We review the topic of Cosmic Microwave Background Anisotropy measurements carried out by means of balloon-borne telescopes. After a short description of the experimental methodology, we outline the peculiar problems of these experiments, and we describe the main results obtained and the perspectives for future developments.

1 Stratospheric Balloons and CMB Anisotropy Measurements

1.1 Stratospheric Balloons

Stratospheric balloons are space carriers offering flights at 30-40 Km altitude, for payloads with mass up to 2500 Kg, with reasonable cost and short development time scales. The available time at float ranges between a few hours and a couple of weeks. The intrinsic payload stability is of the order of a few arcminutes. The observable elevations are between $0^\circ$ and $65^\circ$ (or up to the zenith placing the payload on top of the balloon).

The team of NASA-NSBF (USA) offers 6-48 hours flights over North America and 1-2 weeks flights in Artic and Antarctic (Long Duration Balloons). The team of CNES (France) offers balloon flights of a few hours over France and up to 60 hours in Sweden. The team of ASI (Italy) offers 20-40 hours transmediterranean flights from Sicily to Spain. Balloon flights are also carried out by teams in Russia, Brazil, Japan and in China.

Infrared mongolfiere have been used for ultra long duration flights of lightweight payloads ($\sim 50$ Kg). Superpressure balloons are being developed, providing in the near future ultra-long ($\sim 3$ months) balloon flights for medium-mass payloads.
1.2 CMB measurements from Stratospheric Balloons

The main advantage of placing a CMB telescope on a stratospheric balloon is a large reduction of the atmospheric brightness (temperature) and noise. This effect is wavelength dependent. The advantage is huge for observation wavelengths above 100 GHz, while it is not too important for wavelengths below 40 GHz, where longer observation time and easier access to the experiment favour high mountain observations. For wide band bolometric receivers the balloon environment offers an additional advantage, since the reduced radiation background permits to reach a lower temperature of the sensor, thus increasing significantly its sensitivity.

A generic instrument for the measurement of CMB anisotropies is composed by the following main subsystems: the gondola, usually an aluminum or carbon fiber tubular lightweight structure with an inner frame (containing the telescope, the receiver and a star sensor for attitude reconstruction) and an outer frame containing the elevation mechanism for the inner frame, the azimuth mechanism and a pivot to rotate the entire payload with respect to the flight chain, the data processing and storage electronics and lithium batteries to power the system. The space agency provides the uplink and downlink telemetry and the navigation hardware (GPS, altitude sensors, ballast, balloon valves etc.).

Placing the telescope below a stratospheric balloon has a number of disadvantages. Interaction with the experiment is greatly reduced, and the duration of the measurement is only a few hours for normal balloon flights. So all the tests for systematic effects must be planned in advance, with great care, and inserted in the flight sequence, taking advantage of the increased sensitivity of balloon systems to perform quicker test. Also, the balance between time devoted to integration, time for calibration, and tests for systematics must be optimized. Long Duration Ballooning offers unique extensive possibilities of systematics tests.

The telescope must point/scan the sky regions selected for calibration and observations. Pointing a telescope attached to a stratospheric balloon is much more difficult than pointing a ground based telescope, and also more difficult than pointing a satellite, due to the presence of gravity and of perturbations induced by the residual atmosphere. A huge effort has been paid by X-ray and IR astronomers to develop Attitude Control Systems (ACS) suitable for balloon borne experiments. These systems are based on gyroscopes, magnetometers and star cameras as sensors, and on motorized high inertia flywheels as actuators to control the payload motion. Receiver calibration is usually achieved observing a planet. The performance of the ACS should be good enough to provide a pointing stability of at least FWHM/20, with the additional necessity of making good raster scans for beam shape and calibration purposes. An advantage of balloon experiments with respect to ground based experiments is the possibility of measuring the large scale dipole anisotropy of the CMB, which provides a calibrator with the same spectrum of the (sub-)degree scale anisotropies. In this case, the ACS should be able to rotate the experiment over 360° in azimuth, with a scan speed large enough to maintain the dipole signal inside the useful electrical bandwidth of the instrument and with negligible pendulations. Due to atmospheric inhomogeneity and sidelobes spillover, this calibration mode is practically impossible for ground-based experiments.

The balloon - flight chain - payload system is a pendulum. The balloon drifts with the stratospheric jet-stream. Inhomogeneities in the wind can excite pendulations of the system, which has three main pendulation modes: a rigid pendulation of the system (period ~ 30s); a pendulation of the payload in opposition with the balloon (period ~ 10s), and a pendulation of the gondola around the pivoting point (period of a few s). Pendulations of the experiment can also be induced by the attitude control system itself, due to the non-diagonal nature of the inertia tensor of the payload and to static and dynamic unbalancing of the flywheels. Pendulations modulate the residual atmospheric brightness, thus producing a periodic signal in the receiver. If $I_{ATM}(e, \nu)$ is the atmospheric brightness, $E(\nu)$ is the spectral efficiency, and $e$ is the beam
elevation, pendulations $\Delta e$ produce brightness fluctuations equivalent to CMB temperature fluctuations, of the order of

$$\frac{\Delta T_{\text{CMB}}}{\Delta e} = \frac{T_{\text{CMB}}}{\tan e} \int B(T_{\text{CMB}}, \nu) \frac{\text{sec}^e}{\nu} E(\nu) d\nu,$$

Bolometric systems are prone to this problem, since their spectral efficiency is intrinsically quite wide, and the $E(\nu)$ is defined by means of suitable blocking / mesh filters. In fig.1 we compare the spectrum of the atmosphere to the spectrum of the CMB anisotropy as seen through a suitable filters chain defining a 90 GHz nominal bandpass. The pendulation induced signal can be reduced to $\sim 1\mu K/\text{arcmin}$ with extreme care in the quality and choice of the receiver filters, and with good performance of the ACS (pendulations lower than a few arcmin peak to peak).

Radio Frequency interference due to powerful telemetry transmitters is difficult to fight, especially for the ultrasensitive bolometric microwave receivers used for CMB anisotropy research. To understand the extent of the problem, one should notice that the telemetry transmitters have a power of a few W at a frequency of a few GHz, while the CMB receivers have a sensitivity of the order of $10^{-17}$ W at a frequency only 100 times higher. Extensive filtering of the signal lines exiting the receiver and wavelength selection / filtering on the optical path of the receiver must be carefully optimized.

The problem of sidelobes rejection is common to all the CMB experiments. These experiments try to detect $10\mu K$ signals embedded in a 300K environment. Balloon experiments cannot take advantage of drift scans, due to the very long integration time required by such an observation mode. Very clean (low sidelobes) off-axis telescopes and shielding systems have been developed. The problem is more severe for long wavelength HEMT-based receivers. Measurements of the same sky patches carried out at different locations during the balloon flight are the only way to test for sidelobes contamination in the cosmological data. In this respect balloon experiments cannot compete with the planned lagrangian point space missions. Anyway, no evidence for spillover contamination has been found in sensitive balloon-borne CMB surveys.

Balloon borne experiments devoted to CMB anisotropy (recent, ongoing and planned) are listed in table 1. The general trend is towards higher angular resolution. Sub-degree resolutions allow to detect the acoustic peaks in the power spectrum of CMB anisotropy, inferring cosmological parameters, and testing for gaussian versus non gaussian CMB fluctuations. The detectability of higher $\ell$ acoustic peaks depends on both the angular resolution and noise performance of the instrument. In general, a beam FWHM smaller than 20 arcmin is required to start to make a reasonable $\ell$-space spectroscopy of the acoustic peaks. 10 arcmin FWHM beams are optimal.

First generation experiments made statistical samples of the sky temperature fluctuations $\Delta T_i$. Second generation experiments are making maps of the CMB temperature field $\Delta T(RA, \text{dec})$, thus producing a lot more information. Transition from the first to the second generation of experiments has been possible because of the development of new detectors: Spider-web bolometers and sensitive HEMTs receivers. The two techniques are in competition. Also, the map making experiments are based on scanning techniques rather than on pointed observations.

### 1.3 Bolometers versus HEMTs

High Electron Mobility Transistors (HEMTs) are used to make sensitive, wide band (10 GHz), coherent detectors. They work up to 50 GHz, with good noise performances: $\text{NET}_{\text{CMB}} \sim 500\mu K\sqrt{s}$ is the state of the art for the noise figure. These devices work at reasonable cryogenic temperatures (4 K) and feature high speed and high rejection of out of band radiation. As a result, they are quite insensitive to atmospheric emission and fluctuations. Also, the fast response
allows for fast scans of the sky, with tendency towards large sky coverage. Working at relatively low frequencies, they need large telescopes to get a given beamsize: getting a diffraction limited beam of 10 arcmin FWHM at 40 GHz requires a 3 m diameter telescope. At higher frequencies (up to 150 GHz), coherent detection systems use SIS junctions as mixers between CMB radiation and radiation from a stable local oscillator. The down-converted intermediate frequency signal is amplified by low noise cryogenic HEMTs and detected.

Cryogenic Bolometers are used to make incoherent, wide band (30-100 GHz) detectors, operating at frequencies higher than 90 GHz with extremely low noise: $\text{NET}_{\text{CMB}} \sim 100 \mu K \sqrt{s}$ is the state of the art. They need very low temperatures (0.3K-0.1K), so require complex cryogenic systems, which must be especially rugged in the case of balloon-borne experiments. Being thermal detectors, feature slow response (tens of ms) and are sensitive to the load from the radiative background. The telescope emissivity needs to be really low, and spillover from ambient temperature blackbody radiation can significantly degrade the bolometer performances. Moreover, bolometers need sophisticated out of band radiation rejection / filtering techniques. Working at higher frequencies, they feature higher angular resolution for the same telescope size: a 0.9 m diameter telescope at 150 GHz already produces a diffraction limited beam of 10 arcmin FWHM. Bolometers are sensitive to any kind of energy deposited in the sensing element. Ionization by cosmic rays (mainly protons) in the stratosphere represents an annoying source of excess noise in bolometric receivers. The problem has been only recently solved with the development of web-like absorbers, which feature negligible cross section for cosmic rays while maintaining full sensitivity to CMB photons and reduced heat capacity, resulting in quicker response.

1.4 Sky scan techniques

The first generation of experiments performed chopped measurements. The beam direction was moved periodically in the sky, thus allowing synchronous detection. The signal to noise ratio was improved spending a long integration time for each selected observed direction. The measured quantities are $\Delta T_{\text{meas},i} = \frac{1}{\sqrt{\tau}} \int_0^\tau \Delta T(\vec{x}(t))R(t)dt$ and the mean square value of the measured signals was compared to the theoretical $\langle \Delta T^2 \rangle = \sum_\ell \frac{2\ell+1}{4\pi} \ell \omega_\ell$. Here the window function $\omega_\ell$ depends on the beam shape and on the details of the modulation performed by the chopper and of the demodulation performed by the signal processing electronics in the receiver. For example, for a total power gaussian beam experiment $\omega_\ell = \exp\left[-\frac{1}{2}(\ell+1)\sigma_B^2\right]$, while for a square wave chop with peak to peak amplitude $\alpha$, $\omega_\ell = 2[1-P_\ell(\cos \alpha)] \exp\left[-\frac{1}{2}(\ell+1)\sigma_B^2\right]$. The results of these experiments are one or a few (if multiple window functions can be obtained from the signals processing) data points in the CMB anisotropy power spectrum. Typical combined analysis of results from these experiments can be found e.g. in [19 20 21].

The second, new generation of experiments performs scan measurements. The telescope beam scans the sky at constant speed. Different spherical harmonic components of the CMB temperature field produce different electrical frequencies in the detector. This experimental approach requires extremely low detector noise and extremely high system stability. $\ell$-space spectroscopy is possible using a scanning instrument and an averaging signal analyzer. The procedure to get power spectra from these data is outlined in [22]. Sky maps can also be recovered from the time ordered scan data. However, drifts and $1/f$ noise project in the map in a non-trivial way, producing the characteristic striping well known for the IRAS and DIRBE maps. The best way to reduce this effect in the data analysis is a hot important topic since the same problem will be present in the data from the future satellite missions MAP and Planck. It must be stressed that scanning balloon experiments represent the only available testbed for studying and reducing the effect, experimenting on both the hardware and the software. From the experimentalist point of view, the first problem is to setup the scan so that the CMB
information is encoded in a frequency band matching the electrical band of the detection system, and as far as possible from system noise and disturbances. Assuming a scan at constant zenith angle $\Theta$, the temperature fluctuations of the CMB along the scan can be expressed as a Fourier series $T(\Theta, \phi) = \sum_m \alpha_m e^{im\phi}$. If the azimuthal scan rate is $\dot{\phi}$, the $m$-th component of the CMB signal (which has a mean square amplitude $\Gamma_m = \langle \alpha_m \alpha_m^* \rangle$) will produce in the detector a signal at the electrical frequency $f = \frac{\dot{\phi}m}{2\pi}$. So a frequency analysis of the detector signal can be performed to get $m$-space spectroscopy of the CMB anisotropy. Moreover, the 1-D $m$-space spectrum $\Gamma_m$ is related in a simple way\(^2\) to the 2-D $\ell$-space power spectrum $c_\ell$ of the CMB: $\Gamma_m = \sum_{\ell \geq |m|} c_\ell B_\ell^2 P_\ell^m(\Theta)$. This relationship is valid for scans along full circles; shorter scans on circle sections have a lower $\ell$-space resolution. All the spherical harmonics components of the CMB with $\ell > m$ contribute to the detector signal at frequency $m\dot{\phi}/2\pi$. If $\ell_{\min}$ is the lowest spherical harmonic of interest, the experimentalist will setup the scan in such a way that noise in the system is confined at frequencies lower than $f_{\min} = \ell_{\min} \dot{\phi}/2\pi$. This condition is quite strict for bolometric receivers, which feature higher 1/f noise knee. On the other hand, if the highest spherical harmonics of interest is $\ell_{\max}$ (which depends on the beam size of the experiment), the scan speed should be adjusted so that the frequency $f_{\max} = \ell_{\max} \dot{\phi}/2\pi$ is lower than the high frequency cut-off of the experiment. This condition is quite strict for bolometric receivers, which feature $\sim 10 \text{ ms}$ thermal time constants. HEMT based experiments can afford faster scan rates, but good tradeoffs are also possible with bolometer based systems, which, in addition, feature a lower general noise level. The situation is depicted in fig. 2, where we plot the typical noise spectrum for a balloon borne CMB experiment, resulting from 1/f and white noise from the detector and the atmosphere and broadened lines from pendulation-induced atmospheric noise. We also plot in fig.2 the transfer function of the bolometer and the frequency spectrum of the CMB signal, as encoded by the scanning procedure and by the beam of the instrument. For beam sizes of the order of 20 arcmin, scan speeds of the order of 3 deg/s, and bolometer time constants below 100 ms, all the interesting CMB anisotropy information can be encoded in the lowest noise frequency band of the system.

2 A small zoo of balloon-borne CMB anisotropy experiments

In the following we summarize the highlights of several recent, ongoing and planned Balloon measurements of the CMB anisotropy at sub-degree scales (see table 1 for a synoptic and for references). It is evident that widely different approaches are used, mainly because different laboratories developed and optimized in their past different detection and processing techniques, and also because we do not know too well the observable to be measured and the related systematic effects.

- Flown experiments:
  - ARGO is a first-generation experiment, developed at the University of Rome La Sapienza, ENEA Frascati and IROE-CNR Firenze, and flown in 1993. The experiment features a 1.2m cassegrain telescope with wobbling secondary, resulting in a 0.8º FWHM beam chopped by 1.4º p-p. The large throughput bolometric receiver had four detectors with bands centered at 2.0, 1.2, 0.8, 0.5 mm. CMB anisotropy was detected in the 2.0 and 1.2 mm bands in the regions of Hercules and Aries/Taurus, with S/N of the order of one per pixel (on $\sim 200$ independent pixels). Spectral ratios and comparisons with local contaminants templates were essential to asses the cosmic nature of the detected fluctuations, excluding local contaminations.

  - BAM is a first generation experiment developed by the British Columbia group and flown in 1995. It features a cryogenic differential Fourier Transform Spectrometer with two bolometric receivers, in the focus of an off axis 1.65 m telescope, resulting in two beams 42 arcmin FWHM on the sky separated by 3.6º. Analysis of the rapid-scan interferograms provides the useful CMB data in five spectral bands (from 93 to 276 GHz), plus important checks for systematics.
A problem in a memory chip reduced the time available for data taking during the flight. CMB anisotropy was detected in a set of 10 sky directions. A new flight of the payload is scheduled for May 1998.

BOOMERanG is a second generation experiment, developed by a collaboration headed by University of Rome La Sapienza and Caltech, with contributions from ENEA, IROE-CNR, QMWC, UCSB, U.Mass. It was flown two times in August 1997 with a total power bolometric receiver and a 1.3 m off-axis telescope, producing four 20 arcmin FWHM pixels at 150 GHz and two 30 arcmin FWHM pixels at 90 GHz. The flight demonstrated the outstanding performances of system, mainly the low background on the bolometers, the extremely low level of the sidelobes, and the absence of excess noise in the total power bolometers readout. The system performed 40° wide azimuth scans (forward-back with a rounded triangle waveform), covering a 5° × 80° region in Cetus, Aquarius, Capricornus. The system was calibrated in flight observing Jupiter and the CMB Dipole. Custom spider-web bolometers reduced drastically the rate of cosmic ray events (down to about 60 events in the full flight). Excess noise is limited to very low frequencies, unimportant for CMB anisotropy signals. The data analysis is currently in progress. This flight represents also a qualification of the payload for the long duration flight to be done at the end of this year (see below).

HACME is a second generation HEMT experiment developed by the group of University of California at Santa Barbara. It features 39, 41 and 43 GHz receivers with \( \sim 500 \mu K \sqrt{s} \) noise. The gregorian telescope produces 46 arcmin FWHM beams. The most interesting feature of the experiment is a rotating flat mirror mounted in front of the telescope. The flat is tilted 2.5 degrees relative to its spin axis, and spins at 2.5 Hz. So the beam scans the sky on 5° diameter circles, thus pushing toward large sky coverage, with very well cross-linked scans. The beam elevation changes along the circle, but the low frequency makes the resulting atmospheric signal negligible. Also, any residual atmospheric signal at the spin frequency is well outside the signal frequency band occupied by the degree/scale CMB anisotropy. It was flown two times in 1996, observing about 5000 independent pixels. The disadvantage of this scan technique is the very short integration time per pixel. Maps recovered from the time ordered data are already published\cite{28}, but the sensitivity is not high enough to pick-up by-eye cosmic structures from the maps. The statistical analysis of the data is in progress.

MAX/ACME is a first generation experiment, developed by a collaboration between the University of California at Berkeley and the University of California at Santa Barbara. It has been flown five times since 1989. It features a 1.3 m Gregorian telescope with wobbling secondary mirror and several multiband bolometric receivers, resulting in \( \sim 0.5^\circ \) FWHM beamsize at wavelengths between 3.3 and 0.8 mm. MAX detected CMB anisotropies in 7 different sky regions, with \( \Delta T/T \) ranging from \((1.2^{+0.4}_{-0.3}) \times 10^{-5}\) to \((2.9^{+4.3}_{-1.8}) \times 10^{-5}\). Spectral arguments, taking advantage of the multiband nature of the system, allow to reject the hypothesis of Galactic contamination of the data. All these detections may be consistent with coming from a single parent population.

MSAM is a first generation experiment, flown in 1992, 1994, 1995, developed by a collaboration headed by University of Chicago and NASA/Goddard SFC. It features a 1.4 m off-axis Gregorian telescope with a mutating secondary. The cryogenic bolometric receiver has four wavelength bands between 2.0 and 0.42 mm. The instrument had a resolution of \( \sim 0.5^\circ \) and sampled a ring centered on the NCP. Data from the different wavelengths were combined to create separate CMB and dust channels, thus rejecting local contamination of the cosmological data. Repeated measurements of the same sky regions in different flights reproduced the same anisotropy detection of the CMB, which is also consistent with the measurements of the ground-based Saskatoon experiment on the same NCP ring. The second phase of the MSAM experiment, flown in 1997, used an adiabatic demagnetization refrigerator to cool five detectors at 0.1K.
QMAP is a HEMT-based second generation experiment developed at Princeton and University of Pennsylvania. It is basically the Saskatoon experiment mounted on a balloon platform: a chopping flat is mounted in front of an off-axis 1 m primary, feeding two Q-band (39 arcmin FWHM, 8 GHz bandwidth), one K-band (54 arcmin FWHM, 8 GHz bandwidth) and one D-band (20 arcmin FWHM) receivers. The elevation of the beam is 41°, and the chop sweep at 4.4 Hz was 10° or 20° depending on the flight. The azimuth scan of the gondola produced a second level of chop with 10° amplitude, centered on the NCP. The system has been flown in 1996 and 1997, and observed about 700 independent pixels in the NCP region. The data analysis is in progress.

- Experiments to be flown:

BEAST is a scaled-up version of HACME, developed by UCSB with contributions from JPL, CNR-Bologna, CNR-Milano, EFEI-INPE (Brazil). The instrument has a 2.2 m lightweight primary, with 7 Q-band detectors (275$\mu$K$\sqrt{s}$ noise, 19 arcmin FWHM beam) and 2 Ka-band detectors (180$\mu$K$\sqrt{s}$ noise, 26 arcmin FWHM beam). Using a spinning flat in front of the primary, all pixels scan on 10° circles at 5 Hz, while the telescope is swept through different azimuth angles depending on the mission. The LDB version of BEAST will cover about 4000 square degrees, with final sensitivity of about 70 $\mu$K per 10 arcminutes pixel. A second LDB flight will have 10 additional W-band (90 GHz) receivers (500$\mu$K$\sqrt{s}$ noise, 9 arcmin FWHM beam). The test flight will be in 1998 and the LDB flights are planned for 1998 and 1999. ACE is the lightweight Ultra Long Duration version of BEAST, planned for 100 days flights.

BOOMERanG LDB is the long duration flight of BOOMERanG N.A., currently planned for the Antarctic flight in 1998. The LDB hardware, including the long duration $^{3}$He cryostat, the spider web bolometers, the ACS sensors and actuators, the sun shield system and the fully automated flight programmer / data logger, has been tested successfully in the August 1997 flight. The experiment will feature an improved focal plane, with 16 detectors: four 90 GHz bolometers (75$\mu$K$\sqrt{s}$ noise, 20 arcmin FWHM beam) and four three-band photometers (90$\mu$K$\sqrt{s}$ @ 150 GHz, 120$\mu$K$\sqrt{s}$ @ 220 GHz, plus a 450 GHz dust monitor, all with 12 arcmin FWHM beam). The experiment will scan the Orologium region, the lowest dust contrast region in the sky, which happens to be opposite to the Sun in the Antarctic summer. The scan strategy and focal plane setup provide several confirmation levels for the detected signals. At short times (few seconds), the detected signal should reproduce in the second detector of the same row, and both the detectors should see in time-reverse in the back-scan the structure seen in the forward-scan; a few minutes later the second row of detectors should see the same structure. All this should reproduce the day after, with only a slight sky rotation, which becomes significant at the end of the flight. The forecast for the final sensitivity of 15 $\mu$K per 20 arcminutes pixel at 90 GHz and 25 $\mu$K per 12 arcminutes pixel at 150 GHz, with a sky coverage of 2500 square degrees.

MAXIMA is developed by the University of California at Berkeley, with contributions from Caltech, QMW, Universita’ di Roma La Sapienza, IROE-CNR Firenze. A 1.5 m off axis primary feeds an array receiver with 14 bolometers (8 at 150 GHz, 3 at 240 GHz, 3 at 420 GHz). All the detectors have a 11 arcmin FWHM. Sky chop is obtained by nutating the lightweight carbon-fiber primary mirror, thus obtaining a 4 deg/s, 6° amplitude scan of the beam. In addition, a slower azimuth slew of the gondola (50° p-p) will produce a significant sky coverage. Two partially overlapping regions will be scanned in a regular 6 hours north-America flight, in order to check for systematics and make easier the map reconstruction. The experiment is expected to map about 26000 independent pixels, with final sensitivity of $\sim$ 24$\mu$K/pixel at 150 GHz and $\sim$ 66$\mu$K/pixel at 240 GHz. The flight of MAXIMA will be in spring 1998.

TOP-HAT is a new-generation payload mounted on-top of the balloon, and designed for Long Duration Ballooning. The system is developed at NASA-Goddard and Bartol, U. of Chicago, U. of W. at Madison. The peculiar location of the payload features better ground
shields and absence of signals reflected from the balloon, allowing observations near the zenith. The disadvantages are a stricter weight limit, a complex ACS and the difficult recovery of the payload after test flights. The experiment has a low sidelobes Cassegrain telescope with a single pixel receiver (5 bands from 150 to 630 GHz, 20 arcmin FWHM beam). The test flight of TopHat Pointer (planned for the spring of 1998) will cover the same NCP region observed by MSAM and Saskatoon, with improved sensitivity and high frequency coverage. In the LDB flight (1999), the telescope, tipped 12 degrees off the zenith, spins observing a 24 deg circle. Sky rotation allows the system to map 1800 square degrees of sky and about 20000 independent pixels.

3 Conclusions

Ballooning for CMB Anisotropy measurements is a very active field worldwide. The activity is growing, for two main scientific reasons:

1) High frequency (>90 GHz) and high angular resolution (∼ 10 arcmin FWHM) measurements are possible and effective.

2) These measurements complement the forthcoming data from MAP and are a very important test-bed for Planck technologies.

Moreover, good science is being produced, and promises for important results (like the \( \ell \)-space spectroscopy of the acoustic peaks, or detection/falsification of non-gaussian statistics for the CMB fluctuations) are quite convincing.

As an example relevant for this conference, we can mention the fact that determination of several cosmological parameters is possible with very good accuracy from LDB experiments. For example, if all the systematics effects are properly removed, a single LDB experiment with 12 arcmin FWHM beams, 16 total power bolometric detectors with sensitivity of 80 \( \mu K \sqrt{s} \), 10 days of observing time spent over a \( 50^\circ \times 50^\circ \) sky region, can measure the power spectrum of the CMB anisotropies with very good accuracy\(^2\). Fits can be done on the measured power spectrum\(^3\), allowing to recover \( \Omega_{\text{tot}} \) with a 3% error, \( \Omega_\Lambda \) with 6% error, \( \Omega_B \) with 1% error, \( n_s \) scalar with 18% error, \( H_0 \) with 1% error, \( Q_{\text{rms},PS} \) with 4% error. Here the errors for any parameter make no assumptions about the value of the other parameters. These measurement errors can be significantly reduced if one or more of the cosmological parameters are constrained by other observations or fixed by assumptions.

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Fig. 1

90 GHz band

Atmosphere x filter

1 μK CMB anisotropy x filter
Fig. 2

- **White noise**
- **1/f noise**
- **Pendulations**
- **First acoustic peak**
- **Second acoustic peak**

**Beam 20’ FWHM**

- $\tau_{\text{bol}} = 50$ ms
- Azimuth scan @ 3°/s
- $z = 50°$

**Graph details:**
- System noise spectral density ($\mu$K$^2$/Hz)
- Bolometer + electronics transfer function
- CMB 1-D power spectrum x beam: $\Gamma_m$ ($\mu$K$^2$)
| Experiment | Ref. | Technology | Bands (GHz) #detectors | Beam FWHM (arcmin) | Sky Chop - p-p - form | Scan | Data |
|------------|------|------------|------------------------|-------------------|----------------------|------|------|
| Recent     |      |            |                        |                   |                      |      |      |
| ARGO       | 2    | BOLOs      | 150+270+490+600 / 4    | 53                | WS - 1.4° - S        | AZ - SI | ~200 differences |
| BOOMERanG NA | 3    | BOLOs      | 90+150 / 6             | 22                | TP                   | AZ - 2°/s | ~2000 ind.pix. |
| BAM        | 4    | BOLOs      | Interf. 111 to 255 / 2 | 42                | DIFF - 3.6°          | AZ - SI | 10 differences |
| HACME      | 5    | HEMT       | 39+41+43/3             | 46                | SF - 5° - TP         | C        | ~5000 ind.pix.  |
| MAX / ACME | 6    | BOLOs      | 105+180+270+420 / 4    | 30                | WS - 1.4° - S        | AZ 4° sine | ~300 differences |
| MSAM I     | 7    | BOLOs      | 170+280+500+680 / 4    | 37                | WS - 40° - 3F        | AZ - slow | ~40 differences |
| MSAM II    | 8    | BOLOs      | 70+90+120+150+170 / 5  | 20                | WS - 40° - 3F        | AZ - slow | under analysis |
| QMAP       | 9    | HEMT       | 30+40 / 3(x2 polar.)   | 54+39             | CF - 10°/20° - S     | AZ 10° sine | ~700 ind.pix.  |
| Future     |      |            |                        |                   |                      |      |      |
| ACE (ULDB) | 10   | HEMT       | 90 / lots              | 9                 | SF – 10° - TP        | C        | ~200,000 ind.pix. |
| BEAST I (LDB) | 11  | HEMT       | 30+40 / 9              | 25+19             | SF – 10° - TP        | C        | ~3600 ind.pix.  |
| BEAST II (LDB) | 12  | BOLOs      | 30+40+90 / 19          | 25+19+9           | SF – 10° - TP        | AZ – 120° | ~140,000 ind.pix. |
| BOOMERanG (LDB) | 13 | BOLOs      | 90+150+240+400 / 16    | 20-12             | TP                   | AZ - 2°/s –120° | ~6600 ind.pix. |
| MAXIMA     | 14   | BOLOs      | 150+240+420 / 14       | 11                | WP –6° sawtooth      | AZ – 7° sine | ~26000 ind.pix. |
| TOP-HAT    | 14   | BOLOs      | 70+90+120+150+170 / 5  | 20                | WS – 40° - 3F        | AZ - slow | ~500 ind.pix. |
| TOP-HAT (LDB) | 14  | BOLOs      | 170+280+420+500+630 / 5| 20                | TP                   | AZ - S   | ~20,000 ind.pix. |

**Notes:** Sky Chop: WS = Wobbling Secondary; TP = Total Power; CF = Chopping Flat; SF = Spinning Flat; S = sine wave chop; T = triangle chop; 3F = three fields. Scan: AZ = azimuth scan by means of payload rotation; SI = step and integrate; slow = slow rotation; C = circle; S = spin at constant elevation

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