NATIONAL RADIO ASTRONOMY OBSERVATORY
GREEN BANK, WEST VIRGINIA

ELECTRONICS DIVISION TECHNICAL NOTE NO. 126

Title: 140-FOOT CASSEGRAIN BASELINES

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Date: December 28, 1984

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Charles J. Brockway

July 1984

Background

Several observers using the 140-ft Cassegrain spectral line receiving systems have pointed out that the limits of detection are set by baseline perturbations. This seems to be especially so for the X-band system in the 7.3 to 10 GHz range when the Model IV autocorrelator is opened up to bandwidth of 20 MHz and broader. The baselines giving trouble limit detection sensitivity to typically 20 MK, sometimes appear periodic but usually do not, and nearly always get worse as the source contains higher continuum. Sometimes the perturbations shift with the choice of IF frequency, but not always. M. Bell/H. Matthews and R. Brown usually nutate the subreflector in a double beam switching and subtraction method that gives good results. Others have tried a similar method with no improvement over total power ons and offs, or cannot consider it because their sources are too extended. Some tests run by B. Turner indicate that at least part of the baseline problem originates in an early front-end stage or even ahead of the front end. B. Rood/T. Bania have had three observing sessions in which baselines were a problem in the first and third; the second session produced significantly better ones. Turner and Matthews have had, in general, better baselines at

14 GHz than at X-band using the same receiver. From all of this and some additional notes and comments, one is left with the following impressions:

1. The "bad" baselines are called bad because:
   a. They are indeed the limiting factor in sensitivity.
   b. They may have been better at other times using the same equipment and under similar weather conditions.
   c. They are worse than those obtained with the same system at another frequency band.
2. Although "bad", the baselines are apparently comparable in quality to those obtained at other telescopes with broadband detection capability.
3. The X band baseline problem exists at about the same level for both Cassegrain receivers in which there is an independent signal path from feed to autocorrelator. This has not been confirmed yet for the identical frequency, only for the same band and not at the same time.
4. Several conditions exist simultaneously to cause the imperfect baselines. The better the baseline the less likely a single condition dominates its character and the more difficult it will be to improve.
5. At times, baselines are noticeably better at night presumably due to some of the sun getting into the feed.

6. A sinusoidal baseline component exists at about 11.5 MHz due to reflections between subreflector and feed that is diminished by a factor of about three when modulating the focus by one quarter wavelength.
7. Baselines of poor quality seem not to change between a clear and overcast sky but they get worse when it rains. The effect of an overcast sky is uncertain on good baselines that have been obtained under clear conditions.
8. Some, but perhaps not all, baseline problems appear to be not caused by a system time instability because the baseline structure is uniform to a few mk when subtracting scans taken a half hour apart.

Spectral Equation

Suppose it is assumed that the front-end properties dominate baseline performance. It is desirable to derive an equation that might give some insight into the contributions of the various parameters.

The output spectrum for the total power mode is given by

$$T_{out}(f) = \left(\frac{T_{on}(f)}{T_{off}(f)} - 1 \right) T_{sys}$$

where

$T_{out}(f)$ = output (quotient) spectrum.

$T_{on}(f)$ = normalized spectral power for on scan.

$T_{off}(f)$ = normalized spectral power for off scan.

$T_{sys_{on}}$ = system temperature for on scan.

$$T_{on}(f) = 2\,\frac{G_N(f)\left[T_L(f) + T_{RN}(f) + T_C\right]}{\int_0^B G_N(f)\left[T_L(f) + T_{RN}(f) + T_C\right] df}$$

$$T_{off}(f) = 2\,\frac{G_F(f)\,T_{RF}(f)}{\int_0^B G_F(f)\,T_{RF}(f)\,df}$$

where

$G_N(f)$, $G_F(f)$	=	system gain function for on, off scans.
$T_{RN}(f)$, $T_{RF}(f)$	=	system noise less source continuum for on, off scans.
	≡	receiver spectral noise.
T_C	=	source continuum. (Assume uniform spectral power.)
$T_L(f)$	=	line spectral power.
B	=	autocorrelation bandwidth. (Assume less than RF, IF bandwidths.)

Note noise cal neglected.

The factor 2 appears in these equations because the autocorrelator signal and reference alternations are accumulated in the total power mode.

The output equation becomes:

$$T_{out}(f) = \left[\frac{\dfrac{G_N(f)\left[T_L(f) + T_{RN}(f) + T_C\right]}{\int_0^B G_N(f)\left[T_L(f) + T_{RN}(f) + T_C\right] df}}{\dfrac{G_F(f)\,T_{RF}(f)}{\int_0^B G_F(f)\,T_{RF}(f)\,df}} - 1\right] T_{sys_{on}}$$

where:

$$T_{sys_{on}} = \frac{\int_0^B G_N(f)\left[T_{RN}(f) + T_C + \frac{T_{cal}}{2}\right]df}{\int_0^B G_N(f)\ T_{cal}\ df}\ T_{cal}$$

The output equation can be put in a more manageable but very much less rigorous form with the simplifications:

1. $G_N(f) = G_F(f) = \text{constant.}$

2. $\int_0^B \left[T_L(f) + T_{RN}(f) + T_C\right] df = B(T_{RN} + T_C) = B(T_R + T_C)$

3. $\int_0^B T_{RF}(f)\ df = BT_{RF} = BT_R$

The normalization integrals are simplified by assuming the receiver spectral perturbations average to T_R and the source spectral power is much smaller than T_R. It is noted that, even though the on and off gain functions are taken to be constant, the on and off receiver spectral powers are allowed to be different.

The output equation simplifies to:

$$T_{out}(f) = \left[\frac{\dfrac{T_L(f) + T_{RN}(f) + T_C}{T_R + T_C}}{\dfrac{T_{RF}(f)}{T_R}} - 1\right](T_R + T_C) \qquad (\text{Neglect } T_{cal})$$

and after some algebra can be put in the form:

<u>Total Power</u>

$$\boxed{T_{out}(f) = \frac{T_R}{T_{RF}(f)}\ T_L(f) + T_C\left(\frac{T_R - T_{RF}(f)}{T_{RF}(f)}\right) + T_R\left(\frac{T_{RN}(f) - T_{RF}(f)}{T_{RF}(f)}\right)}$$

The last two terms of this equation can cause a non-uniform baseline; the first term is like a line distortion factor. For an ideal system, $T_{RN}(f) = T_{RF}(f) = T_R$, the equation goes to $T_{out}(f) = T_L(f)$ as it must.

In a like manner, spectral equations can be derived for the S power observing modes. The results are:

Beam Switching

$$\boxed{T_{out}(f) = \frac{T_R}{T_{RR}(f)} T_L(f) + T_C \left(\frac{T_R - T_{RR}(f)}{T_{RR}(f)}\right) + T_R \left(\frac{T_{RS}(f) - T_{RR}(f)}{T_{RR}(f)}\right)}$$

Frequency Switching or Beam Switching with Noise Adding where $T_{add} = T_C$

$$\boxed{T_{out}(f) = \frac{T_R + T_C}{T_{RR}(f) + T_C} T_L(f) + T_C \left(\frac{T_{RS}(f) - T_{RR}(f)}{T_{RR}(f) + T_C}\right) + T_R \left(\frac{T_{RS}(f) - T_{RR}(f)}{T_{RR}(f) + T_C}\right)}$$

where:

$T_{RS}(f)$, $T_{RR}(f)$ = receiver spectral power for S (signal), R (reference) of autocorrelator cycle.

It is interesting to note the effect of the so-called line distortion for a special case; that of frequency switching such that a strong, narrow line is placed in the R (reference) alternation of the autocorrelator cycle as is done in overlapped frequency switching. Then, with the same constraints as before, the output is given by:

$$T_{out}(f) = \frac{- T_L(f) + \left\{T_{RS}(f) - T_{RR}(f)\right\}}{T_L(f) + T_{RR}(f) + T_C} \left(T_R + T_C\right)$$

and for the ideal system where $T_{RS}(f) = T_{RR}(f) = T_R$:

$$T_{out}(f) = -\frac{T_L(f)}{1 + \frac{T_L(f)}{T_R + T_C}}$$

It follows that the ratio of the line when in signal to that in reference is:

$$\frac{T_{out}(f)\ \text{signal}}{T_{out}(f)\ \text{reference}} = 1 + \frac{T_L(f)}{T_R + T_C}$$

Thus, a strong, narrow (H_2O) line, say equal to the system temperature, will appear with only half the amplitude in reference compared to signal.

Possible Contributions to Baselines

1. One of the most persistent comments on baselines is that they worsen when a source has high continuum temperature. The spectral equation gives some hint of the reason for this in the term $T_C \left(\frac{T_R}{T_{RF}(f)} - 1\right)$. That is, if the off scan receiver temperature is non-uniform, baseline irregularities appear that are proportional to source continuum. In a 10 K continuum source, a baseline variation of 0.1 K will result from a receiver noise variation of only 1%. Many receivers, especially a maser upconverter, could be expected to vary this much over a frequency range of 20 MHz due to non-uniform gain, input match, and second stage noise. In addition, structure waves and even IF line standing waves will contribute to a variable spectrum. Changing the focus one quarter wavelength allows the cancellation of part of the telescope structure wave but this often seems not to be the dominant feature. A single strong structure wave would tend to produce a sinusoidal baseline in contrast to several waves of various frequencies and amplitudes that would produce a non-sinusoidal baseline.

A gain null noticed on a receiver bandpass is a potential baseline problem that worsens when the source has high continuum. This is certainly true of a maser receiver where such a null (or maximum) means a substantial variation in T_R. An RF null would be expected to produce an output feature in absorption that moves with LO like a sky signal.

2. In the spectral equation derivation it was assumed that the average receiver powers in the on and off scans were the same even though they might have different spectral densities. This might be close to reality if the atmosphere were constant, telescope moves were small, and receiver was stable. But any kind of broadband instability, such as changing weather producing different atmospheric temperatures between the on and off, will complicate the equation by the addition of another baseline disturbing term:

$$\Delta T_R \left(\frac{T_R}{T_{RF}(f)} - 1 \right) \text{ similar to } T_C \left(\frac{T_R}{T_{RF}(f)} - 1 \right)$$

where

$$\Delta T_R = \int_0^B T_{RN}(f)\, df - \int_0^B T_{RF}(f)\, df$$

Since T_C is constant and ΔT_R more likely a variable, it is expected that the total effect on baselines will be quite different when several scans are combined and on the time synchronization between scan and instability. But in both cases it is seen that the reason for this form of baseline problem is not due to a difference between on and off spectral powers but because of a non-uniform receiver spectral power for the off.

3. Suppose that noise equal to T_C is intentionally added to the receiver during the off scan. Then the continuum dependent term is

$$T_C \left(\frac{T_{RN}(f) - T_{RF}(f)}{T_{RF}(f) + T_C} \right) \quad \text{instead of} \quad T_C \left(\frac{T_R - T_{RF}(f)}{T_{RF}(f)} \right)$$

It appears that the baseline disturbance would be diminished by noise adding compared to straight total power whenever the difference in receiver spectral powers between the ons and offs was better than the non-uniformity of the receiver noise. Noise adding capability has been built into the Cassegrain receivers but has not been used so far. The inconvenience of balancing the added noise has to be considered, as well as the possibility that the baselines could be worsened if the added noise were non-uniform.

4. The third term of the spectral equation, $T_R \left(\frac{T_{RN}(f)}{T_{RF}(f)} - 1 \right)$, shows baseline variations proportional to receiver temperature whenever the on and off receiver spectral densities are different. It is expected that this difference would be greater for frequency switching expecially if switching more than a few MHz, and the receiver gain functions for signal and reference would be expected to be different as well. The Cassegrain receivers are frequency switched sometimes but usually for narrow autocorrelator bandwidths where baselines are less of a problems.

There are certain frequencies where bad (100 MK peak to peak) baselines are produced by beam switching on cold sky with the telescope fixed near zenith. But time stability is apparently good because subtracting alternate scans show excellent cancellation of structure. Baselines like these could be caused by different receiver spectral noise for the two beam positions.

5. Sometimes the baseline structure moves with respect to a real or imagined sky test line when the front end is LO shifted indicating a problem in the front end mixer or downstream from it. This behavior is almost always worse for high continuum sources and can be caused by a non-uniform $T_{RF}(f)$ due to early IF gain and/or noise structure, reflections in the IF, front end mixer conversion gain structure, and possibly local oscillator noise and mixer image

noise. These conditions can worsen baselines whenever maser gain is reduced to broaden bandwidths to more than about 100 MHz. Improvement might be noted when low noise K band amplifiers become available to be placed ahead of the mixer.

6. The spectral equations show the levels of non-ideal behavior necessary to produce a given baseline. Typical numbers for X band are:

T'_R = 27 K receiver temperature at feed aperture.

T_F = 8 K spillover, scatter, background.

T_{atm} = 5 K atmosphere on overcase sky at 45 degrees elevation.

T_C = 12 K source continuum on Virgo.

$$T_{sys} = (T'_R + T_F + T_{atm}) + T_C$$

$$T_{sys} = (27 + 8 + 5)\ K + 12\ K$$

$$T_{sys} = 40\ K + 12\ K = 52\ K$$

Under these conditions, a baseline structure amplitude of 50 MK can be caused by a non-uniform receiver spectral power of 0.17 K due to a 0.62 percent structure in $T'_R(f)$ or 2.1 percent in $T_F(f)$. It can also be caused by a difference of 0.05 K in the spectral powers between the ons and offs due to a 0.19 percent difference in $T'_R(f)$ or 0.62 percent in $T_F(f)$. The same receiver spectral power characteristic will cause a baseline amplitude of only about 4.2 MK for a 20 percent change in the atmosphere between an on and off.