BOOMERanG: BALLOON OBSERVATIONS OF MILLIMETRIC EXTRAGALACTIC RADIATION and GEOPHYSICS

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Abstract

The BOOMERanG experiment is an international effort to measure the Cosmic Microwave Background (CMB) anisotropy at an angular resolution of $12 \div 20$ arcmin, with unprecedented sensitivity, sky and spectral coverage. The telescope will be flown from Antarctica by NASA-NSBF with a long duration stratospheric balloon (7-14 days), and is presently scheduled for a test flight in 1996 and an Antarctic flight in 1997. The experiment is designed to measure the power spectrum of the CMB anisotropies up to $\ell \sim 700$ and to produce an image of the CMB sky with high sensitivity and angular resolution. It will be an important precursor of future space-borne missions, producing crucial cosmological data and testing new technologies which are essential to the design of a CMB mapping satellite experiment.

1 General design of the experiment

Antarctic ballooning is very attractive for CMB anisotropy experiments for two reasons. The first is that the flight duration can be between 7 and 20 days, thus allowing for a substantial sky coverage and for a deep check for systematic effects; the second is that very low foreground regions are observable exactly in the direction opposite to the sun during the Antarctic summer. The lowest dust contrast region in the IRAS Sky Survey Atlas is at R.A. $\sim$ 4.5 hours, dec. $\sim$ -45°, and is more than 1000 square degrees in area. The contrast in the dust emission corresponds to CMB temperature anisotropy of less than 3 μK rms in the 4-7 cm^{-1} band, a value negligible with respect to the rms level of the sub-degree CMB anisotropies. A good signal to noise map of the CMB in this region will provide a very strong test for gaussianity of the CMB anisotropies. A much larger region can be observed with a dust contribution lower than 20 μK in the same frequency band. Such an observation could provide a very precise measurement of the power spectrum of CMB anisotropies. We plan to have a test flight from North America, with a $\sim$ 15% sky coverage, and an Antarctic flight with similar sky coverage and higher signal to noise ratio [1]. A general view of the experiment is shown in fig.1. A simulation of the anisotropy power spectrum measurements for both flights is shown in fig.2. In the simulations we have assumed we are operating in a differential observation mode in order to guarantee negligible drifts in the data. We are also assuming that such observation mode is effective in removing completely residual atmospheric fluctuations, an issue still to be experimentally investigated, especially at low ℓ-s.

There are, however, a number of problems peculiar to Antarctic ballooning. The long flight duration requires special cryogenic systems. The cosmic rays flux in polar regions is enhanced by a factor about ten with respect to our latitudes, thus increasing the noise in standard bolometric detectors. The long duration balloon flights are performed during the Antarctic summer: the presence of the sun is a general concern for the thermal performance of the payload and for the sidelobes pickup of the telescope. The balloon is far from the ground equipement, so special data collection / telemetry systems have to be used, and interactivity with the system is reduced.

2 Detectors and Feed Optics

Spider web bolometers have been developed to avoid cosmic rays glitches [2]. These bolometers use micromesh absorbers and support structures patterned from thin films of low stress silicon nitride and have been designed for operation at 0.3 K with a radiation load lower than 1 pW. The small geometrical filling factor of the micromesh absorber provides 20× reduction in heat capacity and cosmic ray cross section relative to a solid absorber with no loss in infrared absorption efficiency. The support stucture is mechanically robust and has a thermal conductance, $G < 2 \times 10^{-11}$ W/K, which is 4 times smaller than previously achieved at 300 mK. The temperature rise of the bolometer is measured with a neutron transmutation doped Ge thermistor attached to the absorbing mesh. The achieved detector NEP at 0.3 K is 1.2×10^{-17} $W/\sqrt{Hz}$ with a 20 ms time constant. The bolometers are mounted in multiband photometers and single pixel detectors in the focal plane. We have developed both single mode and overmoded feeds with high optical efficiency which allows us to optimize the focal plane for angular resolution (12' at 150 GHz) and/or optical sensitivity (35 μK$\sqrt{s}$ at 90 GHz).

To read out these detectors, we use an AC stabilized "total power" amplifier for individual bolometers mounted on a temperature regulated stage. This system contains a cooled FET input stage and contributes less than 7 nVrms/$\sqrt{\text{Hz}}$ noise at all frequencies within the bolometer signal bandwidth down to 20mHz. The warm readout circuit has a gain stability of $<$ 10 ppm/°C and has a rejection of EMI of -120 dB. This readout scheme combined with the temperature control of the 300 mK stage makes it possible to implement scan strategies for total power mapping with bolometers.

Fig.1 : The BOOMERANG Payload

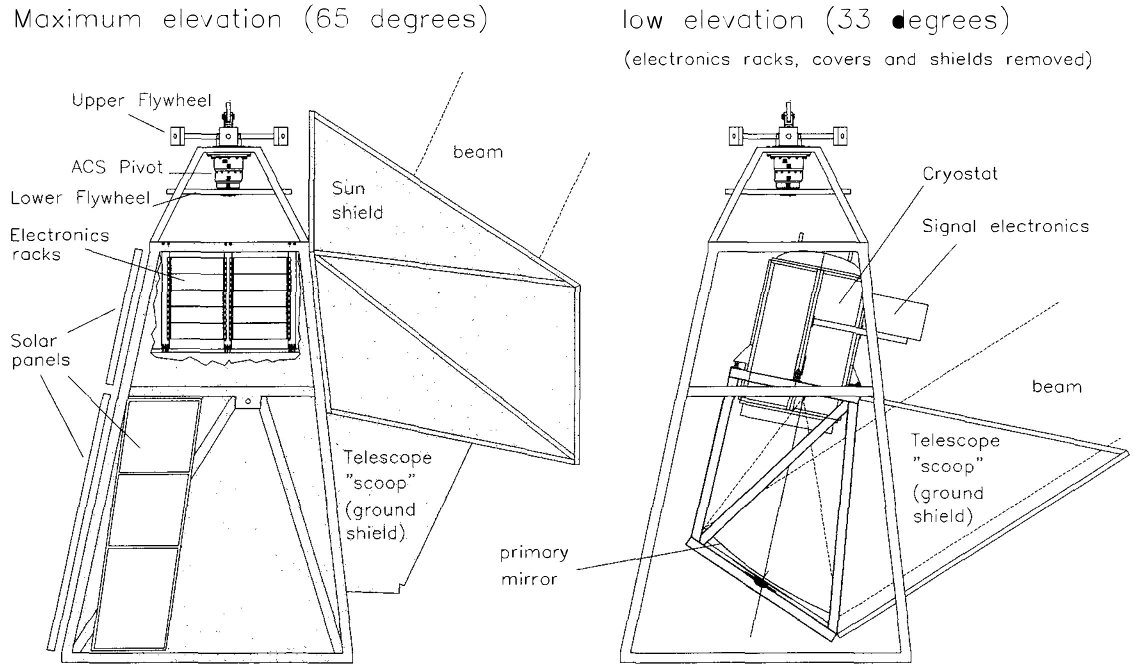
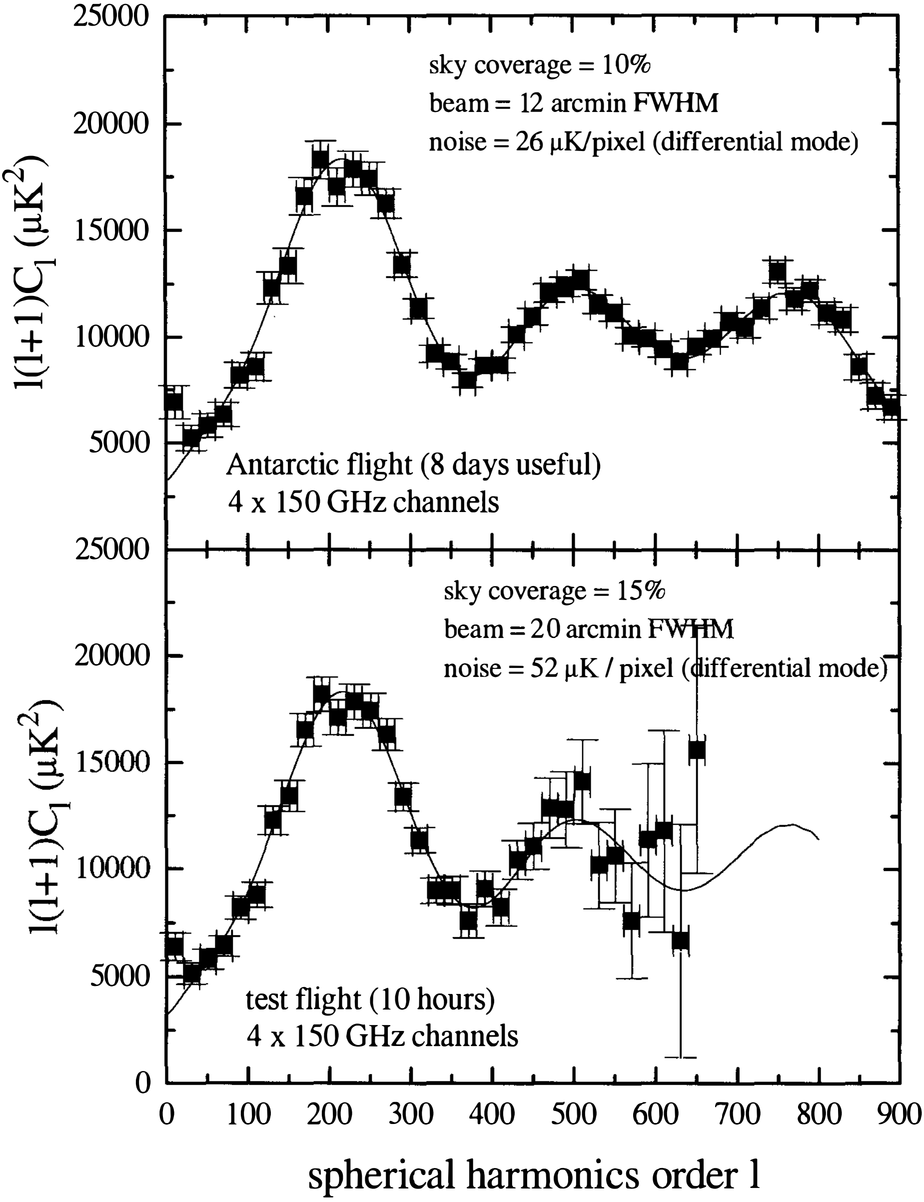


Fig.2 : simulation of BOOMERanG power spectrum measurements



3 Cryogenic system

A "heavy duty" ^{3}He fridge and a large ^{4}He cryostat have been developed specifically for the BOOMERanG experiment. The main ^{4}He cryostat has to be large enough to contain refocusing optics and a wide focal plane with several multiband photometers. The total volume occupied by the cryogenic section of the receiver is about 0.5 m^3. The design hold time is about 20 days; the helium tank volume is 60 liters, the nitrogen tank volume is 70 liters. Conduction thermal input is reduced by suspending both the tanks with Kevlar ropes (1.6 mm diameter). The vibration frequencies of these structures are all above 20 Hz, and the amplitude of the vibrations excited during the flight is expected to be very small. Radiation thermal input on the nitrogen tank is reduced by means of 110 layers of aluminized mylar for superinsulation. The total thermal input on the nitrogen bath is about 3 W. The radiative thermal input on the helium bath is reduced by the use of a copper shield between the He tank and the Nitrogen tank. The shield is mantained at around 25 K by the vapours evaporationg from the He tank. The total thermal input on the helium bath is about 50 mW. The bolometers are cooled by a self contained ^{3}He fridge. The charge is 34 liters STP at 40 bars. The measured working temperature is 0.29 K (in flight), raising to 0.31 K when the ^{4}He bath is at normal pressure (lab tests). The measured hold time is longer than 15 days.

4 Optics

The optical system must be able to define a sharp field of view for the detectors, collecting the largest possible amount of power from the selected region of the sky and rejecting efficiently emission from off-axis sources and foreground radiation. We have developed an off/axis system based on an ambient temperature primary mirror that is a paraboloid with 1.2 m projected diameter, 1.28 m focal length, and 45^o off-axis angle. Two aluminum refocussing mirrors (off axis paraboloid and ellipsoid) are mounted at 4.2 K, inside the dewar. Radiation from the sky is reflected by the primary mirror (the primary is underfilled to improve sidelobes), crosses a thin polypropilene window, and is concentrated at the focus, inside the ^{4}He dewar. A filter reflecting high frequencies is mounted on the 77K shield, and a mesh filter is mounted on the 4 K shield, at the entrance of the refocussing optics box. Eccosorb vanes inside the box reject stray rays. The last mirror defines the cold Lyot stop of the system. The two off axis mirrors produce a large curved focal plane above the optics box. The useful size of the focal plane is 30 by 20 cm. This corresponds to more than 4 by 2.5 degrees in the sky. The large focal plane allows both a large number of detectors and the ability to synthesize many different window functions by differencing between various pixels in order to optimally reject low-ℓ sources of noise. The bolometers are arranged in single-band (S) and multi-band (M) photometers as listed in table 1.

Table 1: Focal plane of the BOOMERanG receiver

flight	band (GHz)	FWHM arcmin	feeds	NET $\mu K\sqrt{s}$
T	90 S	40	2	35
T	150 S	20	4	60
A	90 S	20	4	80
A	150 M	12	4	90
A	250 M	12	4	140
A	350 M	12	4	1000

A set of shields, partially visible in fig.2, is used to achieve high thermal stability of the telescope and to reduce efficiently sidelobes spillover from the sun and the ground.

5 Attitude Control System

The ACS must be able to point a selected sky direction, and track it or scan over it with a reasonable speed. The specs are 1 arcmin rms for pointing stability, with a reconstruction capability better than 0.5 arcmin maximum. Our main modulation is obtained scanning in azimuth, with a saw-tooth scan, with an amplitude of 20 deg (p-p) and a scan rate of about 1 deg/s. A different scan mode, useful to get a wider sky coverage during North America flights, is the full azimuth rotation of the payload at a speed of about one r.p.m.. An ACS capable of the above mentioned performances has been developed from the ACS systems used for ARGO and MAX-5. It is based on a Pivot which decouples the payload from the flight chain and controls the azimuth, plus one linear actuator controlling the elevation of the inner frame of the payload. The pivot has two flywheels, moved by powerful torque motors with tachometers. On the inner frame, which is steerable with respect to the gondola frame, are mounted both the telescope and the detectors cryostat. The observable elevation range is between 25 and 65 deg. The sensors are different for night (North America) and day (Antarctic) flights. For night flights we have a magnetometer and an elevation encoder; additional information on the attitude is obtained by means of a sensitive tilt sensor. A CCD camera is used outside the feedback loop for absolute attitude reconstruction. For day time antarctic flights we have a set of low and high resolution sun sensors and the tilt sensor. A flight programmer CPU takes care of commands handling and observations sequencing; a feedback loop controller CPU is used for digitization of sensors data and PWM control of the current of the three torque motors. A similar system has been tested in the MAX-5 flight in september 1995, with good overall performance.

6 Conclusions

The use of total power readout with overmoded bolometers at 300 mK allows us to get an unchopped sensitivity of $\sim 80\mu K\sqrt{s}$ for the 3 cm^{-1} (20' FWHM) channel; $\sim 90\mu K\sqrt{s}$ for the 5 cm^{-1} (12' FWHM) channel, $\sim 140\mu K\sqrt{s}$ for a 8 cm^{-1} (12' FWHM) channel. If we scan a $50^o \times 50^o$ region (6% of the sky, more than 20000 pixels for the 20' channel and more than 60000 pixels for the 12' channels) for 8 days with four detectors per band, we get an unchopped sensitivity of $7\mu K$/pixel at 3 cm^{-1}, $13\mu K$/pixel at 12 cm^{-1}, and $18\mu K$/pixel at 8 cm^{-1}. Real sensitivity will be degraded from this depending on the level of atmospheric noise, on the analysis algorithm and on the in-flight performance of the system. However, these numbers give already an idea of the high quality and enormous amount of information which will be produced by BOOMERanG.

References

[1] Lange A., et al. 1995, *Space Sci. Rev.* **74**, 145

[2] Bock J., et al. 1995, *Space Sci. Rev.* **74**, 229