BALLOON-BORNE THREE-METER TELESCOPE FOR FAR-INFRARED AND SUBMILLIMETER ASTRONOMY

Grant NAGW-509

Semiannual Status Report No. 2

For the period 1 March 1984 through 31 August 1984

Principal Investigator

Dr. Giovanni G. Fazio

October 1985

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1.0 INTRODUCTION

This is the second Semiannual Report submitted under Grant NAGW-509 for the development of a Balloon-Borne Three-Meter Telescope for Far-Infrared and Submillimeter Astronomy. It covers the period 1 March 1984 through 31 August 1984. This grant covers work at the Smithsonian Astrophysical Observatory (SAO), University of Arizona (UA) and the University of Chicago (UC). SAO is responsible for program management, the gondola structure including the attitude control and aspect systems, mechanical systems and telemetry and command systems; the UA is responsible for optics design and fabrication; the UC is responsible for determining provisions for focal-plane instrumentation. SAO and the UA share responsibility for the ground support data and control computer.

2.0 SUMMARY OF WORK PERFORMED DURING REPORTING PERIOD

2.1 Optical Design

Four important aspects of the scientific requirements of this telescope are to cover the spectral range not observable or only poorly observable from the ground from 30 microns to 1 millimeter, to provide a collecting area much larger than now available from 1 meter size balloon-borne and airborne telescopes for high resolution far infrared spectroscopy, to provide a major advance in far infrared spatial resolution, and to take advantage of the potential sensitivity obtainable from the low thermal background obtainable from observations from balloon altitudes. The specifications resulting from these requirements are given in Table 2-1.

The 3 meter aperture provides the required large step in collecting area and spatial resolution, and is the largest size compatible with current US balloon launch facilities. The spectral range and angular resolution requirements imply diffraction limited optical performance at wavelength of 30 microns. This means a half-power full-width of the central diffraction fringe of 2.5 arcseconds, which determines the acceptable image blur from optical design aberrations, misalignment, and fabrication errors. Conventionally, with optical (visible light) telescopes, this is taken to mean total effective rms surface errors of 1/26 of the wavelength. This yields a Strehl ratio (the ratio of the peak intensity of a point source to that produced by an ideal diffraction pattern) of .8. For radio telescope design, the rule of thumb is to require a surface half as accurate and a Strehl ratio of .5. Thus we interpret a 30 micron diffraction limited performance to mean an image diameter (HPFW) of 2.5 arcseconds and a total surface error of 1 to 2 microns rms. Since much of the most important science done on this telescope will come from observations at 50 and 100 microns and beyond, the 2 micron figure appears adequate.

The specification for operation at visible wavelengths is determined by the desire to use the main telescope for imaging stars for guiding purposes. This places additional constraints on the character of the optics surface error and polish.

The unvignetted infrared field of view of 5 arcminutes is chosen to provide two full Airy disk diameters (diameter to the first diffraction zero) at the longest wavelength of operation (1 millimeter).

Table 2-1 Telescope Optics Specifications

Aperture	3 meters
Spectral Range	Visible to millimeter
Angular Resolution	Diffraction-limited to 30 microns HPFW 2.5 arcseconds
Field of View	IR: 5' unvignetted with ±2.5' chop and diffraction spillover at 1 min. Optical: 15' vignetted only by the Primary
Secondary Chopper Throw	±5 arcminutes
Overall Focal Ratio	f/9 to f/16
Focal Plane Ratio	7.7 to 4.3 arc-sec/min
Back Focus (Primary vertex to Focus)	1.4 meters
Maximum Secondary to Primary Spacing	3.5 meters
Secondary Size	Small as possible
Effective Emissivity	≤10%

Achieving maximum possible sensitivity requires an effective noise-free mechanism for subtracting the thermal background from the telescope and sky from the observations. The most successful technique to date for doing this is beam switching by oscillating the second mirror through an angle either with a square wave of a linear scan. While the use of arrays of detectors in the far infrared may provide an alternative background subtraction technique for some observations, the secondary chopper still appears necessary for this telescope. Maintaining quality images while tilting the secondary places major demands on the optical design. A second aspect of the high sensitivity requirements is minimizing the thermal emission of the telescope by minimizing the obscuration from the secondary and the secondary support and maintaining very low emissive surfaces on the optics. Both the chopper and the low obscuration requirements dictate a small secondary mirror.

The launch equipment and staging facilities for the National Center for Scientific Ballooning dictate the overall size of the telescope and in particular the maximum acceptable primary to secondary vertex separation.

The telescope is a classical Cassegrain telescope with a paraboloidal primary and hyperboloidal secondary. The secondary is undersized relative to the primary so that it acts as the entrance pupil of the system. The undersizing is selected so that for the full field size, the maximum chop amplitude, and the full diffraction width (diameter of Airy disk first zero) at the maximum design wavelength (1 mm) the field of view of a detector at the focal plane will "see" only the secondary, the cold sky, and the primary, but not the warm periphery of the primary.

The telescope design is constrained by our desire to provide as large an aperture as possible within the capability of the US Scientific Balloon Launch Facility. This maximum aperture is approximately 3 meters. In addition the overall secondary vertex to Cassegrain focus distance is constrained by the launch facilities to approximately 4.9 meters. In the design study we have chosen as the variable parameters the aperture, Cassegrain focal ratio, primary-secondary separation, and primary-to-focal-plane distance. We will consider the required field radius, chopper field amplitude, and maximum operating wavelengths to be fixed. The trade-off studies we will perform will investigate the impact of varying the input parameters on the focal plane scale, primary focal ratio, secondary obscuration, chopper induced and field aberrations, and alignment tolerances. These impacts will be examined for five different values of each of the four parameters while the other three are held fixed at the chosen design values.

2.2 Gondola Design

Work focused on defining the preliminary design for the gondola, including the telescope, pointing and stabilization system, and subsidiary support systems.

The gondola we are developing will:

1. Provide a stabilized azimuth platform from which a three-meter telescope can be hung in elevation/cross-elevation gimbals.

2. Meet the scientific requirement of spectroscopy and imaging in the IR with arcsecond level pointing stability.

3. Satisfy all NSBF structural, safety, launch, recovery and facility requirements in a weight-efficient manner using standard materials and fabrication techniques.

4. Provide the telescope and focal-plane instruments landing protection.

5. Be readily recoverable and refurbishable.

6. Accept a wide range of focal-plane instruments.

A three-meter aperture f/13.5 Cassegrain configuration was chosen to provide a substantial scientific gain over present one-meter stratospheric telescopes and as a technologically feasible size for realization using a modern lightweight mirror. This aperture size also matches the largest sized gondola that can be conveniently accommodated by the NSBF staging building, launch, and recovery vehicles, and is a reasonable step between the current one-meter stratospheric telescopes and the 10- to 30-meter LDR.

The gondola employs a rigid yoke frame for telescope attachment to the balloon suspension train. The frame has structural resonant frequencies, mass moments and products of inertia that are consistent with control system requirements when fully assembled as a gondola. The gondola frame is a symmetrical modular concept composed of six structural elements: two diagonal beams, two side columns and two horizontal stabilizer beams. The diagonal beams and side columns are fabricated from aluminum as deep-sectioned structural shapes yielding a load-carrying capacity (30 g's) three times the NSBF on-axis requirement with the lowest structural resonant frequency greater than 50 Hz, far beyond the servo system bandpass. The stabilizer beams are standard aluminum structural beams and are used to maintain parallelism between the side columns.

The telescope is suspended within the gondola frame in an elevation/cross-elevation configuration by a gimbal arrangement that provides the telescope's fine-pointing capability. Coarse azimuthal control is achieved at the gondola attachment point to the balloon. A quadrupod composite material telescope structure was chosen as optimal in terms of obscuration, weight and thermal performance. This structure is load bearing during launch, termination and landing. A ball-and-socket type lock captures the telescope structure and applies a tension load between it and the gondola during these flight phases. All NSBF safety requirements can be met, however, with the telescope unlocked. In selecting this design, consideration was also given to a head ring design which was rejected because of higher telescope weight and the resulting weight and energy impacts on the rest of the gondola. Reaction wheels on the telescope and near the azimuth bearing provide inertial references for the pointing system to work against.

Requirements for telescope and instrument integration, launch and recovery were major drivers of the proposed design. Gondola recovery in particular suggests a modular design approach easily refurbishable by means of replaceable elements.

This telescope requires a means for sky subtraction. At a 30-km balloon altitude, the background radiation is dominated by the telescope rather than the sky, which has an emissivity of less than 1% over most of the spectrum. Because of this, the "sky noise" as experienced from balloon altitudes is very small and the required sky subtraction frequency is determined only by the noise spectrum of the detectors, not the properties of the atmosphere. To perform the background subtraction we plan on using a secondary mirror oscillating between 2-20 Hz to avoid 1/f noise characteristic of detector amplifier systems. For many detectors, the lower frequency would be suitable and can be selected.

The pointing stability specification of 1-arcsecond rms is set so as not to compromise the imaging quality of the optics by telescope pointing wander. We expect this to be achievable with present day designs.

The telescope is oriented in two orthogonal control axes, elevation and cross-elevation. However, telescope motion within its gimbal in the cross-elevation axis is limited to about ±3°. The full range of azimuthal angles requires a third control axis. The entire gondola is therefore controlled in the azimuthal direction.

Acquisition of a celestial source is achieved through two modes of operation that are called the Magnetometer and Inertial Modes. The Magnetometer Mode is used for acquiring the approximate position of the source by rotation of the gondola about the azimuthal axis, using the earth's magnetic field as reference, to an accuracy of about 0.5°; and rotation about the elevation axis, using the local gondola vertical as reference, to an accuracy of about 0.1°. The Magnetometer Mode brings the desired source direction within the range of motion of the cross-elevation axis.

The Inertial Mode is used primarily for science-data gathering and as such has various operational routines. In addition to fixed-pointing, which stabilizes the telescope on a given celestial target, the inertial mode can also be used to step or scan the telescope with respect to a celestial object. For mapping of extended sources a raster pattern can be generated by scanning in cross-elevation and stepping in elevation at the end of each scan line. The angular size of such rasters and the scan rates can be varied on command. In addition to the commanded scan rates and directions, a joystick control at the ground station can be employed for telescope positioning.

Aspect data is provided by three TV-like aspect cameras and a star tracker. We expect to explore a number of approaches to this system although CCD technology appears to meet the needs of the system. Live TV-like presentation of the aspect fields during the flight will provide continuous assurance to the ground crew of correct pointing and pointing stability.

Instrument accommodations will be determined on the basis of a survey. We expect weight, volume, power, command and telemetry capabilities provided will meet the requirements of a wide range of potential users. The instrument area will be designed for ease of access and instrument mounting and alignment and is enclosed in a thermal shroud before launching.

The command and telemetry system is designed for compatibility with present and planned NSBF capability. Battery types and capacities will be chosen on the basis of price and weight tradeoffs. Sufficient energy should be available for flights in excess of 10 hours with the baselined gondola systems and experiment complement.

2.3 Other Design Areas

A detailed analysis of the pointing and stabilization servo system has been performed and a preliminary component evaluation completed. These analyses are presented in technical reports 3M-201 "Analysis and System Design of Momentum Wheel Servo Including Flex Pivot Compensation and Gravitational Imbalance Compensation" and 3M-202 "Derivation of Final Momentum Wheel Speed for Proposed System Using Ancillary Torque Motor Inner Loop". The cover pages of these reports are attached to this report as Appendix A. Component studies focused on bearing selection and control elements for the system.

The command and telemetry system has been studied and will utilize NSBF equipment whenever possible to keep cost and maintenance of equipment at a minimum.

Preliminary weight estimates have been completed for a vertically stowed telescope using either a 2 M glass or 3 M composite material mirror. These data are given in Table 2-2.

Preliminary thermal design studies are underway on the telescope structure and mirror. And a test of convection at balloon altitudes is planned for an early balloon mission.

Table 2-2
Three Meter Infrared Balloon Telescope
Telescope Weight Summary

		3M Mirror		2M Mirror	
I.	Sec. Mirror Assembly				
	Mirror	10.		10.	
	Focus Drive	22.		22.	
	Chopper	25.		25.	
	Head Ring	90.		90.	
	Vanes	19.		19.	
	Truss	110.		110.	
			276.		276.
II.	Primary Mirror Assembly				
	Mirror	234.		485.	
	Frame & Mtg.	300.		485.	
	5° Field TV	20.		20.	
	1-1/2 Field TV	25.		25.	
	Fine Aspect TV	25.		25.	
	Star Tracker	35.		35.	
	Counter Weight Servo	20.		20.	
	Miscellaneous Devices	20.		20.	
			679.		1115.
III.	Cross Elev. Axis				
	Elev. Drive System	80.		80.	
	AZ Drive System	80.		80.	
	AZ Frame	140.		140.	
	Al. (R.W.)	55.		55.	
	AZ (R.W.)	55.		55.	
	Tailpiece Interface	100.		100.	
	Electronic Interface	25.		25.	
	Wire Harness	10.		10.	
			545.		545.
IV.	Experiment Package				
	Tailpiece	50.		50.	
	Experiment A	125.		125.	
	Experiment B	125.		125.	
	FPTV	30.		30.	
	Beamsplitter	12.		12.	
	Trim Weights	5.		5.	
			347.		347.
TOTALS:			1847. pounds		2283. pounds

Three-Meter Infrared Balloon Telescope
Weight Summary
Vertically Stowed Telescope

	Weight (Lbs.)		System Totals	
	Unit	Subtotal	3M Mirror	2M Mirror
Telescope Assembly			1847	2283
Gondola				
Structure		1020		
Upper	180			
Telescope Mount	140			
Side Columns	575			
Miscellaneous Structure	125			
Stabilization and Pointing		500		
Momentum Transfer Unit	60			
Reaction Wheels	200			
Magnetic and Gravity Sensors	40			
Elevation Drive System	200			
Electronics		586		
Command	25			
Control	66			
Batteries	150			
Cables, Connectors, etc.	45			
Enclosures	300			
Reentry Devices		210		
Telescope Latch	20			
Crash Rings	150			
Crash Pads	40			
Total System Weight (pounds)			4163	4599

3.0 WORK PLANNED FOR NEXT REPORTING PERIOD

The design definition effort on the telescope and gondola will be completed and the optical design and trade off studies completed.

Behavior of sample composite mirror blanks under thermal and mechanical stress will be evaluated by test.

A program plan and cost estimate building and operating the 3M telescope will be prepared.

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3M-
Report No. 201

Three-Meter Infrared Telescope Program

Engineering Report

Title: Analysis and System Design of Momentum Wheel Servo Including Flex Pivot Compensation and Gravitational Imbalance Compensation

Author: Stan Fay

Date Prepared: 9 July 1984

Summary and Conclusions:

This report analyzes the momentum wheel servo system. The analysis of this closed loop demonstrates why tachometric feedback cannot be used for stabilization. A feedforward lead network must be employed. For the same reasons, the power amplifier electronics of the momentum wheel torque motor must be configured as a current source in order to avoid the tachometric effects of the motor back e.m.f.

Additionally, a technique is suggested using a subsidiary torque motor between "horseshoe" and mirror to provide effective compensation of the flex pivot torque. Also, by proper design of this compensation loop within the momentum wheel loop, it is possible to simultaneously compensate for gravitationally induced torques due to mass imbalance. This eliminates the need for mechanically positioning ancillary balancing weights.

The math model attached may be used for further investigation of the effects of various noise sources, e.g., motor cogging or bearing noise.

3M-
Report No. 202

Three-Meter Infrared Telescope Program

Engineering Report

Title: Derivation of Final Momentum Wheel Speed for Proposed System Using Ancillary Torque Motor Inner Loop

Author: Stan Fay

Date Prepared: 13 July 1984

The expression for final wheel speed is derived for the servo system analyzed in Report 3M-201.