How to Measure the Cosmic Microwave Background with TV Satellite Equipment

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Introduction

It is possible to measure the temperature of the remnant radiation from the Big Bang with the normal equipment used to receiver satellite television. Timo Stein and Christopher Förster (Sterne und Weltraum, 7/2008, p.84) describe their equipment and technique, which won them a prize in a young science competition. Michel Piat (APC, Université Paris Diderot-Paris 7) developed and used such equipment for practical observation work for his students.

This report discusses both approaches and summarizes the construction, observation, and data analysis.

There are only two important issues that need to be resolved in order to allow normal equipment to furnish meaningful results:

- the antenna must be protected to pick up ground radiation which can reach the LNB in the focus by coming beyond the rim of the reflector dish ("spill-over")
- the receiver must be properly flux calibrated

Spill-over Protection

This can be achieved by limiting the field of view of the antenna's feed to the reflector only, by appropriate metallic shielding of the reflector's rim.

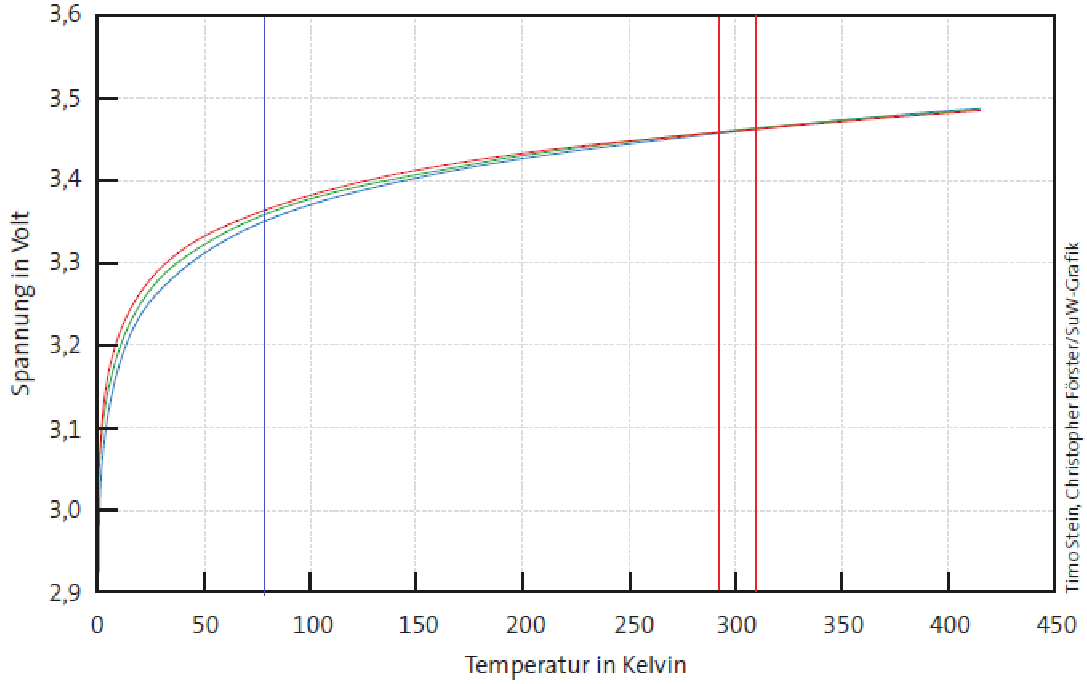
	
Stein and Förster use a cylindrical collar (about 1.5 m length) of aluminum foil put around the rim of the reflector (diameter 1m). The foil is wrapped around a cylinder formed with chicken wire fence material (with mesh size 13 mm)	Piat uses metal panels (or a second, larger parabolic dish) placed behind the reflector (0.6 m diameter).

Flux calibration

In 'normal' radioastronomical observations one may simply assume that the sky has a near-zero or negligible temperature. Thus, the measurement of a single source of known temperature suffices, usually the thermal radiation of the ground. For the measurement of the CMB, the calibration with a second source, at different temperature, is necessary.

For calibration Stein and Förster place the antenna under a 1.6 m high table with acrylic plastic surface covered with two bathroom rugs, well soaked with water, so that they make a good absorber at 10 GHz. Between the rugs there is a sensor for an electronic thermometer. During calibration, the water is heated by a three controllable heating foils. Four sheets of old wood were placed on top, for thermal insulation. Readings are taken at several temperatures.

However, the useable range for the temperature is rather small. Their article mentions 295 to 315 K. Thus, extrapolating the measurements to very low temperatures seems a bit daring!



Calibration curves from Stein and Förster. The vertical axis is the voltage from the receiver. The red vertical lines indicate the temperature range, over which measurements had been taken, from which the three curves were obtained. The blue line marks the boiling point of liquid nitrogen, as is used along with the room temperature (290 K) by Piat.

Piat uses the ambient temperature – by holding a piece of Eccosorb in front of the LNB – for the hot calibrator, and the boiling temperature of nitrogen (77 K) for the cold calibrator, by holding the Eccosorb soaked in liquid nitrogen before the LNB. This gives a much larger range of temperatures, and a much more reliable calibration for low temperatures.

Of course, the relation between received power and the output value of the measurement must be well-known. Most conveniently it could be a linear or logarithmic relationship.
Stein and Förster use the AD 8313 logarithmic detector, which rectifies the broadband noise coming from the conventional satellite TV LNB. They verified the linear response for detector input levels of -60 to -20 dBm.

Observational Technique

The telescope is pointed at the empty sky, at a number of elevations, between 10 and 90°. Since the sky noise varies like 1/sin(elevation), it is somewhat advantageous to use elevation angles that are more widely spaced at high elevations.

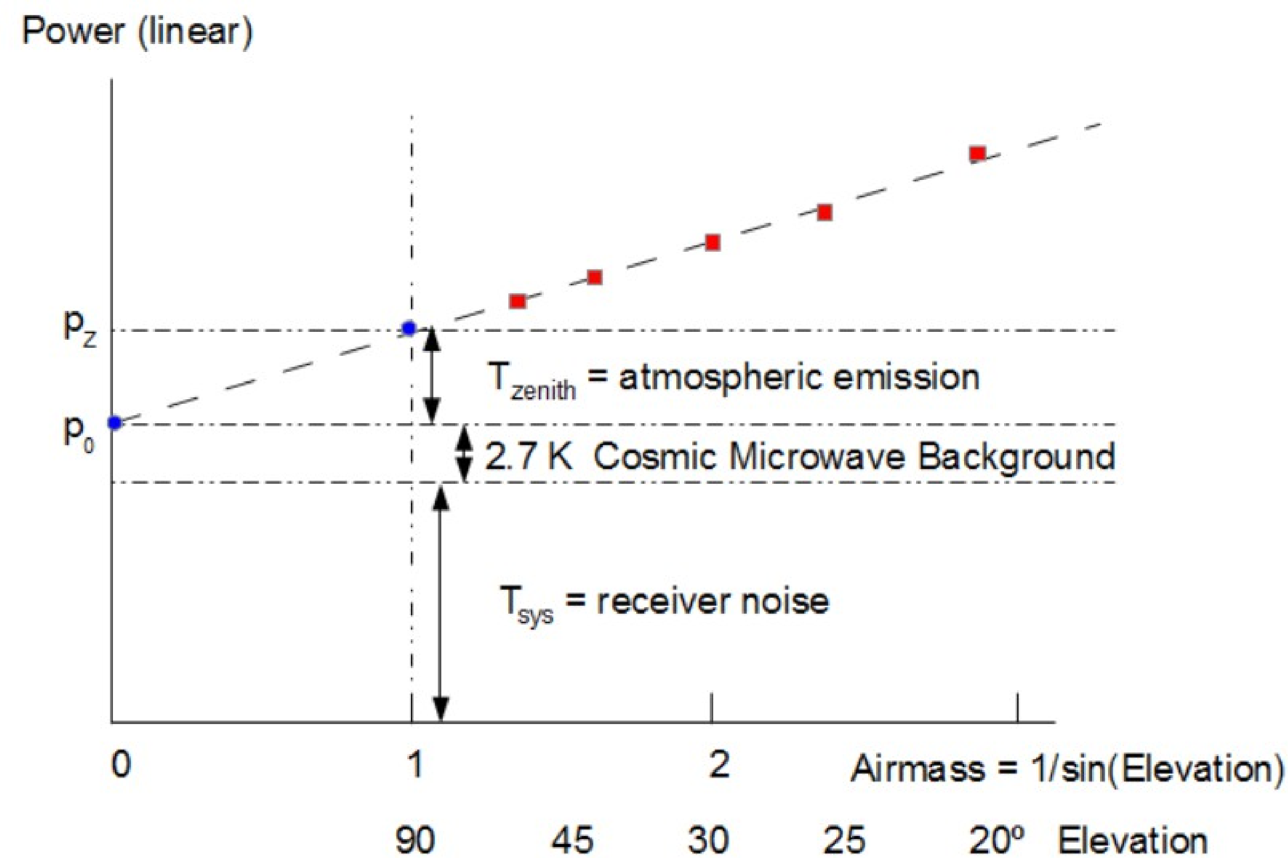
Data Analysis

Since the thermal emission of the Earth atmosphere can well be represented by a plane-parallel isothermal atmosphere which yields a simple relationship between emitted power p and elevation ε

$$p_{sky}(\varepsilon) = T_{zenith} / \sin(\varepsilon) = T_{zenith} * A \qquad (1)$$

we only need to determine the zenith temperature T_{zenith}. It is convenient to introduce the air mass A = 1/sin(ε) which measures the length of a column of air at a given elevation, relative to the column in vertical direction..

All other noise sources, such as the Cosmic Microwave Background and the internal noise of the receiver, do not depend on elevation. Thus, the measurements, taken at several elevation angles, can be modeled by a straight line between (linear) power and air mass:



Fitting the measurements by a straight line, one obtains the slope m and the offset p_0. Hereby p_0 is the power level extrapolated to zero air mass, i.e. as if there was no Earth atmosphere:

$$p(\varepsilon) = p_0 + m * A \qquad (2)$$

As seen in the above diagram, p_Z is the value of the measurements extrapolated to the zenith (at A=1).

The interpretation of the data proceeds as follows: The power measured in the sky at elevation ε is proportional to the sum of the (antenna) temperatures of the various contributions:

$$p(\varepsilon) = a * (T_{sys} + T_{CMB} + T_{sky}(\varepsilon)) \tag{3}$$

where the system temperature T_{sys} stands for the internal noise of the receiver, T_{CMB} is the temperature of the CMB – which we like to measure – and $T_{sky}(\varepsilon)$ is the sky noise. The scale factor a is determined from the flux calibration. Written in terms of air mass, one has

$$p(A) = a * (T_{sys} + T_{CMB} + T_{zenith} * A) \tag{4}$$

Comparison with (2) shows that the slope is $m = a*T_{zenith}$. Thus the zenith temperature is given by

$$T_{zenith} = m/a \tag{5}$$

When the telescope faces the hot calibrator, there are no contributions from the CMB or the sky:

$$p_H = a * (T_{sys} + T_H) \tag{6}$$

with the known temperature T_H . Likewise, the cold calibrator yields

$$p_C = a * (T_{sys} + T_C) \tag{7}$$

These two measurements allow to derive the scale factor a:

$$a = (p_H - p_C) / (T_H - T_C) \tag{8}$$

Then, from (6) the system temperature can be obtained

$$T_{sys} = p_H/a - T_H \quad = p_H/ (p_H - p_C) * (T_H - T_C) - T_H \tag{9}$$

Finally, subtraction of (6) from (4) gives

$$p(A) - p_H = a * (T_{CMB} + T_{zenith} * A - T_H) \tag{10}$$

and the temperature of the microwave background

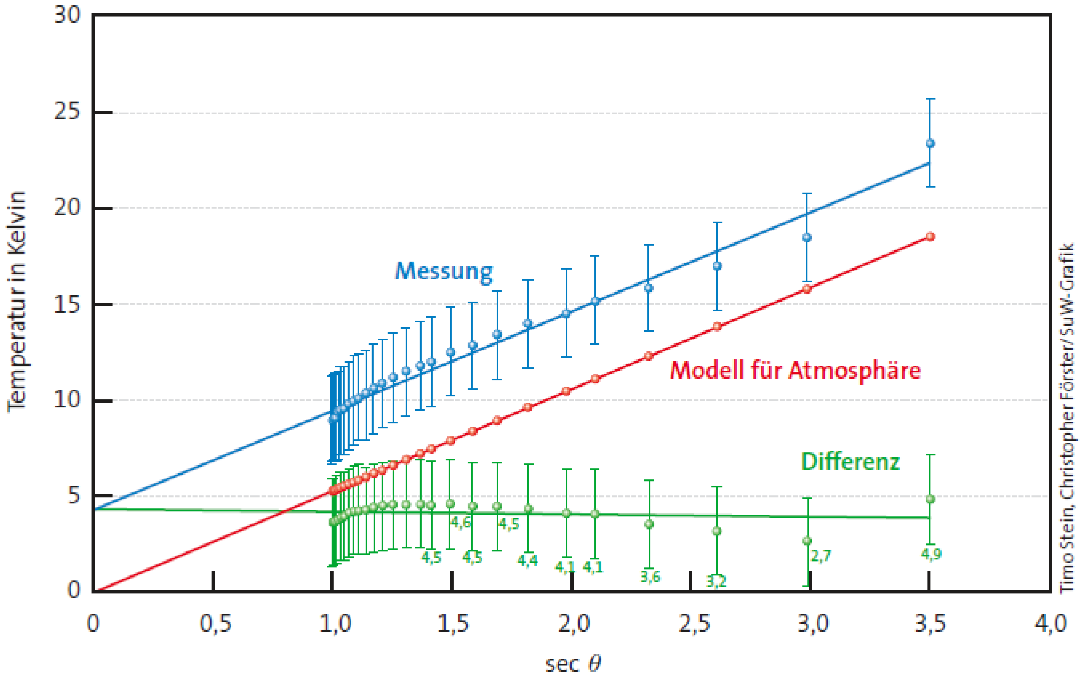
$$T_{CMB} = (p(A) - p_H)/a + T_H - T_{zenith} * A \tag{11}$$

It can be evaluated for each elevation, in particular for A=0 or the zenith:

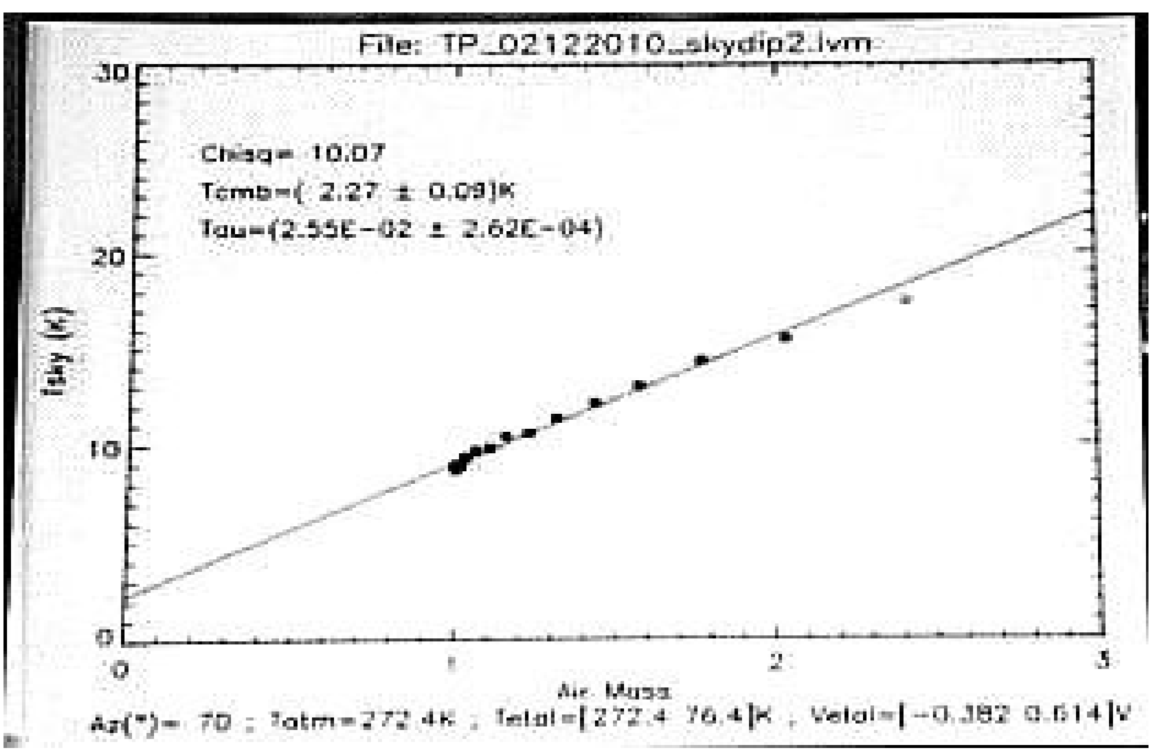
$$T_{CMB} = (p_0 - p_H)/(p_H - p_C) * (T_H - T_C) + T_H \tag{11a}$$
$$T_{CMB} = (p_Z - p_H)/(p_H - p_C) * (T_H - T_C) + T_H - T_{zenith} \tag{11b}$$

Results

Stein and Förster find that the slope of their measurements gives a zenith temperature of 5.2 K (at DL0SHF we measure 5 to 7 K, depending on the weather), and that the temperature of the CMB is between 3.6 and 4.5 K Given the calibration's rather narrow temperature range, this is pretty nice!



The measured antenna temperatures of sky and CMB (blue), the model for atmospheric emission (red) and the difference (green). The abscissa is air mass.



A typical result plot from Piat.(from a presentation)