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AIROSCOPE

AMES INFRARED BALLOON-BORNE TELESCOPE

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ABSTRACT

AIROscope is a balloon-borne telescope system designed for astronomical observations at infrared wavelengths. The telescope is gyro-stabilized with updated pointing information derived from television, star tracker, or ground commands.

The television system furnishes both course and fine acquisition after initial orientation using a pair of fluxgate servo compasses.

Command and control is by a UHF link with 256 commands available. Scientific and engineering data are telemetered to the ground station via narrow band F.M. in the "L" band. The ground station displays all scientific, engineering and status information during the flights and records the command and telemetry digital bit stream for detailed analysis.

The AIROscope telescope has a 28-inch diameter primary mirror and Dall-Kirkham optics. The beam is modulated by oscillating a secondary mirror at 11 or 25 Hz with provision for left or right beam fixed positions by command.

A PM tube behind a multi-density target at the telescope focal plane provides information for fine collimation and focusing which is done by commanded adjustments of the secondary mirror.

A star tracker capable of pointing at visual sources to within ±10 arc-seconds RMS can be switched by command into the gyro control loop in place of the TV for pointing at visual targets.

The primary power source for the gondola is provided by silver zinc battery cells of 80 ampere-hour nominal capacity.

GENERAL

AIROspace is a balloon-borne telescope designed for making astronomical measurements at infrared wavelengths. This system was originally developed at the University of Arizona for operation in the ultraviolet (Frecker 1968, Coyne & Gehrels 1968). It has since undergone extensive modification. Command, control, and data acquisition are by R.F. telemetry. The television system and star tracker are attached to the primary telescope which is gyro-stabilized. Figure 1 is a block diagram of the system. The system weighs approximately 775 kg and is carried to 31 km altitude by a 1×10^5 m^3 balloon. Figure 2 is a photograph of the system at launch. Nominal observation time at this altitude is 10 hours. The gondola is recovered and refurbished after each flight. It can be launched at about 7-day intervals.
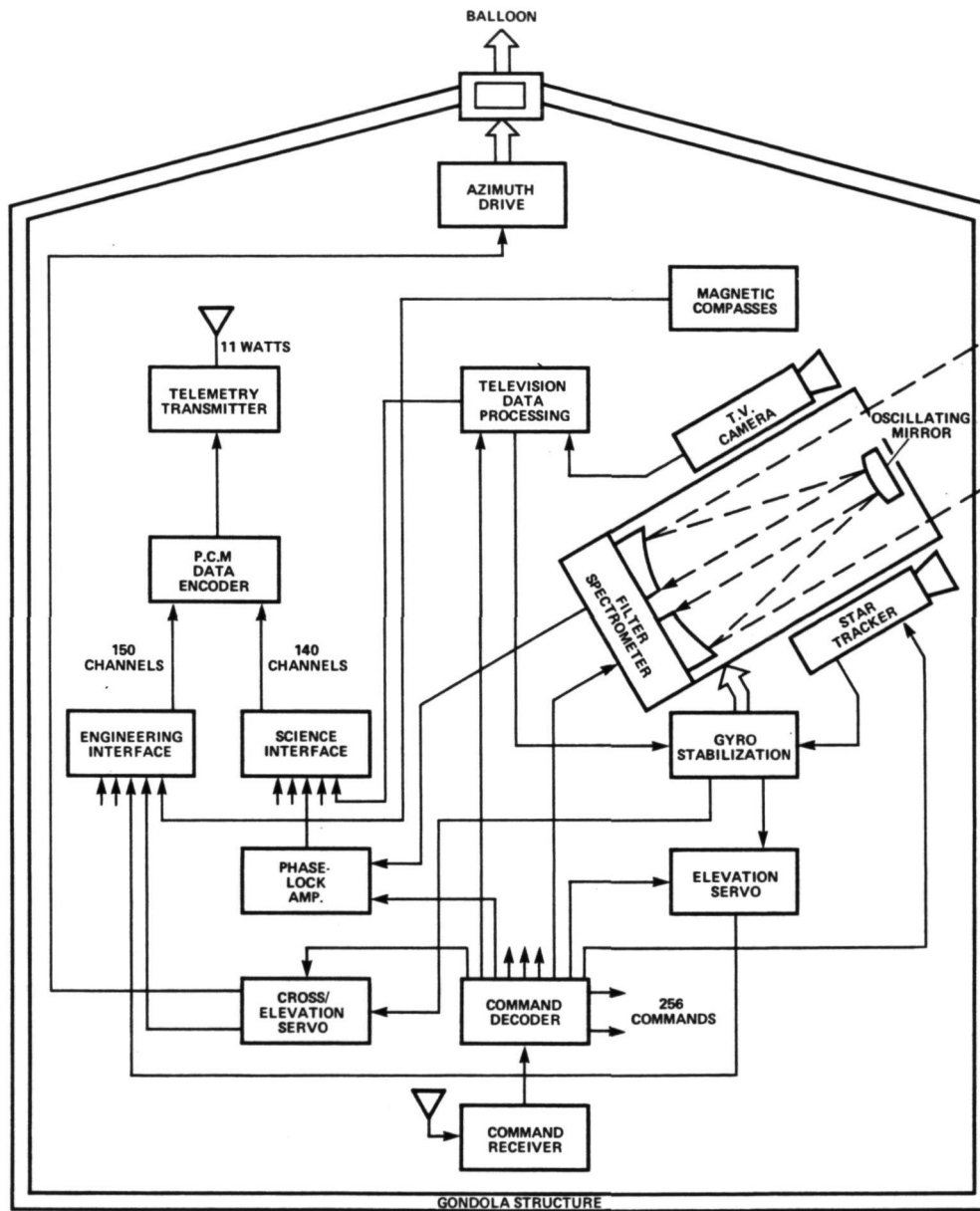
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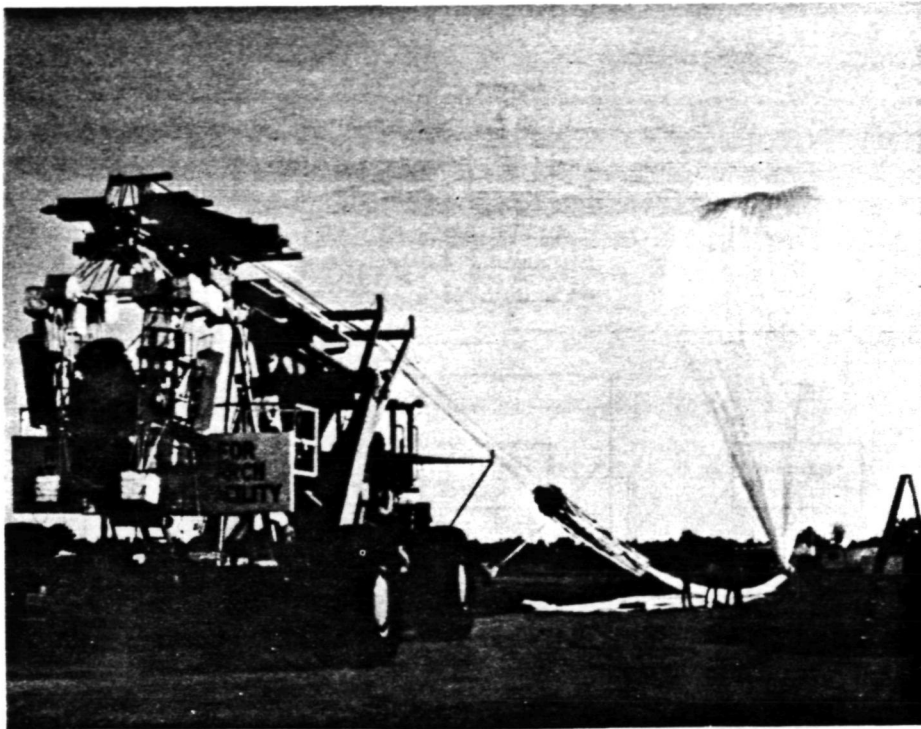Figure 1.   Gondola System Block Diagram

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Figure 2. System ready for launch.

OPTICS

The AIROspace telescope has an elliptical primary and a spherical secondary (Dall-Kirkham optics). This arrangement permits selecting focal ratios to match different requirements by choosing from a group of inexpensive spherical secondary mirrors. With our infrared astronomy program the resulting deficiency in image quality is tolerable even for objects several minutes off-axis.

The primary mirror is 71 cm in diameter but is slightly underfilled by the 13-cm diameter secondary. With the current secondary mirror the f number is 11.2 and the plate scale is 0.4 min/mm. An aperture at the detector limits the field-of-view to 5 minutes of arc. Source modulation at 11 and 21 Hz is produced by oscillating the secondary mirror in a spatial chopping mode often used in infrared astronomy. Each beam position (left and right) is 3.5 minutes off the optical axis. Thus, the movement of the secondary will cause the telescope to first look at the object in the right beam and then to look at the background sky symmetrically to the other side of the optical axis. The resulting modulated signal reaching the detector is primarily from the source since the background noise sources including sky and telescope structure are nearly equal in the two beams. Figure 3 is a diagram of the AIROscope optical system.
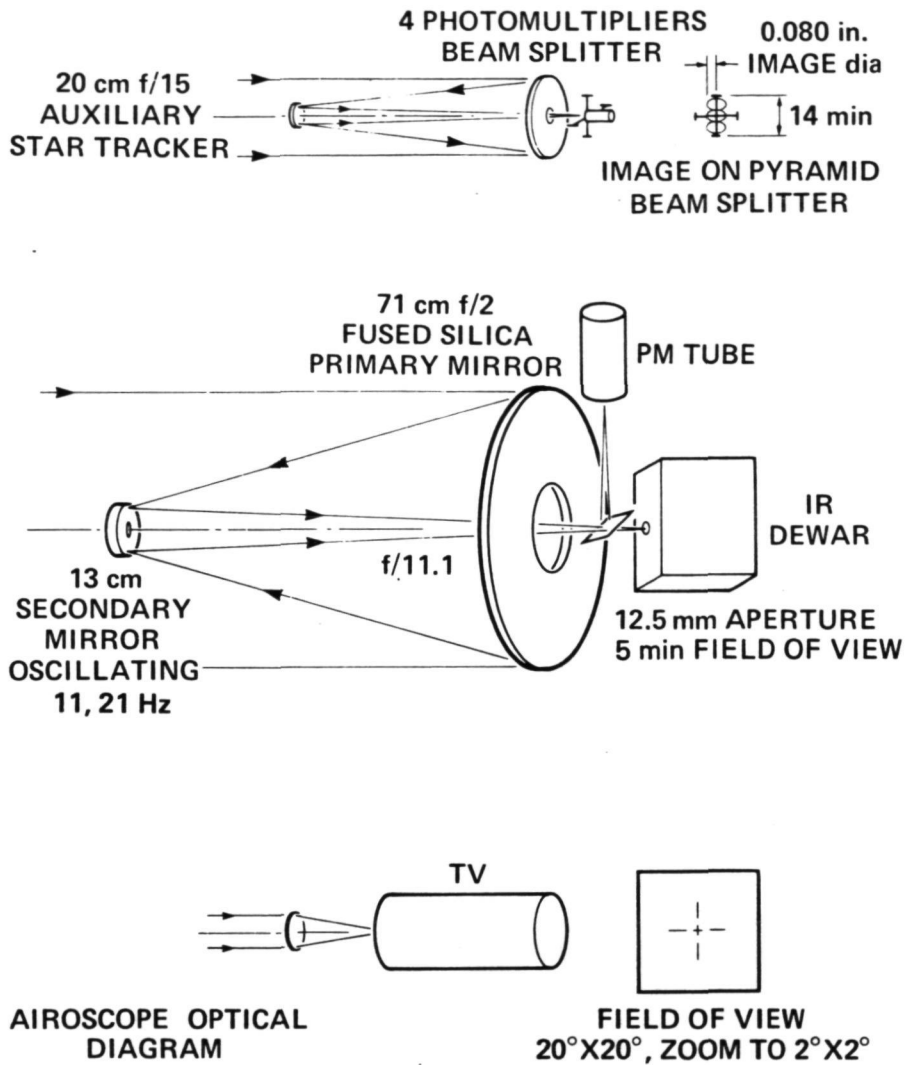
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Figure 3. AIROscope Optical System.

    Image quality with the present optics is poor by optical standards, but
it is entirely satisfactory for use in the infrared. It is believed that geom-
etrical distortion is introduced in the hub mounting of the main mirror. Image
size for an on-axis point source is 1 mm in diameter or less. An interesting
comparison with the ideal on-axis and off-axis image can be made by consider-
ing the results of a ray tracing computer program by Erickson and Mathews. On-
axis and 3.5 minute off-axis image sizes for the AIROscope Dall-Kirkham mirrors
are about 0.04 mm and 0.2 mm diameter. At wavelengths beyond 10 microns the
on-axis image size is determined mainly by diffraction. The diffraction circle
at 100 microns is 3.2 mm corresponding to 1.4 minutes of arc. The image qual-
ity, then, with the 5 minute field-of-view clearly causes no measurement
problem.

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SECONDARY MIRROR ASSEMBLY

The separate functions of mirror oscillation and focus-collimation are built into the secondary mirror assembly. The mirror can be moved axially for focus or tilted for collimation by three stepper motor-driven cams. Cam position data is included in the AIROscope data format. Precision potentiometers for the three cams can resolve mirror position to better than 20 seconds of arc. Axial movement permits refocus of the telescope at float when the structure cools off, shortening the distance between the primary and secondary.

An oscillating mirror mechanism is driven by two solenoids in a square wave mode. Adjustable stops for angular throw are built into the solenoid housings. Figure 4 is a photograph showing the mechanical arrangement of the drivers and how the solenoid base plate is spring loaded and tilted by the underlying cam push rods. Mirror throw is 17 minutes which results in a beam travel of 7 minutes of arc. Each beam position, left and right, is 3-1/2 minutes of arc off the optical axis.

Vibration damping was an early problem. This mechanical noise was transmitted through the structure to the detector electronics. Silicon rubber pads in the solenoid stops and resilient washers at the secondary mounting points reduced this noise considerably. A decrease in solenoid driving voltage to about 16 volts from the bus voltage of 27 quieted the system even more. The mirror is mounted at its center to the oscillating plate. The space between
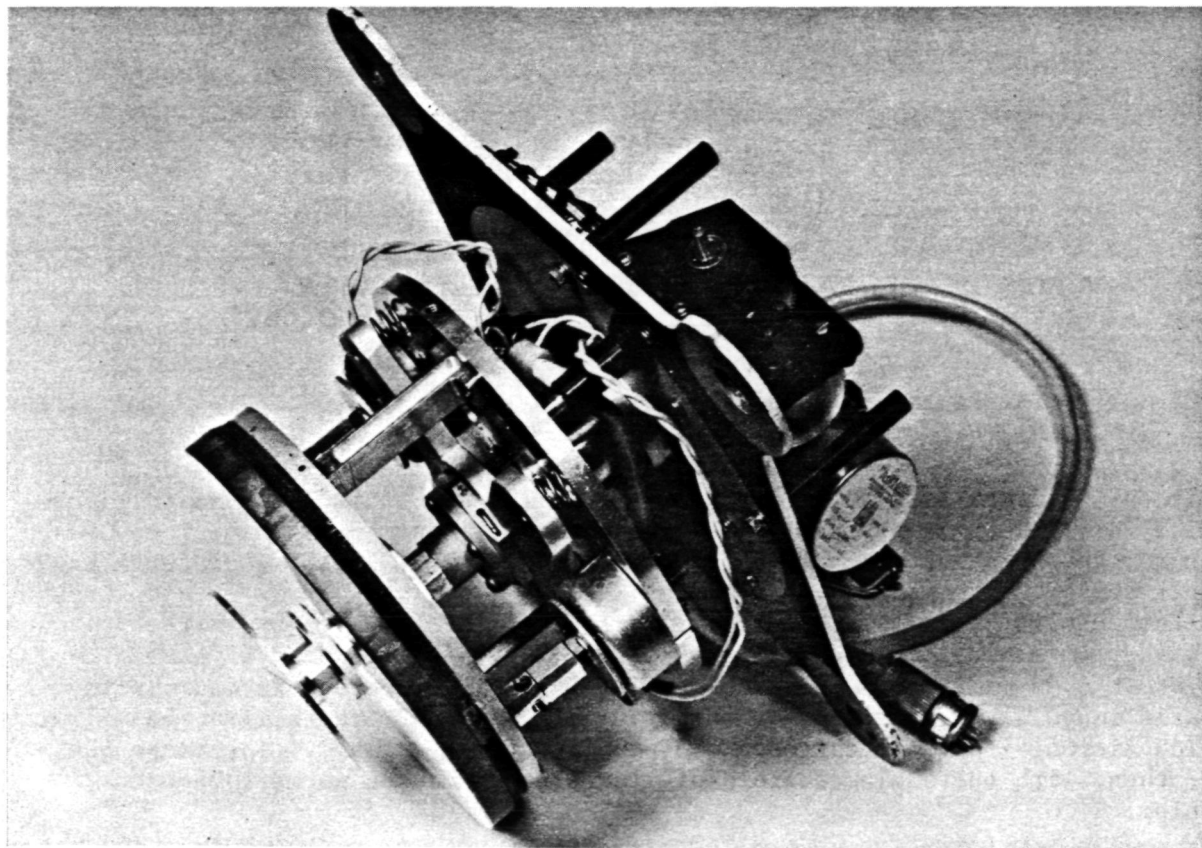

Figure 4. Secondary mirror assembly.

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the mirror and the aluminum backing plate is foam filled to dampen mirror vibration. Mirror bounce and mirror mechanical resonances that affect the optical beam are negligible. The only deviation has been a small bounce that amounts to about 1 minute of arc of mirror oscillation which at the detector amounts to less than 30 seconds of arc change or 1 mm of spot oscillation.

This secondary assembly has accumulated about 120 hours of operation with no failures. Changes in chopper throw have been negligible.

The original secondary support structure for this telescope was a source of background IR because of the structural protrusions into the field-of-view. This was redesigned using a tubular truss structure of 1-1/2 inch aluminum tubing stiffened by two thin annular rings with a slip-in magnesium shroud and an 18-inch shroud extension, both of which are easily removed or installed. All of this structure is out of the field-of-view of the detector. The secondary mirror assembly is installed on a spider structure made of roll-flattened aluminum tubing, which gives a superior rigidity and a small cross section to the light beam. All material exposed is gold plated. Figure 5 shows old and new structures and installation of the spider.

COMPASSES

Initial orientation is accomplished using compass heading information telemetered from the gondola to the ground. Since the success of the mission depends so heavily on this initial heading information, there are two compasses onboard for redundancy.

These compasses use fluxgate magnetometer sensors and generate second harmonics as a cosine function of the azimuth angle and the earth's magnetic field. To avoid the ambiguity normally associated with such a system, the D.C. voltage output from the second harmonic synchronous detector is amplified and utilized to drive a closed loop servosystem that attempts to drive the sensor to a null position at all times. This servo also drives a precision potentiometer upon which a 10-volt reference signal is impressed. The potentiometer wiper voltage is telemetered so that the gondola heading is known at all times.

TELEVISION STELLAR ACQUISITION SYSTEM

The television system of AIROscope is a highly sensitive standard scan system used for initial acquisition and offset tracking (Deboo, 1974). The normal video bandwidth of the camera is compressed by onboard data processing. This data compression ratio is approximately 300 to 1 and the effective bandwidth on the telemetry downlink is about 20 KHz.

The field-of-view of the camera's "zoom" optics is about 20° × 20° maximum and 2° × 2° minimum. The sensitivity, zoom position gates, etc., are fully controllable by command from the ground station.
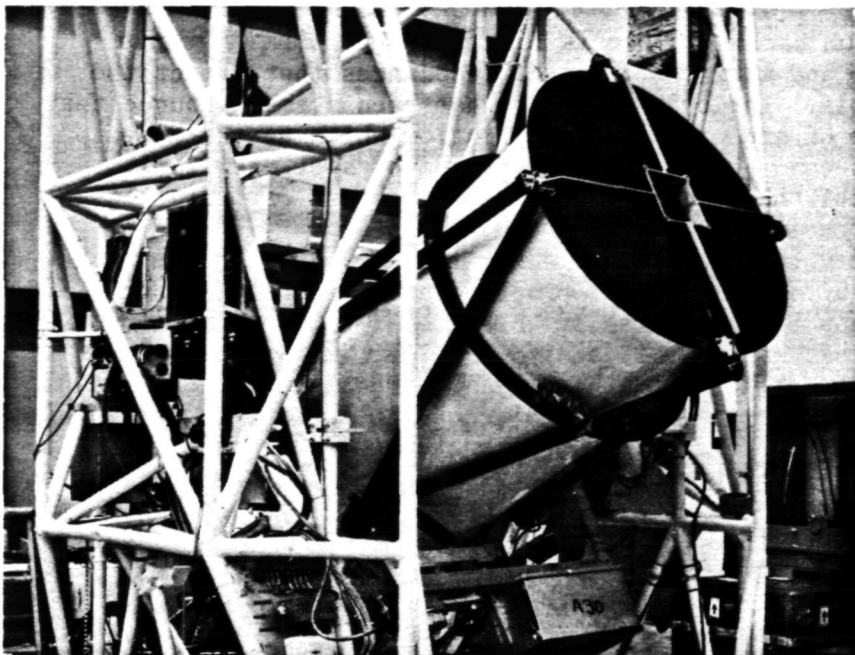
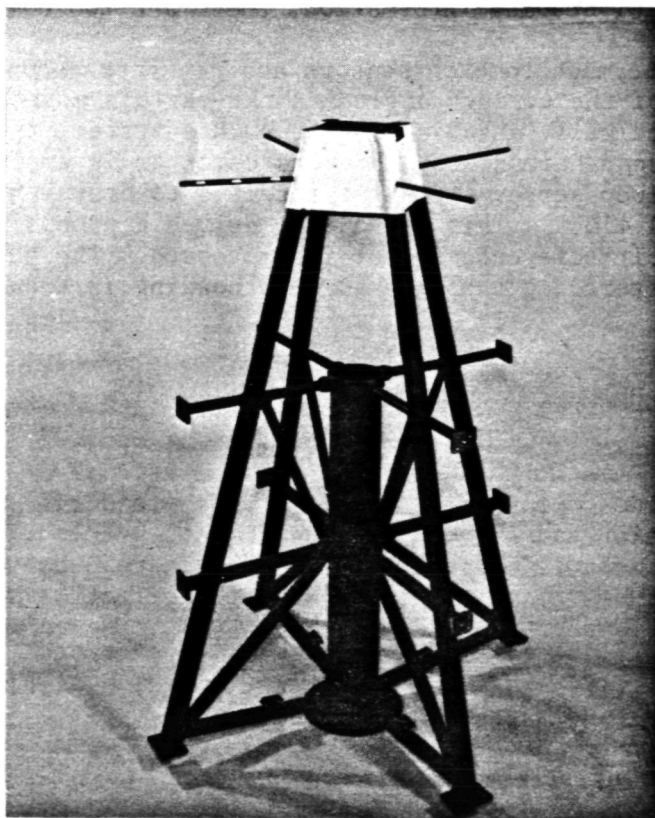Figure 5a. Present secondary support structure.

Figure 5b. Original secondary support structure.

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STAR TRACKER

A star tracker will be used as a backup to the main TV-controlled offset tracking system. It offers no offset tracking capability. The star tracker optical axis is aligned 3-1/2 minutes of arc from the telescope optical axis such that its axis corresponds to the right beam of the telescope which occurs when the oscillating secondary mirror is in its designated right position. The image of the celestial object is then centered in the aperture.

Light enters the star tracker through a small Cassegrain telescope with a 20 cm f/15 primary. The slightly defocused image of about 2 mm diameter is centered on a pyramid beam splitter which is viewed by four PM tubes. When commanded into the stabilization system loop, the deviation of the image from the centered position produces unbalanced output from oppositely placed PM tubes. In this way the tracker will acquire and lock on a star down to about fifth magnitude. Field-of-view is 14 minutes of arc and the pointing capability is ±10 seconds-of-arc peak and about 3 seconds-of-arc RMS.

FOCUS AND COLLIMATION AT FLOAT

Prelaunch optical alignment includes aligning the control TV optical axis 3-1/2 minutes of arc to the right of the primary optical axis. Then, an object on the TV cross hair will be focused on the detector when the secondary is in the right beam position. The star tracker is also aligned 3-1/2 arc-minutes to the primary axis. Normally, inflight measurement can proceed based on these ground alignments. That is, when the object is at the reference center of the TV screen and the secondary mirror is in the right beam, the object would be focused on the detector.

In addition, a means is available to accomplish inflight collimation and focusing. A 2-inch diameter end-on PM tube with a field-of-view of 20 arc-minutes is housed in a sealed can along with a programmable high voltage supply. A 45° mirror, by command, diverts the beam to focus onto a 2-inch diameter glass target whose area is divided into rings of different optical transmission. Figure 6 shows the arrangement of this collimation and focusing device. The mirror mechanism is driven by a stepper motor. The output of this photomultiplier is conditioned and then telemetered and recorded in the ground station. Obviously, when the beam is accurately collimated the signal is a maximum.

The procedure for optimizing the beam collimation has several steps. First, while locked onto a star in right beam, the image is focused using the signal from the photomultiplier. Then, while viewing the blank sky (secondary mirror oscillating) the secondary mirror is adjusted slightly to minimize the imbalance, if any, in the infrared background signal. The next step is to lock onto a planet (visual and infrared source) and adjust the tracking angles electrically until the photomultiplier and infrared detector signals are maximized.

Figure 6 shows also how focusing and boresighting are accomplished and the effect on the scan slopes of spot size. The well-focused spot of 1 mm or less should give sharp knees from one band to another while a defocused spot will produce a rounded edge and greater slopes. The beam should be boresighted
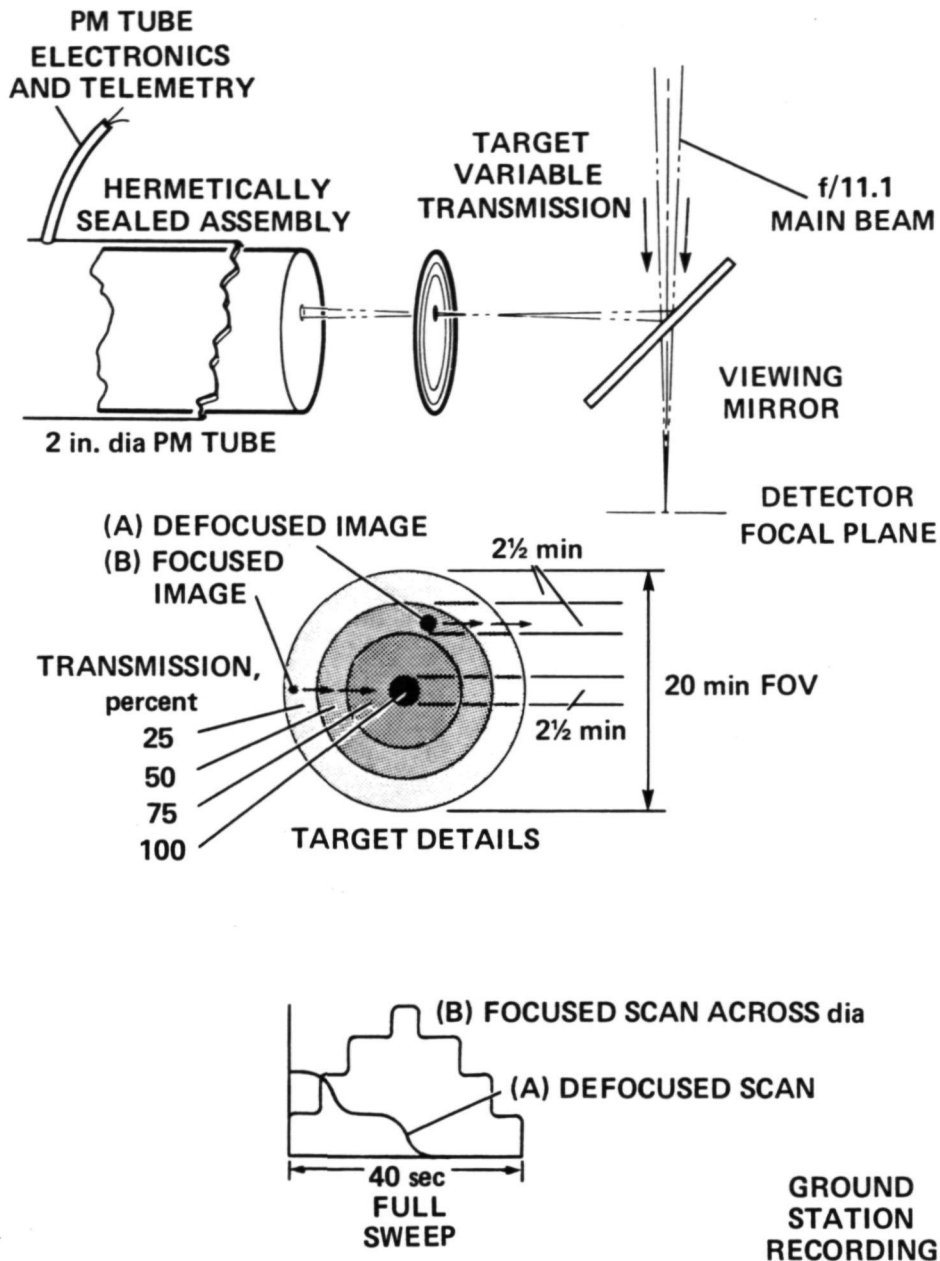
Figure 6. Inflight collimation and focus arrangement.

quickly after a few trial and error scans. Focus should never be far off as corrections for structure temperature can be calculated quite well and the necessary axial adjustment made. For example, at an average temperature of -40° C, the secondary will move about 1.5 mm closer to the primary from where the original prelaunch focus at 20° C was determined. This dimensional change can be corrected for by moving the secondary out from the primary accordingly. The actual uncorrected defocusing of the f/11 beam because of temperature amounts to a change in the focal point of about 4.5 cm.

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GONDOLA

The AIROscope gondola is fabricated of thin wall aluminum tubing. This frame weighs about 70 kg. Refurbishment and repair of broken thin wall tubing requires a high degree of metal working competence and a great deal of time is required for the cutting, fitting and welding of such tubing. Ames Research Center (ARC) is now in the process of designing and fabricating a new gondola. This gondola will be larger and heavier than the present one. The lower portion is being constructed of aluminum channels and L's. Thus, in addition to lower initial costs, it will be stronger and relatively simple to repair in the field. The outboard equipment bays will furnish adequate room and protection and insure ease of integration of different experiments such as those dictated by shuttle payload development requirements. This, along with improvements in the electronic subsystems, will allow several users to share in the opportunity of flying at 31 km on a stabilized platform.

TELESCOPE GIMBAL SYSTEMS

The gondola is suspended from the servo-driven azimuth drive. By torquing against the parachute shrouds the gondolar turns and may be considered as the outer gimbal. The inner gimbal rotates about a horizontal axis within the outer gimbal and furnishes elevation angular movement. Suspended inside the inner gimbal is the telescope, pivoted to rotate about an axis perpendicular to the axis of the inner gimbal. For balance and minimum deflection, these gimbals are each driven by two torque motors. At present, the gimbals are driven by 12:1 toothless friction gears as developed by the Lunar and Planetary Laboratory, University of Arizona and pioneered by G. Newkirk of the High Altitude Observatory (Frecker, 1968). In the future, AIROscope will use direct drive servo motors on all gimbals (Murphy, 1974). The inner gimbal, telescope, star tracker, television and present experiment weigh approximately 160 kg. Other weights associated with AIROscope includes electronic packages, about 120 kg, the batteries, about 100 kg and about 300 kg of miscellaneous hardware and ballast making the total launch weight of about 800 kg. When the new gondola is installed, weight is expected to be 1300 kg.

COMMAND SYSTEM

Commands are transmitted to the AIROscope on a frequency of 405.4 MHz. The transmitter power output is approximately 10 watts of narrow band FM utilizing Bi-phase-L modulation technique (Barrows, 1974). The basic command word is 8 bits making available 256 commands. This number could be easily increased by paralleling two of the present systems.

Parity checks and complementary techniques are used to insure command security for the system.

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TELEMETRY

The AIROscope telemetry system operates on 1483.5 MHz. The transmitter power output is approximately 10 watts of narrow band FM utilizing Bi-phase-L modulation techniques (Pitts, 1974). PCM, pulse code modulation, with 10 bit words is used and the encoder provides 140 data channels for analog signals and 150 discrete digital channels.

Frame length, sync, word length, clock rate, bit rate and other operating parameters of the PCM encoder are controlled by a read-only-memory (ROM) program board. In the ground station, the PCM decommutation equipment may likewise be programmed by IBM punched cards. These boards and cards can easily be changed to accommodate future scientific experiment requirements and insure maximum system flexibility. Furthermore, this system will allow the investigator to reprogram the PCM decommutator or word selectors while the mission is in progress.

SCIENTIFIC INSTRUMENTATION CAPABILITIES

A volume of about 0.25 m^3 is available at the Cassegrain focus for scientific instrumentation. Since this mass is gyro-stabilized, a weight limit of about 40 kg exists. Other instrumentation of much larger size and weight can be mounted at other locations on the gondola.

Helium cooled bolometers, filter spectrometers, preamps, and phase-locked amplifiers exist for the system.

Power (150 watts), commands (50), discrete digital words (50), and analog channels (30) are readily available at the focal plane for use of experiment integration when changing to any other scientific investigation.

GONDOLA PRIMARY POWER CONSIDERATIONS

Most balloon payloads requiring substantial electrical energy use nickel cadmium or silver zinc batteries. These premium batteries are chosen for several reasons, the primary one, in the case of AIROscope, being the reliability of the basic power system. Although simple, it is the one system that is key to the rest of the gondola electrical performance.

AIROscope uses a rated 80 ampere hour, low rate, silver oxide-zinc cell. At the low inflight discharge rates, 10-15 amps, usable capacity is at least 110 amp hours. The silver oxide-zinc cell gives the highest energy to weight ratio of commercially available couples, and has superior low temperature performance with acceptable low rate delivery down to -25° C. Several manufacturers with years of aerospace experience have developed battery cells of outstanding reliability. Charge retention, a flat voltage response through most of its discharge schedule, considerable recharge capability, and ease and safety in charging are additional features noteworthy in this kind of cell. The only drawback is high initial cost, about $700/kWh versus, for comparison, a commercial lead-acid type at about $30/kWh.

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AIROscope batteries are carefully maintained between flights. The cells are discharged completely and stored at -20° C which retards deterioration of the plates and separators. It is expected that the cells can be used up to two years, with 3-4 flights a year.

AIROscope batteries are given a charge-discharge test prior to final constant-current charging. Individual cell voltage is monitored carefully near the end of charge to prevent overcharging. An automatic charger with continuous cell monitoring and appropriate controls would be a valuable piece of equipment in an active balloon program.

AIROscope batteries are unsealed for flight, but boiling and loss of electrolyte is avoided by maintaining batteries at low temperature. Figure 7 shows the saturated vapor curve for water and for a solution of potassium hydroxide (KOH). At 30 km, the batteries may be safely operated vented if held below about 20° C. Slight pressure drops through the cell vent, insulation, and case give an additional safety factor. AIROscope batteries in flight reached a cell case temperature of about -10° C after 8 hours aloft. In future flights, the target low temperature will be raised to around 0° C.

One special problem with silver oxide-zinc cells is the peroxide over-voltage that exists during the first 15-25 percent of discharge. The elevated voltage, between 1.60 and 1.75 V/cell, produces an unacceptable bus voltage of
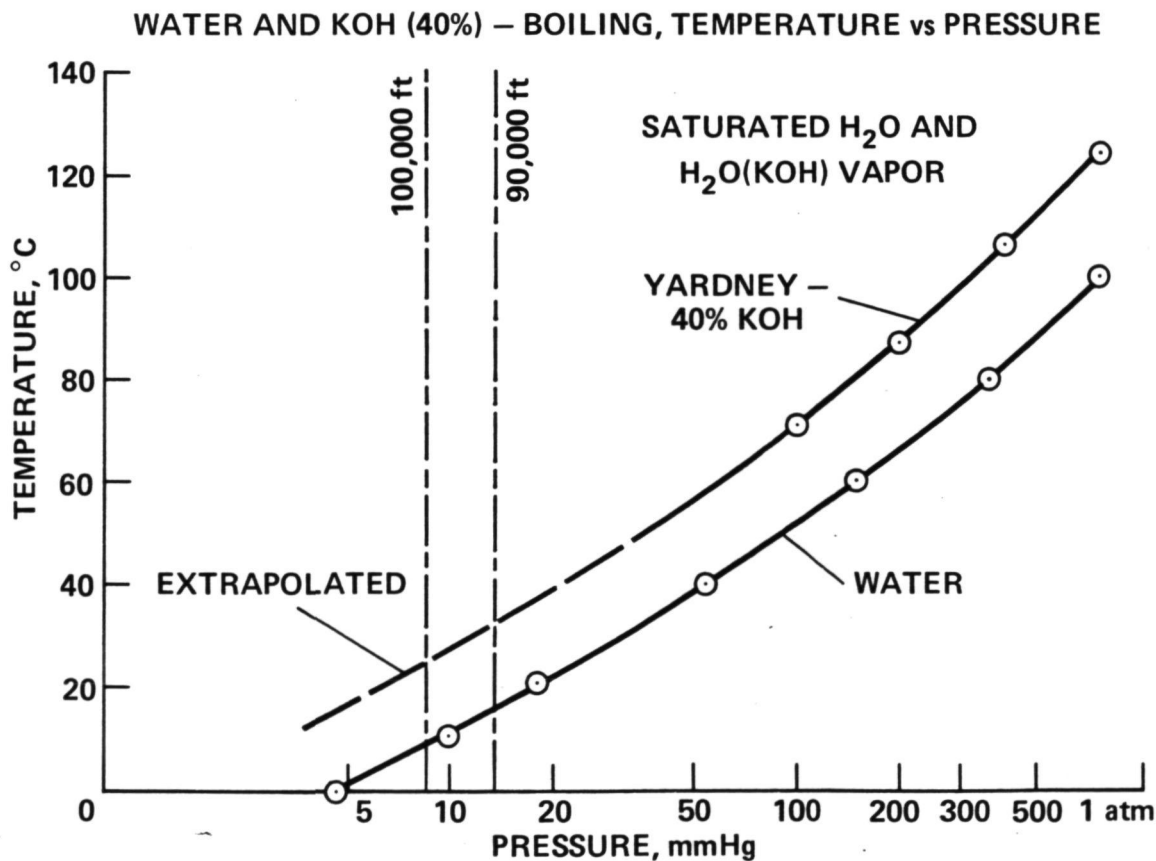
WATER AND KOH (40%) – BOILING, TEMPERATURE vs PRESSURE

Figure 7. Vapor curve.

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up to 31.5 volts compared with the plateau voltage of 27.0 volts. AIROscope bus voltage specification is 24-29 volts. The peroxide overvoltage must be dissipated down to 29 volts before bus connections are made and this means a loss of 12-18 percent in available amp-hours. Since battery energy increments can be made only by new packaging with larger cells or by the addition of another $2000 of battery, it is important that maximum possible utilization be made of existing batteries.

AIROscope employs a battery connection scheme that results in two separate bus voltage levels, isolates one of the two batteries from the other, and actually utilizes all of the peroxide portion of the battery energy in one battery. In one battery one cell has been removed leaving 17 in series, and a diode is located in the return line from the bus. Nominal voltage of this battery is then 24.5 volts instead of the 27 for the other battery, and maximum initial voltage cannot exceed 29 volts. Benefits from this arrangement include elimination of the preflight power dissipation procedure from one battery, two distinct bus levels for ascertaining roughly the energy remaining, and some saving in overall energy. This latter comes about because 15-20 percent of battery amp-hours are saved and bus current remains fairly constant at the lower bus voltage. This will translate into net 8-10 percent savings when a time factor is included in the power demand. A saving of 10 ampere hours would provide an additional 45 minutes of experiment time.

RECOVERY AND DESCENT PROTECTION

The AIROscope gondola is constructed so as to absorb a maximum amount of shock and damage while providing protection to the experiment, telescope and gimbal system. (See Figure 2.) The crash pads utilized by the AIROscope are aluminum honeycomb. It is expected that aluminum pads will generate considerable less moisture contamination at altitude than paper.

The thickness of the honeycomb material pad area and stroke length are dictated by the following landing constraints:

Maximum "g" loading	10 g
Maximum vertical velocity	6.5 m/sec
Maximum horizontal velocity	6.5 m/sec
Maximum slope	15°

To date, AIROscope has flown four times and has incurred little or no damage on descent and landing.

CONTROL STATION

Figure 8 is an external view of the van housing the primary ground control station. Figure 9 is a conceptual view of the control center. The van is configured internally to support and transport the complete AIROscope system. The rear portion of the van provides ample work area once the gondola and antenna are removed at the launch site. The van has been modified by the installation
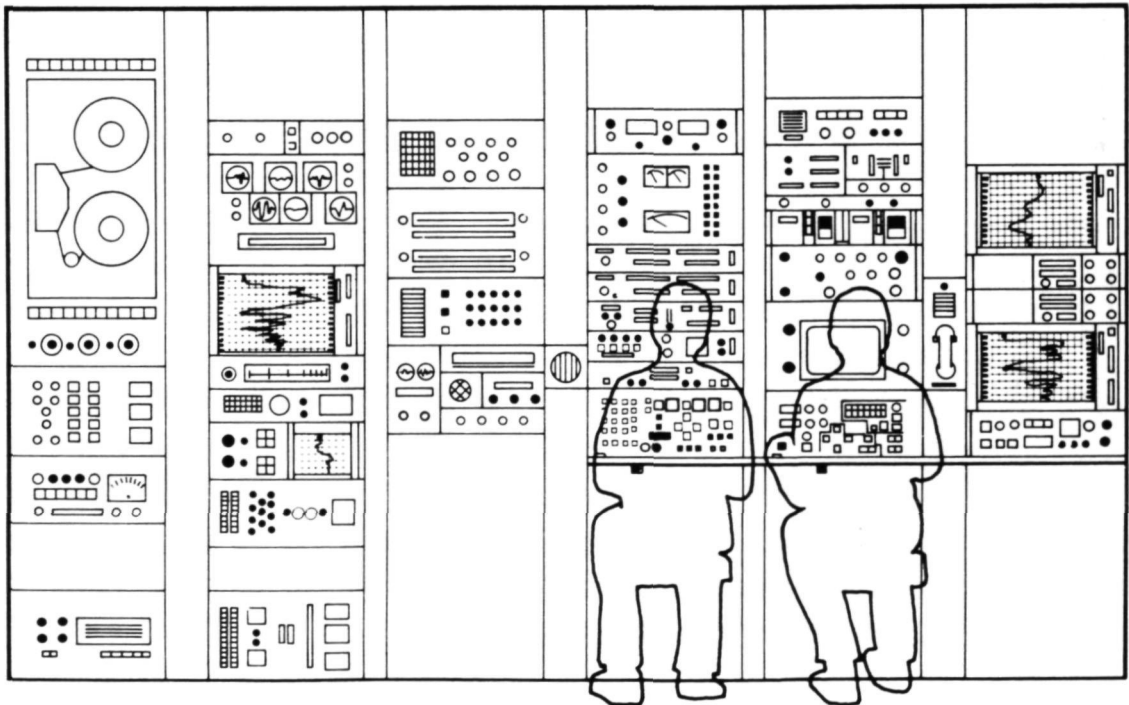
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Figure 8.   AIROscope control van.

Figure 9.   AIROscope control station.

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of an Air-Ride suspension system to further protect the rack-mounted electronic equipment during transit.

CONCLUSION

The AIROscope system offers scientific investigators a highly flexible vehicle for astronomical observation while at an altitude of 31 km. Observations for periods of ten hours are possible while above nearly all of the telluric water vapor and carbon dioxide. The unique television system affords offset viewing of infrared sources over long periods of time. The command, control and telemetry subsystems have been designed for satisfactory operation with different experiments and to afford easy and quick integration of various instruments.

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DISCUSSION SUMMARY — PAPER 2.7

During discussions it was reported that AIROscope had a sensitivity threshold of 10^{-24} watts/m^{2}Hz in the wavelength band of 27-90 microns. This was based on observations of Venus during one flight.

The operating procedure for acquiring celestial objects was described. This consists of first reading an onboard magnetic compass for azimuth, then pointing at a prescribed elevation. Next, information from an onboard TV is used for star field recognition and for star tracking. This TV star tracker should be capable of tracking 8th magnitude stars. Finally, the telescope is collimated and focused by command.

It was estimated that the AIROscope system will cost $200,000 to complete, exclusive of salaries and launch costs. This system will be made available for collaborative investigations in the future if sufficient interest and funding exists.

The present system has a 5-minute of arc field-of-view. In the future, it may be possible to utilize a 1-minute of arc field-of-view.

A background limitation of the AIROscope system was described. The AIROscope uses spatial chopping in cross-elevation by oscillating the secondary mirror. This spatial chopping is horizontal only when the telescope is centered in the gondola. Torsional oscillation of the gondola introduces a vertical component into the spatial chopping and therefore introduces a modulation of the background. This effect is zero at the horizon and becomes significant above 45° elevation. Steps are being taken to limit this effect by limiting the torsional oscillation of the gondola.

The mirror for this system was made at the University of Arizona, it is fused silica and weighs 90 lbs. Mounting is by the central hub which causes an image distortion which has so far not been a problem for infrared work. The mirror by itself has a figure good to one arc-second in visible light.