

# Heterodyne spectrometers with very wide bandwidths

A.I. Harris

Department of Astronomy, University of Maryland, College Park, MD 20742, U.S.A.

## ABSTRACT

New astronomical and remote-sensing instruments require microwave spectrometers with modest spectral resolution over many gigahertz of instantaneous bandwidth. Applications include millimeter-wave searches for distant objects with poorly known redshifts, submillimeter and far-infrared observations of Doppler-broadened spectral lines from galaxies, and observations of pressure-broadened atmospheric lines.

Wide bandwidths and the consequent stability requirements make it difficult to use general-purpose receiver and spectrometer architectures in these applications. We discuss analog auto- and cross-correlation lag spectrometers that are optimized for these observations. Analog correlators obtain their wide bandwidths by a combination of transmission line delays and direct voltage multiplication in transistor or diode mixers. We show results from a new custom transistor multiplier with bandwidth to 25 GHz. Stability becomes increasingly important as bandwidths broaden. We discuss system requirements for single-dish correlation radiometers, which have intrinsic high stability, and present results showing that analog cross-correlators are suitable backends for these receivers.

**Keywords:** Radio astronomy, spectroscopy, spectrometers, correlators

## 1. INTRODUCTION

As a rule of thumb, astronomical heterodyne spectroscopy is appropriate whenever measuring detailed line profile information is necessary at millimeter through long far-IR wavelengths. Observations of line emission over wide bandwidth is important, particularly at these wavelengths, as this is where galaxies emit the bulk of their line and continuum luminosities. Some of the key targets for wide bandwidth spectroscopy with moderate to low resolution are interacting ultraluminous galaxies in the local universe, young galaxies in the era of star formation, the cosmic microwave background, and pressure-broadened lines from planetary atmospheres. Line surveying to characterize the chemical state of molecular cloud cores is a related application that profits from high spectral resolution over wide bandwidths. Below, we first discuss some research topics that currently suffer spectrometer technology limits, then describe the state of wideband analog correlators, and finish with a discussion of correlation techniques for broadband spectroscopy.

### 1.1. Observations of extragalactic submillimeter lines

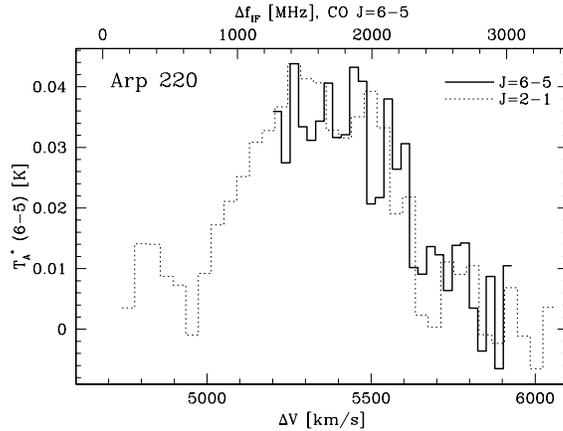
Scaling by the Doppler effect requires an increase in bandwidths as signal frequencies increase from the millimeter-wave band. Submillimeter and far-infrared observations of external galaxies can easily require bandwidths of several gigahertz since the linewidths are constant in velocity and scale linearly with frequency:

$$\Delta f = f_{line} \frac{\Delta v}{c} . \quad (1)$$

Figure 1 is a striking example of this effect, a 690 GHz spectrum of the ultraluminous galaxy Arp 220 made with the WASP analog lag spectrometer. The top scale in the figure shows over 3 GHz of bandwidth (the front-end receiver limited the bandwidth for this measurement), emphasizing the broad bandwidths necessary to observe the warm material in the nuclei of forming galaxies from submillimeter CO lines. Observations of far-IR fine structure lines from galactic disks and nuclei demand bandwidths between 10 and 20 GHz.

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Further author information: (E-mail: harris@astro.umd.edu, Telephone: 301-405-7531



**Figure 1.** Spectrum of the ultraluminous galaxy Arp 220 from the WASP spectrometer at the Caltech Submillimeter Observatory. The light line is the spectrum in the  $CO J = 2-1$  transition using the facility receiver. The heavy line is the  $CO J = 6-5$  line using the SURFER 690 GHz extragalactic receiver.<sup>1</sup> The bottom scale is velocity; the top scale is IF frequency for the  $J = 6-5$  line.

## 1.2. Observations of molecular and atomic lines from high- $z$ objects

Observations of spectral line emission from distant objects probes the Universe in the  $z = 2-4$  era of galaxy formation. Wideband spectrometers with moderate resolution are necessary for this task: wideband because the exact wavelengths (redshifts) of these distant objects are uncertain, and moderate resolution because dynamics within the galaxies Doppler-broaden the lines to approximately  $200 \text{ km s}^{-1}$ . Spectrometers which cover as much bandwidth as possible with a resolution between one and two thousand are therefore well matched to detecting the lines. Matching spectrometer bandwidth to millimeter-wave amplifiers is a sensible goal, implying a spectrometer with 25 to 30 GHz of bandwidth. Several hundred spectral channels provides a good match to linewidths for detection experiments, with resolution a few times higher necessary for measuring source dynamics to provide physical state and mass information.

Search spectrometers are very sensitive to low-level baseline structure that can mimic line detections. This places very tight constraints on spectrometer power linearity when the spectrum is synthesized from multiple sub-bands that are stacked in frequency. Architectures with as few sub-bands as possible are advantageous.

## 1.3. Coarse-resolution spectrometers for CMB interferometers

Interferometers, with their superior stability and ability to “resolve out” the large scale structure in the CMB signal, play an increasing role in imaging fine structure in the CMB, including the clearest detections of the Sunyaev-Zel’dovitch decrement toward the centers of galaxy clusters. The next step is detailed observations of polarization in the Cosmic Microwave Background to constrain models of the formation of the Universe. Some spectral resolution is necessary to preserve the field of view in compact arrays: the fractional bandwidth of the detection channels must be smaller than the antenna diameters divided by the shortest baselines. In contrast to the CBI and DASI interferometers, which array 1 GHz correlators in a filter bank configuration,<sup>2</sup> the AMiBA and AMI interferometers will use analog lag spectrometers as cross-correlators over the entire observing band.

## 1.4. Observations of planetary atmospheres and remote sensing of the Earth’s atmosphere

Remote sensing of atmospheres also demands wide instantaneous bandwidths. Observations of line shapes and intensities probe the pressure, temperature, and chemical stratification structure of atmospheres. Collisions between molecules in planetary atmospheres broaden the lines to a frequency width  $f \approx 2t_c$ , where  $t_c$  is the time between collisions. In the lower, denser parts of the atmospheres (tropospheric pressures for the Earth),

linewidths are consequently many gigahertz wide. Species at lower pressure (mesosphere and stratosphere for the Earth) have narrower linewidths set by their thermal Doppler motion. At present, most atmospheric sounding is made with a few narrow channels strategically placed within broad spectral lines. Broadband spectrometers with tens of spectral channels can separate multiple physical components from each other and from the broadband quasi-continuum contributions to the spectrum. Precisely measuring the water vapor column in the Earth’s atmosphere is also an important step in correcting for electrical pathlength fluctuations above the elements of radio and millimeter-wave interferometers; linewidths of 8 to 10 GHz are useful here.

### 1.5. Line surveys

Spectral surveys map the chemical and physical structure of molecular clouds. Line widths from a given cloud are relatively narrow and are easy to measure with conventional spectrometers, but it is useful to cover as many lines as possible to increase observing efficiency and reduce relative calibration errors. Line survey spectrometers therefore benefit from having very large numbers of spectral channels. Since they do not have demanding requirements on broadband low-level baseline structure, “stacking” individual spectrometers in frequency is usually practical.

## 2. WIDEBAND SPECTROMETERS

Spectrometers fall into two classes: those that measure spectra directly in the frequency domain (e.g. filter banks, acousto-optical spectrometers), and those that measure in the complementary time lag domain (lag correlators). A recent review<sup>3</sup> contains a more detailed discussion of the different wideband spectrometer technologies than this brief summary.

Filter banks can cover arbitrarily large bands at the cost of electrical and mechanical complexity. They tend to be physically large and massive, but are the only spectrometer that can have sparse sampling and unequal channel widths. Acousto-optical spectrometers currently cover bandwidths to about 1.5 GHz with of order 1000 spectral channels in a very compact package that requires little power. A single acousto-optical deflector crystal can have several transducers that convert the microwave signal to acoustic waves. This enables multiple spectrometers to share the same deflector cell and optics, further reducing the size of a spectrometer package.<sup>4</sup> Limits on bandwidth and resolution come from the optically active crystal that deflects an infrared or optical laser beam with frequency. BAe Systems is developing deflector material with a goal of a 3 GHz bandwidth under contract to the University of Cologne.<sup>5</sup> Acoustic attenuation in the crystal limits the physical length of the wave, and therefore spectral resolution.

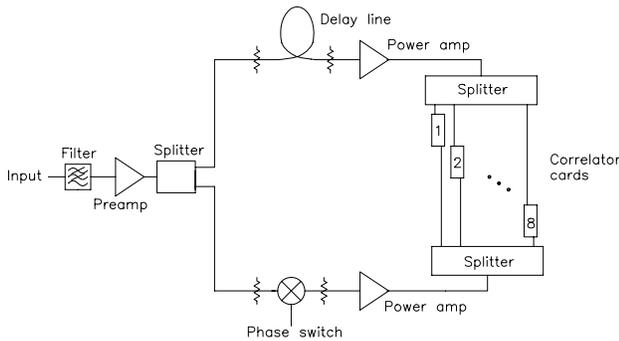
Correlators obtain spectra with the Fourier transform relationship between a signal’s correlation function and power spectrum:

$$S_{xy}(f) = \int_{-\infty}^{\infty} R_{xy}(\tau) \cos(2\pi f\tau) d\tau , \tag{2}$$

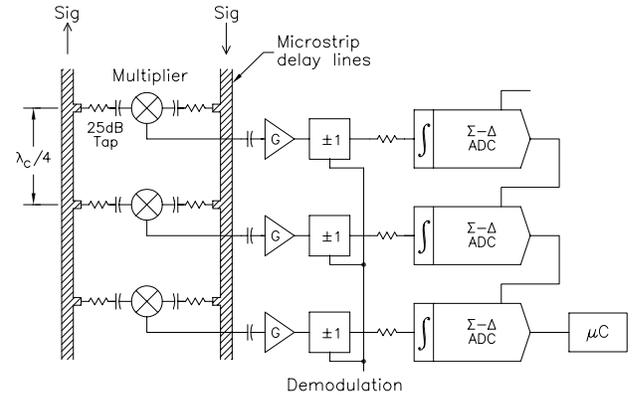
where  $S_{xy}(f)$  is the cross-power spectrum as a function of frequency  $f$  and  $R_{xy}(\tau)$  is the signal’s cross-correlation function as a function of time delay (lag)  $\tau$ . A simple receiver on a single-dish telescope has only one output voltage  $v_x$ , and an autocorrelator spectrometer is then appropriate:

$$R_{xx}(\tau) = \langle v_x(t) \cdot v_x(t + \tau) \rangle . \tag{3}$$

The most common correlator architecture is digital: a fast analog to digital converter samples the input signal voltage, with high-speed digital hardware performing the time shifting, multiplying, and accumulating implicit in equation (3). The bandwidth limit for a single spectrometer is in the analog to digital converter (sampler), which must digitize the signal at a frequency at least twice the input bandwidth. The digital logic need not have a correspondingly high clock rate, as the digital data stream can be divided in different ways and farmed out to slower logic that processes many subsamples in parallel. The fastest samplers that are currently commercially available clock at about 2 GHz, so single correlators have bandwidths of about 1 GHz. Configurations with multiple samplers and processing logic are reported to reach bandwidths of 2.5 GHz.<sup>6</sup>



**Figure 2.** Schematic overview of WASP2’s overall signal path. The autocorrelation function is produced by splitting the input into two streams and cross-correlating these signals. Eight correlator cards, appropriately spaced in time by cable delays, have a total of 128 lags.



**Figure 3.** Schematic view showing a section of the “ladder” of multipliers within WASP2 and the low-frequency signal processing electronics. Sections of microwave stripline provide propagation-time delays between fast transistor multipliers.

Analog correlators bypass the fast sampler problem by shifting all high-speed processing to analog electronics. Correlators of this type have been built at times starting in the mid-1960s.<sup>7</sup> Advances in digital systems now makes an analog approach suitable for applications requiring bandwidths of a few to a few tens of gigahertz and moderate to coarse resolution. Analog processing needs little power compared with high-speed digital processing, and analog correlators fall in the compact and low-power class. We now summarize current performance and near-term future developments for wideband analog correlator spectrometers.

### 3. ANALOG CORRELATION SPECTROMETERS

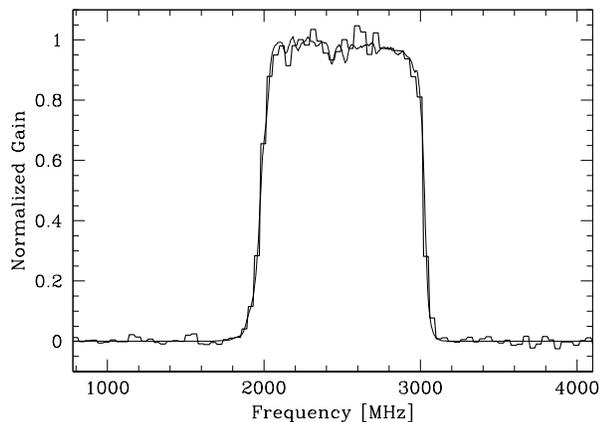
#### 3.1. The WASP Analog Correlator

The WASP correlator<sup>8</sup> is the first of the modern analog correlators to provide good performance over multi-gigahertz bandwidths. Its construction is very simple: tapped microstrip transmission lines provide the time delays  $\tau$ , commercial transistor multipliers form the product of the two input voltages  $v(t)$  and  $v(t + \tau)$ , and low-frequency electronics integrate the multiplier output to provide the time average.

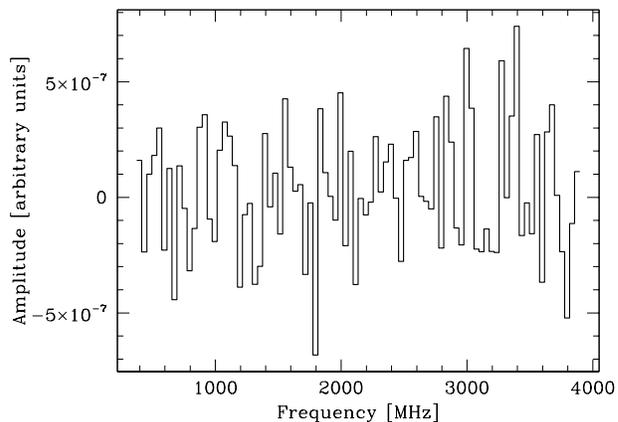
The WASP family of spectrometers are cross-correlators, but easily operate with the inputs connected together to make an autocorrelation spectrometer. Figure 2 is an overview schematic signal path for a WASP autocorrelator. A splitter creates two counter-propagating signal streams that correlate at a series of 128 different time lags. Since the autocorrelation function of a real function is symmetric in time delay (lag), measurement of only the positive lags is necessary; an additional cable delay in one arm puts the zero-delay point just within one end of the correlator string. The multipliers make vector voltage measurements; a  $180^\circ$  phase switch in one microwave signal path produces an AC product signal at the multiplier output. Phase switching at 1.5 kHz reduces the multiplier’s  $1/f$  noise to a suitable level. Phase modulation is very efficient because the signal is always present at the multipliers.

Mechanical and power balance considerations make a single long string of multipliers undesirable, so we break the delay line into staggered shorter segments (Fig. 2, right side). Practical considerations suggest grouping lags and multipliers in sets of sixteen, with each set on a separate circuit board. Eight such 16-lag boards, fed from eight-way splitters, produce WASP’s overall series of 128 lags. The splitters isolate the modules and keep power variations from one end of the board to another to a minimum.

The microwave circuit on each correlator board (Figure 3, left side) contains a ladder of analog multipliers which simultaneously sample the input signal at different positions (delays) along microstrip transmission lines. Nyquist sampling requires measuring the signal along the transmission line at spacing  $v_p/2B\nu_{max}$ . Chip resistors between the line and multiplier input provide  $-24$  dB nominal coupling at each tap. The analog multipliers are



**Figure 4.** Spectrum of a noise source through a 2000–3000 MHz bandpass filter. For comparison, the light line is the filter’s response measured with a network analyzer.



**Figure 5.** Spectrum of a laboratory noise source after a 40 hour chopped and nodded (double beamswitched) integration. The spectrum may show a slight tilt, but there is no sign of the system bandpass.

sensitive commercial monolithic microwave integrated circuit (MMIC) transistor mixers with the same classical Gilbert cell multiplier circuit<sup>9</sup> that are in audio-frequency multiplier chips.

WASP contains simple low frequency circuitry (Figure 3, right side) at each of the multipliers’ IF outputs. A hardware demodulator recovers the phase-modulated total power signal. An amplifier and DC offset convert the bipolar autocorrelation function to a unipolar current for analog-to-digital conversion. This current accumulates for half a phase-switch time in a charge-integrating analog to digital converter (ADC). We switch the polarity of the phase switch each half cycle (double phase switching), then digitally demodulate the signal to restore the correlation function’s bipolar range. WASP’s circuit boards are four layer hybrids of microwave and standard circuit board materials. This construction accommodates all components on a 100 mm high board that fits in a standard rack mount chassis. The integrated microwave and low-frequency electronics layout allows completely automated board assembly by pick-and-place machines.

Transforming the correlation function to recover the spectrum is slightly more complicated than making a plain Fourier transform because the signal is not sampled at perfectly regular intervals. Although the mechanical spacing between the microwave signal taps along the transmission line is precisely defined by lithography, frequency-dependent component variations cause some jitter in the electrical delays between multipliers. The electrical spacing is very stable in time and we correct for irregular sampling in software by establishing the spectrometer’s response to monochromatic signals at known frequencies, then expanding the astronomical input signal on these measured “basis” functions.<sup>8</sup> New calibration data sets are only needed when the spectrometer is dismantled and to characterize the spectrometer at substantially different physical temperatures.

Laboratory measurements are severe tests of particular aspects of spectrometer performance. Figure 4 shows the spectrum of a noise diode filtered by a 1000 MHz bandwidth filter with a network analyzer measurement of the filter for comparison. The small scatter around the network analyzer measurements are multiplicative fixed pattern structure caused by small phase errors in the calibration. This structure, about 0.5% of the peak values, only affects the spectrometer dynamic range since it is constant in shape and scales with input signal power.

Fixed-pattern structure subtracts away well in a differential measurement, the usual situation for astronomical observations. Offset drift is usually the dominant stability problem for analog systems, but is largely removed by the layers of internal phase switching within WASP2. Allan variance characterization of spectrometer stability shows white noise for chop frequencies faster than  $\sim 0.5$  Hz. Figure 5 shows the spectrometer’s high stability with a 40 hour observation of a laboratory noise source with nominally constant power at the normal operating power level. The spectrometer software processed the signals as if they were chopped and

nodded (beamswitched). The spectrum is zero within noise, as it should be, and most importantly, neither passband structure from the noise source nor from the microwave components appear in the spectrum.

### 3.2. Broadband multipliers

The primary practical limit on analog correlator bandwidth lies in the multiplier device. While nearly any nonlinear device can be used as a multiplier, efficiency, stability, and linearity have made diode power detector circuits and Gilbert cell transistor multipliers popular multiplier circuits.

#### 3.2.1. Diode multipliers

Many wideband continuum correlators use diodes operating in the small-signal power detector (square law) regime. Diodes have wide bandwidths and sufficiently low internal noise to operate at low power levels. This input power must be small enough that the diodes are good square-law power detectors and are not envelope or multi-term detectors.<sup>10</sup> The simplest way to produce a product is to sum two input voltages and then square, obtaining the cross-product as well as the total power in each signal:

$$(v_1 + v_2)^2 = v_1^2 + v_2^2 + 2v_1v_2 . \quad (4)$$

A single unbiased diode multiplier of this type is inefficient because it provides output for only half of the possible signal combinations (i.e. ++ and -- but not +- and -+, or vice versa). The most common circuit is therefore a balanced rectifier (balanced mixer), two diodes preceded by a 180° hybrid, a configuration that retains products from all polarity combinations:

$$(v_1 + v_2)^2 - (v_1 - v_2)^2 = 4v_1v_2 . \quad (5)$$

A side benefit of this circuit is some suppression of the total power terms. In practice, this suppression, while helpful, must be supplemented by phase switching to fully remove DC offsets from the cross product. Another variant for multipliers is a doubly-balanced mixer ring.<sup>11</sup> A general problem for these circuits is providing some degree of impedance matching across wide bandwidths to the high-impedance unbiased diodes. Adding parallel matching resistors is one solution, as is biasing the diodes. Biasing reduces the impedance but adds complexity, circumventing much of the advantage to using zero-bias diodes.

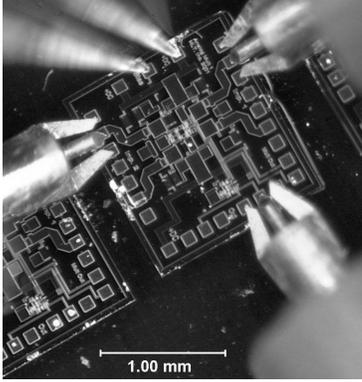
Accepting the complexity of a DC bias allows a single diode to be DC biased to a voltage larger than any product voltage. In addition to providing good sensitivity for all input polarity combinations with a single diode, the bias increases sensitivity and may improve band flatness by reducing the diode impedance for a much better match to the embedding circuit. A multiplier of this type is being tested in a prototype wideband lag correlator for the 50 m LMT/GTM instrument.<sup>12</sup>

Physical size can be a problem for lag correlators that require many balanced multipliers. For broadband microwave applications the hybrid and connecting lines occupy an area of about  $(\lambda/4)^2$ , where  $\lambda$  is the wavelength at band center reduced by a factor of a few by the dielectric constant of the substrate. This size is of little consequence for a single continuum correlator, but becomes awkward for lag correlators that contain hundreds of multiplier circuits.

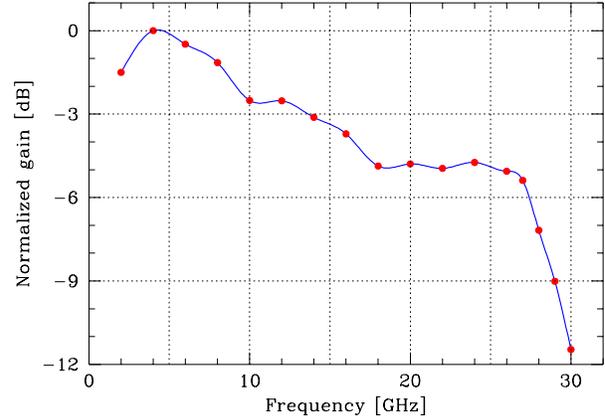
#### 3.2.2. Gilbert cell multipliers

The second type of multiplier is a transistor circuit that directly multiplies the two voltages without also detecting the total power. Many types of transistor mixers exist, but the Gilbert cell multiplier<sup>9</sup> is the most appropriate for this application.<sup>10</sup> A Gilbert cell contains a balanced pair of cross-connected transistor multipliers, a cascade in which one transistor modulates the gain of another transistor amplifier. The circuit topology essentially includes a 180° hybrid, so it computes products from all input polarities. The transistors in the cell must be well matched, so monolithic fabrication (monolithic microwave integrated circuit, or MMIC) is necessary for good performance at high frequencies. The simplest Gilbert cell circuit multiplies in four quadrants with an output of<sup>10</sup>

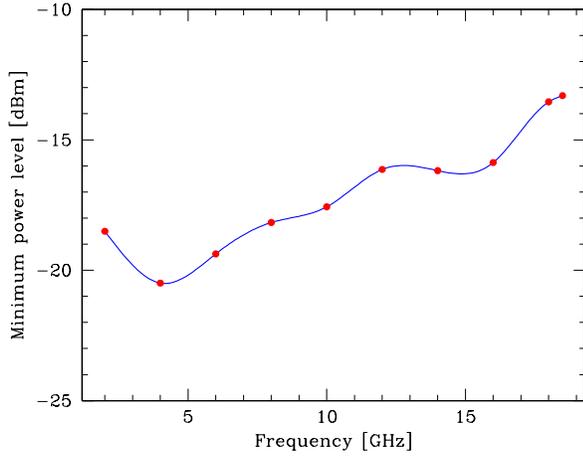
$$v_{out} \propto \tanh\left(\frac{v_1}{v_T}\right) \tanh\left(\frac{v_2}{v_T}\right) , \quad (6)$$



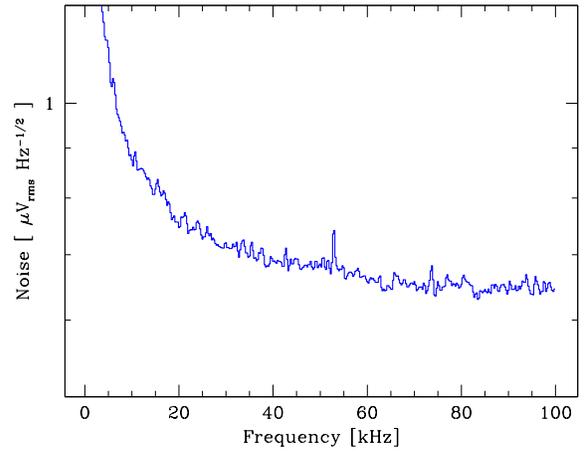
**Figure 6.** Image of a Gilbert cell multiplier MMIC being tested in the probe station.



**Figure 7.** Frequency response of the Maas wideband Gilbert cell multiplier MMIC. Dots represent actual measurements; the solid line is a guide for the eye.



**Figure 8.** Minimum input power level for the prototype multiplier from 2 to 18 GHz.



**Figure 9.** Low frequency multiplier output voltage noise spectrum.

which is reasonably linear,  $v_{out} = v_1 v_2$ , for transistor input voltages less than  $v_T = kT/q \approx 25$  mV. Operating with higher input voltages is useful and carries little penalty since the nonlinearity is often dominated by voltage swings in the mixer output circuit. Nonlinearities in these very reproducible integrated circuits are straightforward to correct in software if necessary.

Dr. Stephen Maas of Nonlinear Technologies, Inc.<sup>13</sup> has designed a Gilbert cell multiplier optimized for use in broadband astronomical correlators. Figure 6 is an image of a prototype multiplier MMIC during testing. The chip is about 1.5 by 1.7 mm in size and was fabricated by Global Communications Semiconductors, Inc. with approximately 70 GHz InGaP/GaAs heterojunction bipolar transistors (HBTs). Figure 7 shows the responsivity versus frequency for the chips: the 3 dB bandwidth runs from about 1 to 14 GHz, and the device works well (6 dB max. deviation) to 27 GHz. The peak responsivity is about 30 kV/W.

Obtaining devices with low noise was an initial concern, but measurement shows that the new multipliers have good performance for bandwidths well beyond 20 GHz. Internal device noise and responsivity sets a minimum input power level  $P_{min}$  for good integration efficiency<sup>14</sup> of

$$P_{min}(f) = \frac{3S_V\sqrt{B}}{R(f)}, \quad (7)$$

where  $S_V$  is the output voltage noise spectral density,  $B$  is the spectrometer bandwidth, and  $R(f)$  is the multiplier responsivity in V/W as a function of frequency. Figure 8 shows this minimum power level as a function of frequency for the new multipliers with typical responsivity and noise values and a 16 GHz bandwidth. This power level is very reasonable from dynamic range and systems points of view. Figure 9 is the multiplier's output noise density, showing that internal phase switching at about 30 kHz is adequate to move out of the  $1/f$  noise regime.

Power dissipation in the prototype chip is 265 mW at its design bias, but it is possible to operate with lower bias and 51 mW dissipation with the sacrifice of 1 dB of input dynamic range. Further test results are available in a series of informal memoranda.<sup>15</sup>

#### 4. MULTICHANNEL CORRELATION RADIOMETERS

Wideband spectrometers place significant demands on the overall system because the channel widths can be as wide or wider than continuum channel widths in conventional radiometers. Removing baseline structure with ad hoc fits to baseline shape becomes impossible once the lines fill a substantial fraction of the spectrometer bandwidth. Systems with broad bandwidth are especially prone to difficulties since systematic noise can more easily overwhelm radiometric noise. In a given integration time  $t_{int}$ , the fractional back-end power fluctuations  $\Delta P/P$  must be small compared with the radiometric fluctuations (first term in the square root of equation (8)), a task that becomes increasingly difficult as the bandwidth  $B$  increases:

$$\frac{\Delta T}{T_{sys}} = \sqrt{\frac{1}{Bt_{int}} + \left(\frac{\Delta P}{P}\right)^2}. \quad (8)$$

Baseline structure can easily come from small gain fluctuations, as the  $\Delta P$  term in equation (8) shows. A conventional (total power) radiometer has an output

$$v_{out} \propto G(T_{source} + T_{receiver} + T_{background}) \quad (9)$$

with large offset terms. A 1% gain fluctuation produces an offset of several kelvins for typical receiver and background temperatures. Mechanically chopping the beam between the source and a nearby reference position helps eliminate the grossest effects, but the differencing is still sequential and the amplifier gain may still fluctuate on timescales short compared with the chop. Correlation radiometers<sup>16</sup> continuously and simultaneously difference the power between two points on the sky, producing

$$v_{out} \propto G(T_{source} - T_{reference}). \quad (10)$$

Removing the receiver and offset temperature terms vastly reduces the sensitivity to gain fluctuations; in the ideal case a 1% drift now causes a small calibration error but does not introduce a large additional error.

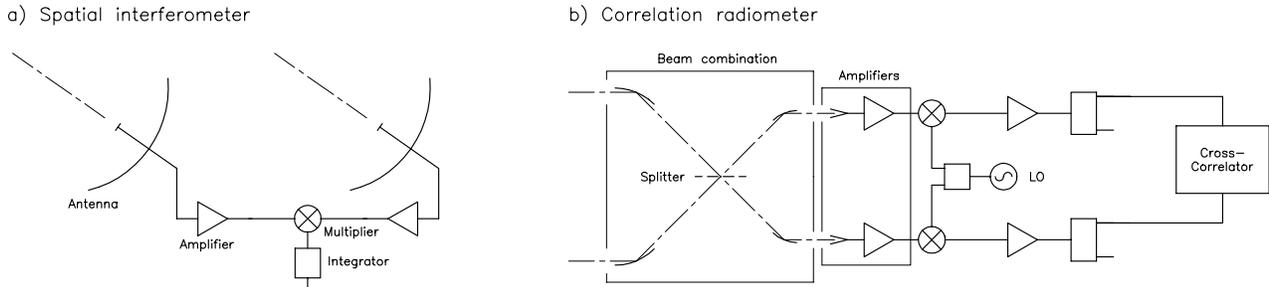
Fundamentally, correlation radiometers and interferometers obtain their stability by multiplying together signal *voltages* together in a device which produces the product of the two inputs: a linear multiplier such as those described above. Power detectors, in contrast, respond linearly to power, or the square of the voltage. Consider the time-averaged output voltage from a multiplier with two input source voltages  $s_m$  and two instrumental noise voltages  $n_m$ :

$$v_{out} \propto \langle (s_1 + n_1)(s_2 + n_2) \rangle = \langle s_1 s_2 \rangle + \langle s_1 n_1 \rangle + \langle s_2 n_2 \rangle + \langle n_1 n_2 \rangle. \quad (11)$$

By splitting the input signal between two amplifiers, the signal voltages are correlated but the amplifier noise terms are uncorrelated with each other and the signal. In this case all terms but the product term with signal information  $\langle s_1 s_2 \rangle$  average to zero, and instrumental instability largely drops out of the detection. A total power detection of the same signal yields

$$v_{out} \propto \langle (s_{in} + n)^2 \rangle = \langle s_{in}^2 \rangle + \langle n^2 \rangle + 2\langle s_{in} n \rangle, \quad (12)$$

containing substantial power from the detected noise term as well as the source signal power since only the last term averages to zero.



**Figure 10.** Schematic correlation detection systems: a) A spatial interferometer; b) A quasi-optical correlation radiometer.

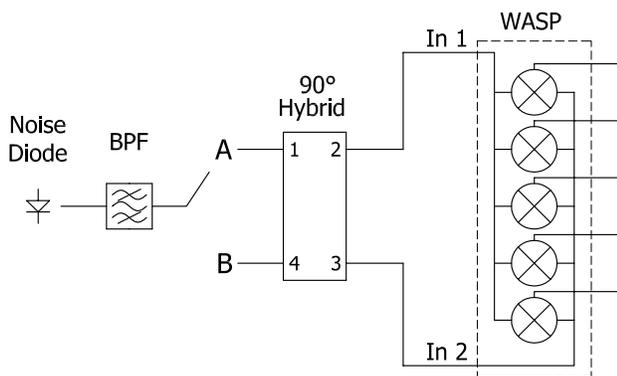
Figure 10 shows the complementarity of two types of correlation detection: a spatial interferometer and a correlation radiometer. A spatial interferometer derives its stability from the fact that the only signal that is correlated in the entire system is that from the source alone. Amplifier gains may fluctuate and add noise power to one branch, for instance, but that affects only this one branch of the signal path and not the common signal. The correlation radiometer is the complement of the spatial interferometer. It images two points in the focal plane instead of two patches in the aperture plane, and extracts the corresponding uncorrelated signal instead of the correlated signal. Figure 10 b) is a schematic sketch of a correlation radiometer showing the combination of signals from the source and reference positions as far upstream in the signal path as possible. In this example the combination is quasi-optical (see Predmore et. al<sup>17</sup> for a full discussion of a quasi-optical input hybrid), but any other type of hybrid may be used. Once the signals from the two positions are combined any subsequent gain or other fluctuations affect both signals equally and at the same time. The cross correlator uses the phase information added by the hybrid to produce the difference of the power at the source and reference positions. The correlator phase is set to cancel any correlated signal and retain the *uncorrelated* signal; the only uncorrelated signals in the system come from the two different focal plane positions.

Correlation detection differences the source and reference signals as rapidly as they can change, a timescale approximately equal to the reciprocal of the IF bandwidth. This differencing rate is in the microwave range, far beyond other electronic or mechanical possibilities, and makes correlation detection extremely stable. A correlation radiometer easily suppresses noise from  $1/f$  gain fluctuations in front-end or IF amplifier transistors, which have corner frequencies of approximately 10 kHz.

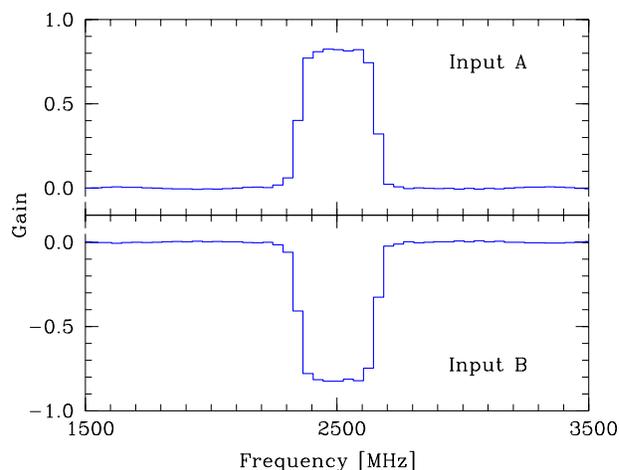
#### 4.1. Correlation spectrometers

Superior stability and efficiency are the reasons that single-channel correlation radiometers are used for continuum observations at centimeter and millimeter wavelengths. As the bandwidths of individual spectral channels increase, it is natural to extend the classic correlation receiver architecture to multiple spectral channels. A correlation architecture has two practical advantages in addition to the improved stability. First, it is a dual-beam system, with one beam always on the source while the other always views a reference position. In principle this gives correlation receivers a factor of two advantage in observing time over receivers that switch on and off the source, although the actual advantage is somewhat reduced by losses in the preliminary signal combination. Second, it is a dual-beam architecture that only requires a single cross-correlator instead of two separate total power spectrometers. This can be a substantial cost savings since spectrometers can be a substantial part of the overall system expense.

Figure 11 shows a simple laboratory correlation spectrometer setup for laboratory tests: a noise source, 300 MHz wide bandpass filter, hybrid, and a WASP2 correlator configured as a cross-correlator. Figure 12 shows the output spectra for signals fed alternately to the two inputs. As expected, the two spectra have opposite polarities: if the two inputs were beams on the sky the spectrum would indeed be the power difference between the two positions. Phase errors cause the low-level fixed-pattern structure in the baseline away from the “line.” Summing the two results in an nearly flat spectrum around zero with fixed pattern structure residuals of about 1% of the peak power. Beamswitching the telescope is still necessary to remove this structure and



**Figure 11.** Setup for correlation spectrometer test with a WASP cross-correlator.



**Figure 12.** A pair of correlation spectrometer spectra with the noise source (Figure 11) switched to inputs A and B.

multiplier gain drifts, but the overall system sensitivity to gain drifts before the multiplier is reduced by orders of magnitude.

An autocorrelator only needs to measure positive or negative lags because autocorrelation functions are symmetrical in lag. The reason for the symmetry is that the signal is real. WASP's internal phase calibration with a family of monochromatic signals at its input (sec. 3.1) also defines a general spectrometer phase: real signals have  $0^\circ$  phase shift with respect to the calibration signals, and imaginary signals have a  $90^\circ$  phase shift. An interesting effect of this calibration method is that the cross-correlation function can also be made pure real if the system is calibrated by a stepped-frequency signal at its input. All internal phase shifts are then common to the astronomical and calibration signals. While it is somewhat unusual to have a purely real cross-correlation function, there is nothing fundamental to prevent it. In this case the correlator can have half the number of lags of a fully complex correlator since measuring the imaginary component is unnecessary.

Comparing spectra taken in autocorrelator mode with those in Figure 12 verifies this prediction. Figure 11 indicates another way to understand this property, since the only difference between the autocorrelator and cross-correlator spectrometers is the hybrid. For an autocorrelator, the hybrid has one input and  $0^\circ$  shift between the two outputs (a fourth port is internally terminated and should have no power flow in the ideal case). The cross-correlator can use either a  $90^\circ$  or a  $180^\circ$  hybrid. In both cases there is a  $180^\circ$  phase shift between the outputs; the difference is in the distribution of the phase shifts relative to the input signal. In all cases calibrating at the hybrid's input eliminates any sensitivity to phase beyond that point.

If it is not possible to calibrate at the system input then a complex correlator sensitive to the real and imaginary components is necessary. A complex correlator is also necessary if the spectrometer itself has some intrinsic phase. Digital correlators have a definite phase relationship at their inputs since the Fourier transform must have knowledge of the lag with zero differential delay.

## 5. CONCLUSIONS

Spectroscopy over wide bandwidths is rapidly coming of age. It is now practical to build spectrometers that match or exceed the bandwidth of most front-end receivers. Wideband analog lag correlators are a relatively new implementation of an old idea that have the advantage of operation either as auto- or cross-correlators. Cross-correlation will become increasingly important in systems optimized for the efficient detection of wide, weak spectral lines from distant sources.

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