A Brief History of the Brazilian Participation in CMB Measurements

Thyrso Villela

Abstract This contribution is a short report on the Brazilian participation in Cosmic Microwave Background (CMB) observational programs. It includes brief descriptions of the experiments aiming to measure both CMB properties and Galactic microwave signals that hamper these measurements. The work done by Brazilian researchers involved in the development of these experiments and in the subsequent observations is briefly described as well.

1 Introduction

The history of Cosmic Microwave Background (CMB) measurements in Brazil began in the early 1980s, when groups from Princeton University and University of California at Berkeley flew instruments on board stratospheric balloon platforms to map the angular distribution of this radiation in the southern sky. These experiments were carried out with the support from the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais—INPE). In particular, the collaboration between the University of California and INPE evolved to a fruitful joint work that produced several scientific and technological results related to CMB measurements and to topics as CMB foreground characterization.

The CMB signal can be measured from a few GHz up to a few hundreds GHz. The full characterization of the CMB radiation field requires measurements of its spectrum, polarization and angular distribution. CMB spectrum measurements have to deal with a signal level of the order of a few kelvins, while CMB anisotropy signal is in the range of millikelvins to microkelvins. The CMB polarization signal, on the other hand, is only detected at a few microkelvins level. These signal intensities impose serious experimental and observational constraints.

T. Villela (✉)
Divisão de Astrofísica, Instituto Nacional de Pesquisas Espaciais - INPE, São José dos Campos, SP, Brazil
e-mail: thyrso.villela@inpe.br

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Depending on the frequency range, this signal can be picked up from the ground, but, in general, it is necessary to use space platforms to avoid the atmosphere during the observations. So, over the years, balloon borne and satellite platforms were employed to allow precise measurements of the spectrum, angular distribution and polarization of the CMB. Besides the atmosphere, other contaminants can hamper CMB observations as well, like the radio and microwave emissions from our own galaxy and extragalactic radio sources. The detailed knowledge of such signals is of pivotal importance to better characterize the CMB data.

In order to measure these weak CMB signals, besides the development of very sensitive experiments, it is necessary to account for the spurious signals that can hamper the CMB observations. Thus, CMB measurement requires a strict control of systematic errors.

Observational efforts in Brazil were carried out over the past three decades to measure all three CMB characteristics and their contaminant foregrounds. This contribution presents a brief report about the history of the work done by Brazilian scientists and technicians in CMB measurements and related programs.

2 CMB Measurements and Related Programs

We show below some of the results related to CMB measurements programs, including hardware development and data analysis, in which Brazilian scientists were involved since 1982. The Brazilian institutions that took part in this effort were INPE and, later, the Federal University of Itajubá (Universidade Federal de Itajubá—Unifei).

2.1 CMB Angular Distribution: 3 mm Experiment

The first Brazilian involvement in CMB measurements was in the 3.3 mm (90 GHz) experiment. This instrument was a test bed and precursor for the Cosmic Background Explorer (COBE) 90 GHz Differential Microwave Radiometer (DMR) channel, which was launched on November 1989. With a noise temperature of 130 K, a bandwidth of 600 MHz and a beam width of 7° FWHM, the 3 mm experiment was mounted on a gondola which rotated with a period of 100 s. It made a very precise measurement of the CMB dipole anisotropy and placed a stringent upper limit for the quadrupole (Villela et al. 1983; Lubin et al. 1985; Lubine and Villela 1985; Villela 1987). Figure 1 shows parts of the experiment and Fig. 2 presents the instrument assembled and taking off for its Brazilian flight.

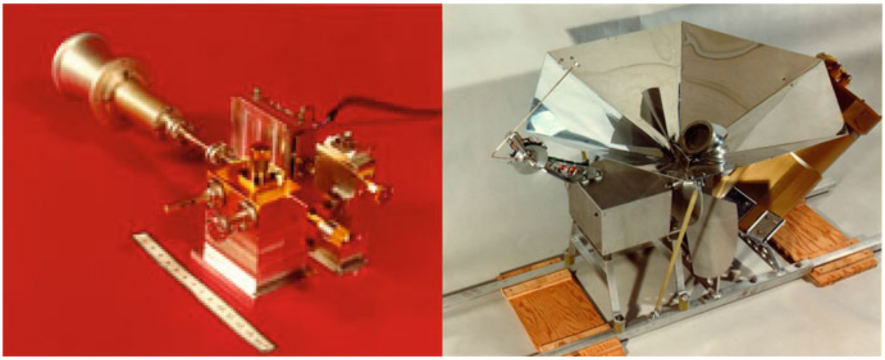

Fig. 1 90 GHz horn (*left*) and radiation shield to avoid spurious ground pick-up (*right*) used in the 3 mm experiment

In this flight, the gondola was launched from INPE's campus in Cachoeira Paulista, state of São Paulo, in November 19, 1982. The instrument performed very well and took CMB data at an average altitude of 30 km for several hours. The CMB dipole could be seen in real time as the gondola rotated at 1 rpm. Unfortunately, due to a failure in the separation mechanism that connects the gondola do the flight ladder and balloon, the flight extended for several hours beyond the estimated duration and the payload was lost, as the batteries ran out of charge causing a communication breakdown between the payload and the ground control station. The gondola was recovered about 2 years later. A history of this flight and the gondola recovery in Tapiraí, SP, in February 1985 can be seen in Villela (1994).

Despite the fact that the payload was lost, the telemetered data were used to analyze the data. A very precise measurement of the CMB dipole was made as well as a stringent CMB quadrupole was set through the combination of these data with data collected in two previous flights from the Northern Hemisphere. The final result of the 3 mm experiment showed a dipole intensity of 3.44 ± 0.17 mK in the direction $\alpha = 11^h.2 \pm 0^h.1, \delta = -6^0.0 \pm 1^0.5$. An rms quadrupole amplitude upper limit was set to a 90 % confidence level as 7×10^{-5} (Lubin et al. 1985; Villela 1987). Figure 3 shows a map of the CMB dipole measured by the 3 mm experiment.

Table 1 shows a comparison of the 90 GHz dipole measurement (Lubin et al. 1985; Villela 1987) with the Relikt (Strukov et al. 1987) and COBE (Smoot et al. 1991) satellite measurements. It can be seen from this table that the 3 mm data were in good concordance with satellite data.

The balloon experiments carried out in the early 1980s (Fixsen et al. 1983; Lubin et al. 1985; Lubin and Villela 1986) paved the way for the COBE satellite, as shown in Fig. 4.

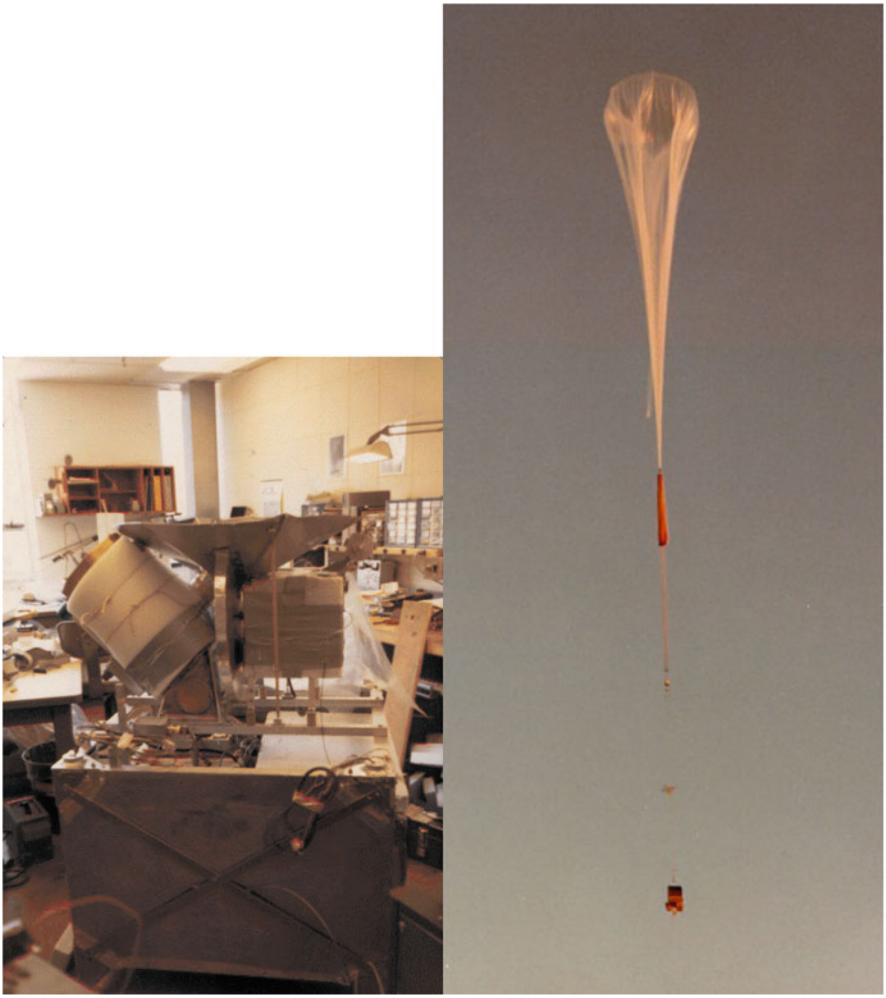

Fig. 2 (*Left*) 3 mm experiment assembled in the laboratory and (*right*) the gondola taking off from Cachoeira Paulista, SP, for its balloon flight in November 19, 1982

With the advent of the COBE satellite, it was possible to use the DMR data to constrain the topology of the universe, work done by an INPE graduate student Angélica de Oliveira-Costa, who went to Berkeley to work with COBE data (de Gouveia dal Pino et al. 1995).

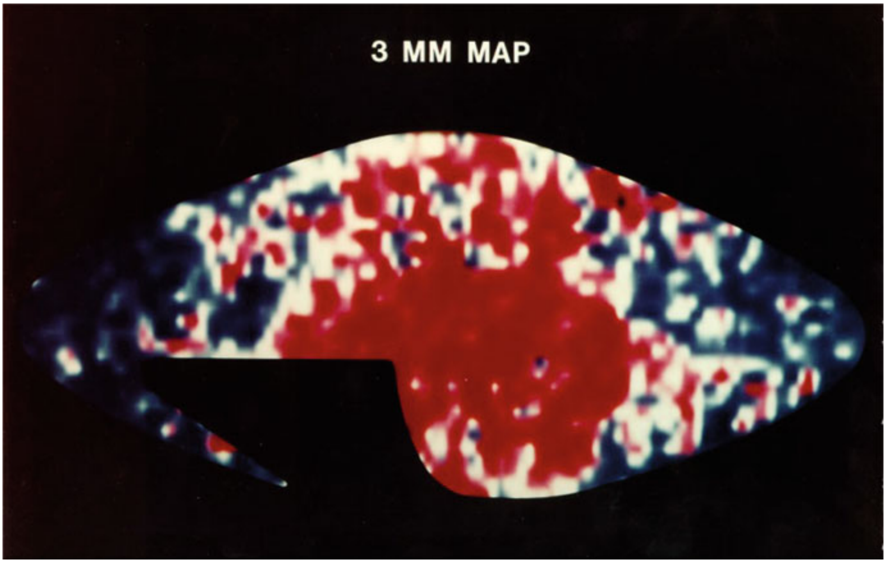

Fig. 3 CMB dipole anisotropy map, in celestial coordinates, covering 80 % of the celestial sphere. The lack of data is evident in the *black region* in the *lower left corner* of the map, which was due to the non-recovery of the experiment during the Southern Hemisphere 1982 campaign

Table 1 CMB dipole measurements

Experiment	Amplitude (mk)	l (^{0})	b (^{0})
Relikt	3.16 ± 0.07	266.4 ± 2.3	48.5 ± 1.6
3 mm	3.44 ± 0.17	264 ± 1.9	49.2±
COBE	3.3 ± 0.1	265 ± 1	48 ± 1

2.2 ACME, HACME and BEAST Experiments

As a natural extension of the large angular scales experiments, a series of experiments to search for CMB anisotropy at medium angular scales was conducted by groups from the University of California (campuses of Berkeley and Santa Barbara) in which INPE's researchers, including graduate students, were involved. These experiments were performed in the 1990s. The Advanced Cosmic Microwave Explorer (ACME), shown in Fig. 5, was developed at that time (Meinhold et al. 1993).

Four balloon flights were performed in which the detectors were bolometers [the ACME-MAX series: e.g. Gundersen et al. 1993; Clapp et al. 1994; Devlin et al. 1994; Tanaka et al. 1996; Lim 1996], and four observational campaigns at the South Pole, in which the detectors employed were High Electron Mobility Transistors (HEMT) [the ACME-SP series: Santos et al. 2012; Gundersen et al. 1995]. For instance, Carlos Alexandre Wuensche worked on the MAXIMA experiment (Wuensche 1995). Newton Figueiredo also participated in these observations. For

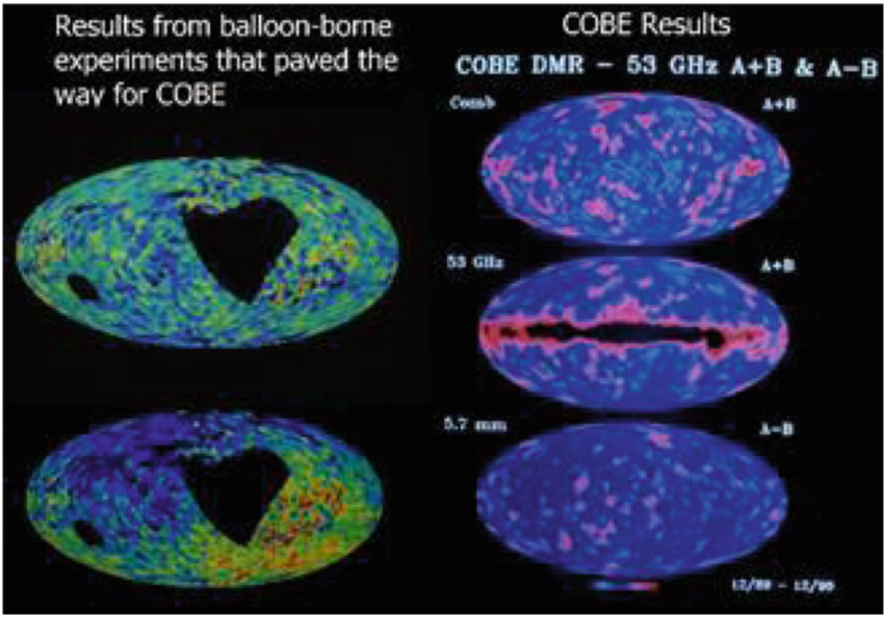

Fig. 4 Results from the balloon-borne experiments that paved the way for COBE. The *left side* of the figure shows a combination of the 12 and 3 mm data obtained from balloon flights, while the *right side* of the picture shows COBE results (P. Lubin)

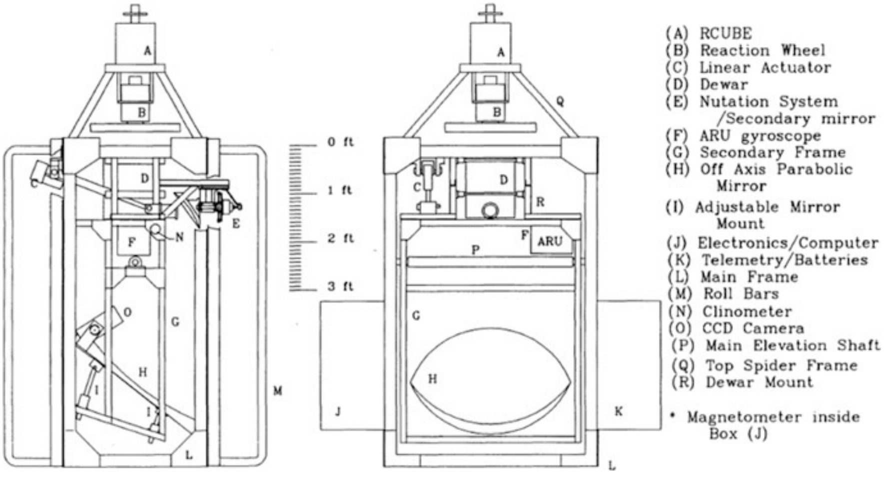

Fig. 5 Balloon gondola of the ACME experiment. This platform was designed to automatically point the telescope during the flights. It used inertial sensors to achieve this goal (Meinhold et al. 1993)

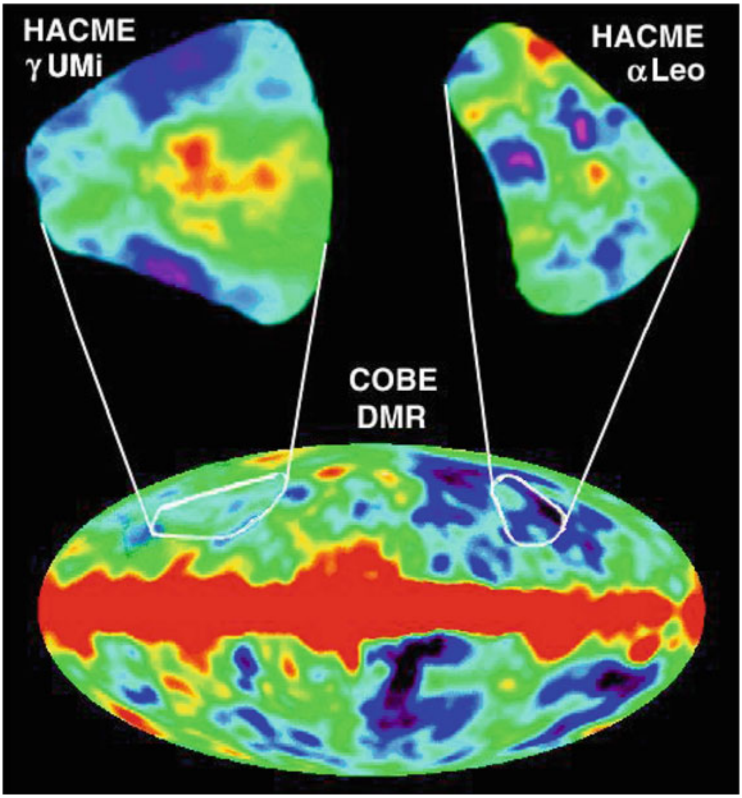

Fig. 6 CMB maps obtained with the HACME experiment

information on the scientific results of these experiments see Wuensche and Villela (2010) and references therein.

The next generation of medium angular scale experiments was the HEMT on ACME (HACME) experiment (Staren et al. 2000). It was flown in 1996 and made observations covering 1150 square degrees of the celestial sphere near the stars γ Ursae Minoris and α Leonis at the frequencies of 39, 41, and 43 GHz, with an $\sim$ 0.077 beam (FWHM). The detected cosmic signal was smaller than 77 μK. Figure 6 shows the CMB maps obtained from these observations (Tegmark et al. 2000).

After ACME and HACME, a new experiment was designed to search for anisotropies in CMB angular distribution with better sensitivity. The Background Emission Anisotropy Scanning Telescope (BEAST) (Childers et al. 2005; Figueiredo 1997) was developed as a collaboration involving the University of California Santa Barbara, INPE, Jet Propulsion Laboratory, Unifei, University of Milan, University of Rome, IASF/CNR, Caltech and University of Illinois. INPE provided several microwave parts for this experiment. The BEAST primary dish is the largest mirror ever flown in a CMB experiment. The BEAST innovative

Table 2 BEAST optical parameters (Figueiredo et al. 2005)

Primary mirror	
Focal distance	1250.0 mm
Semi-major axis	2200.00 mm
Aperture	1966.1 mm
Secondary mirror	
Semi-major axis	600.0 mm
Semi-minor axis	575.4 mm
Focal distance	170.0 mm
Eccentricity	0.2833
Flat mirror	
Diameter	2600.0 mm

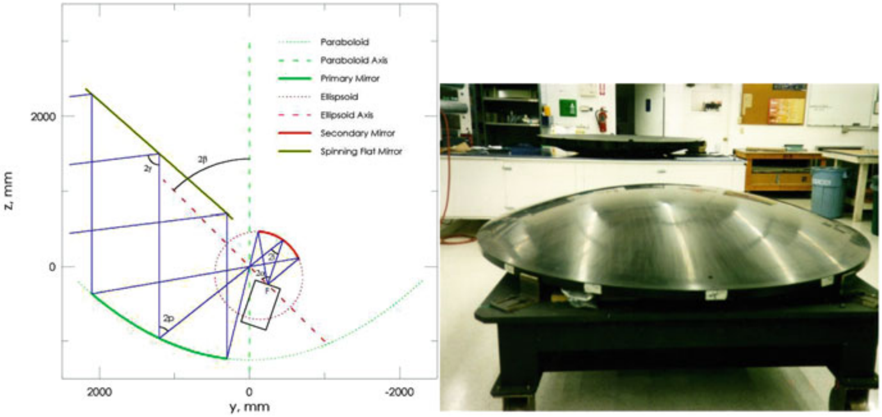

Fig. 7 BEAST optical design (**a**). In (**b**) it is shown the mold for the 2.6-m diameter primary mirror

optical design, which had a large focal plane, was part of the work done by Newton Figueiredo, an INPE graduate student, for his thesis work. Table 2 and Fig. 7 show BEAST optical design parameters.

BEAST, besides data collected in balloon flights, also collected CMB data from the ground at White Mountain Research Station (USA) at an altitude of 3800 m. An astronomical site survey at the Barcroft Facility of the White Mountain Research Station was made (Marvil et al. 2006) in order to better characterize this site for CMB measurements. BEAST maps cover about 2500 square degrees in the celestial sphere in the declination band $33° \leq \delta \leq 42°$ and right ascension band $0\,h \leq \alpha \leq 24\,h$. Most of the observations were in the Ka band (30′ FWHM) and Q band (23′ FWHM). BEAST map results are presented in Meinhold et al. (2005), while Galactic contamination in these maps is described in Mejía et al. (2005), whose author was a post-doc at INPE at the time working on BEAST data analysis (Figs. 8 and 9). The resulting BEAST data CMB power spectrum is presented in O'Dwyer

Fig. 8 BEAST experiment before flight showing the 2.6-m diameter flat mirror

(2005). Figure 10 shows a slice of the BEAST *Q* band sky map compared to the same slice of the sky observed by WMAP.

The BEAST rms signal level was 57 ± 5 μK (noise, without Galaxy, beam smoothed to 30′). The cosmic signal was 30 ± 3 μK. INPE graduate student Agenor Pina worked on the analysis of the BEAST data (Pina 2002). An independent

Fig. 9 BEAST experiment before flight on the crane (a) and the dome where it operated at the White Mountain Research Station

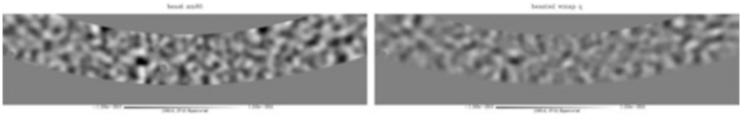

Fig. 10 WMAP map section (*above*) compared to same sky region as observed by BEAST (*below*) in the Q band

calculation of BEAST CMB angular power spectrum has been done by Donzelli et al. (2006).

3 CMB Polarization: WMPol Experiment

BEAST was adapted to operate as a polarimeter and became the White Mountain Polarimeter (WMPol). INPE provided several parts for this instrument and Rodrigo Leonardi, an INPE graduate student at that time, worked in its development and operations. BEAST was deployed at the White Mountain Research Station site and operated there for several months taking data at 42 and 90 GHz. These observations allowed us to set an upper limit of 14 μK for the CMB E-mode polarization in the $170 < l < 240$ multipole interval (Leonardi 2006; Levy et al. 2008) at 42 GHz.

Figures 11 and 12 show some of the microwave parts provided by INPE for the BEAST and WMPol experiments. Some of these parts were jointly developed by INPE and companies in the São José dos Campos and Campinas regions. The know-how acquired in such developments was important for these companies, as they qualified themselves to be providers of precise mechanical parts.

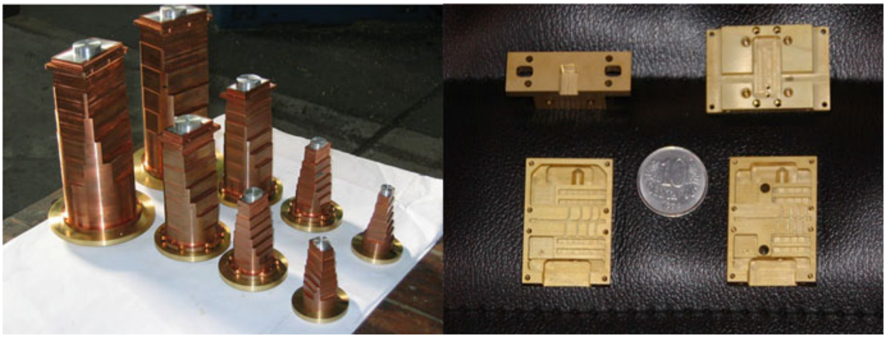

Fig. 11 WMPol transitions (**a**) and amplifiers bodies compared in size to a Brazilian 10 cents coin (**b**)

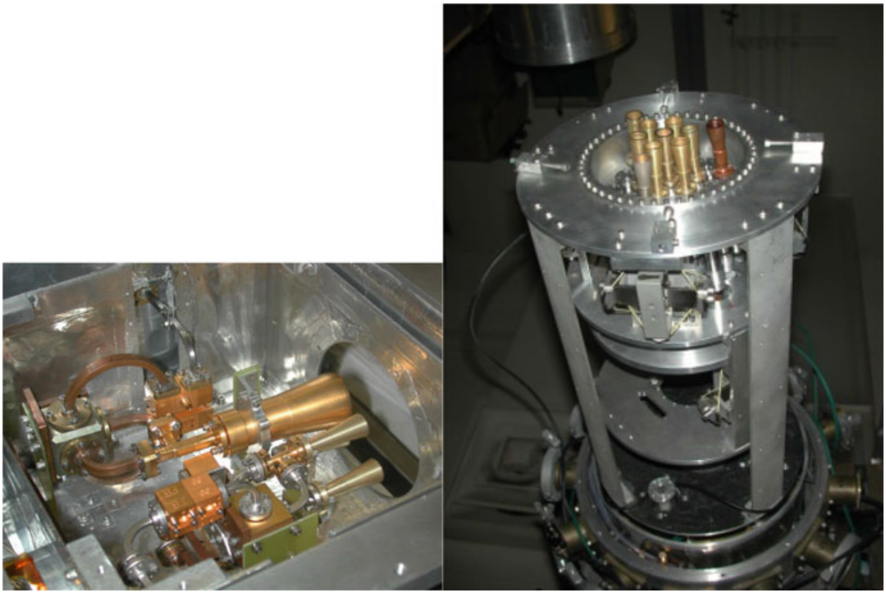

Fig. 12 WMPol microwave hardware (**a**) mounted in the dewar (**b**)

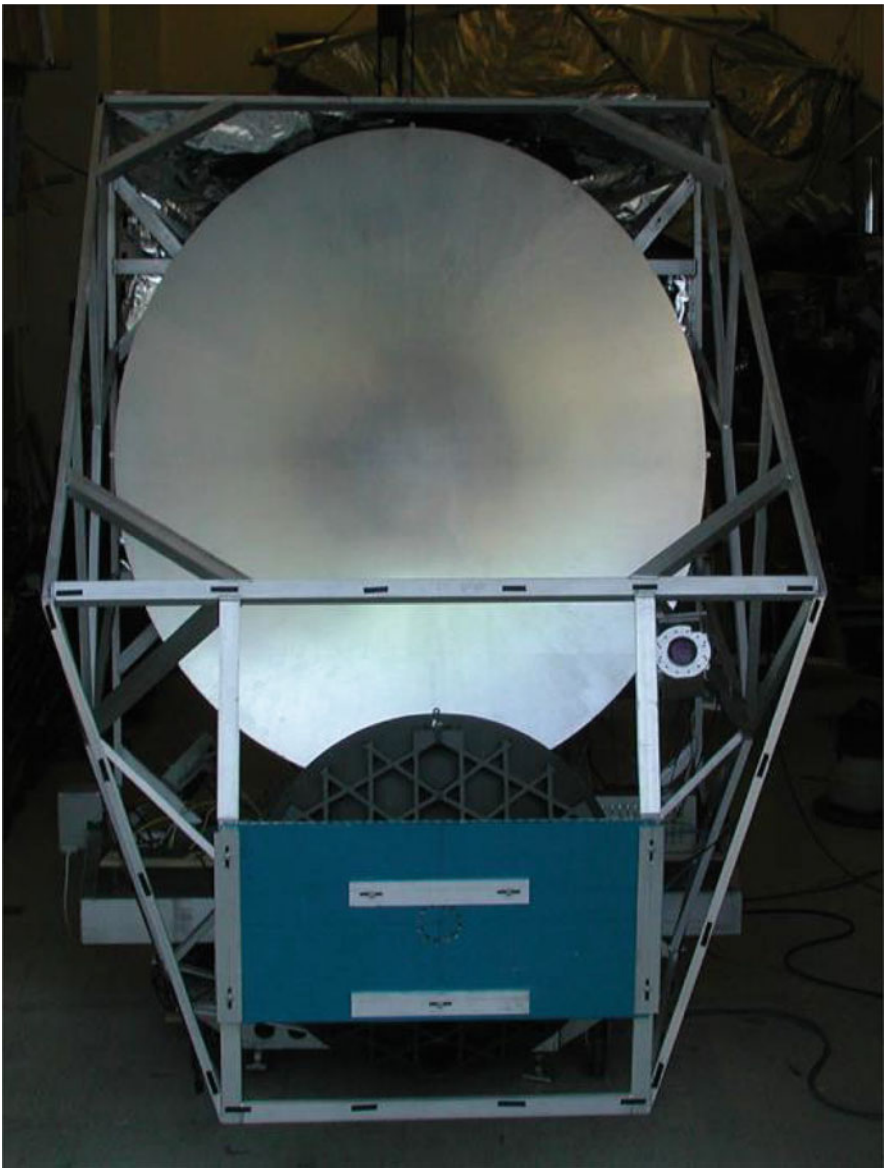

Fig. 13 WMPol fully assembled for observations at its White Mountain Research Station observing site

Figure 13 is a picture of WMPol in its working configuration. It observed the sky at 42 and 90 GHz. These observations allowed us to set an upper limit for CMB polarization at 42 GHz. Figure 14 presents this result.

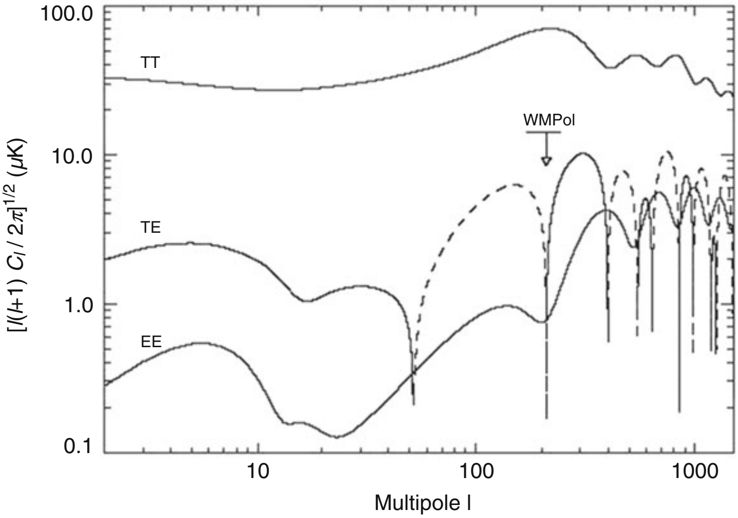

Fig. 14 WMPol upper limit on CMB polarization (Leonardi 2006; Levy et al. 2008)

4 CMB Spectrum: ARCADE Experiment

The search for distortions in the CMB spectrum and the need for precise measurements on the lower frequency part of the this spectrum lead to the development of the Absolute Radiometer for Cosmology, Astrophysics, and Diffuse Emission (ARCADE) experiment, a collaboration involving Goddard Space Flight Center (GSFC/NASA), University of California, Santa Barbara, Jet Propulsion Laboratory (JPL/NASA), University of Maryland, and INPE. ARCADE was designed to operate on board high altitude balloons in order to measure the CMB frequency spectrum at centimeter wavelengths and to search for signals from the first stars to form after the Big Bang. The instrument was cooled down to −270 °C, through a radical thermal design that puts cold components outside the dewar.

INPE provided horns and microwave transitions at 90, 30, 10, 8, 5, and 3 GHz for the ARCADE project. The transitions were fabricated in Copper through electrodeposition process. The corrugated horns were made out of Aluminum. Figure 15 show these horns and transitions, respectively, while Fig. 16a, b show some of them assembled in the instrument.

ARCADE was launched in July 22, 2006 from Palestine, TX, USA. The flight had a total of 4 h at the float altitude of 37 km. Successful thermal operations were carried out during the flight consisting in comparing the sky to an on-board target several times, while maintaining the instrument within 0.1 K of the sky temperature. This procedure allowed 2.5 h of science data to be collected.

The ARCADE data showed a detection of a bright radio background that is six times brighter than the expected combined contribution from all known radio

Fig. 15 Horns (**a, b**) and transitions (**c**) provided by INPE for the ARCADE 2 experiment

galaxies (Fig. 17). This unexpectedly bright radio background has unknown origin up to now. Moreover, this ARCADE result is consistent with existing radio surveys, which makes this detection a very intriguing one, as radio source counts are well known, and their emissions don't even come close to making up the detected background. New sources, too faint (10x) to be directly observed, would have to vastly outnumber (100x) all the galaxies in the universe (Kangas et al. 2005a; Fixsen et al. 2011; Seiffert et al. 2011).

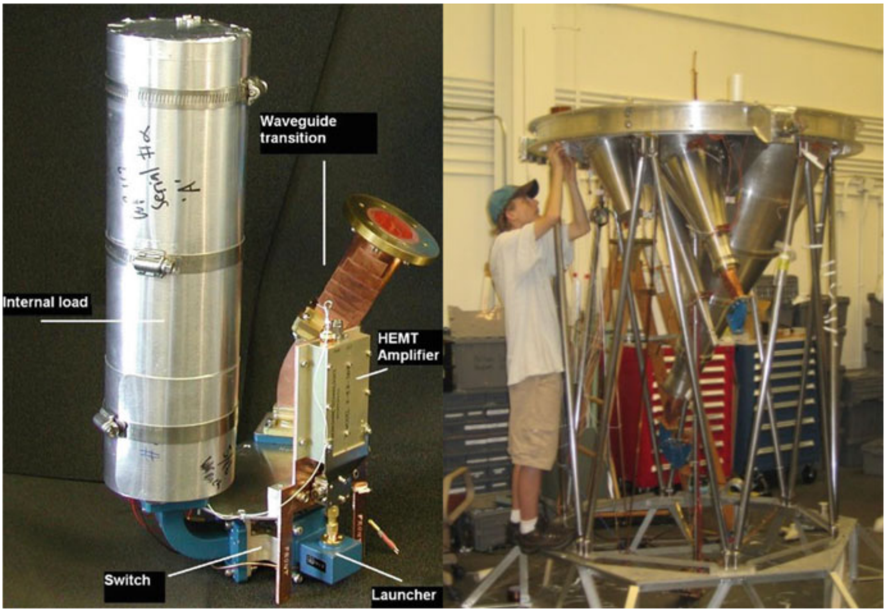

Fig. 16 Transitions (*left*, (**a**)) and horns (*right*, (**b**)) mounted on the ARCADE 2 experiment

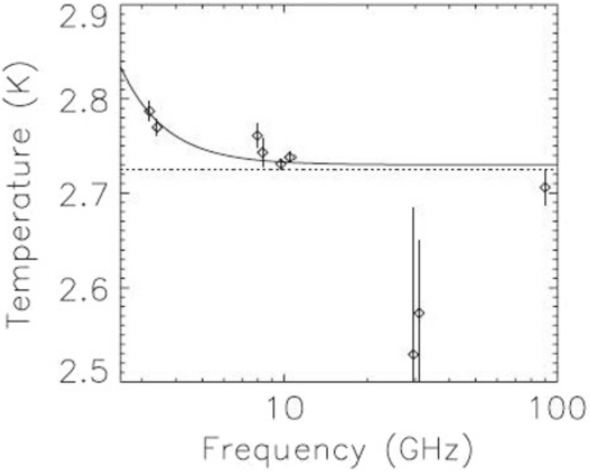

Fig. 17 ARCADE results showing an excess intensity in the lower frequency part of the spectrum compared to the 2.7 K CMB temperature (Fixsen et al. 2011)

5 Radio and Microwave CMB Foregrounds: GEM and COFE Experiments

Brazilian scientists and technicians have also been involved in the characterization of CMB foregrounds. The Galactic Emission Mapping (GEM) project (de Amici et al. 1994; Torres et al. 1996) is a collaboration encompassing the University of California, Berkeley, in the USA, University of Milan, in Italy, Instituto de Telecomunicazioni, in Portugal, and INPE, aiming to map the Galactic synchrotron radiation at 408, 1465, 2.3, 5 and 10 GHz. It employs a 5.5-m diameter dish, which rotates at constant speed to scan the sky, and extension panels to avoid ground emission pick-up (Tello 1997; Tello et al. 1999, 2000). A schematic view of the GEM dish set up, including the fence used to avoid ground emission pick up is shown in Fig. 18. The GEM observational is also presented in Fig. 18.

GEM is currently operating at INPE campus in Cachoeira Paulista, SP (Fig. 19). From this site, it can observe the sky in the declination interval between 52o23'14.1" and +7o 8'50.98", covering about 33 % of the sky. GEM has already produced maps at 1.465 GHz, a work done by Camilo Tello in his Ph.D. thesis (Tello 1997) and 2.3 GHz (Tello et al. 2013). A preliminary map at 408 MHz (Souza 2000) has been produced. Preliminary maps of the polarized Galactic emission at 5 GHz have also been produced by Ivan Ferreira, a former INPE graduate student who worked on the development of the 5 GHz polarimeter (Ferreira 2008). Figure 20 is a picture of GEM in its current observing site in Cachoeira Paulista, SP.

COsmic Foreground Explorer (CoFE) is a balloon-borne microwave polarimeter designed to measure the low-frequency and low-*l* characteristics of the dominant diffuse polarized foregrounds. Short duration balloon flights from the Northern and Southern Hemispheres will allow the telescope to cover up to 80 % of the sky with an expected sensitivity per pixel better than 100 μK/deg2 from 10 to 20 GHz. This

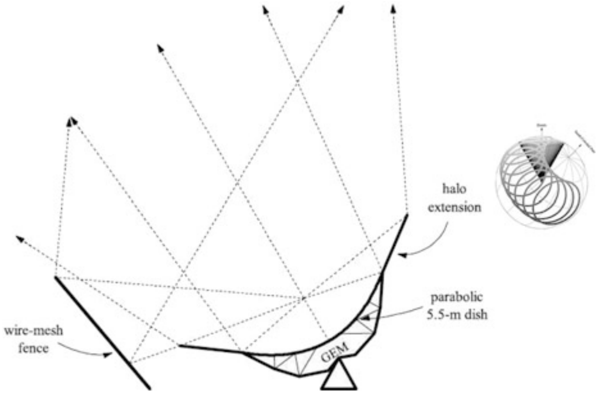

Fig. 18 GEM schematic views of the parabolic dish, extension halo panels, and fence (**a**) and observational strategy (**b**)

Fig. 19 Picture of the GEM experiment in Cachoeira Paulista, SP, Brazil

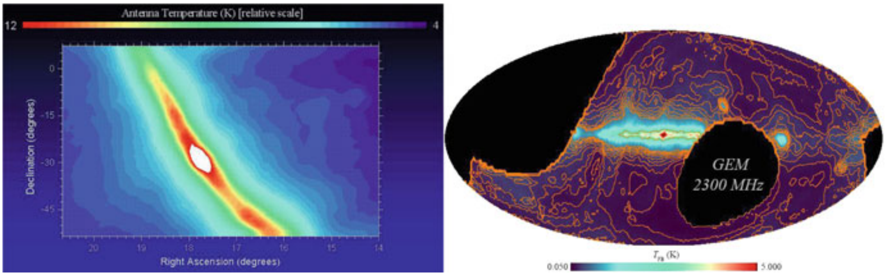

Fig. 20 GEM map of the Galactic Center at 1465 GHz (**a**) and GEM map of the sky at 2.3 GH (**b**)

is an important effort toward characterizing the polarized foregrounds for future CMB experiments, in particular the ones that aim to detect primordial gravity wave signatures in the CMB polarization angular power spectrum (Leonardi et al. 2006).

6 Concluding Remarks

The collaborative works described in this paper benefited a couple of generations of Brazilian and US students. Brazilian students went to the University of California, at Santa Barbara and Berkeley, to work on Lubin's and Smoot's groups. US students visited INPE to work on the GEM project. These collaborations with Philip Lubin and George Smoot are still active.

Regarding instrument developments, all joint projects provided interesting spin-offs for other projects and careers (Kangas et al. 2005a). Camilo Tello quit his position as a researcher at INPE and is working now in the USA in a mobile phone company, where he employs his expertise in microwaves acquired during his thesis work. He is still very involved and active in the GEM project. In particular, the experience acquired with the development of the ACME instrument, where a stabilized balloon-borne platform was built, has been used at INPE to develop a stabilized platform for the Masco X- and gamma-ray imaging telescope (Villela 2000, 2002). A concise compilation of some of the instrumental work done in these collaborations can be found in (Wuensche and Villela 2010; Villela et al. 2011) and a general approach on CMB observations can be found in (Villela and Wuensche 2009).

Besides the instrumental work, emphasis has also been given to the analysis of CMB data obtained with satellites. COBE data were used to investigate possible large scale fractal structure in the universe (de Gouveia dal Pino et al. 1995); investigations of the CMB angular distribution measured by WMAP (Abramo et al. 2006; Bernui et al. 2006a; Santos et al. 2012) and Planck (Santos et al. 2012) were carried out; CMB temperature maps obtained by WMAP have been used to investigate possible Gaussian departures (Bernui et al. 2006a,b). As general approaches for CMB data analysis, an alternative algorithm for the harmonic analysis of CMB distribution has been tested (Wuensche et al. 1994) and simulations of the CMB power spectrum for a class of mixed, non-Gaussian, primordial random fields have been performed (Andrade et al. 2004).

Just for the sake of curiosity, it is interesting to draw a quick line on what happened in CMB measurements after the balloon flights in Brazil in the early 1980s. The Princeton University group leader was David Wilkinson. Dale Fixsen and Edward Cheng completed the team. The University of California, Berkeley, team had Philip Lubin and George Smoot as leaders and Gerald Epstein and myself as graduate students. Cheng, Fixsen, Lubin, Smoot and Wilkinson were part of the COBE satellite team. For their work in this experiment they were awarded the Gruber Prize in Cosmology in 2006, along with John Mather and the COBE team. George Smoot won the 2006 Nobel Prize in Physics for the DMR/COBE results (Smoot et al. 1992), to which he was the principal investigator. He shared this prize with John Mather, principal investigator of the FIRAS/COBE. David Wilkinson became involved in the so-called Microwave Anisotropy Probe (MAP), that later was renamed Wilkinson Microwave Anisotropy Probe (WMAP) in his honor after he passed away in September 5, 2002. WMAP, as COBE, was a great scientific success, being followed by the Planck satellite.

As far as the Brazilian scientists that have been involved in the collaborations and experiments mentioned in this paper, it is worth to mention that all of them made relevant contributions to the field of CMB and its foregrounds. Carlos Alexandre Wuensche is a senior researcher at INPE, where he works on CMB data analysis and is training new students in CMB science. Angélica de Oliveira-Costa left for the USA, where she worked in CMB data analysis and CMB foregrounds. Newton Figueiredo and Agenor Pina hold positions as professors at the Federal University of Itajubá, where they are training new students in CMB related work. Ivan Ferreira is a professor at the Institute of Physics of the University of Brasília. Larissa Santos went to Italy, where she got a Ph.D. in physics from the University of Rome Tor Vergata. She is now a post-doc in China. Rodrigo Leonardi is deeply involved in the Planck satellite mission. He joined the mission in 2005, and provided support for the integration and testing of the Low Frequency Instrument (LFI), one of the scientific payloads on board the spacecraft. In 2009, just after the satellite launch, he went to work for the Planck Science Office at the European Space Agency, supporting the scientific operations of the Planck payload, and helping with the development of the Planck Legacy Archive, a system which distributes Planck's final scientific products to the public.

In summary, over the past three decades, Brazilian participation in CMB measurements programs has produced some interesting scientific and technological results. These results were used for thesis development for both Brazilian and US students and helped the advancement of observational cosmology.

Acknowledgements I thank INPE for the continuous support to the projects I have been involved since 1982, providing the necessary manpower, laboratory facilities and financial support for them. CNPq and Fapesp provided throughout these years the financial support that allowed the completion of all the experimental and observational activities necessary to these projects. These supports were crucial for the developments described in this paper. I also thank the collaborative work of INPE's scientists, students and technical personnel in these projects. I acknowledge CNPq grant 308113/2010-1 for allowing me to continue the work related to CMB measurements.

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