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A BALLOON-BORNE 102-CM TELESCOPE FOR FAR-INFRARED ASTRONOMY

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FINAL REPORT

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FINAL REPORT

A BALLOON-BORNE 102-CM TELESCOPE

FOR FAR-INFRARED ASTRONOMY

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I. INTRODUCTION

High altitude balloons provide a very attractive platform for astronomical observations at infrared wavelengths. Due to atmospheric absorption ground-based infrared observations are limited to studying a very small portion of the infrared spectrum, but at altitudes greater than 28 km the atmosphere is highly transparent (>99%) to the entire spectrum. The atmospheric background emission is one to two orders of magnitude lower at balloon than at aircraft altitudes (14 km), and the balloon platform presents a very quiet environment, free from air turbulence effects. Therefore, balloon-borne telescopes have important advantages for large throughput, sensitive sky surveys and for high resolution large area mapping experiments over the entire infrared spectrum. They also provide a substantially better platform for infrared spectroscopy because of less contamination by atmospheric lines.

It is through the balloon-borne telescope program that new instrumentation is developed and tested and that astronomers gain scientific experience that can be applied to space experiments. The results of the program have already significantly influenced the instrumentation and design of space experiments, and almost all of the principal investigators in NASA's balloon-borne infrared astronomy programs are also principal investigators or co-investigators on space infrared telescope programs.

Other advantages of ballooning in far-infrared and submillimeter astronomy are its economy, as well as its versatility and the relatively quick response time to new ideas and discoveries.

Balloon technology has developed to such a state that today infrared telescopes with mirrors as large as 1.2-meter diameter and telescopes with mirrors cooled to liquid helium temperatures are routinely flown.

II. DESCRIPTION OF THE 102-CM BALLOON-BORNE TELESCOPE

In the early 1970's the Smithsonian Astrophysical Observatory and the University of Arizona (UA) engaged in a cooperative program to develop a balloon-borne 102-cm telescope capable of carrying out far-infrared (40-250μm) observations of astronomical interest above the earth's atmosphere (G. Fazio, 1981; see Appendix B).

Since 1972 the telescope has been flown and successfully recovered a total of nineteen times. Thirteen of the flights have produced high-quality astronomical data, resulting in more than 92.5 hours of photometric and spectroscopic observations of numerous objects, such as H II regions, dark clouds, molecular clouds, a planetary nebula, a galaxy, the galactic enter, the planets, and an asteroid. From the launch site in Palestine, Texas, sources as far south as -50 degrees declination have been observed. Fifty-nine publications have resulted from this work.

The balloon-borne telescope was one of the most sensitive instruments ever used for observations in the far-infrared region of the spectrum. It has been most productive in producing high resolution (1') maps of large areas (typically square degrees) centered on known H II regions, molecular clouds, and dark cloud complexes. In many cases these scans produced the first far-infrared maps of these regions, and many new sources were discovered. Our results have led to a better understanding of the distribution of gas and dust in these regions, the evolution of H II regions, and the processes of star formation in giant molecular clouds. A summary of the properties of the telescope is given in Table 1; the telescope is described in greater detail in Appendix B; and a photograph of the telescope is presented in Figure 1.

Table 1.

Summary of Properties of 102-cm Balloon-Borne Far-Infrared Telescope

Telescope:	
Type	Cassegrain
Aperture	102 cm (40 in.)
Effective Focal Length	13.8 m (545 in.)
Focal Ratio	f/13.8
Optical Materials	Aluminum alloy primary, pyrex secondary.
Coatings	Evaporated aluminum
Image Quality	15 arcsec at a temperature of 220K; diffraction limited at 100μm (25 arcsec).
Gondola:	
Size	5.1 m high, 3.4 x 2.9 m
Weight	1814 kg (4000 lb.)
Attitude Control:	
Type	Position-controlled altitude-azimuth mount.
Reference sensors	Position mode: Magnetic field in azimuth, local vertical in elevation. Inertial mode: Two rate-integrating gyroscopes mounted on telescope tube.
Orientation stability	Position mode: 1 arcmin p-p jitter in azimuth and elevation. Inertial mode: DC drift rate of gyros approximately 3 arcsec/min; <10 arcsec p-p jitter.
Star sensors	SIT television camera (finder telescope with 5° FOV); SIT television camera (focal plane camera with 20 arcmin FOV); star field photographic camera (5° FOV).
Absolute Position	~10 arcsec using focal plane television and video recorder; ±10 arcsec to ±30 arcsec using star film camera post flight.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

Figure 1.

III. FOCAL PLANE INSTRUMENTATION

(1) Summary

During the history of the program, six different instruments have been flown at the focal plane of the 102-cm balloon-borne telescope. A summary of these instruments is given in Table 2. The broad-based photometer using bolometers was described by Fazio (1977). The broad-band photometer (photoconductors), the four color single beam photometer, the far-infrared Michelson interferometer, and the Fabry-Perot spectrometer are described by Fazio (1981). The remaining instruments are described below.

(2) UCL Fabry-Perot/Grating Spectrometer

We have used the University College London (UCL) far-infrared Fabry-Perot interferometer and grating spectrometer at the focal-plane of the 102-cm balloon-borne telescope to measure shock-excited H_2O emission lines between 50 and 100 μm. This spectrometer had been previously flown and operated successfully on the UCL 60-cm balloon-borne telescope (Poulter 1984; Poulter and Jennings 1983).

The instrument consists of a fast scanning Fabry-Perot interferometer combined with a liquid helium cooled grating spectrometer. The Fabry-Perot gives the high spectral resolution required while the grating spectrometer has the dual function of isolating a single Fabry-Perot transmission fringe and at the same time reducing the background radiation flux onto the detectors by restricting the spectral bandwidth. The spectral resolution of the combined system is $\lambda/\Delta\lambda \sim 1000$. The grating spectrometer can also be used on its own for low resolution ($1\ cm^{-1}$) spectroscopy. Measurements during flight indicated that a system NEP (including all instrument and telescope losses) of 5×10^{-13} $WHz^{-1/2}$ was achieved. This has since been improved and laboratory tests provide values approximately 10 times lower.

When account is taken of all losses within the system, it is expected that at 110 μm a 4σ detection of a $1 \times 10^{-18}\ W\ cm^{-2}$ will be possible in 1000 seconds. With 1000 seconds of integration at 60 μm, it should be possible to obtain a 4σ detection of the line with a strength of $\sim 2 \times 10^{-18}\ W\ cm^{-2}$.

Table 2.

102-CM BALLOON-BORNE TELESCOPE

FOCAL PLANE INSTRUMENTS

(1) BROAD-BAND (40-250 μm) PHOTOMETER

- 4 Ge:Ga BOLOMETERS (1.5 X 1.0 ARCMIN; 0.5 X 0.5 ARCMIN)
- COLLABORATOR: F. LOW (UNIVERSITY OF ARIZONA)

(2) BROAD-BAND (40-120μm) PHOTOMETER

- 4 Ge:Ga PHOTOCONDUCTORS (1.5 X 1.0 ARCMIN; 0.5 X 0.5 ARCMIN)
- COLLABORATOR: K. SHIVANANDAN (NRL)

(3) FOUR-COLOR SINGLE BEAM PHOTOMETER (16-23, 35-65, 65-110, 100-120 μm)

- COLLABORATOR: UNIVERSITY OF PALERMO

(4) FAR-INFRARED MICHELSON INTERFEROMETER

- COLLABORATOR: W. TRAUB (SAO)

(5) FABRY-PEROT SPECTROMETER

- COLLABORATOR: CNRS FRANCE

(6) FABRY-PEROT/GRATING SPECTROMETER

- COLLABORATOR: UCL

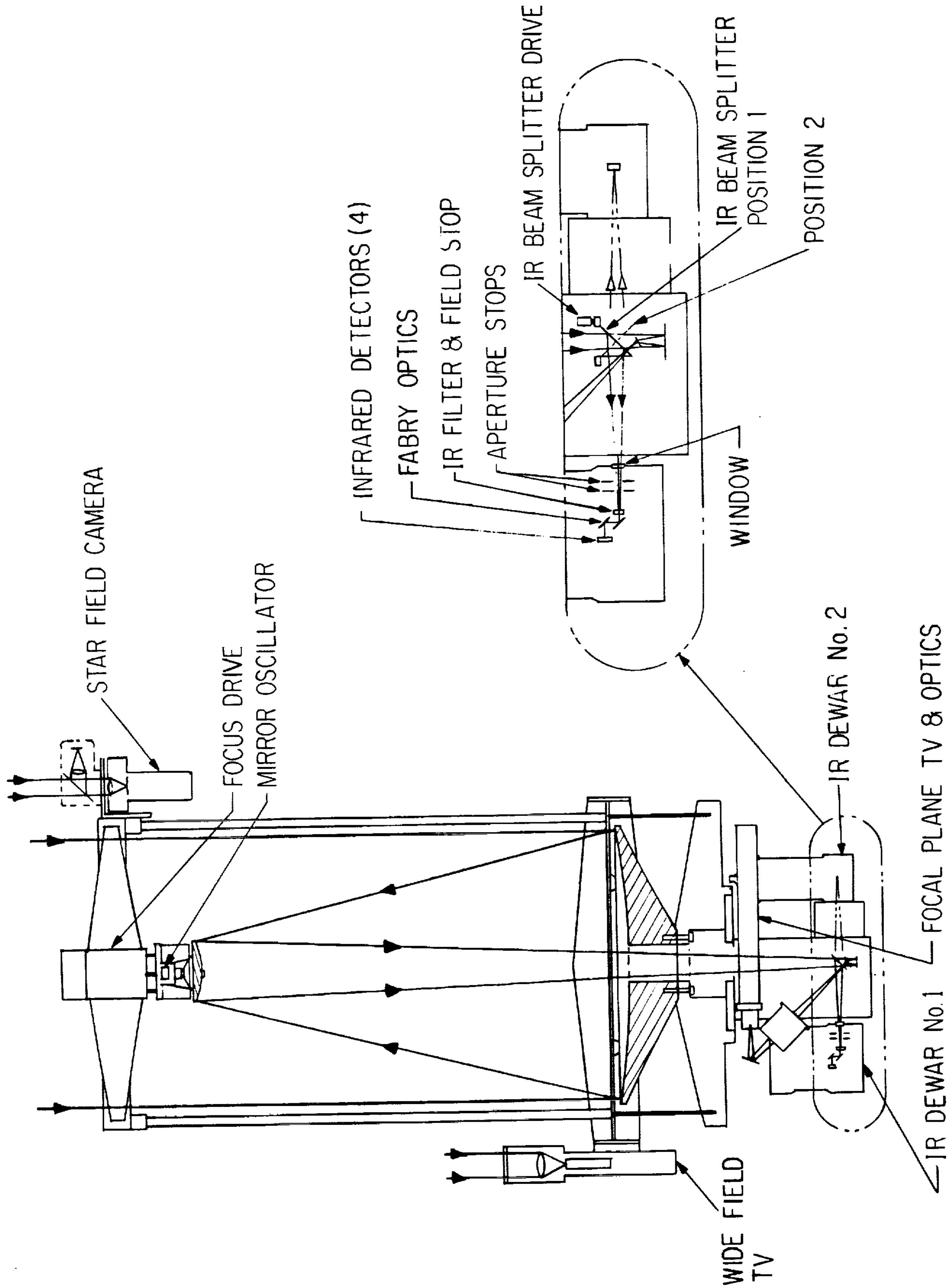
(7) CAPABILITY FOR DUAL FOCAL-PLANE INSTRUMENTS

(3) Dual Focal Plane Instruments

The telescope has the capability of mounting two independent infrared instruments at the focal plane (Figure 2.) A dichroic beamsplitter can be rotated 180° by telecommand to select either one of the two experiments.

Figure 2.

Optical layout of the Focal Plane Instrumentation and Television Guider for the 102-cm Balloon-Borne Telescope



IV. HISTORY AND FLIGHT RECORD

The flight history and flight record are summarized in Tables 3 and 4 respectively.

After nineteen years, the program was terminated in 1989. The gondola, associated electronics, and wiring had become too unreliable. Funds were requested from NASA for a complete refurbishment of the telescope and gondola, but such funds were unavailable. Rather than risk a failure, the program was terminated and the system put into storage.

Table 3.
102-CM BALLOON-BORNE TELESCOPE

FLIGHT HISTORY

1.	ORIGINAL CONCEPT	1970
2.	CONSTRUCTION (SAO/HCO)	1971
3.	FIRST FLIGHT	1972
	SECOND FLIGHT	1973
4.	ENVIRONMENTAL TESTS (NASA/JSC)	1973
5.	FIRST SUCCESSFUL FLIGHT	1974
6.	LAST FLIGHT (19th)	APRIL 1987
7.	PROGRAM TERMINATED	1989

Table 4.

102-CM BALLOON-BORNE TELESCOPE

<u>FLIGHT RECORD</u>

- NUMBER OF FLIGHTS: 19
- SUCCESSFUL FLIGHTS: 13
- TOTAL HOURS OBSERVATION: 92.5
- FAILURES:
  (1) ELECTRONIC - 2
  (2) BALLOON - 3
  (3) REEFING SLEEVE - 1
- NO DAMAGE TO GONDOLA OR FOCAL-PLANE INSTRUMENTS

V. SCIENTIFIC RESULTS AND PUBLICATIONS

Over the past twenty years the 1-meter balloon-borne infrared telescope has contributed very significantly to a number of fundamental astronomical problems. These include:

(1) ORIGIN AND EVOLUTION OF STARS

Large-area mapping of the sky at far-infrared wavelengths, using the 1-meter balloon-borne telescope, has contributed significantly to our understanding of star formation and evolution in giant molecular clouds, a great unsolved problem in modern astrophysics. Numerous surveys of giant molecular clouds in the galaxy were produced. One of these surveys produced the first high sensitivity, high resolution far-infrared map of an entire giant molecular cloud complex, identifying numerous infrared sources in the cloud. When these results were combined with radio continuum, CO, and water maser observations of these sources, theoretical formation mechanisms for the stars in the cloud could be tested. Data from these surveys also measured the total infrared emissions from these clouds, which was used to examine the energetics in the molecular clouds surrounding the embedded infrared sources. The 1-meter telescope has discovered numerous new sites of star formation which were later investigated in more detail by the Kuiper Airborne Observatory.

(2) INTERSTELLAR MEDIUM

Understanding the expansion of H II regions into surrounding molecular clouds and the surrounding low-density interstellar medium is important in determining the global properties of the interstellar medium, the methods by which further star formation is triggered, and the methods by which gas and dust are returned to the interstellar medium. Observations by the 1-meter balloon-borne telescope have made major contributions to our knowledge of H II regions and have provided the first large-area survey of these objects over the galactic plane. Hundreds of these sources have been observed and from this data a coherent picture of the evolution of an H II region in a molecular cloud has emerged which is consistent with current theoretical models.

(3) GALACTIC NUCLEI

Understanding the structure of galactic nuclei still remains an important problem in astrophysics. The dense cores of galaxies are often the source of extraordinarily high far-infrared luminosity. The 1-meter balloon-borne telescope was used to study the cores of M82 and the center of our Galaxy. In our Galaxy the first maps of the distribution of discrete far-infrared sources in the region of the Galactic center were produced.

(4) SOLAR SYSTEM

The outer planets emit almost all of their energy at far-infrared wavelengths. Observations of these planets using the 1-meter balloon-borne telescope measured their temperature and demonstrated that Neptune possesses an internal heat source. The telescope also made the first far-infrared observations of an asteroid, Ceres.

(5) ATMOSPHERIC SCIENCE

In collaboration with Dr. W. Traub, SAO, flights with a Michelson interferometer at the focal plane of the telescope were used to perform far-infrared spectral measurements of astronomical objects during the night and measurements of the far-infrared spectrum of the atmosphere during the day.

Far-infrared spectroscopy of the atmosphere using the 1-meter balloon-borne telescope has played an important role in the early understanding of one of the most important problems in atmospheric chemistry, the perturbation of the stratospheric ozone layer as a result of human activity. In situ measurements were made of compounds in the ozone-destroying catalytic cycles, such as HF, HCl, HOCl, OH, H_2O_2, and HOCl. The theoretical atmospheric transmission at mid- and far-infrared wavelengths, at mountain, aircraft, and balloon altitudes, was also calculated. This latter work has been a standard reference for many years.

The fifty-nine publications resulting from this research are listed in Appendix A and summarized in Table 5.

TABLE 5.

PUBLICATIONS

ASTRONOMY	42
INSTRUMENTATION	6
ATMOSPHERIC SCIENCE	11
TOTAL:	59

ASTRONOMICAL SOURCES

ORION NEBULA	W42
M43	M16
W3	M17
Rho Oph	M17 SW Mol Cld
URANUS, NEPTUNE	NGC 6357
CERES	RCrA
M20	W28 (SN)
M82	GALACTIC CENTER
M8, M8E	W33
W31	W51
M17	NGC 6334
IR12.4=0.5	RCW122
NGC 6334	G351.6-1.3
NGC 6334 (V)	CYGNUS-X
IRC+10216 (SIZE, SPECTRUM)	(DR-6, 7, 22, 15)

VI. EDUCATIONAL ASPECTS

The 1-meter balloon-borne telescope program has produced five Ph.D. theses. four from the Astronomy Department, Harvard University, and one from the Physics Department, University College, Dublin.

Both Professors Brian McBreen, University College, Dublin and T. N. Rengarajan, Tata Institute for Fundamental Research spent one-year sabbatical leaves at SAO, and made numerous shorter visits observing with the telescope and reducing and analysing data.

The gondola design has been copied by three groups, each time with improvements. These results are summarized in Table 6.

TABLE 6

Ph.D. THESES (5)

•	E. L. WRIGHT (HARVARD)	1976
•	M. STIER (HARVARD)	1979
•	D. JAFFE (HARVARD)	1980
•	S. ODENWALD (HARVARD)	1982
•	L. O'LOCHRAINN (DUBLIN)	1986

VISITING SCIENTISTS PROGRAM

- BRIAN McBREEN (DUBLIN)
- T. N. RENGARAJAN (TIFR, INDIA)

GONDOLA DESIGN

- 3 GROUPS HAVE COPIED 1-M TELESCOPE DESIGN:
  - (a) NASA/GODDARD SPACE FLIGHT CENTER
  - (b) HIGH ENERGY ASTROPHYSICS DIVISION, HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS
  - (c) TATA INSTITUTE OF FUNDAMENTAL RESEARCH, INDIA

VII. FUTURE PLANS

A balloon-borne three-meter telescope for far-infrared and submillimeter astronomy has been proposed jointly by the University of Arizona (W. F. Hoffmann), the Smithsonian Astrophysical Observatory (G. G. Fazio), and the University of Chicago (D. A. Harper). The purpose of this project is to provide a facility for photometry, spectroscopy, and imaging in the spectral region 30 micrometers to 1 millimeter, which is largely inaccessible with ground-based telescopes. The three-meter telescope will provide a much needed gain in sensitivity and spatial resolution compared to the present approximately one meter sized balloon and aircraft telescopes. The telescope is to be a Cassegrain design with an angular resolution diffraction-limited to a wavelength of 30 microns. It will be supported on a three axis, gyroscopically-stabilized system with a pointing stability of one arcsecond rms. The overall weight of the telescope and gondola is expected to be approximately 2800 kg, assuming a lightweight mirror formed as a welded structure of Pyrex or fused silica. We are also studying the possibility of using a carbon fiber reinforced plastic sandwich panel for the primary and secondary mirrors and carbon fiber reinforced plastic members for the telescope structure. The intended operation is approximately five 8 to 10 hour flights per year carrying two instruments at a time.

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APPENDIX B

A 102 cm balloon-borne telescope for far-infrared astronomical observations

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Abstract

In early 1971, the Harvard Smithsonian Center for Astrophysics and the University of Arizona engaged in a cooperative program to develop a balloon-borne gryo-stabilized, 102-cm telescope capable of carrying out far-infrared observations of astronomical interest above the earth's atmosphere. Since 1972 the telescope has been flown and successfully recovered a total of sixteen times. Ten of the flights have provided high quality astronomical data resulting in more than eighty hours of photometric and spectroscopic observations of numerous astronomical objects.

The telescope and its modes of operation are described, including the attitude control systems and the methods of aspect determination. A brief summary will be given of the infrared instrumentation used. The experience gained from the operation of balloon-borne infrared telescopes and from development of new infrared instrumentation has been extremely valuable when applied to space experiments, particularly the infrared telescopes planned for operation on the Space Shuttle.

Introduction

Far-infrared observations of celestial objects are essential in solving several important astronomical problems. These include:

- The birth and evolution of stars.
- The structure of our galaxy, particularly the distribution of dust and gas and its relationship to the distribution of stars.
- Properties of the interstellar medium, such as abundances, distribution and chemistry of its constituents.
- The origin of the high luminosity of the nucleus of our own galaxy.
- The source of energy of the extraordinarily high luminosity of the nuclei of some galaxies.
- The origin of the universe, particularly tests of the "Big Bang" theory and the search for protogalaxies.
- The nature of the outer planets.
- The nature of the sun and the solar atmosphere.

Far-infrared observations, however have their difficulties. Ground-based observations are impossible due to atmospheric opacity. The atmospheric constituents absorbing in the far-infrared are primarily water vapor, located below the tropopause, and carbon dioxide, with minor contributions from ozone, methane, nitrous oxide, and carbon monoxide. In the region of the spectrum above 25μm wavelength, except for partial windows at 35, 350, 450, and 750μm, all observations must be made from aircraft, high altitude balloons, rockets, or spacecraft.

Large scientific balloons, in particular, at altitudes greater than 28 km, where the atmosphere is highly transparent (>99%), provide an attractive platform for infrared observations. Atmospheric emissivity is one to two orders of magnitude lower at balloon than at aircraft altitudes (14 km), and the aircraft experiences a "sky noise" presumably due to air turbulence in addition to the steady thermal atmospheric background flux. These differences give balloon-borne experiments an important advantage for large throughput, sensitive sky surveys or low resolution mapping experiments, as well as providing a substantially better platform for spectroscopy because of less contamination by atmospheric lines. Aircraft on the other hand have the advantage of very well stabilized and accurately pointed telescopes with excellent data-handling and real-time analysis capability. They have been most productive in high resolution mapping photometry with long integration times, and low-resolution spectroscopy of moderately bright sources. In the past these two platforms have been very complementary in their capability for infrared astronomy.

Today more than twenty groups from all over the world use balloon-borne telescopes for far-infrared and submillimeter astronomy and over the last few years they have produced major contributions to the understanding of many areas of astrophysics.