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6 October 1993

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To: Millimeter-wave VLBI Group

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Subject: Systematic limits to continuum and spectral line observations

Introduction

For wideband radiometers and spectrometers very long integration times often make systematic effects dominate over the random noise. Dicke and double-Dicke switching has to be introduced to reduce the baseline ripple in spectral line and the drifts in continuum observations. In this memo I attempt a quantitative analysis to help evaluate the expected magnitude of the limits imposed by systematic effects

Quantities involved

$G(f,t)$ - Receiver gain - mostly a function of frequency and time
$R(f,t)$ - Receiver noise
$A(f,\theta,t)$ - Atmospheric noise - mostly a function of pointing and time
- but also a function of frequency as a result of multi-path
- on the antenna
$S(f,\theta,t)$ - Spill-over noise
$W(f,\theta,t)$- "Weinreb" noise - receiver noise reflected back into the feed thereby producing standing waves
$C(f,\alpha,\delta)$- Weak spectral or continuum source we hope to observe - mostly a function of frequency and location in celestial coordinates
Ts - Nominal system temperature

Typical magnitudes of the variations in *G,R,A,S,* and *W*, are given in Table 1.

Table 1. Approximate values for systematic contributions to the total power.

	Total Contribution	Time Variability	Frequency Ripple	Variation With Angle	Comments
GT_s	100K	100mK/s	1K/MHz	-	depends on radiometer
R	50K	10mK/s	100mK/MHz	-	
A	2K	10mK/s	-	10mK/deg	at 4 GHz
A	20K	100mK/s	-	100mK/deg	good condx. at 86 GHz
S	20K	1mK/s	100mK/MHz	100mK/deg	no radome
S	40K	2mK/s	200mK/MHz	1K/beam	with radome
W	1K	-	100mK/MHz	100 mK/beam	"
Sun	20mK	-	-	20mK/beam	"

Assume T_s = 100K, $G \approx 1$

Received power

The received power P is given by

$$P = G(R + A + S + W + C) \tag{1}$$

which provides a very poor measure because the variations in gain will dominate the output so we form the first Dicke difference (assuming C is only present in the "signal" portion of switch cycle).

$$\begin{aligned} D_1 &= T_S \left[\frac{P_S - P_R}{P_R} \right] \\ &= T_S \left[\frac{(S_S - S_R) + (A_S - A_R) + (W_S - W_R) + C}{R + A + S + W} \right] + \frac{T_S}{G} \frac{dG}{dt} \Delta t_1 \end{aligned} \tag{2}$$

where we assume that the only remaining time drift is the residual gain drift. This term will decrease as the switch period Δt_1 is made shorter.

Now assuming that the gain variations have been removed we are still left with large systematic variations as S, A, and W are still likely to be different for the signal and reference. In the case of beam switching however, we might assume that the atmospheric noise cancels so that

$$\begin{aligned} D &\approx T_S \left[\frac{(S_S - S_R) + (W_S - W_R) + C}{R + A + S + W} \right] \\ &\approx (S_S - S_R) + (W_S - W_R) + C \end{aligned} \tag{3}$$

If we now introduce a second difference ("double-Dicke") for which the pointing θ and frequency f is the same for the signal and reference cycles

$$\begin{aligned} DD &= (D_S - D_R) \\ &= C + \left[\frac{d}{dt} (S_S - S_R) + \frac{d}{dt} (W_S - W_R) \right] \Delta t_2 \end{aligned} \tag{4}$$

There are two ways to match the angles for the double-Dicke cycle. The first method is to hold θ constant and let the source drift through the beam and the second method is to match the range of θ during an integration on-source with an off-source integration which covers the same range of angles (i.e., a radome retrace). The time variable contributions can be minimized by minimizing Δt_2 i.e. making the on/off cycle as fast as possible.

The "Weinreb" Effect (Also see Memo dated 17 May 1993)

The "Weinreb" effect is very sensitive to geometry, especially at high frequencies, because this contribution to the noise is the result of a portion receiver noise *W* being radiated out of the feed and then received back into the feed. In many amplifiers this noise is correlated with the receiver noise *R* and so the final contribution depends on the phase or precise distance of ther reflected noise. The phase of reflections from the radome, for example, will change on the scale of a beamwidth of antenna motion.

Additional sources systematic variations

a) Sun

The large radio flux from the sun also adds to the total power (especially for antennas in a radome). Unfortunately the solar contribution is not the same for the on/off portions of the double-Dicke switching since either the pointing relative to the sun can be repeated or the pointing relative to the ground but not both. The solar flux is likely to limit daytime observations for antennas in a radome.

b) Change in continuum level

If the source itself is strong or is a weak source spectral with strong continuum the double-Dicke cycle will fail to produce good baselines if there are significant standing waves or the back-end frequency response is level dependent. (An AGC might be helpful in making the back-end frequency response less dependent on level.)

Summary of the level of systematic variations

Table 2 summarizes the expected levels of systematic effects for total power, Dicke switched and double-Dicke switched.

Table 2.

Mode	Continuum	Spectral	Theoretical Noise[1]	Comments
Total Power	10K	1K/MHz	0.5mK	drift in 100 sec
Beam Sw.	1K	200mK/MHz	1mK	fast enough to remove gain var.
Double-Dicke	20mK	-	2mK	10 sec cycle
Double-Dicke	2mK	-	2mK	1 sec cycle

Notes: 1] For 500 MHz Bw, T_s = 100K, τ = 100 sec, nighttime

While the levels of systematic effects are wild guesses, the analysis demonstrates the need to reduce reflections and spill-over as much as possible and the need for double-Dicke switching. Unfortunately, in most cases, double-Dicke increases the random noise by a factor of 4 unless the first or second difference has the signal in both halves of the cycle as is possible, for example, in the case of frequency switching.