

A. Use of interferometry in CMB observations

Cosmic microwave background astronomy requires extremely high brightness sensitivity and very good control of systematic and instrumental effects. The use of interferometric techniques allows total power fluctuations from the atmosphere to be subtracted. The use of heterodyne mixers allows each receiver to be phase switched independently by phase switching the local oscillator, so that the individually modulated redundant baselines can be used to eliminate other instrumental systematic effects. Achieving high brightness sensitivity in interferometry requires that the instantaneous bandwidth of each baseline be as wide as possible, and that the array be as filled as is practical within the limits of antenna shadowing.

Interferometry has been widely used in cosmology instruments at centimetre wavelengths, particularly for observations of the primary temperature anisotropy and E-mode polarisation of the cosmic microwave background e.g. CBI, DASI, VSA, and in observations of secondary anisotropies such as the Sunyaev-Zel'dovich effect, e.g. AMI, CBI-2, SZA.

Although measurements of the CMB and S-Z effect at millimetre wavelengths are regularly carried out, the limitations of the low instantaneous (IF) bandwidth of SIS mixers and backend systems, and the poor noise performance of other mm-wave coherent detectors, have resulted in an absence of successful CMB instruments using heterodyne interferometry in the millimetre-wave band. Recent advances in SIS mixer design and wideband correlator technology make it feasible to build a mm-wave heterodyne interferometer capable of carrying out novel CMB observations.

II. Galaxy cluster science with GUBBINS

The Sunyaev-Zel'dovich effect is the distortion of the spectrum of the CMB due to inverse-Compton scattering off the hot gas in clusters of galaxies [2]. This tends to boost the energy of the CMB photons, leading to a decrease in the CMB brightness below a frequency of about $220\,\mathrm{GHz}$, and an increase above this frequency. One of the key features of the S-Z effect is that its surface brightness is independent of the distance to the cluster, although the angular size on the sky does decrease with distance. This means that S-Z measurements can be used to study galaxy clusters over a very wide range of redshifts [3], [4].

The exact null frequency varies with the temperature of the cluster gas (thermal S-Z effect) and the peculiar velocity of the cluster (kinematic S-Z effect) (fig. 1). The shift in the null frequency due to the thermal S-Z effect is approximated by $217 + 0.45T\,\mathrm{GHz}$ where T is the cluster gas temperature in keV. A typical rich cluster has a gas temperature in the range $5 - 15\,\mathrm{keV}$, leading to shift in the null frequency of $2.5 - 7.5\,\mathrm{GHz}$. Hence by measuring the SZ spectrum and finding the null frequency we can measure the cluster temperature without the need for X-ray spectral measurements.

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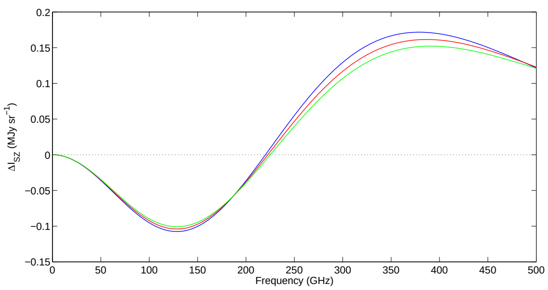

Figure 1. The change in CMB spectrum due to the thermal Sunyeav-Zeldovich effect in a galaxy cluster for three cluster gas temeperatures: $5\,\mathrm{keV}$ (blue), $10\,\mathrm{keV}$ (red) and $15\,\mathrm{keV}$ (green).

Table I
TARGET PERFORMANCE FOR GUBBINS PHASE I

Frequency	$185 - 275\,\mathrm{GHz}$
Antenna aperture	$0.4\,\mathrm{m}$
Baseline	$0.5 - 0.6\,\mathrm{m}$
Primary beam (220 GHz)	$11.4'$ FWHM
Spatial resolution (220 GHz)	$7.5' - 11.4'$
IF band	$3 - 13\,\mathrm{GHz}$
Instananeous bandwidth	$2 \times 10\,\mathrm{GHz}$
Correlator channels	16
Correlator bandwidth	$2 - 20\,\mathrm{GHz}$
Channel bandwidth	$1.125\,\mathrm{GHz}$
Target system temperature	$50\,\mathrm{K}$
Brightness sensitivity per channel	$1.5\,\mathrm{mK}/\sqrt{\mathrm{s}}$
Total brightness sensitivity	$350\,\mu\mathrm{K}/\sqrt{\mathrm{s}}$

GUBBINS will be able to detect a the brightest galaxy clusters in the sky in one night's observing per cluster, and will be able to constrain the null frequency of the S-Z effect to $\pm 1\,\mathrm{GHz}$ with several nights observing. In conjunction with low frequency S-Z data e.g. from CBI-2 ($26 - 36\,\mathrm{GHz}$), we should be able to measure the cluster gas temperature to within a few keV.

III. INSTRUMENT DESIGN

The design goals of this instrument are somewhat different to current mm-wave interferometers, in that we want to achieve maximum sensitivity to extended continuum sources, but with only moderate spatial and spectral resolution. The specifications of the GUBBINS instrument are given in Table I. These figures are for the initial GUBBINS design, but future developments are planned, particularly to increase the mixer IF bandwidth to the full $2 - 20\mathrm{GHz}$ band of the correlator and backend.

The prime design targets are for a single $0.5\,\mathrm{m}$ baseline (dictated by the angular size of the brightest S-Z clusters) with the maximum achievable filling factor; a target system temperature of $50\,\mathrm{K}$; a total instantaneous bandwidth of at least $10\,\mathrm{GHz}$ in each sideband divided into at least 8 spectral channels and an LO tuneable by at least $20\,\mathrm{GHz}$ either side of the nominal null in the S-Z effect at $217\,\mathrm{GHz}$.

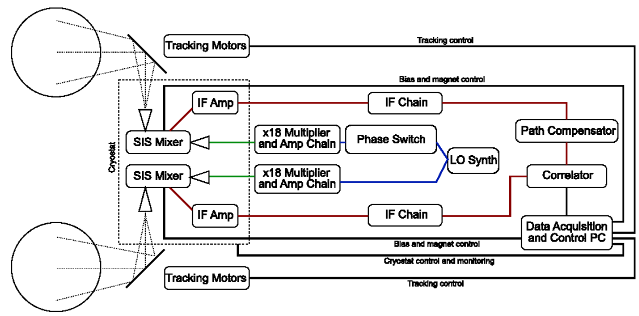

Figure 2. System diagram for the GUBBINS instrument. Data and DC signals are shown as black lines, LO signals as blue (low frequency, coaxial cables) and green (mm-wave, quasioptical) and IF signals as red. The optics are on the left of the diagram.

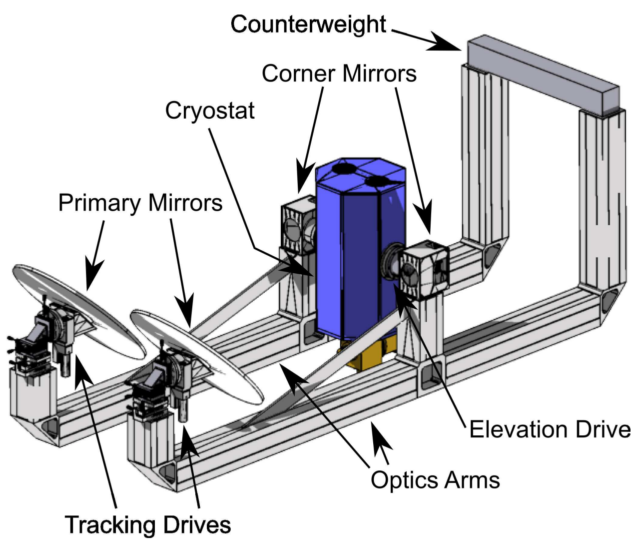

Figure 3. CAD model of the GUBBINS instrument. The telescope is supported on the base of the cryostat body, between the two optics arms.

A diagram of the GUBBINS system is given in Fig. 2 and a CAD model of the complete instrument in Fig. 3. To avoid the complexity and cost of using two cryostats and coolers, both SIS receivers are mounted in a single cryostat at the centre of the instrument, with the optics for each antenna mounted on either side. The SIS mixers mounted on either side of the coldhead, looking out of opposite sides of the cryostat, with LO signals being fed into cryostat through windows in the top of the cryostat, before being coupled to the mixers via smooth-walled horns and waveguide directional couplers.

A. Optics design

The optical design of each telescope employs the maximum primary mirror size that can be accommodated on a $0.5\,\mathrm{m}$ baseline without shadowing. If the antennas are to be scanned up to 45° from the zenith, the no shadowing condition gives a primary mirror projected aperture of $\sim 0.4\,\mathrm{m}$. The optical layout is shown in Fig. 5 and Fig. 4. Each telescope is fed by corrugated horn-reflector antenna with a 7° FWHM beam at $220\,\mathrm{GHz}$. The primary mirror is a 45° offset paraboloid with a focal length of $1020\,\mathrm{mm}$. GRASP simulations of the telescope beam are shown in Fig. 6.

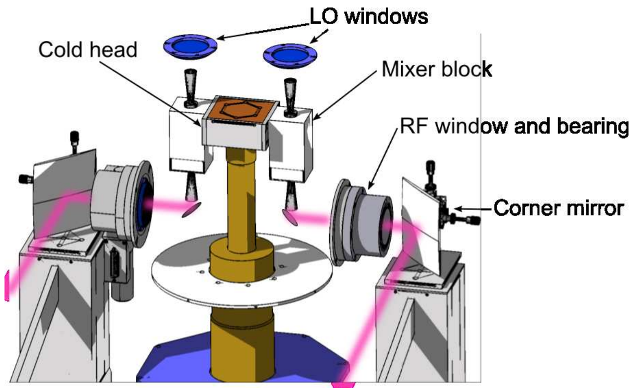

Figure 4. CAD model of the inside of the GUBBINS cryostat. The beams from the sky are shown in pink, and are reflected into the cryostat from the corner mirrors and through the elevation motor and bearings before passing through the cryostat windows and radiation shields to the horn-reflector antennas.

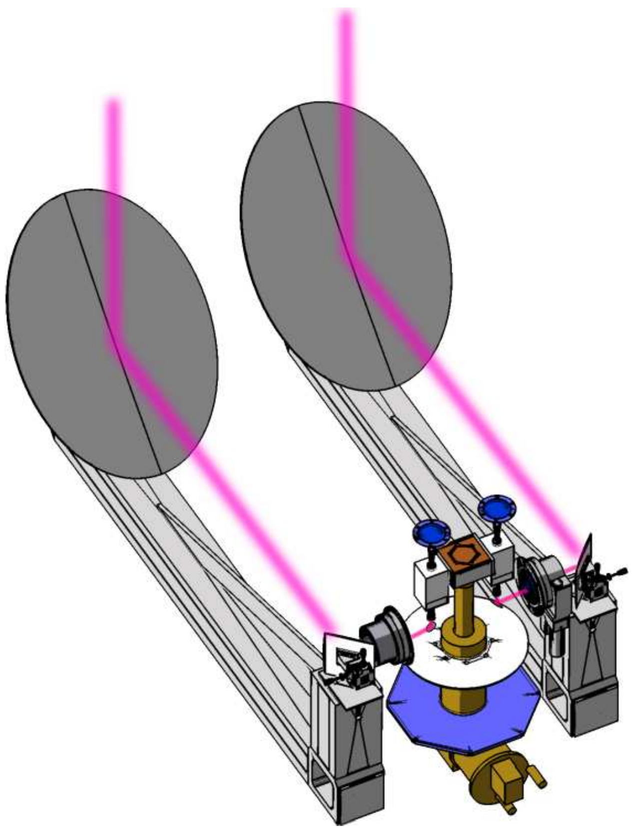

Figure 5. CAD model of the GUBBINS optics. The beams from the sky are shown in pink, and are reflected from the 45° offset primary mirrors to the 45° offset corner mirrors and into the cryostat. The telescope is pointed by rotating the primary mirrors about the axis between the primary mirrors and the corner mirrors, and by rotating the entire optics arm assemblies in elevation about the axis between the corner mirrors and horn-reflector antennas.

In order to allow the necessary degrees of freedom in the optics so that the telescopes can be pointed in elevation and azimuth, the telescopes are folded by a 45° offset corner mirror between the primary mirror and feed. The corner mirror is a convex paraboloid (focal length $-120\,\mathrm{mm}$) to reduce the length of the telescopes, at the expense of introducing slight aberrations when the telescopes are pointed far from the zenith.

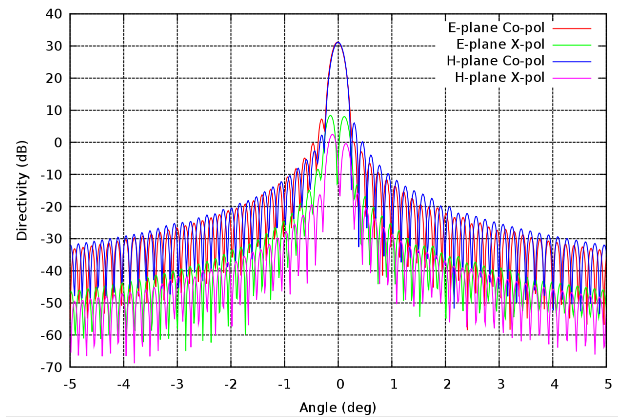

Figure 6. GRASP simulation of the primary beam of the GUBBINS optics.

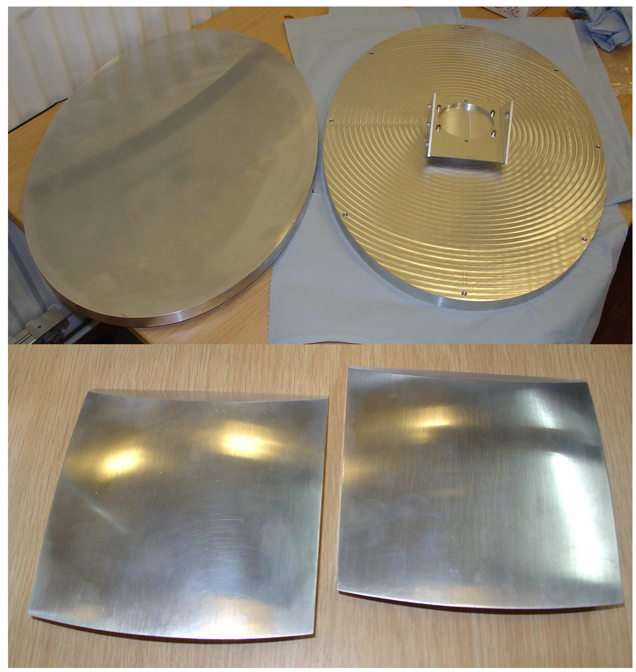

Figure 7. The GUBBINS primary (top) and corner mirrors (bottom) prior to assembly.

Both the primary and corner mirrors have been CNC machined from aluminium billets (fig 7). The surface figure has been measured on a CMM, giving a measured surface figure deviation of slightly less than $\pm 10\,\mu\mathrm{m}$. The corner mirrors are mounted on 2-axis goniometers, while the primary mirrors and drives are mounted on 2-axis tip/tilt stages and XYZ stages to allow the optics to be aligned.

B. Telescope mount and cryogenics

The two optics arms supporting the telescopes are mounted on a ring bearing and a servo motor fixed around the cryostat windows, and are connected by a counterweight at the rear end of the arms (see Fig. 3). The telescopes are tracked across the sky by rotating the primary mirrors on two servo motors about the optical axis between the primary and secondary mirrors. This allows both antennas to be pointed individually

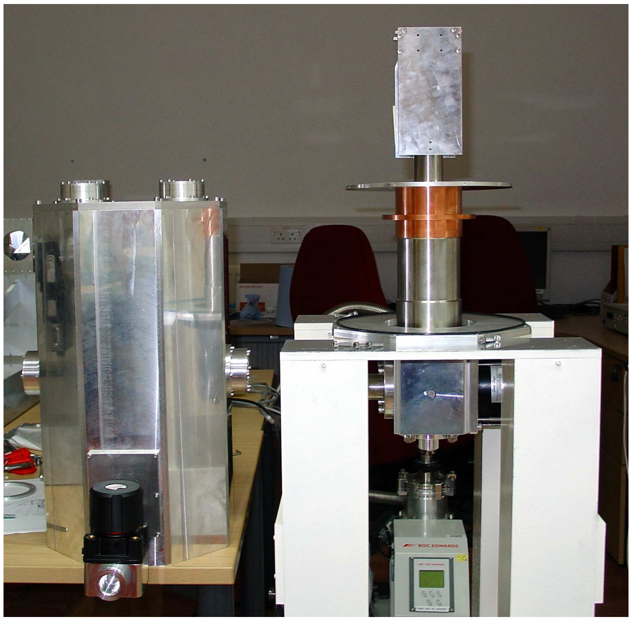

Figure 8. The GUBBINS cryostat, mounted on the telescope support pillar, and open to show the G-M cold-head, mixer mounting jig and radiation shield support.

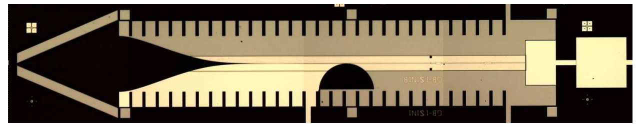

Figure 9. GUBBINS wide-IF band finline SIS mixer chip [5].

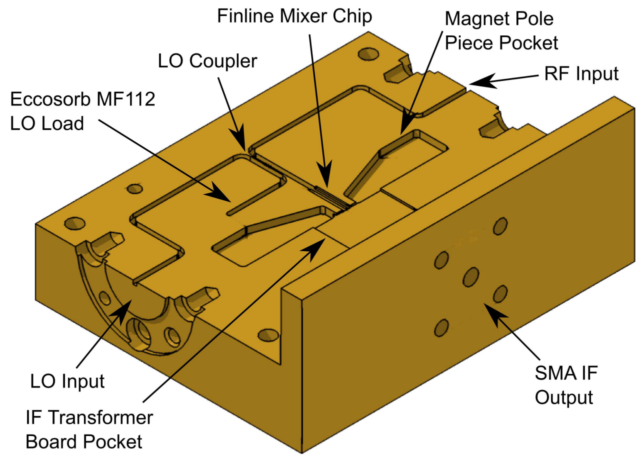

Figure 10. CAD model of the lower half of the GUBBINS mixer block.

in azimuth, while keeping the number of drive components to a minimum.

The whole instrument is supported on a pillar attached to the base of the cryostat and to a concrete plinth on the ground. The instrument is mounted on the plinth on a bearing, and can be secured in a number of orientations, allowing the projected baseline direction to be changed.

The cryostat is a structural element of the instrument mount, and is being custom designed and built by Oxford Physics (figs. 4 and 8). The cryostat is cooled by a two stage Gifford-McMahon cooler from Sumitomo Heavy Industries. It provides $1\,\mathrm{W}$ of cooling power to the $4\,\mathrm{K}$ stage, where the SIS mixers and first stage IF amplifiers are mounted, and $40\,\mathrm{W}$ to the $40\,\mathrm{K}$ stage where the electrical connections are heat sunk, and the second stage IF amplifiers are mounted.

C. SIS mixers and cryogenic IF amplifiers

GUBBINS will use the single-ended ultra-wide IF band finline mixers described in [5], with a waveguide directional coupler in a split mixer block for coupling LO to the mixer. These ultra-wide IF band mixers are based on an earlier $230\,\mathrm{GHz}$ finline mixer design [6], with a number of additions and improvements for ultra-wide IF band operation. An RF band-pass filter is used between the finline taper and the mixer tuning circuit to prevent the IF signal from leaking into the finline. The mixer tuning circuit and RF choke use relatively narrow microstrip lines to keep reactances in the IF band low, and a 5-stage microstrip transformer is used to match the $16.5\,\Omega$ SIS junction(s) to the $50\,\Omega$ input of the IF amplifiers over the $2-20\,\mathrm{GHz}$ IF band.

The first batch of SIS mixer chips (fig. 9), fabricated at KOSMA, are currently being tested in Oxford without the microstrip IF transformer and using a $4-6\,\mathrm{GHz}$ IF system with the GUBBINS $3-13\,\mathrm{GHz}$ cryogenic LNAs.

The split mixer block (Fig. 10) contains a $-16\,\mathrm{dB}$ directional coupler used to combine the LO signal with the astronomical signal, a termination load to dump the uncoupled LO power and the mounting position for the SIS mixer chip. The mixer block also holds the IF transformer board used to transform the $16.5\,\Omega$ output of the mixer to the $50\,\Omega$ input impedance of the IF amplifier and the SMA IF/DC bias connector. A superconducting electromagnet is mounted to the block to provide the magnetic field required to suppress Josephson tunnelling in the mixer, with magnet iron pole pieces used to concentrate the field at the mixer chip. The mixer block is currently being machined by Chris Groppi at the University of Arizona.

The $-16\,\mathrm{dB}$ directional coupler uses three $0.4\,\mu\mathrm{m}$ thick gold radial probes connected by suspended stripline and deposited on $65\,\mu\mathrm{m}$ thick quartz chips to couple power between the waveguides (fig. 11). The coupling of each chip is chosen according to the binomial distribution, with each chip and suspended stripline being one quarter wavelength long. The chips are glued into shallow slots between the waveguides, spaced at quarter wavelengths along the waveguides. The design parameters of the coupler are shown in table II, and the HFSS simulated performance in fig. 12. This design of coupler gives excellent return loss, directivity and insertion loss, while avoiding the difficulty of machining narrow and deep slots in the split mixer block.

The astronomical signals are coupled into the mixer block via corrugated horns mounted to waveguide flanges on the mixer block, while the LO signals are coupled via drilled, smooth-walled horns. The IF outputs from the mixer blocks are connected to commercial bias tees before being amplified by the first stage IF amplifiers. The cryogenic first stage IF amplifiers are $3-13\,\mathrm{GHz}$ InP LNAs supplied by Sander Weinreb at Caltech. They have excellent measured performance at $20\,\mathrm{K}$

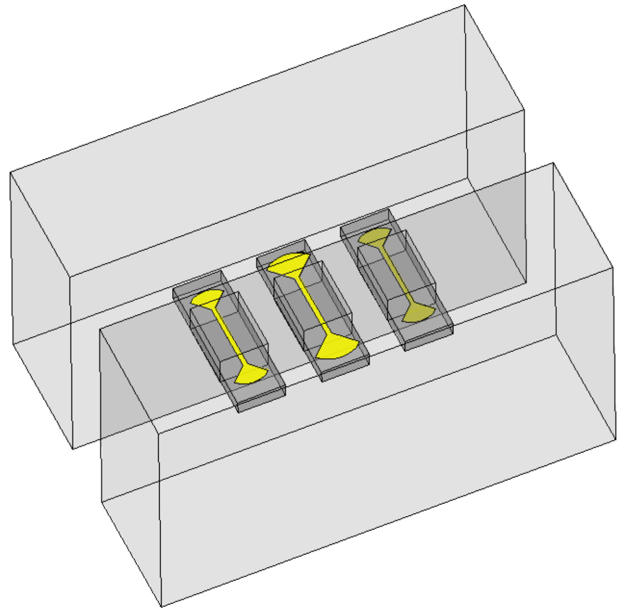

Figure 11. HFSS model of the waveguide directional coupler. The quartz chips (dark grey) are supported in shallow slots in the waveguide wall (light grey). 3 radial probes couple power between waveguides via suspended stripline.

Table II
DIMENSIONS OF THE WAVEGUIDE DIRECTIONAL COUPLER

Waveguide size	WR-4
Coupler spacing	$350\,\mu$m
Waveguide slot width	$200\,\mu$m
Waveguide slot height	$130\,\mu$m
Coupler chip thickness	$65\,\mu$m
Coupler chip width	$190\,\mu$m
Coupler chip length	$600\,\mu$m
Stripline width	$20\,\mu$m
Stripline length	$275\,\mu$m
Outer probe radius	$100\,\mu$m
Inner probe radius	$130\,\mu$m

over > 10 GHz bandwidth, which should be slightly improved on further cooling to 4 K.

D. LO system

Two 180° phase-switched LO signals are coupled into the two SIS mixers blocks via smooth wall horns on each of the mixer blocks and on the LO sources. The feed horns on the mixer blocks are coupled through two windows on the top of the cryostat via two Gaussian beam telescopes to the LO sources mounted on the side of the cryostat (fig. 13).

The LO signals are generated by two $195 - 260$ GHz multiplied LO sources from Radiometer Physics GmbH, with a multiplication factor of 18 and an output power level of $200\,\mu$W with ± 3 dB flatness across the LO band. Both LOs are driven by a single $10.8 - 14.5$ GHz synthesizer. To provide the required 180° phase shift between the two LO signals, the

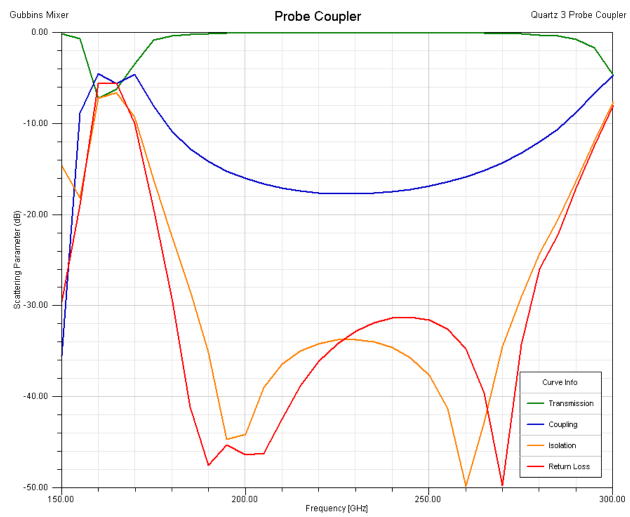

Figure 12. HFSS simulation of the LO directional coupler.

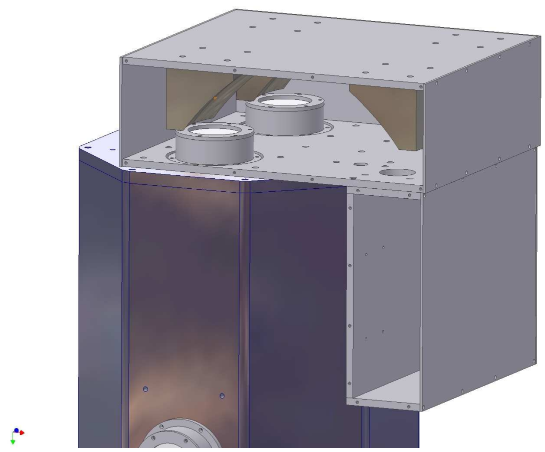

Figure 13. CAD model of the LO box and injection optics on top of the GUBBINS cryostat. The two RPG LO multipliers are housed in the box on the right, and coupled into the windows on top of the cryostat via two Gaussian beam telescopes.

input to one (or both) multiplier chains will be phase switched by a 10° Schiffman phase switch.

We also intend to investigate 180° phase switching the SIS receivers by switching the bias voltage of the SIS mixers from the positive to negative side of I-V curve. Since SIS mixers have antisymmetric I-V characteristics, switching the direction of the bias voltage changes the sign of the down-converted signal.

We are also working in collaboration with the Millimetre Technology Group at Rutherford Appleton Laboratories who are developing phase-locked photonic LO sources for use in SIS receivers [7]. These have the potential to greatly simplify the LO injection scheme of GUBBINS by providing individual phase switched LO sources for the SIS mixers, directly coupled to mixer blocks inside the cryostat.

E. IF chain

The IF signals from the cryogenic LNAs are then further amplified and individually processed before entering the correlator. The latter stages of IF amplification are provided by a number of gain blocks, each of which uses two Hittite HMC462LP5 $2 - 20\mathrm{GHz}$, $13\,\mathrm{dB}$ cascadable amplifiers in surface mount packages. These gain blocks show excellent performance for a relatively low cost device, with a noise figure of $3.5\,\mathrm{dB}$ at room temperature. The noise of these amplifiers can be significantly improved by cooling, and we have successfully measured noise temperatures below $80\,\mathrm{K}$ for these amplifiers at $4\,\mathrm{K}$. Although we have plenty of gain available from the cryogenic LNAs, the first gain block will be mounted on the $40\,\mathrm{K}$ stage of the cryostat, to ensure that the noise figure of the first of these gain blocks has minimal effect on the overall system noise.

As well as being amplified, the IF signals are also bandpass filtered and have slope compensation applied across the IF band. The final step before correlation is to apply path compensation to the signal to remove the path delay introduced by scanning the two antennas of the telescope. The path compensator is made up of seven time delay switches, providing 2.5, 5, 10, 20, 40, 80 and $160\,\mathrm{mm}$ of path compensation, and made up of differential lengths of microstrip line switched by Hittite HMC547 $0 - 20\,\mathrm{GHz}$ FET surface mount packaged switches.

F. Correlator and data acquisition

The IF signals from the two antennas are combined in an analogue correlator, developed at Oxford in collaboration with Andrew Harris at University of Maryland. The correlator is a 16 lag complex Fourier transform correlator, with the full 2-20 GHz bandwidth being processed simultaneously. The architecture of a single-sideband version of the correlator is shown in Fig. 14.

The correlator cross-correlates the IF signals from the two antennas at discrete time delay steps, forming both real and imaginary parts of the cross-correlation. A sideband separating version of the correlator, capable of working with double-sideband receivers is made by duplicating the single-sideband version but applying the quadrature split to the IF signal from the other antenna, thus forming all linear combinations of IF signals. Applying a discrete Fourier transform to the set of lag data gives two independent complex power spectra for each of the receiver sidebands.

For each half of the double-sideband correlator, one half of IF signal from one antenna is split in a commercial quadrature hybrid, with other split in phase using a Wilkinson power divider, before being fed to two 16 lag correlator boards. The two signals on each board are then split sixteen ways using Wilkinson power divider trees before they are combined and detected by Gilbert Cell multiplier MMIC chips. The Wilkinson power dividers are a seven-stage design fabricated on alumina with a $50\,\Omega/\square$ resistive sheet used to define the resistive elements. These dividers show excellent performance from $1.5 - 23\,\mathrm{GHz}$.

Gilbert Cell multiplier MMICs are used to both combine the two IF signals and to detect the combined signal. These devices (Fig. 16) were developed by Andrew Harris at University of Maryland and Steve Maas at Nonlinear Technologies

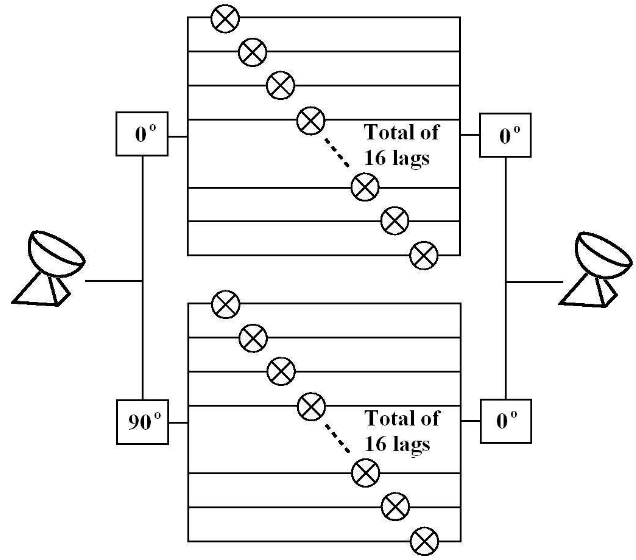

Figure 14. Architecture of one half of the GUBBINS $2 - 20\,\mathrm{GHz}$ analogue complex correlator. The other half is duplicated, but with the $90°$ phase shift applied to the signal from the other antenna, allowing the cross-correlations for both receiver sidebands to be obtained.

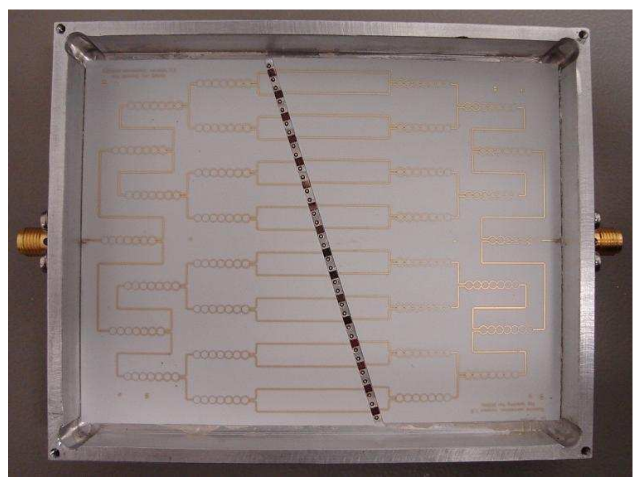

Figure 15. The prototype GUBBINS correlator board. Signals from each antenna are fed from the SMA connectors at each end of the board, and divided 16 ways in the Wilkinson power splitter trees, before being delayed in the lengths of microstrip and combined and detected in the multiplier chips along the centre of the board.

Inc. [8]. These devices provide both the sum and difference measurements of the combined signals, each replacing two power splitters, a $180°$ phase shift and two detector diodes in a conventional diode detector correlator [9].

The full correlator board is fabricated on two wafers of alumina, with the multiplier chips being mounted between the two boards (figs. 15, 16). The aluminium box is used as the ground plane for both the microstrip boards and the multiplier chips. Each multiplier chip is biased and read by two pins inserted through the back of the correlator box and bonded to the multiplier chips.

The first prototype 16 lag correlator board has now been fabricated and tested [10]. The frequency response, lag spacing uniformity and required power input are shown in figs. 17, 18

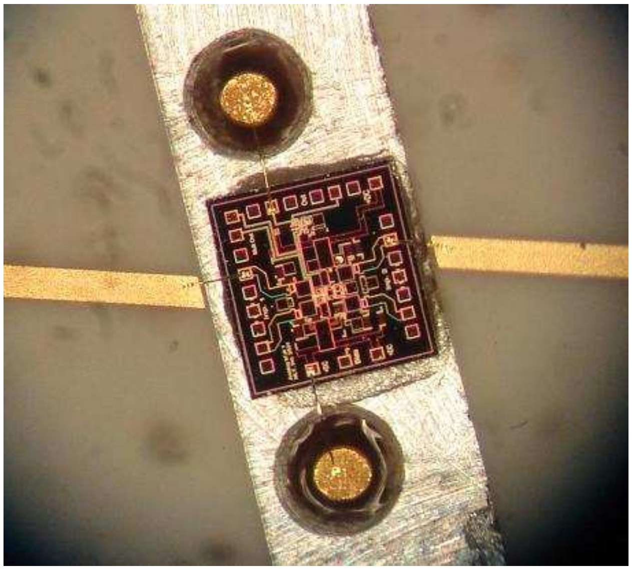

Figure 16. Close-up of a Gilbert Cell multiplier chip in the GUBBINS correlator.

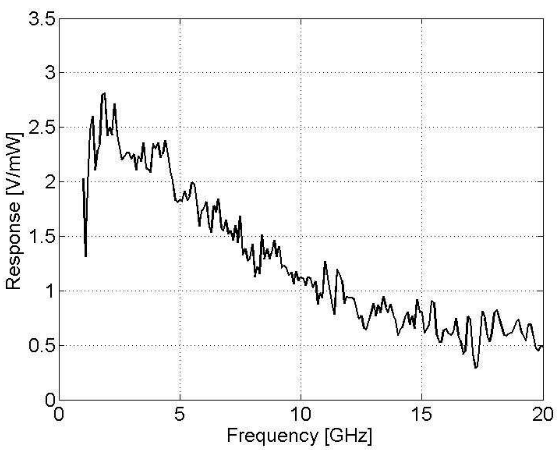

Figure 17. Frequency response of the prototype GUBBINS correlator board.

and 19.

The multiplier chips are read by low noise amplifiers and an A-to-D conversion board developed by the Oxford Central Electronics Group. This board uses 2.8 MSps ADCs feeding an FPGA processor that demodulates the phase switching of the signals and provides a USB output to the data acquisition computer. The required readout boards are now in production at Oxford (fig. 20).

IV. Conclusions

We are building a prototype single-baseline mm-wave heterodyne interferometer to demonstrate high brightness sensitivity mm-wave interferometry. This instrument will accommodate many of the new technologies we are currently developing in Oxford, particularly ultra-wide IF band SIS mixers, ultra-wide band analogue correlators and phase switched photonic LO sources.

The instrument is in the middle of construction, with prototypes of the SIS mixers, IF system and correlator having

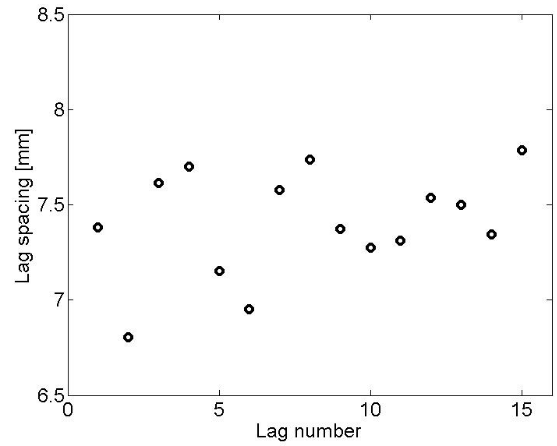

Figure 18. Lag spacings for the 16 lags on the prototype GUBBINS correlator board.

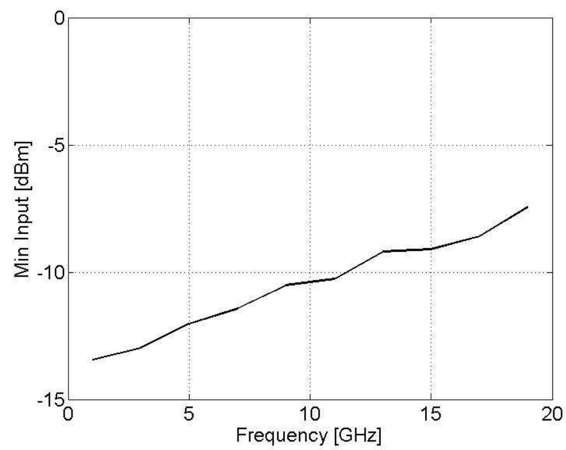

Figure 19. Required input power for the GUBBINS correlator.

been tested. The GUBBINS cryostat and optics are being assembled, and final versions of SIS mixers, LO system, correlator and read-out are currently being produced.

There is a niche for a future mm-wave interferometer with exceptional brightness sensitivity and wide field of view, complementary to ALMA and large mm-wave single dish telescopes, with key science goals of following up on the large numbers of S-Z clusters detected by current surveys, and for wide field imaging of faint extended continuum sources over wide frequency ranges. GUBBINS is intended to be an initial proving ground for the technology required for such an instrument.

Acknowledgements

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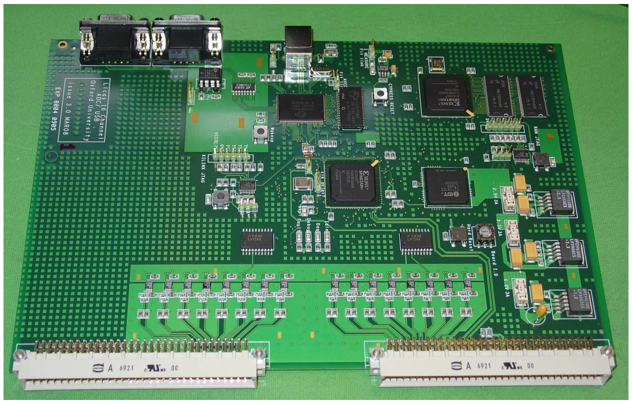

Figure 20. A GUBBINS correlator readout board. Signals from the correlator are read via the backplane connectors at the bottom, before being filtered and amplified in the lower section of the board. The signals are then digitised and processed by the FPGAs in the centre of the board, and then sent to the telescope control computer via the USB connection at the centre top of the board.

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