The long duration flight of the TopHat experiment

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ABSTRACT

The TopHat instrument was designed to operate on the *top* of a high altitude balloon. From this location, the experiment could efficiently observe using a clean beam with extremely low contamination from the far side lobes of the instrument beam. The experiment was designed to scan a large portion of the sky directly above it and to map the anisotropy of the Cosmic Microwave Background (CMB) and thermal emission from galactic dust. The instrument used a one-meter class telescope with a five-band single pixel radiometer spanning the frequency range from 150-600 GHz. The radiometer used bolometric detectors operating at ~250mK. Here, we report on the flight of the TopHat experiment over Antarctica in January, 2001 and describe the scientific goals, the operation, and in-flight performance.

1. INTRODUCTION

For many scientific experiments the near space environment of a high altitude balloon is adequate to get above the limiting effects of Earth's atmospheric blanket. Numerous far infrared and sub-millimeter astronomical experiments have successfully operated from this platform, but the conventional method of hanging the scientific payload below the large balloon poses some restrictions and limitations for instruments which cannot observe through or near the balloon and it's associated rigging. Clever schemes using letdown reels have allowed observations to be done at great distances below the balloon[1], but this technique can increase risk and limits the stability of the observing platform when it is suspended on a very long line.

The advent of Long Duration Ballooning (LDB) has greatly expanded the possibilities for scientific ballooning. These LDB flights allow sufficient time at a float altitude to perform significantly better science and permit repeated measurements with greatly improved reliability. TopHat was specifically designed to take advantage of the Antarctic LDB flight trajectory. Below, we show that its observing strategy capitalizes on the nearly circular trajectory that these flights typically make around the South Pole.

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1.2 TopHat Scientific Objectives

The spectrum of the CMB is nearly that of a 2.73K blackbody[2] and contains the historical record of the processes that released energy in the early universe. The anisotropy of the CMB contains detailed information about the physical conditions in the very early universe and minute spatial temperature fluctuations (~50μK) provide an imprint of the matter distribution at the epoch when the universe cooled enough for atoms to form from the fully ionized material filling the universe. This pattern of anisotropies in the CMB specifies the initial boundary conditions for developing any theory of large-scale structure formation in the early universe and allows us to estimate cosmological parameters to characterize the universe[3,4].

Recently, detections of anisotropy have been reported[5,6,7,8] using both balloon-borne and ground-based experiments. In this paper, we describe TopHat, another technique for optimizing the balloon-borne observing platform for observations designed to achieve precision measurements of the anisotropy of the CMBR. This instrument is mounted on *top* of a balloon to make a map of a portion of the sky in a region uncontaminated by "local" astrophysical phenomena. The sky sampling is highly redundant so it provides many checks on contamination from undetermined systematic error sources and should provide highly reliable data.

2. THE TOPHAT EXPERIMENT

On the top of the balloon there is a clear observing region with no obstructions for nearly a hemisphere. This platform is above more than 99% of the atmosphere and more importantly for observations at millimeter and sub-millimeter wavelengths, above an even greater fraction of the atmospheric water vapor. At altitudes of ~38 km the balloon and its suspended payload move nearly as a unit because the wind shear over its length is small. With LDB flights from Antarctica, flights of 10-20 days are now "routinely" carried out. Operation on top of the balloon, however, places some serious limitations on instrumentation. Currently packages are limited to ~120 kg in mass and the center of gravity can be no higher than about 60 cm above the base for launchability reasons. There are also height and size restrictions and the launch is more complex than a conventional balloon launch. However, only the much more costly option of orbital platforms offers better viewing and longer observing times.

The TopHat experiment has two major components: 1) the top payload, containing the front-end of the experiment mounted on the *top* of the balloon and 2) the bottom payload, a larger and heavier component suspended in the conventional location below the balloon. The top payload contains the experiment front-end and is composed only of the major components required to be on top of the balloon. The lower payload contains the remainder of the electronics for top-bottom communications, additional electronics for data processing and compression, data storage, data transmission, commanding and power generation and distribution.

Since the balloon is capable of carrying much larger payloads under it than on top of it, the lower payload was designed using commercial components and these were housed in a large pressure vessel. This approach sacrificed weight and expends some extra power, but saved time and cost by relieving us from a great deal of design and testing of components capable of withstanding the wide range of conditions imposed by the ambient balloon-borne environment.

The top payload components were: the telescope, a cryostat containing a multi-channel radiometer, detector readout and communication electronics, the telescope scanning mechanism, power conversion system, and aspect and attitude sensors to allow reconstruction of the telescope pointing.

2.1 The telescope

The telescope is a lightweight aluminum one-meter on-axis Cassegrain configuration. The telescope beam is ~20 arcminutes. The secondary mirror is suspended at the proper position by an array of Kevlar fibers that constrain the secondary position and tilt. The use of Kevlar assures that there are no highly reflective or scattering components near the field of view of the radiometer other than the secondary mirror itself. The other end of the Kevlar fibers are tied to aluminum support bars that are out of the telescope beam. The Kevlar fibers are anchored on the aluminum support bars using a spring mechanism so that small changes induced by thermal expansion/contraction leave the secondary mirror position fixed and maintain tension in the Kevlar fibers.

The telescope is mounted on a rotation table that allows it to turn about the perpendicular to the top plate at 4 rpm. The telescope is within a lightweight double-walled aluminum structure constructed as a truncated cone. The double wall allows the shell to be very stiff and strong while still being lightweight (Figure 1) and to support the entire upper payload during a portion of the launch sequence. In flight, this shell serves as a Sun-Earth shield and is designed so that neither the telescope nor the telescope secondary mirror can be directly illuminated by the Sun during the austral summer at the latitude of McMurdo Station, Antarctica. Wiring carrying power and communications signals passes through a multi-pole slip ring at the rotation table center so the rotating portion of the experiment gets continuous power and bidirectional communications.

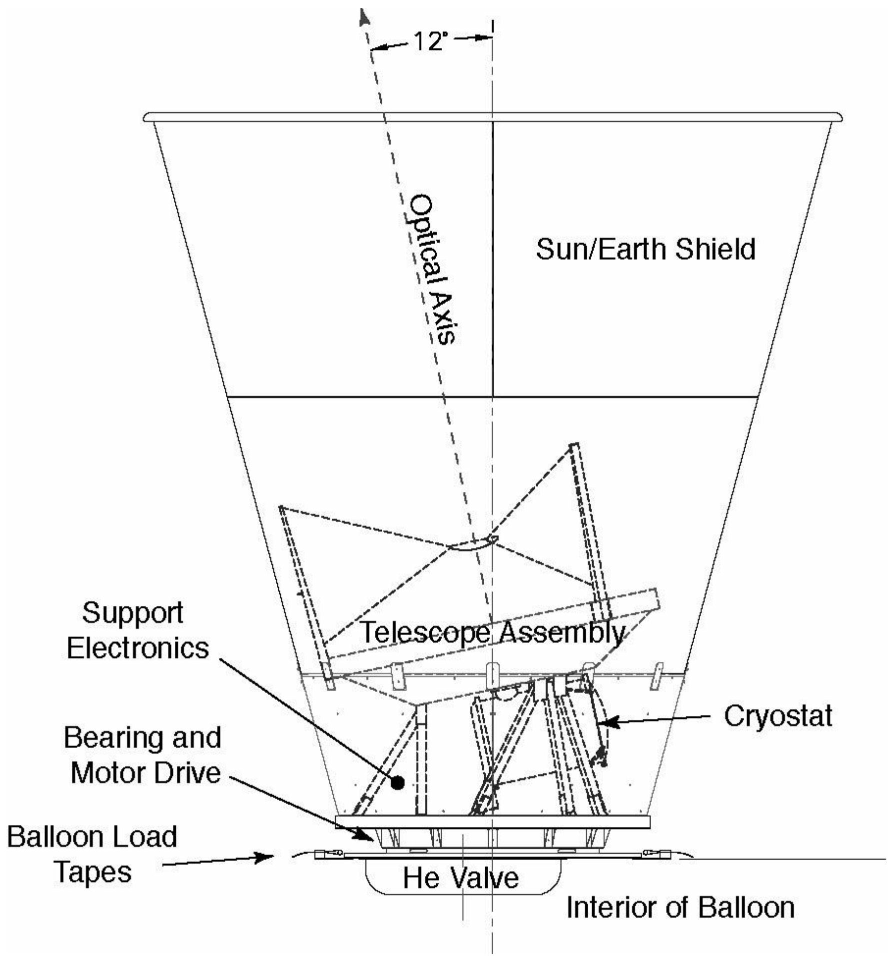


Figure 1. Cutaway drawing of the TopHat upper payload. This portion of the instrument is mounted on top of the balloon. It is bolted to the balloon "apex" plate, a standard part of the balloon. The telescope is canted over 12^{o} from the vertical so a large patch of the sky is scanned each day as the telescope platform rotates. The support electronics are not shown in this cutaway drawing.

2.2 The Radiometer and Detectors

Due to weight, size and center of gravity restrictions for top-mounted payloads, the entire upper payload of TopHat had to be designed carefully. The long hold time cryostat is at center of the design. This cryostat has a mass of 10 kg when it is filled with cryogens and was capable of maintaining the radiometer at 270 mK for about 8 days, long enough for the average Antarctic LDB flight capability developed by NASA's National Scientific Balloon Facility.

The TopHat cryostat is designed as an internally pumped ^{3}He refrigerator with outer tanks containing LN_2 and ^{4}He. Extensive thermal blanketing and low thermal conductivity fill lines give the cryostat a long lifetime for its small size. The internal pump is a zeolite adsorption pump with a large diameter short pumping tube. A thin-walled re-entrant folded pump line reduces the thermal conductivity of the pumping line from the pump to the liquid ^{3}He fluid reservoir while allowing high volume pumping. A detailed description of this cryostat is provided elsewhere[9].

The radiometer is designed as a multiple dichroic beamsplitter to achieve a five-channel instrument spanning the 150-600 GHz range. A "blind" sixth channel is blanked off from the incoming telescope beam and is included in the instrument to monitor pickup or any other non-optical signal that might also couple to the optical channel data. The detectors are ion-implanted monolithic silicon bolometers designed and built at the Goddard Space Flight Center. To achieve the required optical throughput, the devices are 2.4mm in diameter with narrow (~30μm) supporting legs about 2.3mm long. The entire detector is fabricated on 5μm thick silicon. A thin metallic coating of bismuth is applied to the underside of the bolometer to improve the radiation absorption of the devices and a thermistor is added to the devices by ion implantation doping of the silicon. Two of the four supporting legs are degenerately doped to provide electrical contact to the thermistor. Despite their relatively large detector area, we experienced only an average cosmic ray hit rate of ~2/min during the flight even though no efforts were made to reduce the cosmic ray cross section of the devices.

2.3 The lower payload

The remainder of the TopHat experiment was suspended from the bottom of the balloon, the conventional location for balloon-borne payloads. This lower payload contained additional electronics for data processing and compression, ground commanding, data storage and transmission, and power generation and distribution. Redundant wiring built into the gores of the balloon at the time of the balloon's manufacture was used for communications between the top and bottom payloads and power distribution to the top payload. Since weight was not severely restricted for the bottom payload, commercial (COTS) components were used where possible and most of the electronics were contained in a pressure vessel at ~one atmosphere with forced-air cooling. This approach saved time and cost by relieving us from a great deal of design and testing of components that would have to operate in the near vacuum of the ambient environment at balloon altitude.

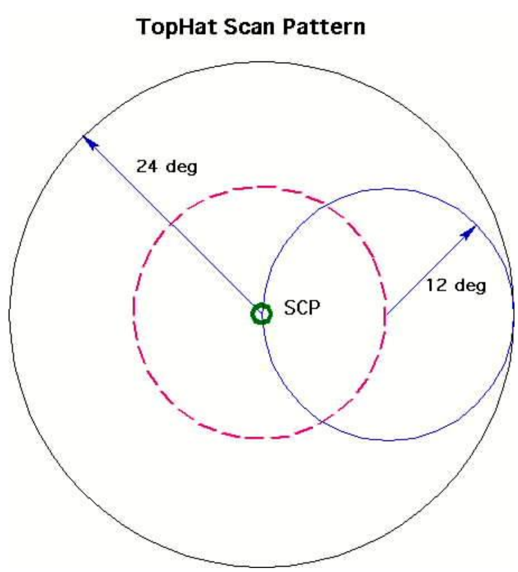


Figure 2. The TopHat Observing Strategy. The telescope beam sweeps out a 12^o radius circle (right side of figure). As the Earth rotates, the local vertical (dashed circle) moves around the SCP causing the swept circular pattern to fill in the inner portion of large 24^o radius circle centered on the SCP.

2.4 Observing Strategy

The TopHat observing strategy takes advantage of the top-mounted payload and the nearly constant latitude flights available for Antarctic long duration ballooning. As discussed earlier, most of the top payload rotates as a unit. This rotation causes the telescope beam to sweep out a highly redundant pattern on the sky (See Figure 2). As the earth rotates, the center of the 12^o radius circle that is being swept on the sky slowly moves around the South Celestial Pole (SCP). The result of this motion is that after one day a nearly circular patch of sky ~48^o diameter is observed with sparse sampling. After several days, the sampling is more complete and highly repetitive for a substantial number of the pixels in this patch. While the drifting latitude of the balloon due to high altitude winds will modify this idealized pattern, the approximately circular patch of sky will still be covered. This strategy provides a highly redundant sampling of the sky with most samples of the sky being crossed at a number of different approach angles and at different times.

The telescope pointing is reconstructed after the flight using information from GPS to determine the position of the instrument and solar glint sensors to determine the location of the Sun with respect to the telescope beam. There are four solar glint sensors located about every 90^o around the circumference of the telescope's Sun-Earth shield. Each sensor is composed of a small lens, a 3-slit mask (see Figure 3) and a photodiode. As the Sun crosses the lens it is imaged on the 3-slit mask. A solar crossing causes 3 large amplitude pulses to occur. The central pulse records the time of solar crossing, and the position of the first and last pulse position relative to the central pulse are sensitive to the Sun's elevation. The positions of the four glint sensors relative to the telescope beam were carefully measured on the ground, but small offsets from their preflight positions were determined from the flight data. A shaft encoder on the rotation axis showed that the telescope rotation was constant throughout the flight, so pointing of the telescope beam at any time could be interpolated from the frequent solar crossings and rotation velocity.

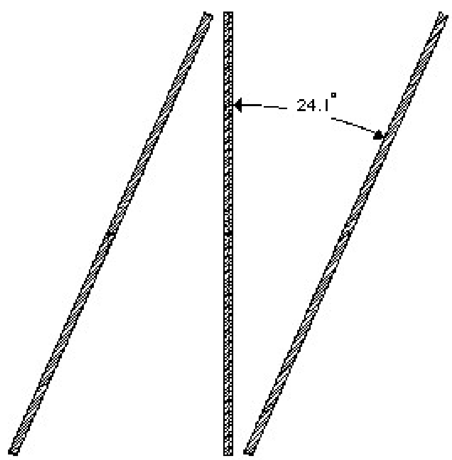


Figure 3. Mask for the solar glint sensor. The 3-slit mask gives an accurate and unambiguous measurement of the time of the Sun's crossing. When combined with the balloon's location and the time, the telescope's pointing can be accurately determined.

3. THE FLIGHT

The TopHat experiment was launched from Williams Field near McMurdo Station, Antarctica on January 4, 2001. The launch sequence had several stages. Initially, the top payload is mounted on a vehicle. A small balloon (the tow balloon) is attached to the top rim of the Sun/Earth shield and was inflated to support the weight of the top payload while the main balloon is inflated under the top payload and is prepared for launch. The entire sequence of events leading to the launch involved the coordination of more than a dozen individuals and several pieces of heavy equipment. A smooth launch was conducted thanks to the expertise and experience of the crew from the National Scientific Balloon Facility.

After reaching float altitude of ~37.5 km, commands were sent to start the telescope's rotation and modify the instrument configuration to optimize the detector and glint sensor performance for the observing conditions at altitude. As the balloon approached its float altitude, housekeeping sensors indicated that the upper payload was tipped over at ~4^o (Figure 4). This was significantly larger than ~1^o that we had experienced in an early instrumented test flight. The effect of this significant tilt is discussed below.

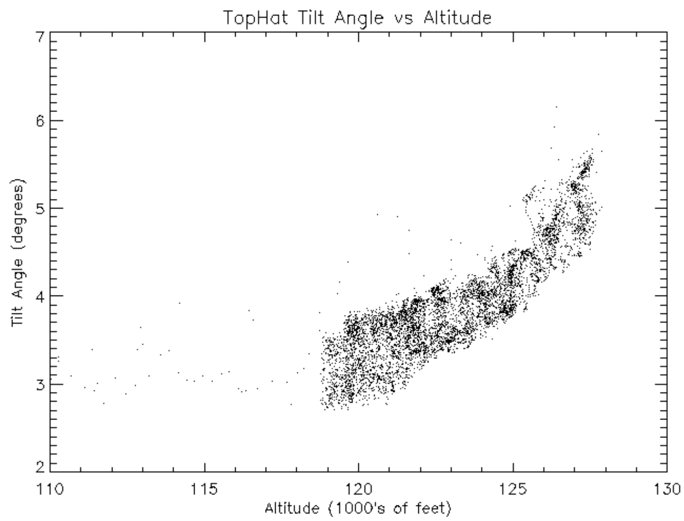


Figure 4. TopHat tilt angle vs. altitude. The tilt angle shows a clear correlation with the balloon altitude.

Communications with the payload were initially conducted using a line-of-sight (LOS) high bandwidth downlink and a low bandwidth uplink for commanding. After about 30 hours the balloon approached the horizon (~300 miles away) and these links were lost. Further communications with the payload were supposed to use NASA's Tracking and Data Relay Satellite (TDRSS).

After the initial setup, few additional commands were required for the experiment to take useful data. The flight plan included daily changes to the rotation direction of the telescope and reversal of the polarity of the detector bias. Both of these improved our ability to detect and remove systematic errors. Initially communications with TDRSS proceeded as planned, but significant data dropouts occurred. By the third day of the flight the TDRSS link was entirely lost. Because TopHat had been designed for nearly autonomous operation, this did not present an immediate problem, but the planned commands to reduce/detect systematic errors could not be sent to the payload. Initial tests indicated a failure of the TDRSS transmitter onboard the balloon. Since the balloon was drifting so slowly, it was decided to launch an underflight of the balloon using an aircraft to determine the status of the instrument. An aircraft equipped with communications gear was sent to the Russian base at Vostok where it refueled and then conducted an underflight of the balloon using the LOS links. At that point it was determined that the experiment was still operating correctly, but the cryogens had been exhausted and the experiment was shut down.

Due to the TDRSS link failure, it was imperative that the data disks be recovered. Because the terrain under the balloon was unsuitable for recovery of the payload at the time the experiment was shut down, it was decided to let the balloon proceed on its flight trajectory around the South Pole. The balloon had been proceeding slowly west around Antarctica (Figure 5), but as it worked its way around we realized that we were going to set a record for the longest LDB flight to date. Approximately three weeks into the flight the payload started to head south resulting in an even slower progress toward its goal of getting to an appropriate recovery region. On January 31, 2001, the balloon finally reached a region near the Ross Ice Shelf that was deemed safe for recovery. At this point the flight was terminated. A recovery team located the bottom payload containing the data disks. Both data disks were recovered intact and found to contain identical copies of the data from the entire powered portion of the flight.

The anomalously large tilt of the top mounting plate led to increased pickup from the residual atmospheric, thermal changes in the telescope, and gravitationally induced motions in the optical system. The repeated observations of the sky have allowed us to separate and remove these effects from the data and recover the sky signals. The early exhaustion of the cryogens is probably the greatest impact from the anomalous tilt. We expect that continuous sloshing of the liquid ^{4}He caused by the tilt resulted in the reduced hold time compared to our pre-flight tests of the cryostat hold time.

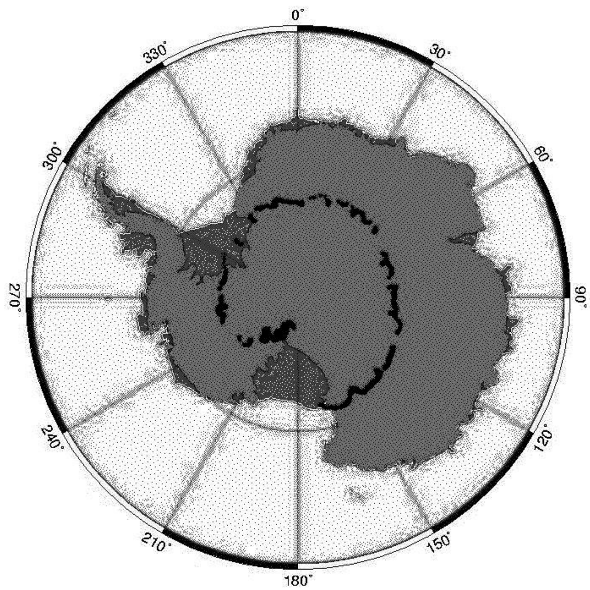
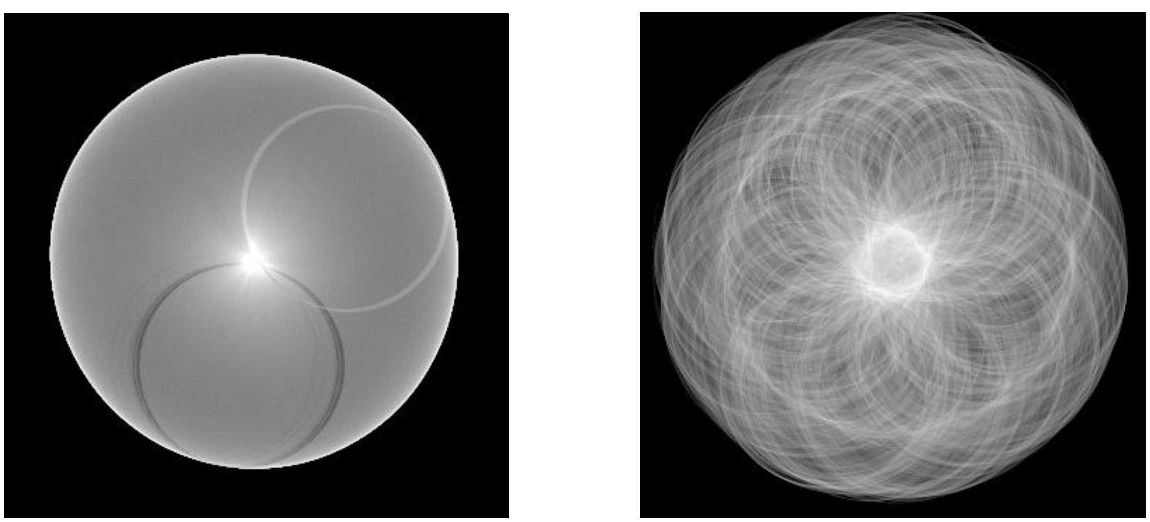


Figure 5. The flight path of TopHat (broken black line). The TopHat experiment was launched from McMurdo Station (longitude ~170^o) and slowly drifted west around the South Pole. At about 230^o longitude, the winds at float altitude took the balloon in a southerly direction and its circumpolar progress slowed dramatically. The flight was finally terminated near the Ross Ice Shelf on January 31, 2001 after it had been aloft for ~644 hours.



(a) (b)

Figure 6. Ideal and actual sky coverage. Whiter areas indicate greater integration time. (a) The left hand panel shows what the sky coverage would have been for the first day of operation of TopHat without the anomalous tilt. The dark circle near the bottom shows up because of data dropouts in the telemetry (later recovered) and the light circle in the upper right is due to overlapping coverage because of balloon drift. (b) The right hand panel shows the actual sky coverage over four days. The diameter of the covered patch is ~56^o, about 35% larger in area than our preflight estimate of sky coverage.

3.1 Attitude Reconstruction

The ~4^o tilt of the top plate of the balloon has complicated the reconstruction of the telescope pointing. However, the high redundancies in the observations and simple scanning scheme have made high accuracy pointing possible even with this anomaly. An iterative technique is used. First a direct measurement is made using the onboard sensors-gyro, inclinometer, solar glint sensors and GPS information. Then, in a second step a sky map is made and the per pixel variation is minimized by determining the small unknown offsets between the axes of the aspect sensors and the telescope beam. By iterating this process, stable offsets are found for the sensors and self-consistent minimum variation maps are generated.

Due to the tilt of the top package, the planned scanning pattern was modified (Figure 6). The resulting sky coverage is greater than was planned, but the resulting integration per pixel is slightly smaller. We estimate that the final pointing accuracy of the telescope beam will be determined to ~2 arcminutes or about 10% of our beam diameter. This is quite adequate to achieve our scientific goals. A sample map is shown in figure 7.

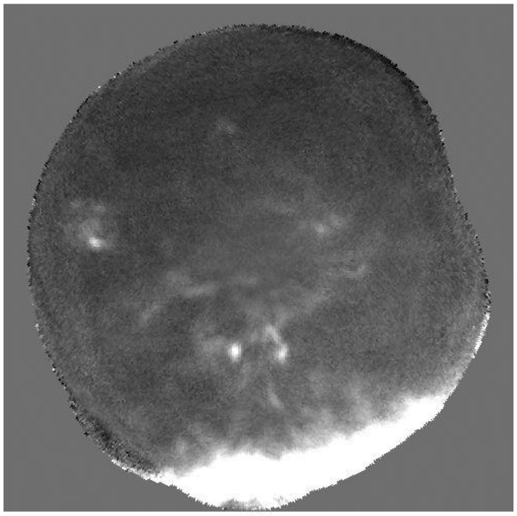


Figure 7. A TopHat sky map at short wavelengths. The South celestial pole is at the center of the map. The bright (white) linear structure near the bottom of the figure is the galactic plane where there is a great deal of thermal emission from dust. Large areas of the map are nearly free of dust emission and are prime regions for study of CMB anisotropy.

4. CONCLUSIONS

The TopHat experiment successfully flew on a mission which mapped ~6% of sky at five wavelengths spanning the 150-600Ghz range. While the anomalous tilt of the top plate where TopHat was mounted has caused some delays in completing the data analysis, we expect that the TopHat data will meet its scientific objectives and provide precision data on the anisotropy of the CMB.

The location of a payload on top of an LDB flight provides significant advantages for some astrophysical and atmospheric measurements. Our experience shows that the top is relatively stable and rigid. Payloads of about 250 lbs are practical and may be competitive with satellites for some scientific objectives. While the cause of the relatively large tilt of the top plate of the balloon remains unknown, its stability and slow change with altitude made it tractable to handle in our data analysis.

ACKNOWLEDGEMENTS

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