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A HIGH SENSITIVITY BALLOON-BORNE X-RAY TELESCOPE SYSTEM

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ABSTRACT

Despite remarkable advances in the field of low-energy X-ray astronomy during the past few years, the sky remains relatively unexplored in the high energy regime. This situation exists because of the fundamental limitations in performing extensive observations at the required sensitivity. Recent developments in the use of phoswich configured scintillation detectors now allow the attainment of collecting areas on the scale of 1000 cm^2 or more with optimal background and field of view characteristics. Such a system, now under construction at UCSD, will have 1350 cm^2 of sensitive area and allow photometric observations of roughly one order of magnitude improved sensitivity in the 15 to 150 keV energy range. For stronger sources, a modulation collimator may be utilized to obtain angular resolution in excess of .5 min of arc. To support these observations a gondola having an alt-azimuth gimbal with absolution pointing accuracy of 6 arc min and stability of .5 arc min is under development. Azimuthal stability is maintained through a reaction wheel which is referenced to the local magnetic field. Absolute pointing accuracy is obtained by readout of a stellar or solar azimuth sensor. All pointing and control decisions are performed in real-time using results of on-line processed gondola housekeeping data. In order to fully realize the potential of this system, stringent requirements must be imposed upon the balloon control and tracking systems.

INTRODUCTION

Progress in X-ray astronomy in the above 15 keV energy band which is accessible to balloon-borne instrumentation has lagged the lower energy field due to the generally inadequate sensitivity available for observations. The problem is further compounded by the inherent weak fluxes present at higher energies in many sources. High energy observations remain fundamentally important, though, in the study of cosmic X-ray sources since the physical characteristics of a given source are seldom determined unambiguously by isolated low energy measurements. Other potentially fruitful areas of investigation which remain unexplored in the high-energy regime include spectroscopic and imaging measurements.

In this paper, we describe a new large area, high sensitivity X-ray telescope system suitable for photometric type observations from balloon altitudes. We also describe the balloon gondola system, its performance requirements and the overall performance requirements of the balloon/gondola support system.

HIGH SENSITIVITY BALLOON-BORNE X-RAY OBSERVATIONS

In general, high sensitivity can be defined as the ability to detect a weak source given sufficient integration time or the ability to measure features of a stronger source to some significance level given a limited integration time. For example, the source complex in the Perseus Cluster of galaxies is expected to be weak, though observable, at balloon X-ray energies (Ulmer et al., 1973). Another example, Cyg X-1, may exhibit interesting variability features on sub-millisecond time scales which could only be observed at enhanced sensitivity (Rothschild et al., 1973).

While the above examples represent specific observations, one may more generally evaluate the versatility of an observing system through consideration of its limiting sensitivity as follows. The third UHURU catalog lists 150 sources above the 3.0 counts per second detection level in the energy range 2 to 6 keV. This compilation represents a nearly complete survey of the sky at that sensitivity. Figure 1 indicates the integral number distribution of these sources as a function of source strength. Of these 150 UHURU sources about 20 have been observed in the greater than 15 keV balloon-accessible energy band (Peterson, 1973). Assuming that cosmic X-ray sources can be characterized in some sense by an average spectrum, one can use the relation in Figure 1 to estimate the number of sources observable at an enhanced sensitivity level. By this argument one might expect a total of 55 observable sources in the hard X-ray energy band if sensitivity improves by one order of magnitude. While this is a crude approximation at best, it does serve to indicate the diversity of new observational objectives that are possible with a high sensitivity balloon-borne telescope system.

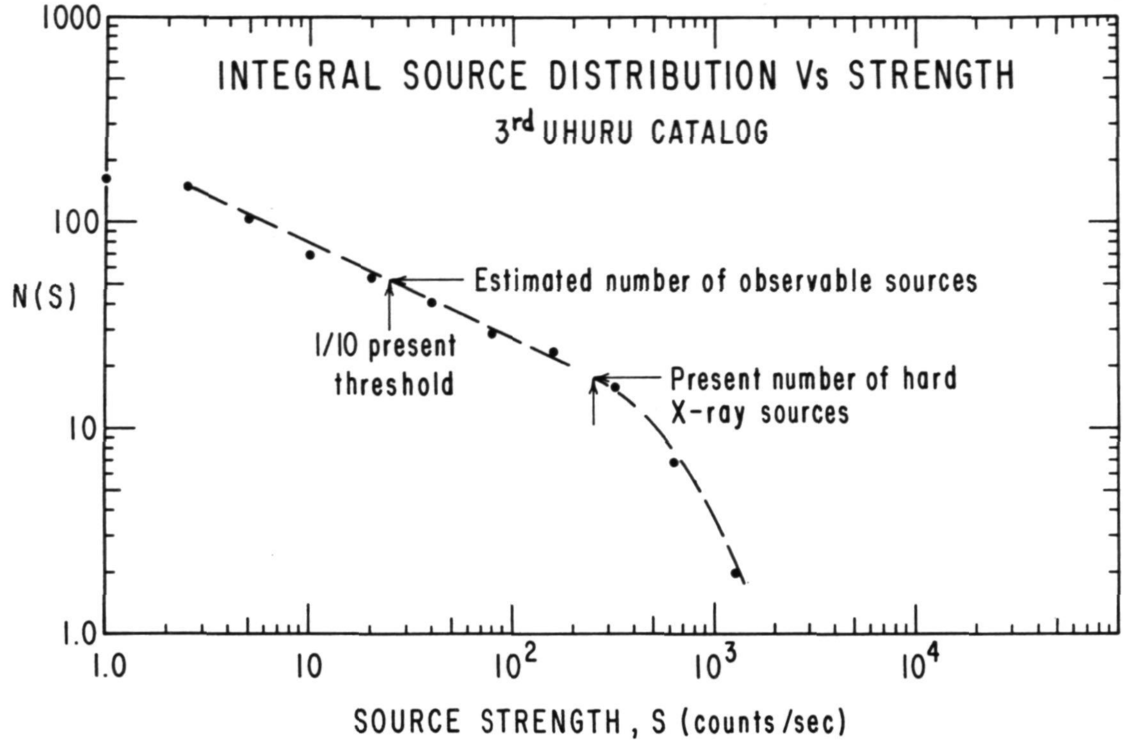


Figure 1. The 20 presently detected high energy X-ray sources have about a 75 percent correspondence to the strongest UHURU sources.

A LARGE AREA LOW BACKGROUND X-RAY TELESCOPE

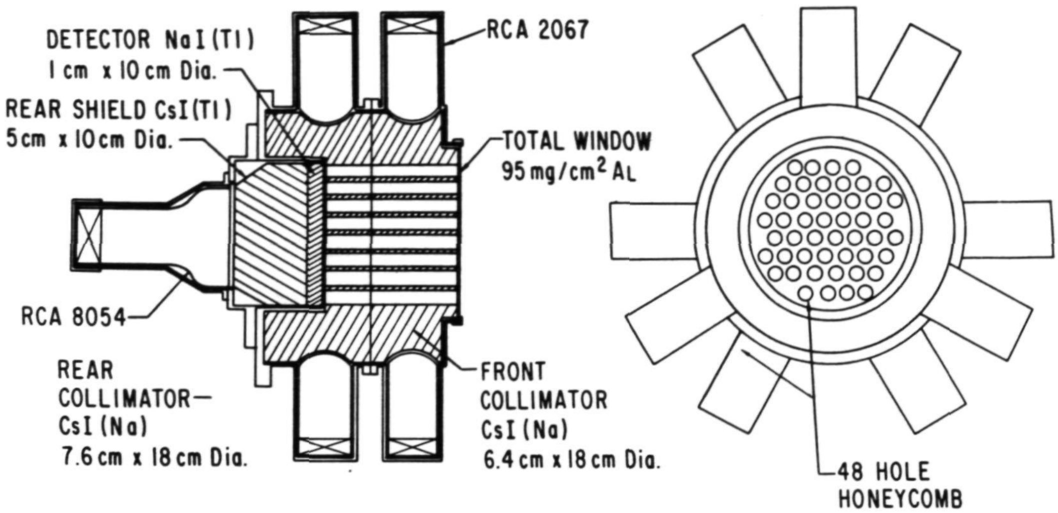
The sensitivity of a detector system for an observation limited only by counting statistics can be expressed in terms of its specific background rate in the energy interval of interest B (in counts-cm^{-2}-sec^{-1}), the effective collecting area, A, the observation time interval, $\Delta\tau$, and the inherent detection efficiency, η.

$$S = 1/\eta \sqrt{\frac{B}{A \cdot \Delta\tau}} \quad \text{counts-cm}^{-2}\text{-sec}^{-1}$$

The detection efficiency is in general a strong function of photon energy but can be taken as unity for observations using scintillator techniques in the 15 to 150 keV range. For attainment of enhanced sensitivity, one's choices are limited, then, to some combination of increased area and observation time or to lowering the specific background counting rate of the detection system. Actually, the choices are more restricted since the observation of time varying X-ray emitters may preclude arbitrarily long integration periods. An additional consideration, often overlooked when applying the above sensitivity relation, is the implicit assumption that the system background is determined to an accuracy consistent with the limitation of counting statistics. An observation , in fact, consists of a background measurement as well as the integration period on the source. Since the instrument background is subject to a number of variational mechanisms one must design his observational technique to properly compensate for such effects. We will discuss these considerations in more detail later; however, for present purposes we adopt the somewhat arbitrary background integration period limit of one hour.

Thus, to improve detection sensitivity one is limited to either lowering the specific background or increasing the collection area of the detector. The first approach has been the objective of extensive studies at UCSD over the past few years. The culmination of these efforts is the honeycomb phoswich detector shown in Figure 2. The background properties of this configuration are analyzed at length by Matteson and Pelling, 1974. The basic concept of this system is that minimal background can be attained by completely surrounding the primary detection element with active absorbing shield material. In this configuration the forward and lateral shielding are provided by the honeycomb drilled CsI(Na) scintillators. Shielding from the rear is provided by pulse decay analysis of the CsI($T\ell$)/NaI($T\ell$) phosphor sandwich (phoswich) combination. Events having significant energy loss in the thicker shield portion of the phoswich are discriminated from desirable events originating in the primary detectors by their longer (1.0 μs vs .25 μs) decay characteristic. The thick absorbing shield allows anti-coincidence of events in the primary detector which do not originate in the forward acceptance cone defined by the honeycomb collimator. For further discussions of the origin of such background effects see Peterson, 1967 and Dyer and Morfil, 1971. For this discussion, though, it is sufficient to note that the extent to which background can be lowered has definite practical limitations due to such factors as detection efficiency within certain regions of the shielding and ultimately the property of the detector crystals to become radioactive in the cosmic ray environment encountered under flight conditions. (Matteson and Pelling, 1974). These factors result in an effective background lower limit in the neighborhood of 5×10^{-4} counts-cm^{2}-sec^{-1}-keV^{-1} around 30 keV. The present configuration, shown also in Figure 2 consists of a large diameter 3.1 mm thick primary detector crystal CsI(Na) shielded from the rear by a thicker NaI($T\ell$) crystal. Lateral shielding is provided by a 3.8 mm layer of lead contained within the aluminum crystal housing. Collimation is obtained by modular arrays of tantalum slats of thickness .125 mm. The net field of view characteristics for the telescope is tailored to the specific observational objective by stacking these modules in various relative orientations. A single

ACTIVE HONEYCOMB DETECTOR



LARGE AREA PHOSWICH DETECTOR

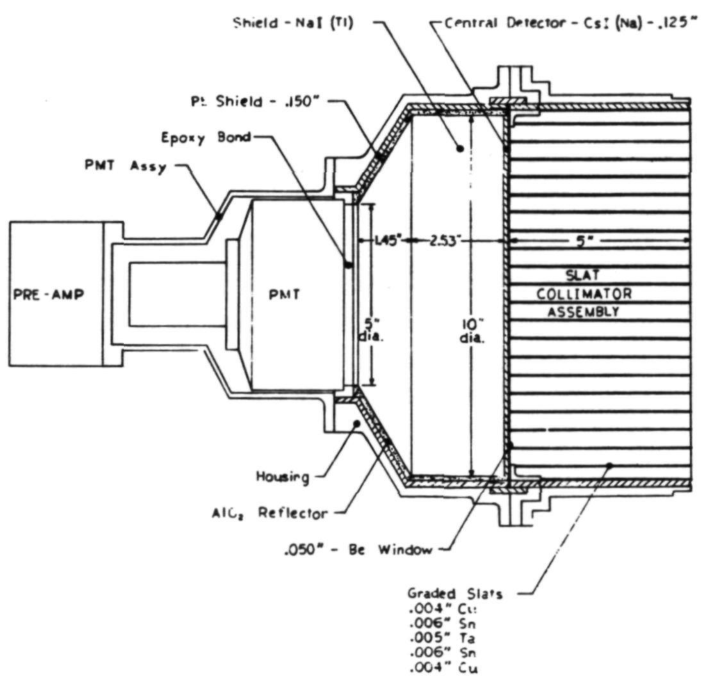


Figure 2. The new large area phoswich module and the detector which it replaces are shown on the same scale.

module has 12.5 cm high slats spaced at 1.25 cm intervals to produce a triangular response pattern along one dimension of slightly less than 6 degrees full width half maximum (FWHM). All housing and collimator surfaces which have direct exposure to the primary detector crystal are plated with successive layers of tin and copper having thicknesses, .1mm and .15 mm respectively. This "graded Z" layering suppresses the characteristic K escape radiation from the higher Z lead tantalum shielding resulting in reduced background in the 80 keV range as well as removal of complicating features in the background spectrum.

Comparing the present configuration with the honeycomb phoswich several significant differences can be noted. The honeycomb drilled CsI(Na) collimator is replaced by entirely passive material. This passive matter is a source of cosmic ray produced secondary background; however, the extent to which this effect lowers the net sensitivity is lessened since the relatively poor light collection efficiency of the honeycomb drilled crystal does not allow efficient background rejection. A second factor in favor of the new design is the improved area efficiency or fraction of the total primary detector collection area that is exposed to a source. Looking at the relation for overall sensitivity, we see that this factor effectively enters twice, once in the useful collecting area and second in the specific background, resulting in the sensitivity varying inversely as the first power rather than the square root of the area efficiency. The new system has an area efficiency in excess of 90% compared to the old system's value of less than 50%. Thus, the use of passive collimation results in increased production background but improved area efficiency offsets this effect and is expected to result in only a small net change in sensitivity.

A second major difference to be seen when comparing the two systems is the reversed role of the phoswich scintillators. The large shield crystal is now NaI(Tℓ) which is significantly less expensive relative to CsI. Also, the pulse shape discrimination process now accepts the slower CsI pulses, automatically rejecting photomultiplier noise at low energies and possible spurious fast pulses associated with particle interactions in the crystal surface (Cranell, 1972, Matteson, 1971). In the balance the new detector system is at least as sensitive per unit root detector area than the older honeycomb phoswich while being significantly less complicated and expensive. Table 1 compares the overall characteristics of the two configurations. The complete new system will be modular, employing three of the large phoswich modules for a net collecting area of 1350 cm^2. This system will be roughly one order of magnitude more sensitive than the one which it replaces.

COMPARISON OF DETECTOR PROPERTIES

	Honeycomb Phoswich	New Detector (3 Modules)
Collecting Area	34 cm^2	1350 cm^2
Background Flux at 3.0 gm-cm^2 residual depth (counts/cm^2-sec-keV)	$8x10^{-4}$ at 30 keV $1.5x10^{-4}$ at 100 keV	$5x10^{-4}$ at 30 keV $5x10^{-4}$ at 100 keV
Field of View	6^o FWHM (Circular)	3^ox6^o (Rectangular)
Weight	27 kg	50 kg
Envelope	30cm dia x 37cm length	33cm dia x 66cm length

Table 1.

THE POINTING AND CONTROL SYSTEM

The modular detector array weighing roughly 400 lbs is carried in the gondola shown in Figure 3. Pointing control is obtained through an elevation-azimuth gimbal system with the upper suspension support providing the azimuth pivot (gondola rotor) and telescope elevation being controlled by a simple horizontal axis pivot driven by a lead screw.

Under normal flight conditions the telescope azimuth is maintained by torquing against a reaction wheel located in the lower part of the gondola with the upper suspension pivot acting as a free bearing. The wheel has a mass of 25 kg on a radius of .5 m and is driven by DC torque motor having a maximum output of 1.28 kg-m^2-sec^{-2} and a maximum speed in the neighborhood of 600 rpm. Under the assumption that the most significant external torque operating on the gondola is the bearing friction of the upper suspension rotor, the system can operate for more than 30 minutes before the reaction wheel reaches the saturation point. If the wheel should attain this saturation speed, circuitry within the gondola will switch the azimuth control to a DC torque motor located within the gondola rotor while simultaneously causing the reaction wheel to despin. Thus, the angular momentum accumulated and stored within the reaction wheel is unloaded via azimuth rotor coupling through the suspension to the balloon. These control operations can also be initiated by ground command should observational conditions demand.

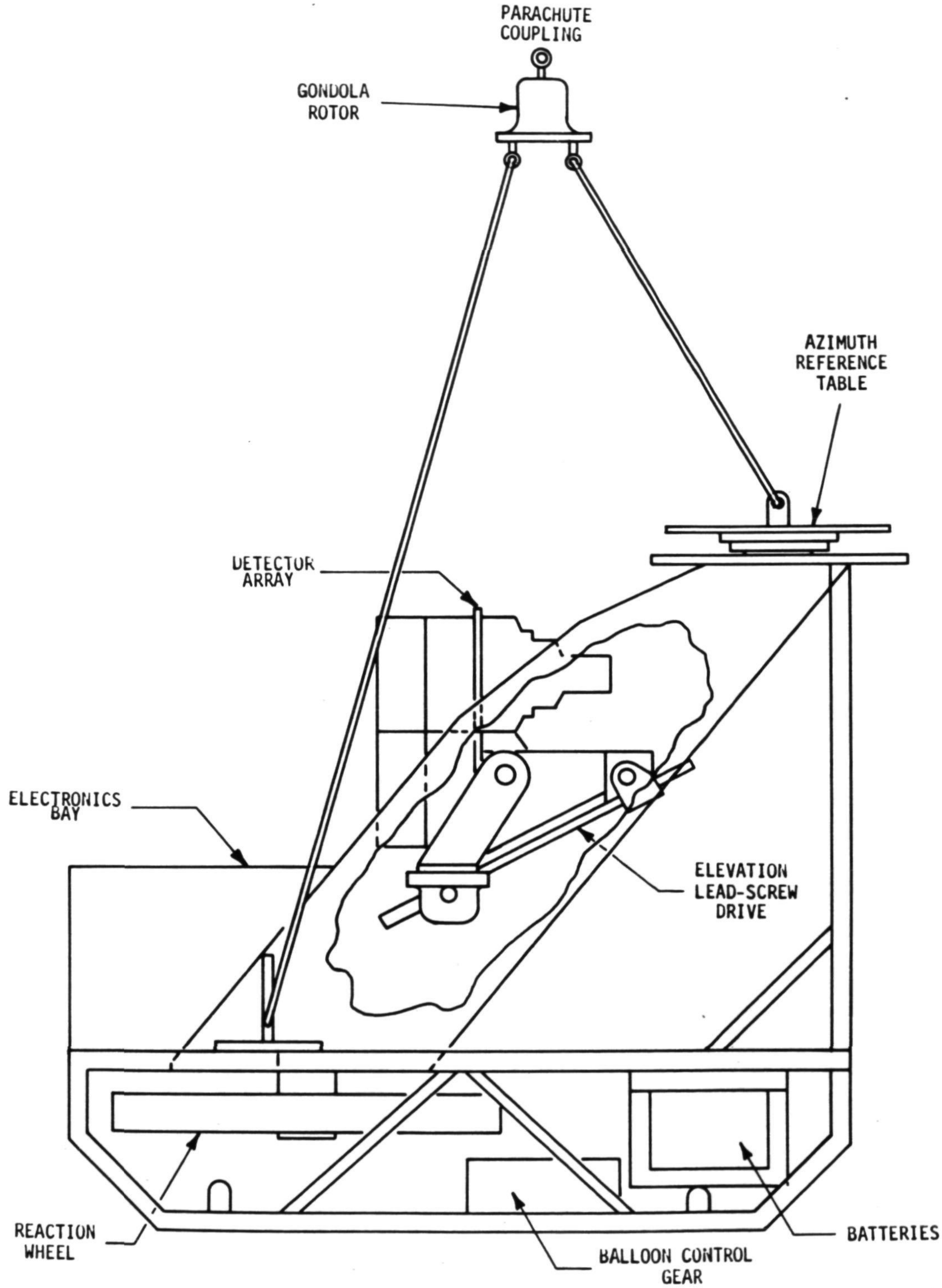


Figure 3. Side view of the gondola. The height of the apparatus to the parachute coupling is approximately 12 ft.

The azimuth servo uses a null sensing reference magnetometer to maintain a given azimuth angle. Absolute pointing accuracy is maintained by periodic update of the magnetometer null angle through use of a solar sensor for day or star sensor for night operation. Additional aspect information is obtained at night by continuous photography of the star field. All azimuth control and readout apparatus including the magnetometer, the stellar and solar sensors, and the aspect camera are fixed relative to one another on the azimuth reference table. This platform maintains its orientation relative to the local magnetic field independent of the gondola azimuth orientation. The actual azimuth angle is then determined by the position of the reference table relative to the lower portion of the gondola. In Figure 4 the mechanics of this scheme is indicated by showing the top view of three possible gondola orientations as they might occur in flight. The major advantage of this arrangement is that for night operations the star field moves slowly relative to the local aspect reference and readout apparatus. Indeed, if Polaris is used as an azimuth reference, its position changes less than 10 degrees throughout a typical flight.

The positioning of the azimuth reference table and the elevation gimbal is maintained via a command transmitted reference to 14 and 12 bit digital shaft encoders respectively. This allows positioning accuracy of 1.3 arc minutes commensurate with operational requirements. A command controlled variable speed clocking system will eventually be incorporated to allow tracking of object sources.

In Figure 5 we show additional details of the mechanisms of the gondola. Components requiring precise orientation, the reaction wheel, the telescope gimbal and the azimuth reference table, are contained within a single rigid structure which is suspended via the three cables from the gondola rotor. Other systems such as the control electronics and data systems, the batteries, and balloon control gear are mounted within lighter peripheral structure which may easily be repaired if damage is sustained on descent or landing.

OPERATIONAL REQUIREMENTS

A high sensitivity X-ray observation may, depending upon the specific objective, may impose variously stringent requirements on the performance of the gondola and balloon support systems. As an example, when attempting to observe a weak source, the major problem becomes the determination of background within limits defined by the statistical precision possible with the system. In the case of the system described here, the observation of a source to an accuracy determined by counting statistics in one hour of observation time requires determination of the average background within the observation time interval to a precision of

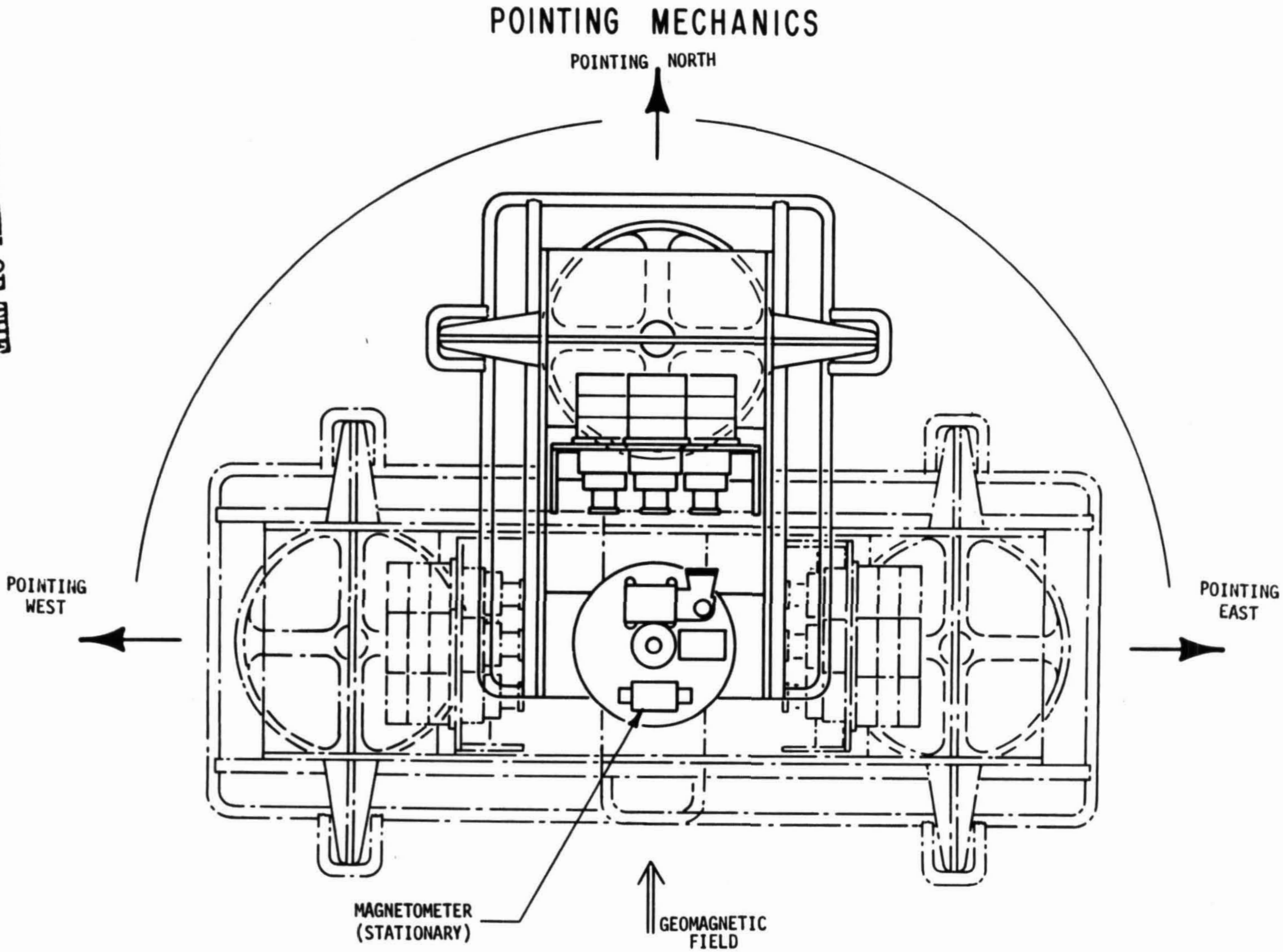


Figure 4. Top view of the gondola. The gondola may be thought of as rotating under the azimuth reference table.

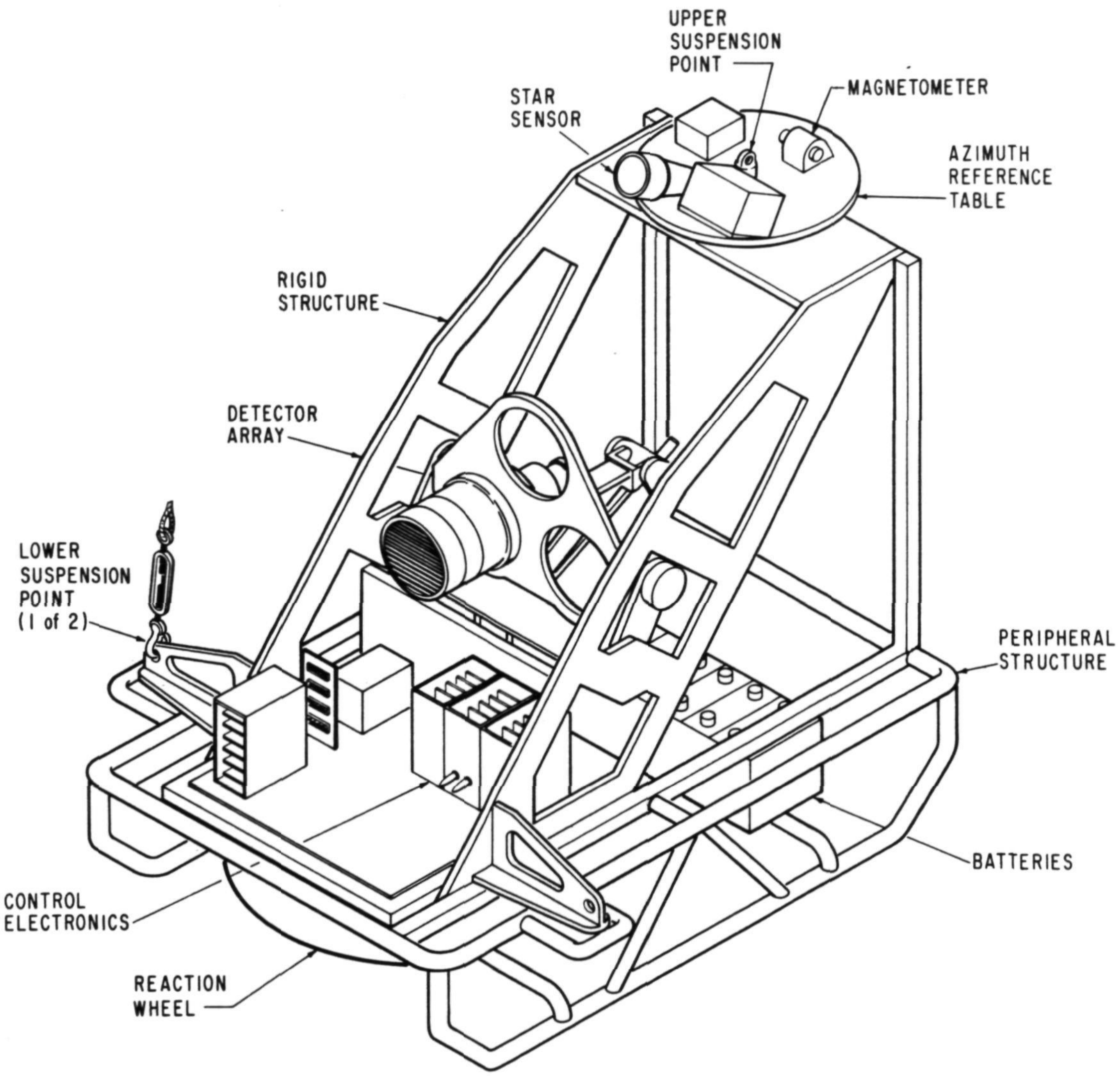


Figure 5. Perspective view of the gondola. The upper suspension pivot is omitted for clarity.

.3 percent. Assuming that one obtains the background measurement by means of a simple scan offset procedure the true background of the detector system must be constant or at least determined throughout the "miniscan" time interval, which might be a few minutes. Background variations significant on these scales may be caused by altitude fluctuations as small as 50 m. This, then, gives rise to a requirement for altitude stability or at least determination precision on this order.

As a second example, one can consider a high precision measurement of spectral variability. The spectral slope of Cyg X-1, for example, can be measured to an accuracy of 5 percent in 2 minutes using the new system. An altitude variation of only 250 m. occuring within the same period could easily mask or simulate such an observation by changing the opacity characteristics of the residual overlying atmosphere.

Finally, we consider the measurement of variability as an objective. In this case the limiting performance characteristics become the aspect control and readout systems. For example, for a source whose nominal strength is equal to the background a .3% variation in apparent intensity will result from an aspect error of only 1.2 arc min if the telescope has a FWHM of 6 degrees. This, then, imposes a requirement for aspect accuracy of this order on the overall system. The aspect requirement translates directly into a requirement for balloon tracking precision of about 1.5 km throughout the duration of the observation. In Table 2 we summarize these general requirements on the performance of balloon and gondola systems.

OPERATIONAL REQUIREMENTS SUMMARY

Gondola Pointing Accuracy	6 arc min
Gondola Pointing Stability	.5 arc min
Gondola Stability Rate	.1 arc min/sec
Balloon Tracking Accuracy	1.5 km
Balloon Float Altitude	39 to 45 km*
Balloon Altitude Stability or Determination	50 to 250 m*
Balloon Float Duration	4 to 16 hours*

* Depending on Observational Objectives

Table 2.

Clearly, as devices of the complexity discussed here are developed, the use of automated data processing systems becomes desirable if not mandatory. The high sensitivity X-ray telescope discussed here will require real-time processing of housekeeping, aspect and in some cases scientific data of its full capabilities are to be realized. Initial flight operations will require only minimal real-time command control of temperature control, power, and aspect systems. Future operations, especially those in which continuous tracking of object sources is performed will require more extensive computer support, eventually tying such systems directly into the command control system.

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DISCUSSION SUMMARY — PAPER 4.2

Several questions arose in regard to the pointing system. These and the answers by the speaker are summarized below:

Q. Do you generate your altitude-azimuth corrections on the ground?

A. Yes.

Q. How many commands do you give to keep pointed to one arcminute.

A. The requirement is six arcminutes. Two digital commands per pointing operation are required. Eventually, within about a year an onboard tracking capability is intended.

Q. What will be the error in pointing due to pendulum motion?

A. In a previous performance of the system (in which a reaction wheel was not being used for stabilization) the pendulum motion was less than 0.1 degree. A group from the University of Tokyo used a spheroscopic device to establish that pendulum motion on some of their systems was below an arcminute. The effect on the present system is not yet known and may necessitate a cross-elevation axis.

It was noted that measurements on a gondola of similar size and inertial properties had pendulum motions of two or three arcminutes. The speaker commented that the stability is a strong function of the gain in the system and what you are pointing at.

In a discussion of the X-ray device, the speaker noted that he expected his value of B in the expression for sensitivity

$$S = \frac{1}{\eta}\sqrt{\frac{B}{A\Delta T}} \qquad \text{(uncorrected for air absorption)}$$

to be lower than on previous flights, particularly at the lowest energies. Tests show that their detector's spectral response is flat relative to the honeycomb detector, so that at lowest energies its sensitivity is lower than other systems. At highest energies, it is higher. The modulation collimator is to be used on the next flight and is the reason for the high stability pointing requirement. The field is five degrees but the highest sensitivity would detect fluctuations below one percent.