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HYBRID SPECTROMETER USER MANUAL

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I. Introduction

This document presents an overview of the NRAO-Tucson hybrid spectrometer. The goal of this discussion is to provide users with information about the features and instrumental effects of the hybrid spectrometer. Hopefully, this information will be useful to astronomers that plan to use the spectrometer and provide an introduction to engineers interested in the architecture. A second document provides more detailed information about the implementation of the instrument. The second document (called: "Technical Description of the Hybrid Spectometer") will be more technical, while this document will be more general.

A very general specification of the hybrid spectrometer is given in table #1.

Total bandwidth processed	2.4 GHz
Total corrlation lags (Effective lags)	2048 (1536)
Maximum resolution possible	2.44 KHz
Number of separate IF channels	1,2,4,8
Sampling rate (fixed)	100 MHz
Quantiation levels	3
Quantization degradation (SNR)	0.81
Observational modes	Position, Frequency, Beam, Total Power

Table 1 - Hybrid spectrometer specifications

II. Theory of Instrument

The hybrid spectrometer is classified as a hybrid because it combines an analog filter bank and digital correlator into a single instrument. The strengths of each approach are combined into a versatile and powerful spectrometer. This synergy of techniques also produces a substantial savings in total system cost. Naturally, this new instrument type has some unique problems. Hopefully, this discussion will provide information on the features and short-comings of this instrument and allow maximum utilization of its unique capabilities.

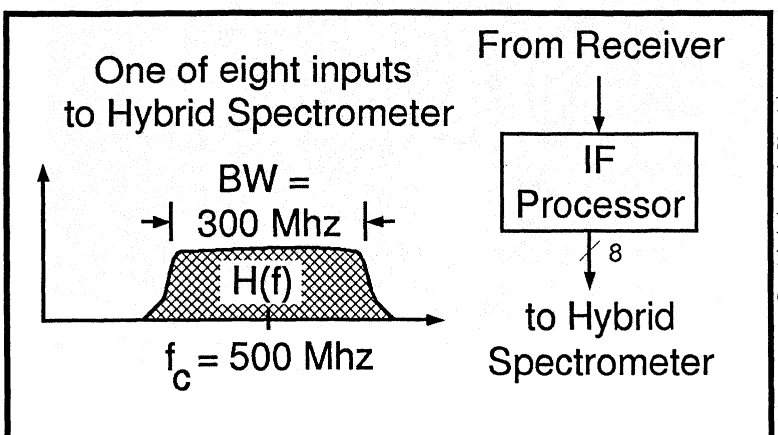


Figure 1 - Hybrid spectrometer input

The best source of general information on the subject of hybrid spectrometers is the original article by Weinreb[1]. Information about total power detectors in hybrid spectrometers is given by Dowd[2]. These two articles deal explicitly with hybrid spectrometers. However, there are a large number of articles on digital correlators and analog filter banks that can also provide useful information.

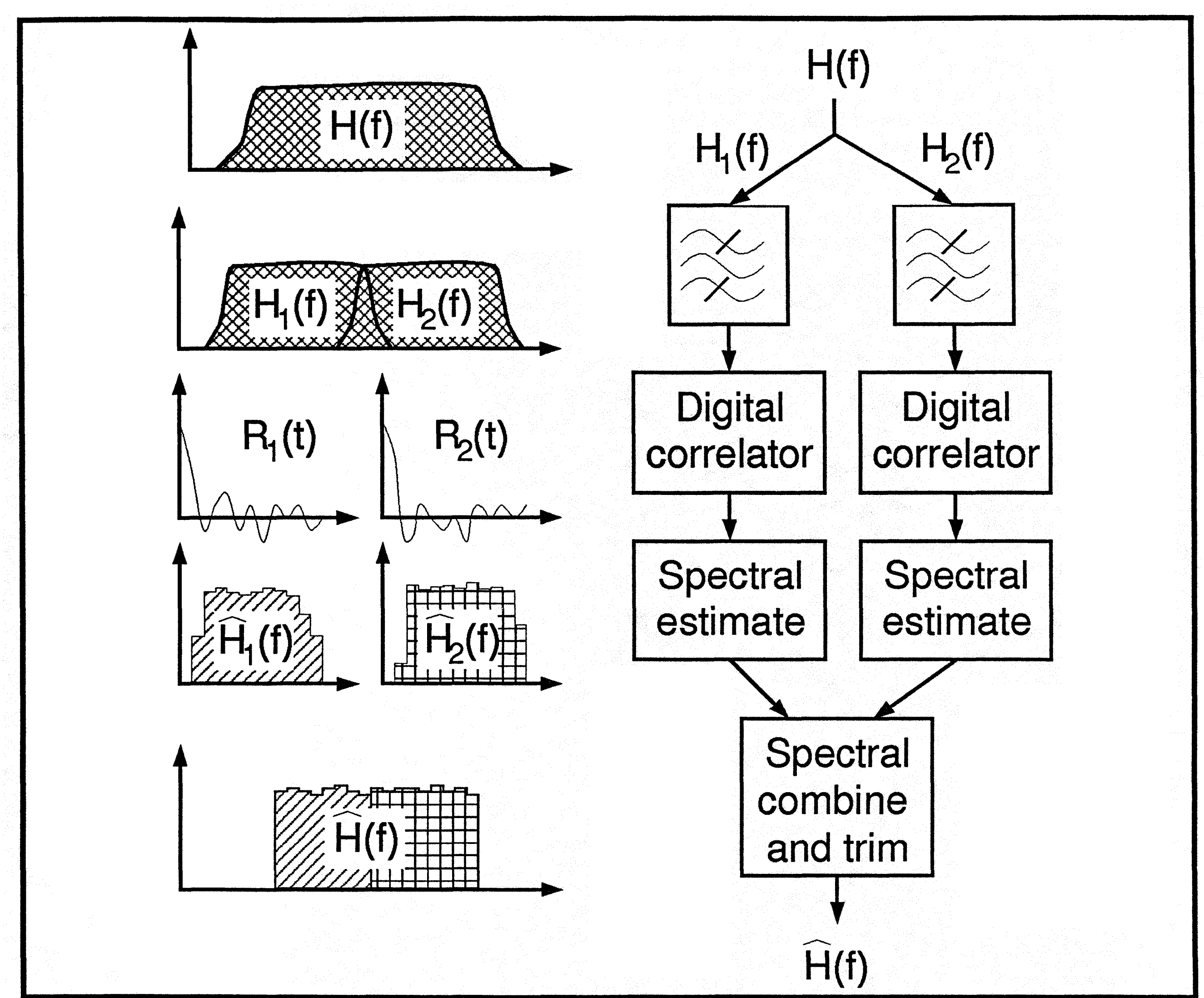


Figure 2 - Hybrid mode applied to 600 Mhz bandwidth

A. Analog Filter Bank

After receiving the astronomical signal, it must be downconverted to a reasonable frequency band. Downconversion occurs in three steps; first in the receiver itself and next in an instrument called the IF processor. The IF processor is an important aspect of the hybrid spectrometer instrumentation. However, for convince the IF Processor will be described in a separate document. The final downconversion takes place within the hybrid spectrometer proper..

After passing through the IF processor, the analog radio signal has a fixed bandwidth of 300 MHz and a fixed center frequency of 500 MHz. (See Figure 1) . The hybrid spectrometer/IF processor combination can handle up to eight of these 300 MHz IF channels. This allows processing eight-beam data (eight IF channels are used), dual polarizations (two IF channels are used) and 600 MHz bandwidths (two IF channels are used per beam or polarization). Control of the effective sky frequency is handled by the receiver and IF processor. Selection of bandwidths below 300 MHz is

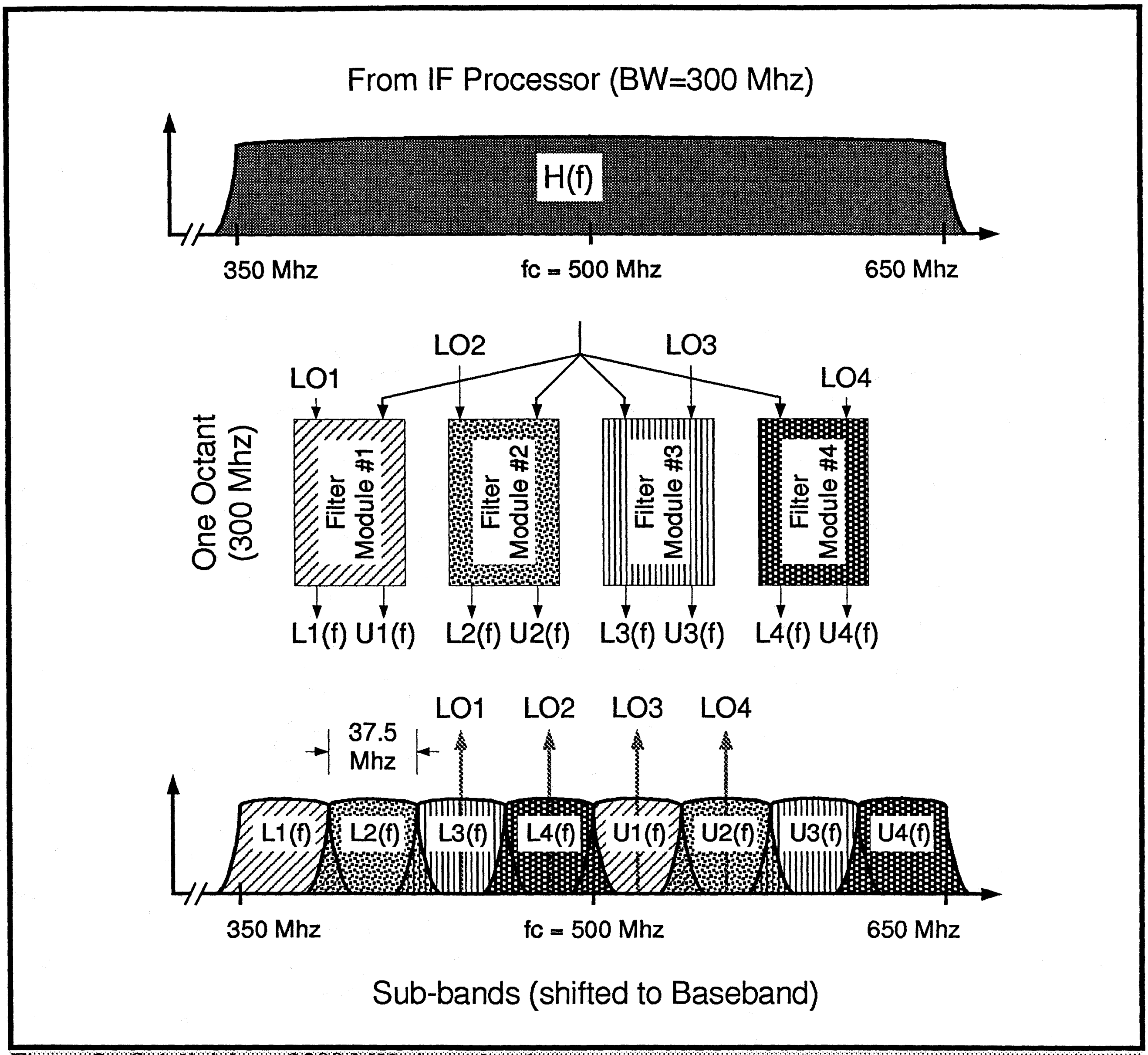


Figure 3 - Subdivision of 300 MHz input band.

performed within the hybrid spectrometer. Bandwidths of 600 MHz are achieved by presenting the hybrid spectrometer with two 300 MHz bandwidths. (See Figure 2). The effective center frequency of one band is shifted by the IF processor to create two 300 MHz bands offset to cover the full 600 MHz. After measuring the separate 300 MHz spectra in the spectrometer, the software combines the pieces (or sub-bands) to create the complete 600 MHz spectrum. This discussion illuminates the hybrid spectrometer's inability to perform complete 600 MHz processing with the eight beam receiver. That mode would require sixteen - 300 MHz inputs. The spectrometer has only eight, thus limiting the eight beam bandwidth to 300 MHz. However, it is possible to process four beams at the full 600 MHz.

The 600 MHz mode gives a simplified representation of the hybrid technique. A hybrid spectrometer handles wide bandwidths by slicing the analog input signal into small frequency bands and processing the each sub-band, independently. An analog filter bank does much the same division of the IF into small sections. However, a filter bank spectrometer takes the filtered sub-bands and simply measures the total power of each;Thus giving one frequency sample per filter. A hybrid spectrometer processes each filter output into at a multi-point estimate of power spectra. Then, the sub-band spectra are then pieced together to produce the full-bandwidth spectral estimate.

The hybrid spectrometer implements the filter bank with 8 filters that select 37.5 MHz from the 300 MHz input band. Thus, the entire spectrometer has 64 filters; 8 filters per input with 8 inputs. In effect, the hybrid spectrometer front-end can be viewed as a 64 channel filter bank.

Figure 3 indicates the the 8 separate filters that cover the 300 MHz input bandpass. The processing is performed with single-side band mixers which use a phasing techniques to separate sidebands. This allows one filter module (and LO) to produce two of the required baseband signals. Thus, the filter modules downconvert both the upper and lower bands. By staggering the LO's it is possible to cover the full 300 MHz input using 4 modules (8 sub-bands). This convenient result is facilitated by the use of a baseband output which is between 50-100 MHz, and not 0-50 MHz.

As indicated in Figure 3, this conversion method tends to place the LO's within the input band. However, within a given filter module, the internal LO is out-of-band. LO leakage between different modules is minimized by physical separation between filter modules. However, out-of-band LO leakage can still be a problem within a filter module Out-of-band LO leakage causes an offset in the total power of a sub-band If this leakage is not stable, the result is platforming (see section V.A.).

B. Digital Correlator

Much of the flexibility of this instrument is created by placing a digital correlator at the output of the analog filter bank. A true analog filter bank has no ability to change resolution and bandwidth. A different resolution/bandwidth mode would require a new filter bank. Conversely, a digital correlator has several techniques for changing bandwidth and resolution. The VLA uses recirculation to process the same data more than once. The Owens Valley correlator slows down the sampler and correlator clock to process narrower bandwidths. The NRAO 12meter hybrid spectrometer uses a simpler technique to change bandwidth and resolution. Higher resolution is achieved by reallocating correlation channels to concentrate the available lags to a smaller set of available band segments.

This simple scheme of changing resolution/bandwidth has some nice advantages. For most modes, the analog filters and samplers operate in the same way regardless of mode. (There are some exceptions to this statement, which will be discussed.) Modes are implemented by re-routing the sampled data to the correlators.

The hybrid spectrometer has a grand total of 2048 correlator channels (lags). However, the electronics shop was fresh out of ideal filters, so some of the measured correlation lags are lost in the anti-alias filtering, which is necessary before sampling. The edge channels are overlapped to

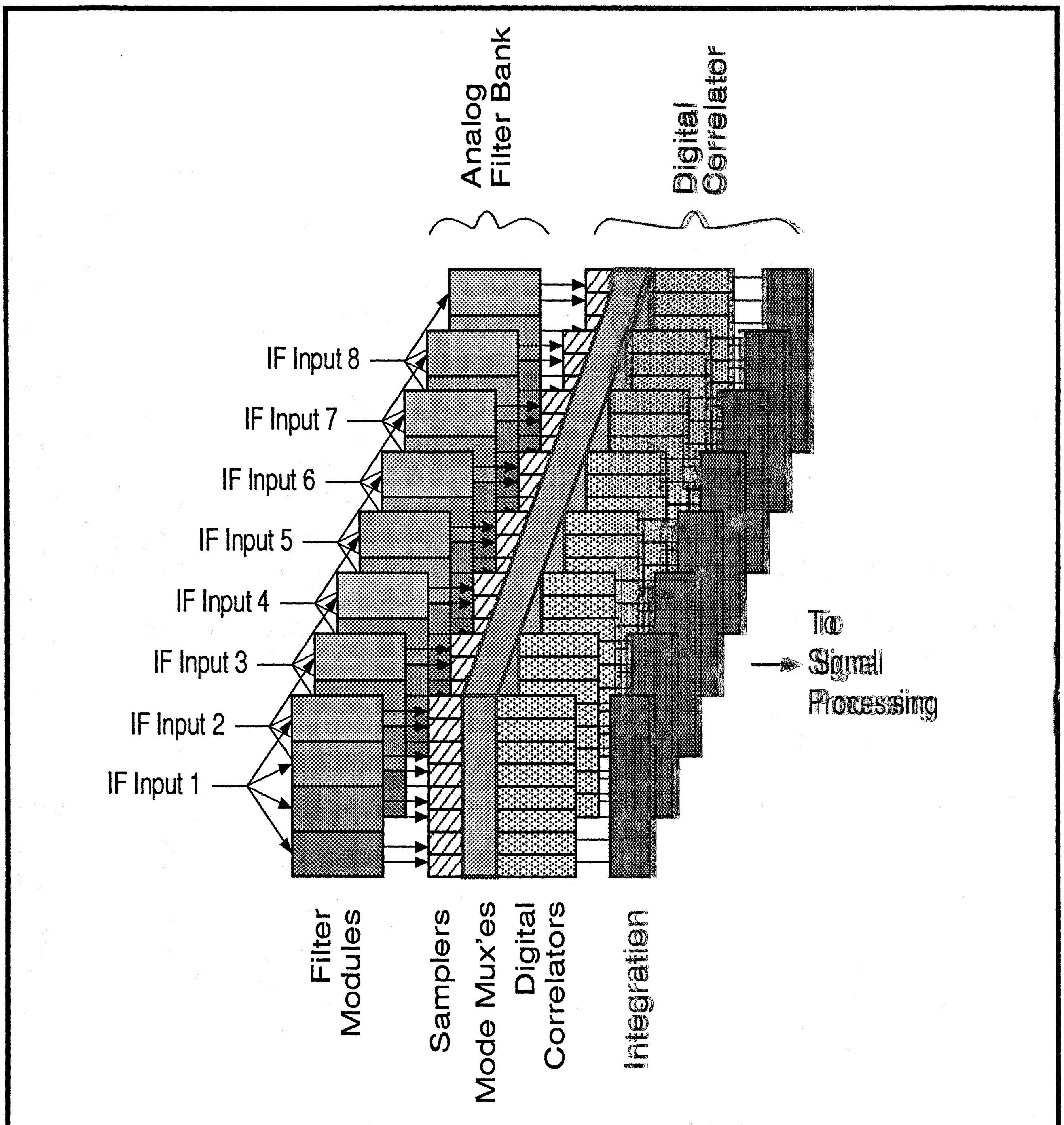


Figure 4 - Block diagram of hybrid spectrometer

provide a continuous coverage in the band-of-interest. Thus, even though the spectrometer is only interested in 37.5 MHz chunks of the spectra, the processed bandwidth is actually 50 MHz. This translates into a 6.25 MHz safety band,which is implemented on both sides of a 37.5 MHz spectral chunk. The sampling frequency is 100 MHz (equals the Nyquist rate). The digital correlator operate at 100 MHz.

After the analog processing by the hybrid spectrometer filter bank, a 37.5 MHz chunk is sampled at 100 MHz using a 3 level quantizer. This quantization scheme creates a degradation

After processing in the Hi-Resolution hardware, the single 37.5 MHz band is sampled and correlated. The digital hardware views this mode as identical to the one beam/37.5 MHz mode. Thus, all 2048 correlation lags are daisy chained into a single unit attached to a single 37.5 MHz input. The signal processing software is responsible for separating the two independent IF's from the frequency domain data. This mode represents a reversal from the normal hybrid situation. In this case, a single spectral chunk is dissected into two separate IF's.

B. Timing Modes

The present implementation of the hybrid spectrometer data acquisition timing is a direct synchronization to the filter bank acquisition cycle. The hybrid spectrometer acquires telescope data in concert with the filter banks. At this time there is no way to operate the hybrid spectrometer independently of the filter banks. However, the converse is not true; the filter bank can operate without the hybrid spectrometer. The slaving of the hybrid spectrometer timing to the filter bank seems to work very well, but there are some small differences that deserve mention.

The hybrid spectrometer timing is fixed by two major timing cycles. The digital correlator chips have an internal integration buffers of 14 bits. To avoid overflow, data is removed from these buffers every 100 μsec. The 100 μsec cycle is an internally generated, free running clock that **cannot** be locked to an external signal. After the data is removed from the fast buffers, it is integrated using the hybrid spectrometer hardware integrator. Data that has been added into this second buffering system cannot be rejected (without rejecting previous data in the buffer). This

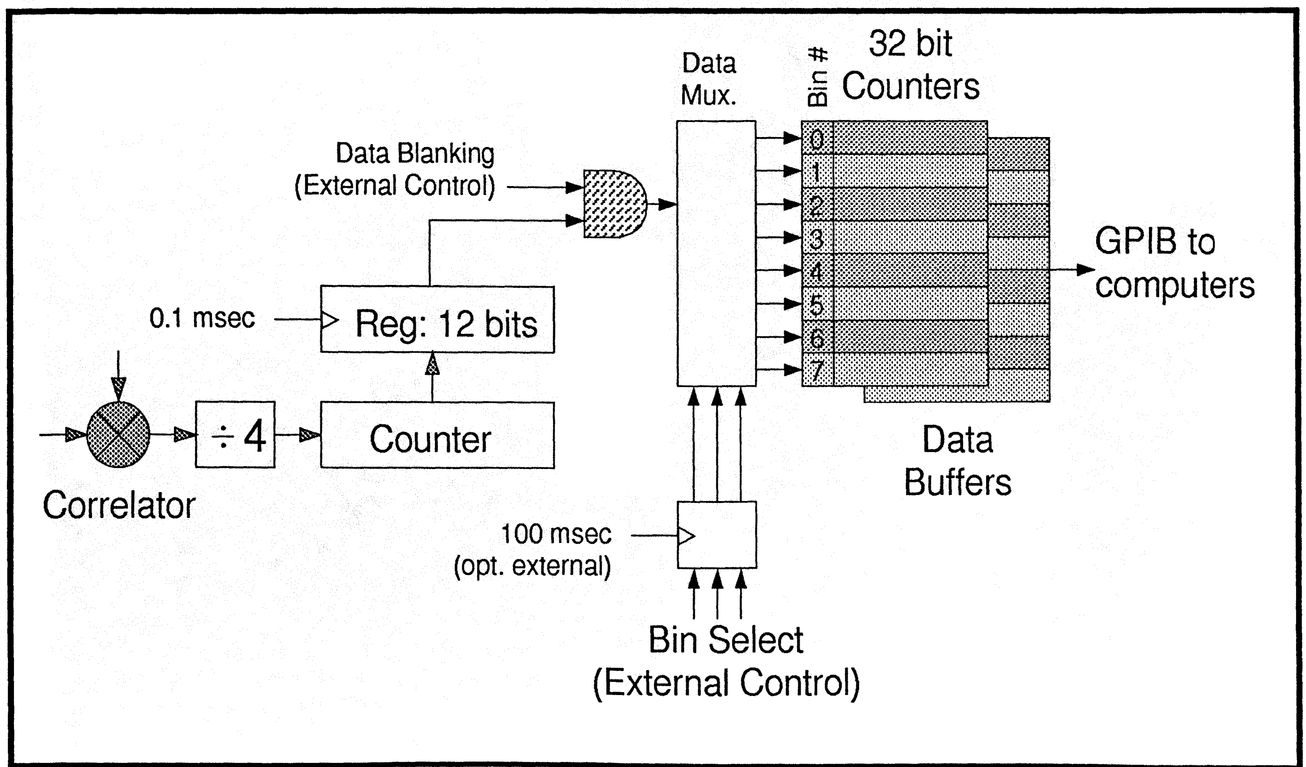
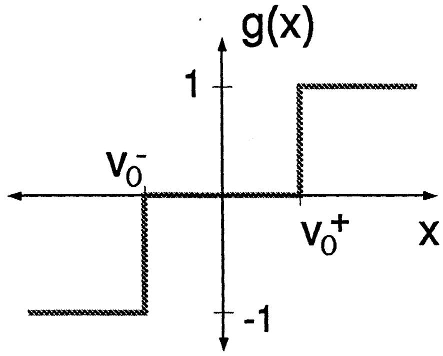


Figure 11 - Hybrid spectrometer timing block diagram

factor of 0.81, in terms of SNR. In terms of integration time, this means an observation that uses the hybrid spectrometer would require one hour to achieve the same SNR that an ideal correlator could give in 0.64 hours. The quantization degradation is effected by power level. If the power level changes dramatically during an observation, degradation will increase. The transfer function of the sampler is given in Figure 5. A plot of quantization degradation versus power level (normalized to threshold level) is shown in Figure 7.



•	+1	0	-1
+1	+1	0	-1
0	0	0	0
-1	-1	0	+1

Figure 5 - 3 Level quantization and multiplication table

The specified quantization degradation is dependent on the threshold levels, relative to the input power. During normal observations, the power levels are adjusted very close to optimum. This adjustment is performed during the calibration cycle. Once an observation has begun, the system gain is not changed. Therefore, a large change in signal power between calibrates could adversely affect the spectrometers SNR. A plot of the degradation function is given in Figure 7. In general, situations that could cause substantial changes in power level, would have much more perverse effects on the observation. For example, clouds passing through the beam. In this situation, a slight loss in SNR is probably the least of the observers problems.

In the widest bandwidth mode, each sampler is followed by a lag 32 correlator. In this case, the frequency channel spacing will be 50 MHz / 32 (or 37.5 MHz / 24) = 1.5625 MHz. This is the value given in the mode table for the 8-beam 300 MHz mode and the 4-beam 600 MHz mode. Other modes de-allocate some of these 32 channel groups from one sampler, and append them to the end of another set of lags, effectively increasing the resolution of the active 37.5 MHz chunk. (Note, in general frequency resolution will be worse than frequency channel spacing, depending on the data windowing factor. However, this distinction will not be rigorously noted in most of this discussion).

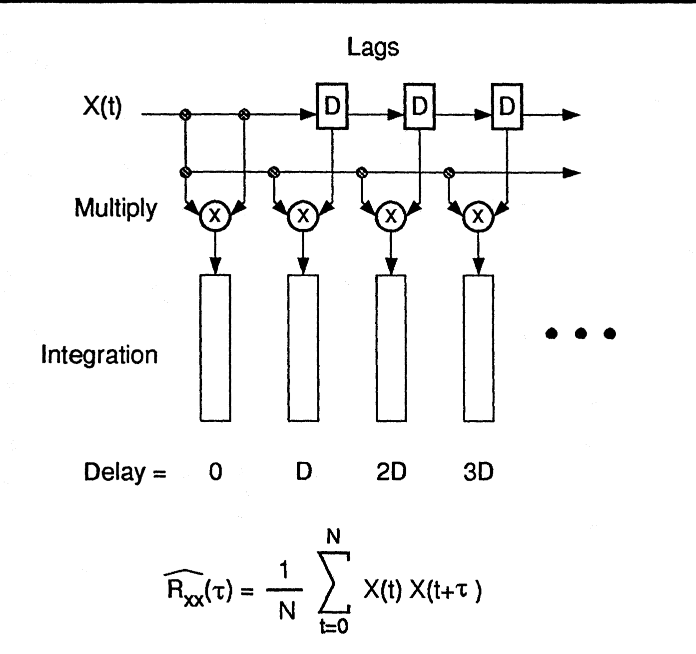


Figure 6 - Block diagram of digital correlator

A review of the mode table (Table 2), indicates one unexpected omission: the 4-beam 150 MHz mode. This mode is lost due of a limitation in the hybrid spectrometer multiplexing hardware. To

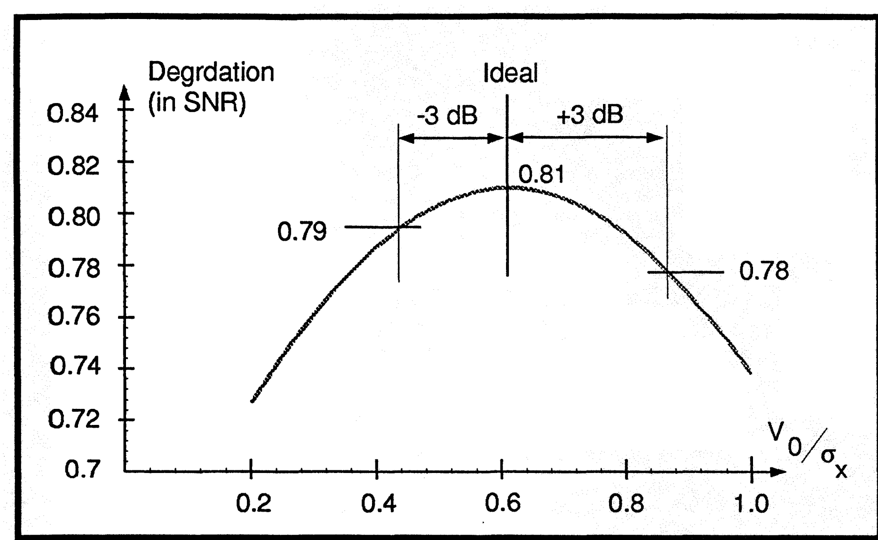


Figure 7 - Degradation in SNR versus power level (normalized)

achieve different modes, the spectrometer must re-direct 100 MHz digital signals. This is an expensive and complicated business, so the multiplexing hardware does not allow absolute flexibility. The hardware was optimized allow the maximum (useful) flexibility for the minimum number of parts. As a consequence this mode was lost.

III. Major Observational Modes

The hybrid architecture achieves many possible resolution/bandwidth modes. Table 2 shows some of the available modes. All the modes described in this table are available on Kitt Peak under computer control. Many of these modes come out directly from the hybrid architecture. However, several of these modes were achieved using variations on the standard architecture. A brief description of the modes is presented for reference. This discussion is useful for a general understanding of the instrument, but also indicates other modes which may be possible for special programs.

Another discussion is given in this section on the timing modes implemented by the hybrid spectrometer. For most users, the timing discussion can be skipped.

A. Bandwidth/Resolution Modes

1. 300/150/75 MHz Modes

This group of bandwidth modes is readily generated using the hybrid architecture. To produce the different resolutions requires a simple re-routing of the sampled data to fully utilize all the available correlation lags. In the widest bandwidth mode, (see Figure 4), each filter/sampler is attached to a 32 lag correlator board. In effect, this mode creates 64 essentially independent 37.5 MHz digital spectrometers. This mode produces the eight-IF, 300 MHz bandwidth mode. A simple reduction in bandwidth of all the IF's to 150 MHz causes ½ of the filter/samplers to become inactive. Now the 64 correlator cards will be distributed to only 32 filter/samplers. Thus each 37.5 MHz spectrometer has 64 lags, increasing frequency resolution by a factor of 2.

As another example, Figure 8 gives the configuration of the spectrometer in the two beam-300 MHz mode. In the widest bandwidth mode (eight beams - 300 MHz), each filter/sampler is followed by a 32 lag correlator. While the two beam mode uses only two of the available 300

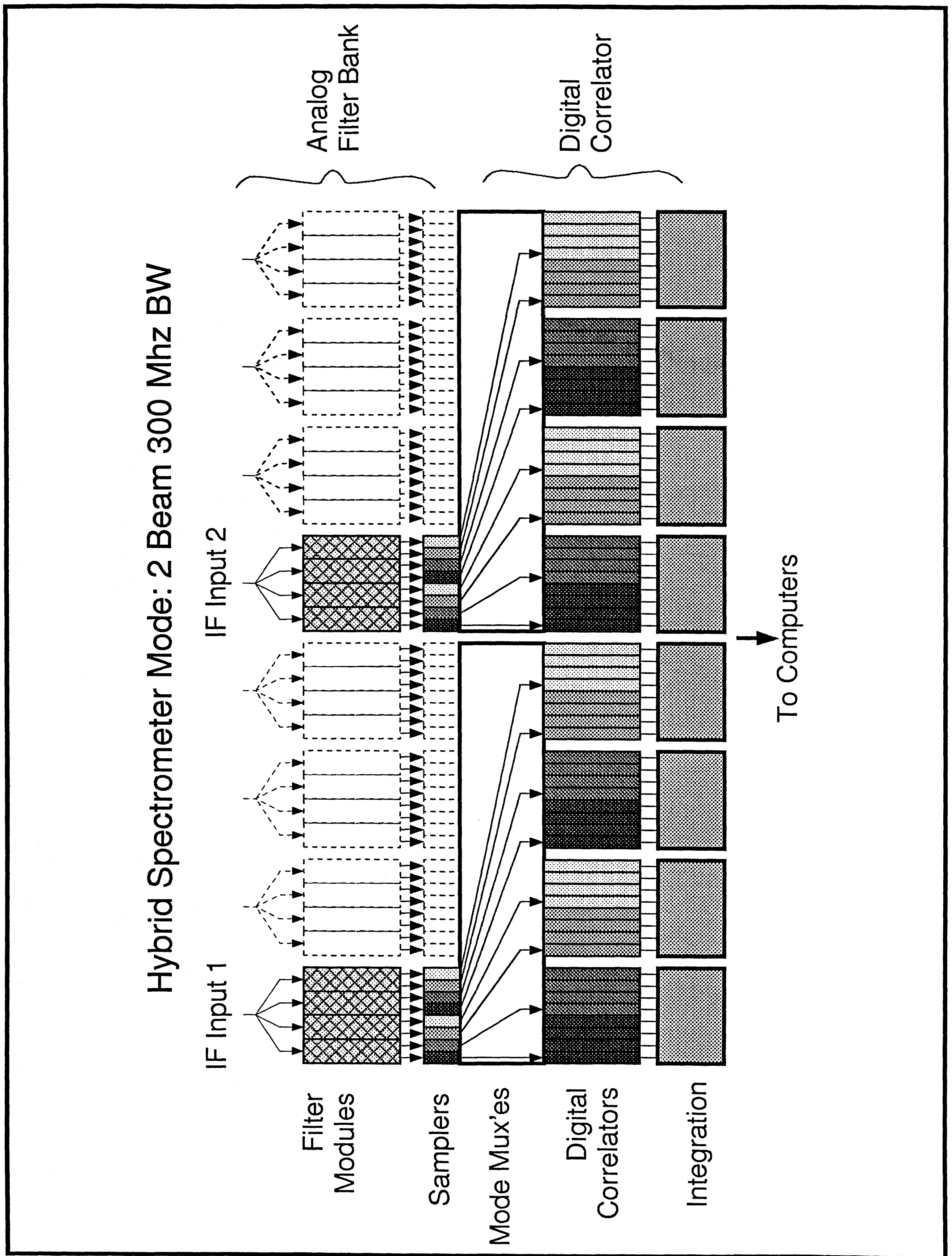


Figure 8 - Two beam - 300 MHz mode

No. of IF's	Bandwidth (MHz)	No. of Channels per IF	Channel Spacing (kHz)	Effective Resolution (kHz)
2	600	768	781	1125
2	300	768	391	563
2	150	768	195	281
2	75	768	98	141
2	37.5	768	49	71
2	12.5	512	24	35
1	37.5	1536	24	35
8	300	192	1562	2249
8	150	192	781	1125
8	75	192	391	563
8	37.5	192	195	281
4	600	384	1562	2249
4	300	384	781	1125
4	75	384	195	281
4	37.5	384	98	141

Table 2 - Hybrid spectrometer bandwidth/resolution modes

MHz spectrometer inputs, leaving six inactive. Therefore, the digital correlators from the inactive sections (or octants) are reallocated to the 2 active sections. Thus, each 37.5 MHz section has four correlator boards at its disposal instead of one. This indicates how the number of beams can be reduced to improve frequency resolution in much the same way as bandwidth.

Most of the other modes are achieved in much the same fashion. Thus, a change in mode is achieved by simply changing a few ECL multiplexers to re-route the samples.

2. 600 MHz - 2 IF Mode

This mode seems a straight forward application of the previously described switching scheme. However, the digital multiplexers for this mode were not implemented in the first version of the instrument. Eventually this mode was implemented, but it is achieved using an non-intuitive approach to simplify retroactive design. Therefore, this mode deserves some brief discussion.

The most obvious approach to achieving this mode is to utilize four - 300 MHz IF's. Each 600 MHz receiver signal would be split (by the IF Processor) into two - 300 MHz chunks and be distributed to the hybrid spectrometer. Unfortunately, the ECL multiplexers were not implemented to directly handle this mode and achieve the maximum possible frequency resolution. Therefore, a small trick in the filter modules was applied to assist the ECL multiplexers in dissecting the IF.

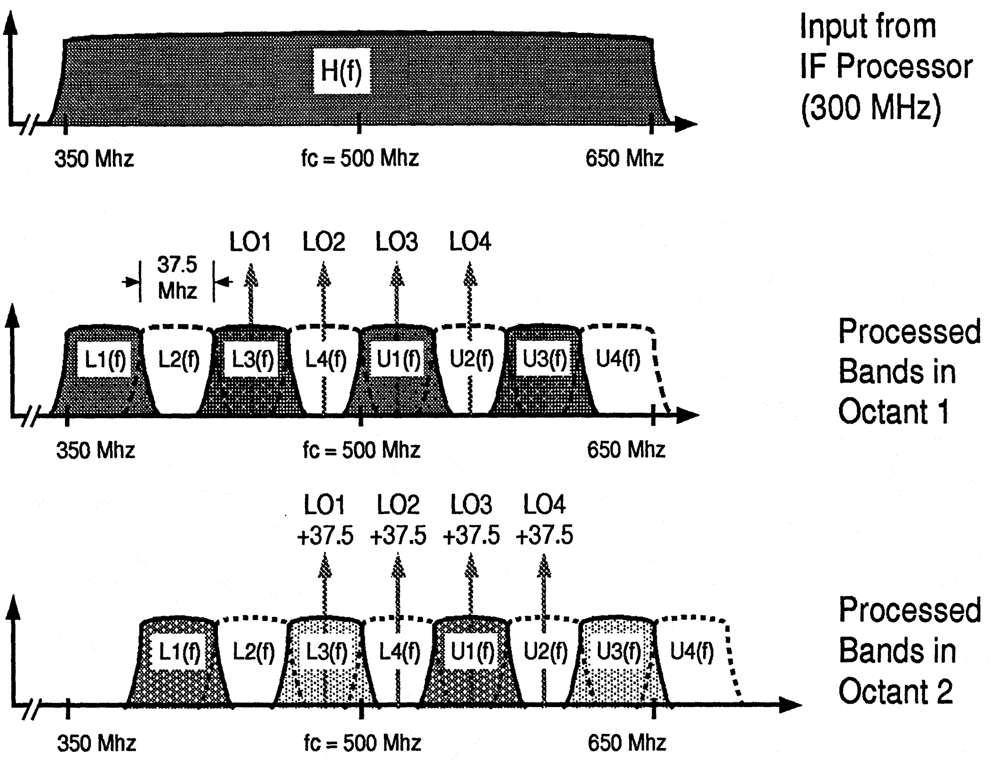


Figure 9 - Subdivision in 2 IF - 600 Mhz mode

To implement this mode, the filter modules actually process eight -300 MHz signals. The four extra signals are identical copies of the four independent signals (i.e., two IF's with two 300 MHz chunks each). Thus all eight sections of the spectrometer are presented with a full 300 Mhz. The four redundant IF's use their LO's to shift the input IF by 37.5 MHz (a familiar number !). Then, instead of processing continuous chunks of spectra, each octant processes every other spectral fragment. Thus the 300 MHz band is processed separately by two octants, with each handling 150 MHz in an offset picket fence fashion. (See figure 9) The spectrometer combine-and-trim software reconstructs a continuous spectra from this mess.

3. 37.5 MHz Mode

In the previously described modes (Bandwidth = 300,150,75 MHz), the number of active filter modules was eight, four, or two respectively. In these modes, it is easy to place the processed band at the center of the input IF. By simply deactivating filters on the outside of the band, and daisy chaining the free correlators to active filter, frequency resolution is increased. This change does not require any modification in the filters or IF. However, if the number of active filters drops to 1 (i.e., total BW=37.5 MHz), the resulting band is no longer at the center of the IF. Therefore, the active filter modules must change their LO's by 18.75 MHz (37.5 / 2) to maintain the same effective band center. The same result could be accomplished by changing the LO in the IF processor. However, the first version of the IF processor did not have this capability. Consequently, the filter

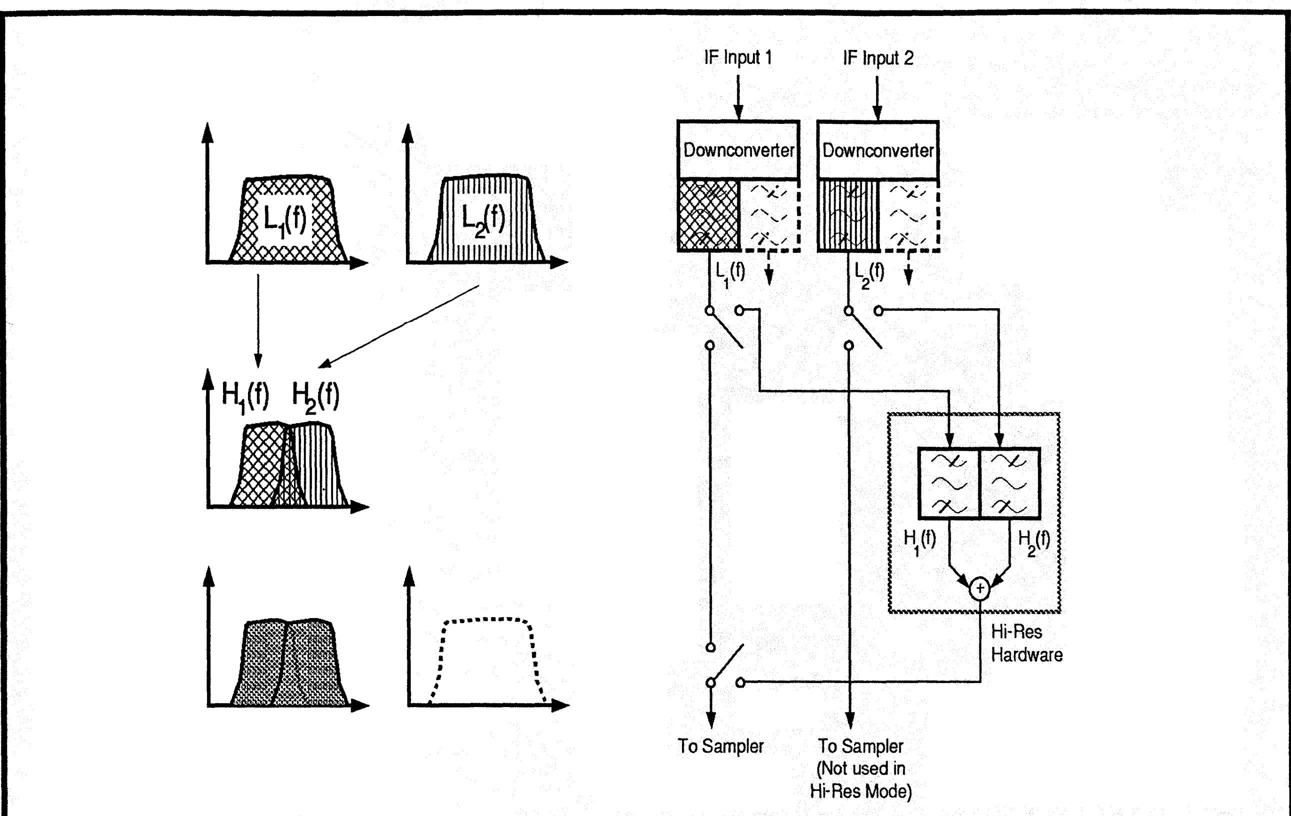


Figure 10 - Hybrid spectrometer hi-res mode

modules in the spectrometer were recruited to perform the necessary shifting operation.

4. Hi-Res Mode (12.5 MHz)

In general, the selection of resolution modes requires changes in the digital data distribution and sometimes in the filter module LO. However, there is one mode that requires some special hardware: the two beam *Hi-Resolution* mode. This special mode is created by application of some additional signal processing in the analog data path. The additional hardware is needed to overcome the inherent limitation of fixed filter with 37.5 MHz bandwidths.

This mode was a late addition to the hybrid spectrometer hardware. It could have been implemented in digital hardware using recirculation. Unfortunately, this mode it was not considered in the late stages of the spectrometer development. Therefore, it was constructed as an add-on signal processing box in the analog filter portion of the hybrid spectrometer.

The Hi-Resolution hardware takes the output from two 37.5 MHz filters bank modules and combines them into a single 37.5 MHz. To avoid image problems, each of the separate IF's is filtered to give it exclusive access to the upper or lower half of the active 37.5 MHz band. Thus each band is given slightly less than half of the 37.5 MHz band. The active band isn't exactly one half of 37.5 Mhz, because the image filters are non-ideal and need some room to roll-off This gives each beam a 12.5 MHz active band. The Hi-Resolution scheme is sketched in figure 10.

situation forces data rejection (or *data blanking*) to be performed in 100 μsec blocks. Conversely, the filter banks perform all data rejection on 100 msec data blocks. Thus the spectrometer has a finer control over data rejection, but less backward rejection time. When an error is reported, it is reasonable to assume the blanking signal will arrive at the correlator after the data has already been corrupted. In the filter bank, the data rejection window will extend from 0 to 100 msec into the past. The variation is due to the random nature of failures, relative to the fixed data cycles. The maximum possible backward rejection time in the hybrid spectrometer is only 0 to 100 μsec.

The second major timing cycle of the hybrid spectrometer is the maximum switch rate of data between hardware integrators. The hybrid spectrometer hardware integrator has 8 independent storage locations to hold correlations(called *bins*). The hardware can switch between these bins every 100 msec. Naturally, these 8 bins can be used repeatedly to permit beam switching modes where the data toggles back-and-forth between two sky positions. Unlike the 100 μsec cycle, the 100 msec cycle can be locked to an external source. It can also be internally generated. When the hybrid spectrometer is locked to the an external 100 msec source, the 100 μsec cycle is still free-running. Therefore, these clocks will have phase differences. This is not generally a problem because the spectrometer always rejects a 400 μsec window of data at the beginning of 100 msec cycle. This time is used to perform a system self-test. It represents a loss of 0.4 % of the available integration time.

There is another less important cycle in the spectrometer; the transferring of data from the hardware integrators to the computer systems. This cycle must be performed before the hardware integrators overflow. There is no safeguard in the spectrometer hardware to prevent an overflow. The timing of this cycle is completely controlled by the telescope control system. The hardware integrators are 32 bits long (unsigned), which means an overflow could occur in about 130 seconds. The projected overflow time is the total integration time into one of the 8 bins. Thus, the 130 seconds defines the limit on integrating a single sky position into a single bin. All the data is double buffered, so no integration time is lost during the data transfer to the control computer.

Most of the timing control signals are TTL-type inputs. This permits fairly easy interfacing (at least for timing) for special applications. Details of the input timing specification will be provided in the hybrid spectrometer technical manual. Figure 11, gives a block diagram of the internal hybrid spectrometer timing arrangement.

1. Position Switching

Implementation of the timing for position switching is fairly simple. The position of the telescope is maintained by the control system When the telescope is *on-position,* the spectrometer is informed by setting a bin control to a logic 1. When the telescope is in transit, the data is rejected using the spectrometer blanking control. Finally, the *off-position* is maintained in a different hardware register by setting the bin control to logic 0. When a pair of sky positions is complete, the control system sends a *dump* command which causes the spectrometer to upload the data to the computers for processing. The result is two separate correlation blocks. One of these correlation blocks representing data taken during the on-position, the other was measured during the off-position observation.

In this mode the spectrometer internally generates the necessary 100 msec signal. Therefore, the telescope position signal is only recognized on 100 msec timing boundaries. This is fairly coarse. However, this is probably reasonable considering the slow transit of the telescope from one position to another.

2. Frequency/Beam Switching

Frequency and beam switching require much faster switch rates between integration bins. Similarly, the acceptable latency period between the data windows is much smaller. These fast switch rates require the external 100 msec synchronization mode of the hybrid spectrometer. A 100 msec lock signal is taken from the filter bank timing hardware. Similarly, the actual beam position (or frequency value) is tapped from the filter bank hardware. The beam position signal allows separation of the *on-beam* and *off-beam* information into separate data storage bins. In this mode the control system only controls the dump command and the data blanking. To the hybrid spectrometer, beam and frequency switching are equivalent in terms of timing considerations.

3. Calibration

This observation type is implemented much like the position switching mode. The entire observation is run by the control computer. Once again the control system sets a TTL level to specify bin 0 and 1. In this case the two bins represent the reference position and the calibrator position. Another important job of the calibration cycle is to adjust the power levels at the samplers to the optimum value (see figure 7). When the hybrid spectrometer is instructed to perform a calibration, the telescope should be pointing at a sky reference position. This will allow the spectrometer to set optimum power levels. This process takes only a few 100 millisecond at which time the spectrometer is ready to perform the calibration. If the calibration source is in place when the calibration command is issued to the spectrometer, the results will be unpleasant.

4. Zero Check

The total power detectors use V/F converters to convert the voltage levels produced by the square law diodes into a pulse train. To avoid a non-linear response, the V/F detectors are tuned to produce a small output with zero input power. This avoids a negative offset in the power conversion function by forcing a measurable positive offset. The resulting offset is measured during the *zero check* cycle.

The zero check measurement is normally performed just prior to the calibration cycle. During the zero check, the spectrometer controls all aspects of the measurement. The TTL control lines are (such as data blanking) are disabled to avoid any problems. The length of the zero check measurement is set by the spectrometer. During the zero check measurement, the IF signal which enters the spectrometer is turned off using internal attenuators.

IV. Signal Processing

The ultimate goal of the hybrid spectrometer is to produce estimates of power spectrum. One important step in this process is the conversion of the measured autocorrelation function into an estimate of power spectrum. Additional processing is necessary to correct the data for quantization bias. Also, distinct to hybrid spectrometers is the combining and trimming of spectra to produce full-bandwidth estimates from the spectral fragments. This section will briefly discuss some of this processing.

All signal processing is performed in a 68030 computer running VxWorks in a VME crate. The code is written in "C", and is available for reference in the directory ../cactus/hyspec. All signal processing parameters have default values, but can be changed over the ethernet link to the VxWorks computer.

A. Quantization Correction

The conversion to digital signals uses extremely coarse quantization. In the case of the hybrid spectrometer only three possible numbers are generated by the sampling process: {1,0,-1}. Figure 5 demonstrates this quantization scheme. The effects of this extremely coarse quantization is a degradation in the SNR, plus a bias in the measured correlation function. Both the bias and the degradation are fairly small, which is surprising considering only 1.5 bits are retained from the input signal. The degradation (quantization noise) in terms of SNR is 81% versus an ideal (no quantization) correlator. The bias can be derived and removed by applying an inverse operation to the measured correlation (the quantization correction). A general discussion on this matter is given by Hagen[4] and Davis[3]. This nice result is possible because the bias is proportional to the measured correlation. Note, the quantization correction used by the hybrid spectrometer assumes ideal threshold levels and purely Gaussian input noise. This correction will be erroneous in the presence of strong deterministic signals (interference) or mistuned threshold levels. Figure 12 plots the quantization correction which is applied when the threshold levels are optimum (i.e.,threshold voltage/std dev. input signal = 0.612).

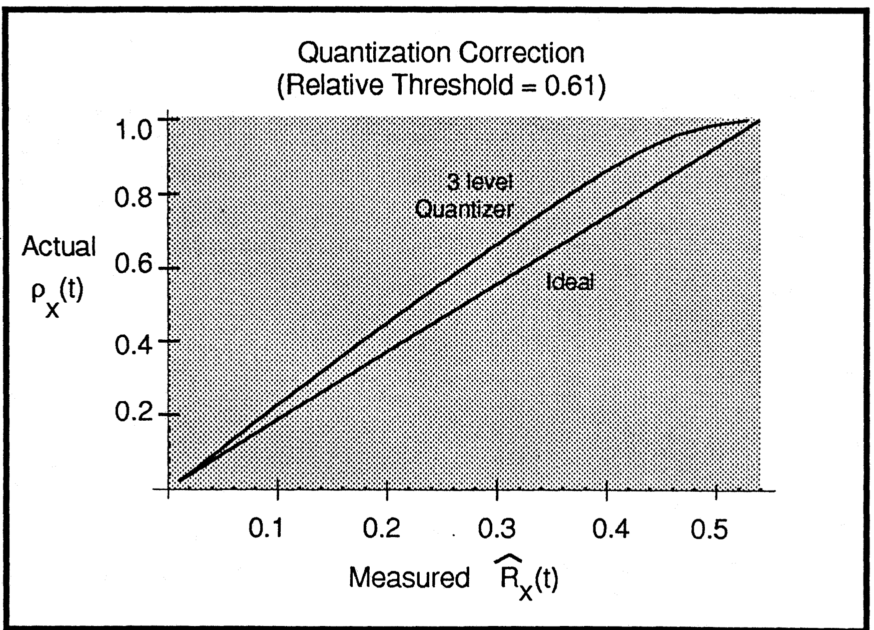


Figure 12- Quantization Correction (at optimum power level)

B. Data Windowing

The measured correlation function represents a finite length window of the true autocorrelation function. A direct conversion of this measured window is equivalent to passing a rectangular window across the true data. This tends to create strong sidelobes, i.e., leakage in the estimated power spectrum. This leakage can be reduced considerably by performing data windowing to alter the inherent rectangular window. Unfortunately, reducing leakage will also tend to degrade frequency resolution. The default mode of the hybrid spectrometer is to apply a Hanning window to the data. This tends to increase the effective frequency sample shape by 1.44 (in terms of half-power point as compared to a rectangular window). A good reference on this matter is Harris[5].

The default window represents a reasonable trade-off for most applications. However, the default window can be changed if required by the observing program. Please refer to Weinreb[6], which gives a description of the windowing types available to the user.

C. Fourier Transform

At this point in the processing the data is a windowed, unbiased estimate of the input autocorrelation function. To produce an estimate of power spectrum requires application of the Fourier transform. According to the Wiener-Khinchin theorem, applying a Fourier transform to the autocorrelation function produces power spectrum. However, in practice the discrete Fourier transform (DFT) is applied on a limited number of estimated autocorrelation values. To reduce computer overhead, the DFT is performed using the FFT algorithm. One constraint of the FFT is its preference for data blocks of length: 2^x (where x = integer). This does not appear to be a problem because the hardware of the correlator was built in multiples of 32. However, the FFT actually requires the full autocorrelation function, i.e., both positive and negative values. The autocorrelation function is even, so the negative-time lags can be taken from the measured positive lags. Thus, the autocorrelation is reflected around the zero lag. The result is 2X -1 points, i.e., one value short of an exact power of 2.. The missing value is due to the zero lag, which is not duplicated in the reflection. An additional value is needed to produce a data block that can be processed with by an FFT. A detailed discussion of this point is provided by Weinreb[6]. He found a value for this extra sample that would reduce data bias from the correlation at zero time delay.

D. Power Measurement

One important aspect of constructing an estimate of power spectrum is the measurement of total power in the 37.5 MHz spectral chunks. For non-hybrid digital correlators, the detection of total power is only used for calibration purposes. In filter bank spectrometers, a total power detector is used to measure every single point in the spectrum. Conversely, hybrid spectrometers use a power detector to determine the absolute level of a spectral chunk (sub-band). This is represents a more difficult technical challenge than either the traditional filter bank or traditional correlator.. Small errors in power level over a chunk of the measured frequency band will be readily visible against

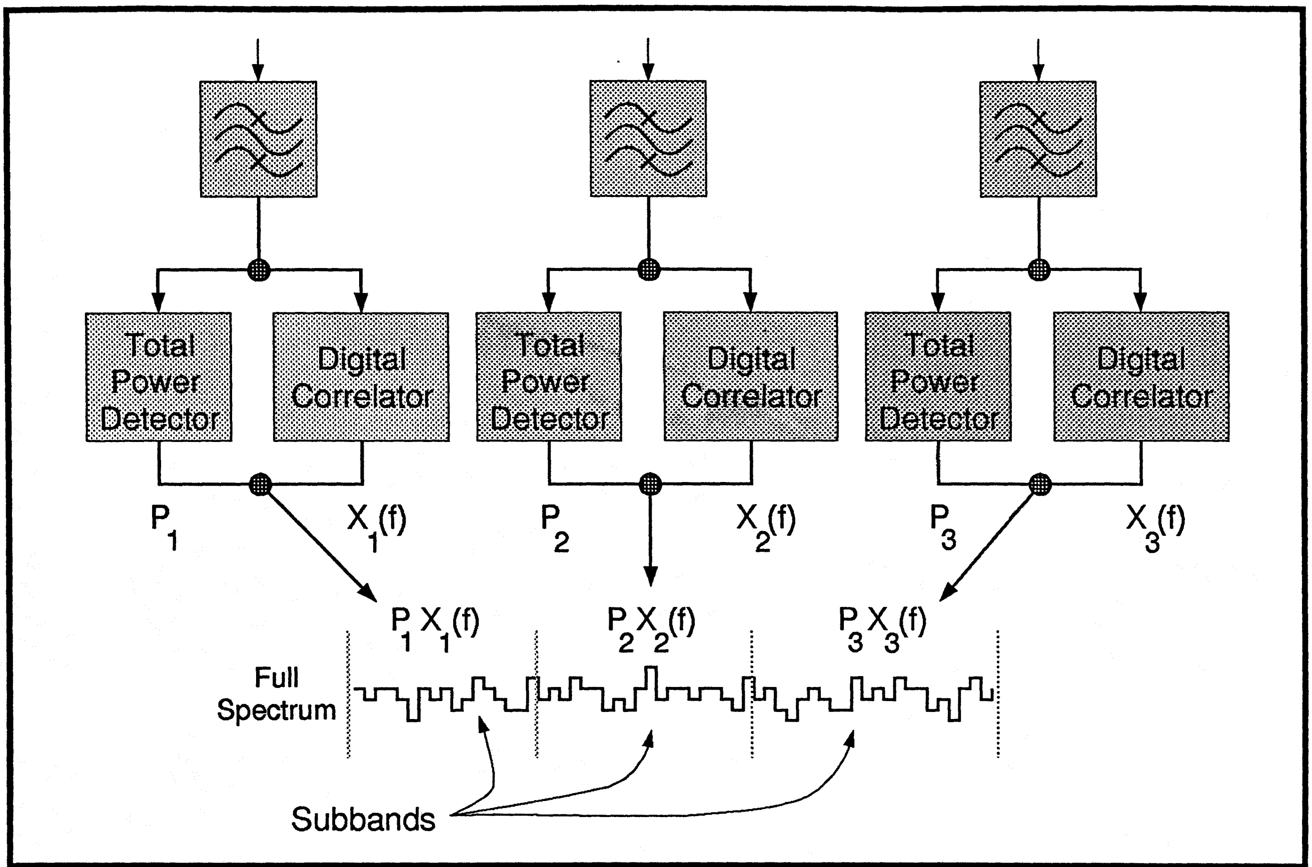


Figure 13 - Total power measurement

the independently measured baseline shapes. Thus, the total power detectors in hybrid spectrometers have the more difficult problem of ensuring continuity between the independently measured spectral chunks. If this power measurement is wrong, the result is discontinuities in the final spectrum (see "Platforming").

The NRAO 12m telescope uses square-law diodes to convert the noise power from a 37.5 MHz band into a voltage. The detector signal is processed with a voltage-to-frequency converter. This gives a pulse train that is integrated much like the correlation values. After the correlation values are converted to power spectrum (and normalized), the power measurement is used to set the absolute power level.

One additional value is used to correct the measured power counts (measured output from the V/F converter). The V/F converters are tuned to produce pulses when no input power is present. This is necessary to ensure a linear conversion. Therefore, during the calibration cycle, a *zero check* is performed to remove this offset from the measured power counts. This step is identical to the zero check operation performed by the 12meter filter bank spectrometer.

E. Spectral Reconstruction

The final step in signal processing is to put the various spectral chunks back together into a contiguous estimate of the input spectral band. There are two steps in this process. First, channels in the overlap regions (i.e. on the tails of the anti-alias filters) are trimmed to select the center 37.5 MHz chunk. The trimming process reduces the measured 50 MHz bandpass into a clean 37.5 MHz. Next, these chunks are strung together, depending on mode, to produce the final data segments. During this step it is necessary to reverse some of the spectral chunks to negate frequency reversals which occur in the downconversion.

The overlap regions are often cited as potentially useful data points for use in removing reliance on the power detectors and ensure proper matchup of spectral chunks. This seems a reasonable assumption; however, tests with this technique have been less than satisfactory. However, more testing of this approach is planned.

V. Instrumental Effects

Ideally, the subtle details of instruments should be hidden from the user. Unfortunately, in the real world, this goal is not always achieved. Instrumental effects are produced by failures in the spectrometer or misuse of the instrument. This section will present some of the more common effects encountered when using the NRAO 12meter hybrid spectrometer.

A. Platforming

The most common problem in hybrid spectrometers is *platforming*. This descriptive name refers to a sub-band of the spectra appearing to hover above or below the expected baseline. The erroneous fragment may appear to have the correct shape and noise power, but the wrong level. This failure is a feature of the parallel structure of the hybrid architecture. Because the hybrid spectrometer is composed of many virtually independent 37.5 MHz spectrometers, a single failure can appear as platforming. Therefore, a platforming error is analogous to a bad channel in a filter bank spectrometer. When a single channel goes wrong in the filter bank, it will appear as a single erroneous frequency point. However, in hybrid spectrometers a single bad filter may corrupt many frequency samples. The number of erroneous frequency samples is dependent on the organization of the digital correlator. However, the bandwidth of the erroneous spectral chunk is fixed by the architecture at 37.5 MHz.

The most likely cause of platforming is a failed filter module. In such a case, the generally recommended cure is to swap out the troublesome filter module with a spare. Actual repair will done off-line. If this does not fix the problem, the next likely culprit is a failed sampler. Care should be taken when swapping filter modules or samplers. The translation from a bad 37.5 MHz section in the spectra to the physical location of a filter module is somewhat complicated. It is easy to swap the wrong filter module. Before swapping modules, disconnect the module which is suspect and take a data scan. If the null spectrum appears in the position of the previously detected error band, then the module has been located correctly.

Not all occurrences of platforming are due to hardware failures. Other causes of platforming are inherent effects in the instrument. The most common of these is the occurrence of platforming around strong spectral features. A discussion of this problem is given by Dowd[2]. Briefly, this effect seems be caused by limited dynamic range in the power detectors. This causes errors in the gains (calibration observation) due to non-linear detector response. This error will tend to be exasperated around strong lines. Figure 14 gives a sketch of a spectrum that contains this problem..

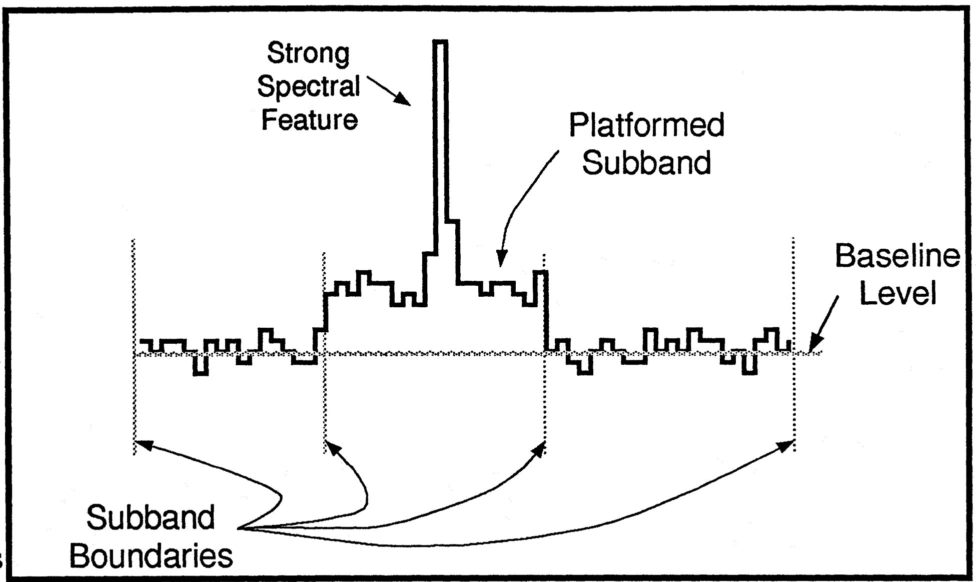


Figure 14 - Spectrum indicating platforming error

The previous effect is normally not subtle, and is strongly centered on spectral features. LO leakage in the filter modules causes another, much weaker form of platforming. If the LO leakage was fixed, there would be no real effect on the spectrum (only in calibration). However, the leakage is strongly dependent on physical geometry, it tends to be vary with temperature. This causes the LO to fluctuate and cause the measured power to change with time, reducing system stability. The result is small incongruities in deep observations. A recent effort to improve system wide LO leakage should greatly reduce this problem.

Another, as yet unexplained effect can occur if there is a strong slope in the passband. In general operation, a slope in the passband is not common. However, there are some receivers with slightly narrow IF filters that can have substantial roll-off near the edges of the 600 MHz bandpass. This roll-off will tend to predominate on the edge of bands in the widest bandwidth mode (i.e., 600 MHz). This phenomenon is still under investigation, but should not be a problem for the vast majority of observing. At worst, it reduces the useful bandwidth to 562.5 MHz.

B. Noisy Spectrum or Spectral Chunk

Sometimes the spectra produced by the hybrid spectrometer will appear to have more baseline noise (spectral variance) than the filter bank spectra. There is some inherent losses in a digital correlator due to the quantization noise. Also, the hybrid spectrometer has higher frequency resolution in most modes, therefore the baseline noise will be larger. However, if this effect is too large to be justified or if the noise appears to have structure, there may be a problem.

If the entire spectrum appears too noisy or "ratty" (i.e., structured) , than one possible cause is a problem in the data blanking. Data blanking refers to the spectrometer's ability to reject erroneous data (for example, when the telescope slues). If data blanking is forced "off", the spectrometer will take data during the telescope slues or sub-reflector movement. This error can be verified by noting the integration time. If the spectrometer integration time is somewhat larger than the filter bank integration time (> 5 %), then something is wrong. Small differences (< 5%) in integration time can be explained by differences in timing circuits. Small differences are not a problem. Note, there is a method to disable data blanking from the control system (used for testing). Therefore, if this problem is suspected, the operator should check to ensure normal blanking has been enabled by the control computer.

Another possible failure involves a single 37.5 MHz chunk of the resulting spectrum. If the mean of the spectral chunk is incorrect, the problem is platforming. However, it is possible for the mean level to be OK, but the "spectral shape" to be incorrect. This indicates a failed correlator or sampler. This problem will generally require assistance from an engineer to fix.

C. Missing Lines

One relatively infrequent failure mode is the lack of an expected spectral line. This is typically caused by an LO failure. Consequently, the measured spectrum is actually shifted from the expected location (in the frequency space). This problem can be caused by a failed LO or a computer communications error. Starting this summer(1992), the hybrid spectrometer LOs will be given a *lock detect* indication light. If LO failure is suspected, these lights should be checked. Generally, internal communication within the hybrid spectrometer to the LO's is quite robust. However, communication with the IF Processor is more susceptible to failure. Conversely, the LO's within the spectrometer seem to be more prone to general failure. This is due to a passive system of temperature stabilization which places the hybrid spectrometer LO's in a fairly hot enviroment.

D. Image Rejection

Image rejection refers to the relative strength of an unwanted frequency domain sideband. The erroneous sideband is injected during the IF downconversion process. At the 12m telescope, downconversion is performed in several steps from the receiver to baseband. Each stage will have its own distinct image rejection specification. Within the hybrid spectrometer, a conversion from 500 MHz to baseband is performed. This frequency step has an image rejection that is generally worse than other stages in the telescope IF chain. The image rejection of this last stage was measured to be 22dB (minimum). At most positions in the spectrum, it will be much more than 22dB. Figure 15 gives a sketch of the final downconversion.

The hybrid spectrometer image rejection should be adequate for most applications. However, this image rejection may be a problem when strong spectral features exist close to a line of interest. In all cases, the strong line must be between 187.5 MHz - 112.5 MHz of the frequency-of-interest to be a potential image problem.. Also, the image always maps one-for-one. Therefore , only one point in the image maps to one point in the active region.

The mapping between a frequency point and its image is quite complicated. The simplest check for image problems is to move the effective sky frequency. If the suspect spectral feature moves in the wrong direction (up when it should have moved down or vice versus), then the suspect line is probably an image.

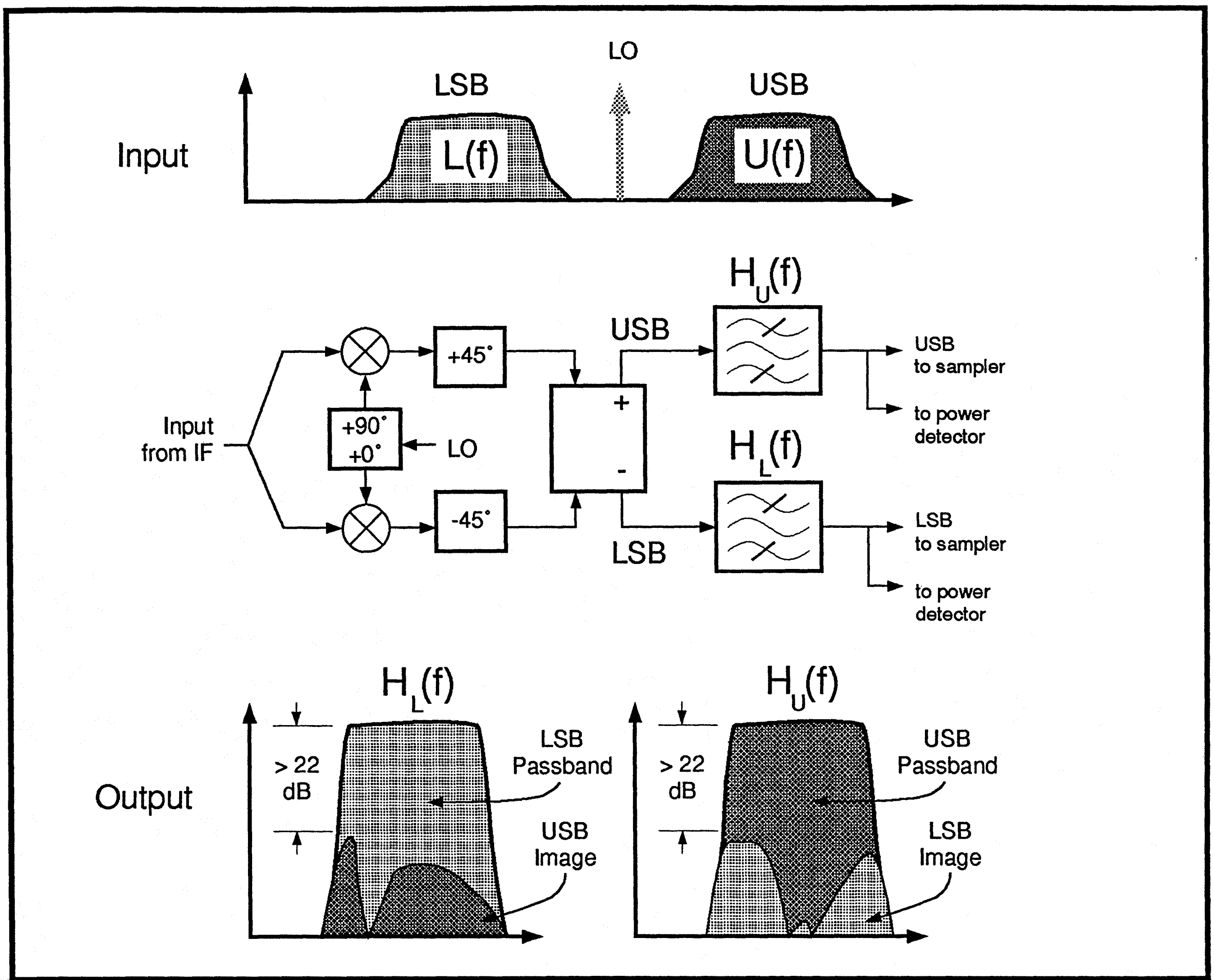


Figure 15 - Final mixing stage: image reject

This solution may not be practical for weak lines. It may be necessary to determine the exact mapping to images. To determine the image location requires the bandwidth/IF mode and the offset of the suspect frequency from the center of the measured band. Using these facts, it's possible to determine the LO which controls a frequency chnuk. The LO information is given in figure 16. Next, apply the equation:

$$F(\text{image}) = 2\,F(LO) - F(X)$$

The resulting value is the image location in the IF band where the band center is 500 MHz.

A simple rule should help image determination in the wide bandwidth modes (300 and 600 MHz). In these modes, the image is always within the measured band. Therefore, any strong features should be easily identified as a potential image problems.

For all modes (except BW =37.5 and 12 MHz), the center of the measured spectrum is actually a cusp point between two separate filters. Therefore, the frequency samples on the left side of the band center have an image frequency which is completely different from points on the right

F(image) = 2 LO - F(x)

Where: (all frequencies taken within IF scale 350-650 MHz)

LO = Local Oscillator Freq for the subband

F(x) = Frequency of interest

F(image) = Frequency of image

<u>Mode: 300 MHz - 8/4/2 beams and 600 MHz - 4 beams</u>

LO	443.75	481.25	518.75	556.25	443.75	481.25	518.75	556.25
Band Type	LSB	LSB	LSB	LSB	USB	USB	USB	USB

Frequency									
within IF	350	387.5	425	462.5	500	537.5	575	612.5	650
from band center	-150	-112.5	-75	-37.5	0	+37.5	+75	+112.5	+150

<u>Mode: 150 MHz - 8/4/2 beam</u>

LO			518.75	556.25	443.75	481.25		
Band Type			LSB	LSB	USB	USB		

Frequency					
within IF	425	462.5	500	537.5	575
from band center	-75	-37.5	0	+37.5	+75

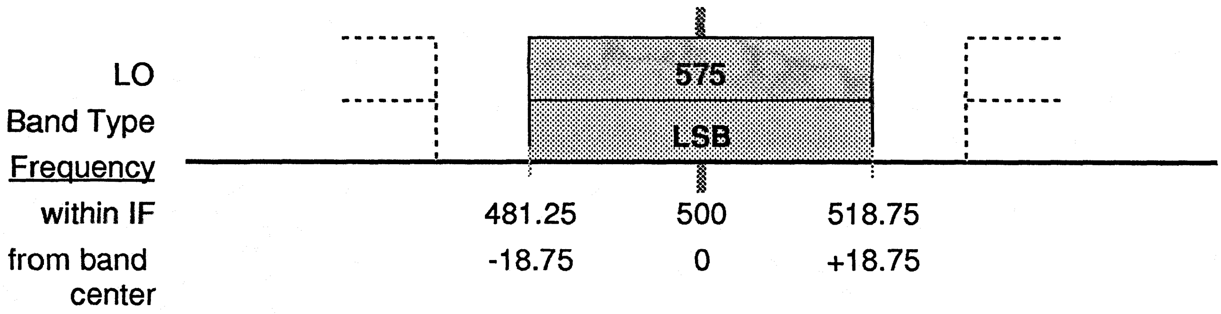
<u>Mode: 75 MHz - 8/4/2 beam</u>

LO				556.25	443.75			
Band Type				LSB	USB			

Frequency			
within IF	462.5	500	537.5
from band center	-37.5	0	+37.5

Figure 16 - Image rejection information

Mode: 37.5 MHz - 8/4/2/1 beam



Mode: 12.5 MHz - 2 Beams

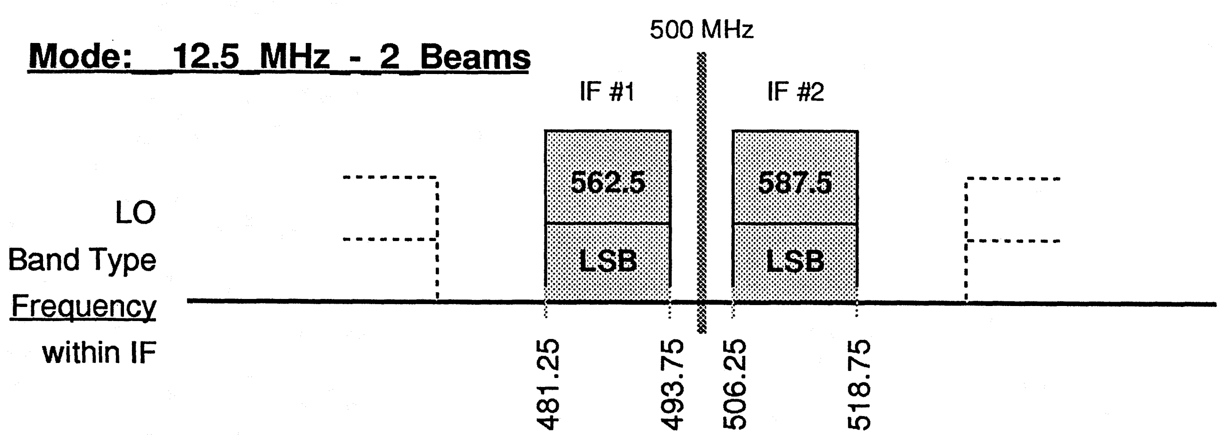


Figure 16(cont) - Image rejection information - hi resolution modes.

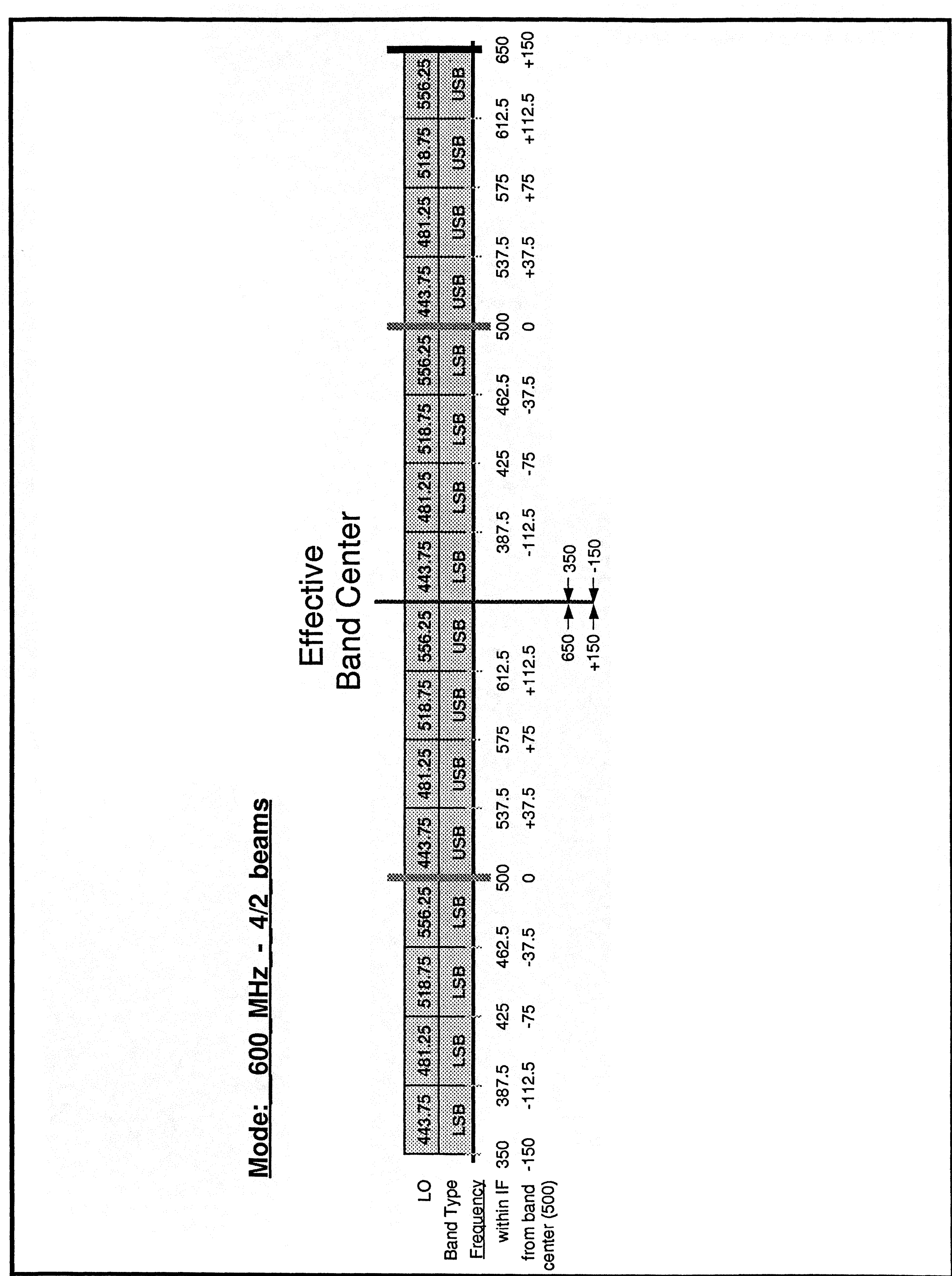


Figure 16(cont.) - Image rejection informtion: 600 MHz - 4/2 beam mode.

side of the measured band center. Thus any suspect image would not span the center, but instead be unceremoniously divided down the middle.

VI. Conclusions

It would be ideal if the instrumentation effects of astronomical instrumentation could be removed and allow astronomers to contemplate more important matters. Unfortunately, this is not practical so some knowledge of an instrument often is necessary to allow maximum utilization of its capabilities. Like any device, the hybrid spectrometer has strengths and weaknesses. Astronomers who have used this instrument may be aware of some of its weaknesses. Hopefully this document has shed some light on the roots of these issues. On the positive side, this instrument is available now and has been used successfully by many examiners.

VII. References

[1] Weinreb, Sander, Analog-Filter Digital-Correlator Hybrid Spectrometer, *IEEE Transactions on Instrumentation and Measurement,* No. 3, p670-675, Dec 1985.

[2] Dowd, Andrew, Total Power Measurement in Astronomical Hybrid Spectrometers, *IEEE Transactions on Instrumentation and Measurement*, Oct. 1992.(pending)

[3] Davis, W.F., Real-Time Compensation for Autocorrelation Clipper Bias, *Astron. Astrophys. Suppl.*, No. 15, pp381-382, 1974

[4] Hagen, J.B. and Farley, D.T., Digital-correlation techniques in Radio Science, *Radio Science*, No. 8, p775-784, 1973

[5] Harris, Fredric, On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform, *Proc. IEEE,* No. 66, pp51-83, Jan. 1978.

[6] Weinreb, Sander, Correlation Function to Power Spectrum Transformation, *NRAO Electronics Division Technical Note,* No. 136, March 4 1986.