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AN ORIENTABLE, STABILIZED BALLOON-BORNE GONDOLA FOR AROUND-THE-WORLD FLIGHTS

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ABSTRACT

A system capable of pointing a balloon-borne telescope at selected celestial objects to an accuracy of $\sim$ 10 arc minutes for an extended period (weeks to months) without reliance on telemetry is described. A unique combination of a sun/star tracker, an on-board computer, and a gyrocompass is utilized for navigation, source acquisition and tracking, and data compression and recording. The possibilities for "intelligent" activities by the computer are also discussed.

DISCUSSION

The success of NCAR's Project Boomerang in demonstrating the possibility of around-the-world balloon flights has ushered in a new era for scientific ballooning. The phrase "low-flying satellite" which has been used to describe this new concept in superpressure ballooning is most apt, even though not strictly accurate, because of the comparable observation times attainable from both around-the-world balloons and true satellites. Unfortunately, the comparison also extends to many of the same experimental difficulties. For an experiment that requires pointing a gondola-mounted telescope with a narrow field of view, among these difficulties are finding answers to three rather fundamental questions:

- Where is the gondola? (Longitude and Latitude)
- In what direction is the telescope pointed? (Elevation and Azimuth)
- What time is it? (UT)

An ideal system for long duration ballooning should make these determinations without assistance from a ground controller because of the potential difficulty of maintaining a secure (though not necessarily continuous) telemetry link for weeks or even months at a time.

The last question is the easiest to answer: low power, accurate (i.e., stabilities of a few parts in 10^9-10^{10}) flights clocks are commercially available. The first part of the second question is also relatively easy, since we can use gravity for a vertical reference. A simple tiltmeter system will suffice, at least for coarse aiming. The remaining questions - determining the gondola geographic location and telescope azimuth - are fundamentally more difficult to answer. During the last year at MIT, we have been working on a system which answers these difficult questions by linking together three components that are not normally present on balloon gondolas: 1) Combination Sun/Star Tracker; 2) Gyrocompass; and 3) Flight Computer. This system that we envision will not require any ground commands once it is in "orbit". It will be capable of an absolute pointing accuracy of a few arc minutes. This level of accuracy is sufficient for the experiments which we are planning in infrared and x-ray astronomy, where we contemplate fields of view ranging upward from 6 arc minutes.

An on-board computer opens up a number of other possibilities for such things as in flight data compression or automatic cutdown over a predetermined recovery area. This point will be discussed in more detail later.

Figure 1 is an overall view of an around-the-world gondola that might use the system which we envision. The torque motor is the driving element for stabilizing the entire gondola in azimuth. The sun/star tracker is the ultimate reference for this azimuth stabilization. It is mounted on a platform that is coupled by rigid bars to the torque motor housing (above) and to the main gondola (below). The tracker will be gimbled only about an elevation axis. During the day, the side of the gondola on which the solar cells are mounted will be continuously pointed in azimuth toward the sun. This arrangement greatly simplifies solar panel pointing, as a straightforward lead screw will suffice to point the panel normal toward the sun. The principal scientific detector, an x-ray or infrared telescope, will be offset-pointed in elevation and azimuth with respect to the gondola frame. A gyrocompass (discussed below in more detail) will provide a continuous readout of platform geographic azimuth, including any oscillatory component.

Figure 2 is a detail of the combination sun/star tracker, shown in a top view relative to Figure 1. Schematically, the situation shown is one that might exist near sunrise with the sun rising in the east and two stars setting in the west.* The elevation axis is pointing north-south. Two independent optical sensors sharing a common focusing mechanism are shown. Both are Fairchild Semiconductor CCD201 charge-coupled device area image sensors. At night, only the star tracker would be active; conversely, during the day, the sun tracker would be active. The relevant operational characteristics of this tracker are given in the following table.

STAR/SUN TRACKER
(Fairchild CCD201, 10,000 Element Area Image Sensors)

	Star Mode	Sun Mode
Field of View (FWHM)	1.5°	5.0°
Resolution	1'	4'
Accuracy	1'	2'
Signal/Noise (Per resolution element)	10:1 (m_V=3,G3)	> 100:1
Weight	← 8kg →	
Power	← 1 watt →	

*This situation is somewhat hypothetical, as the sky brightness for a solar elevation >0° would probably be too great for the system to simultaneously detect both the sun and stars.

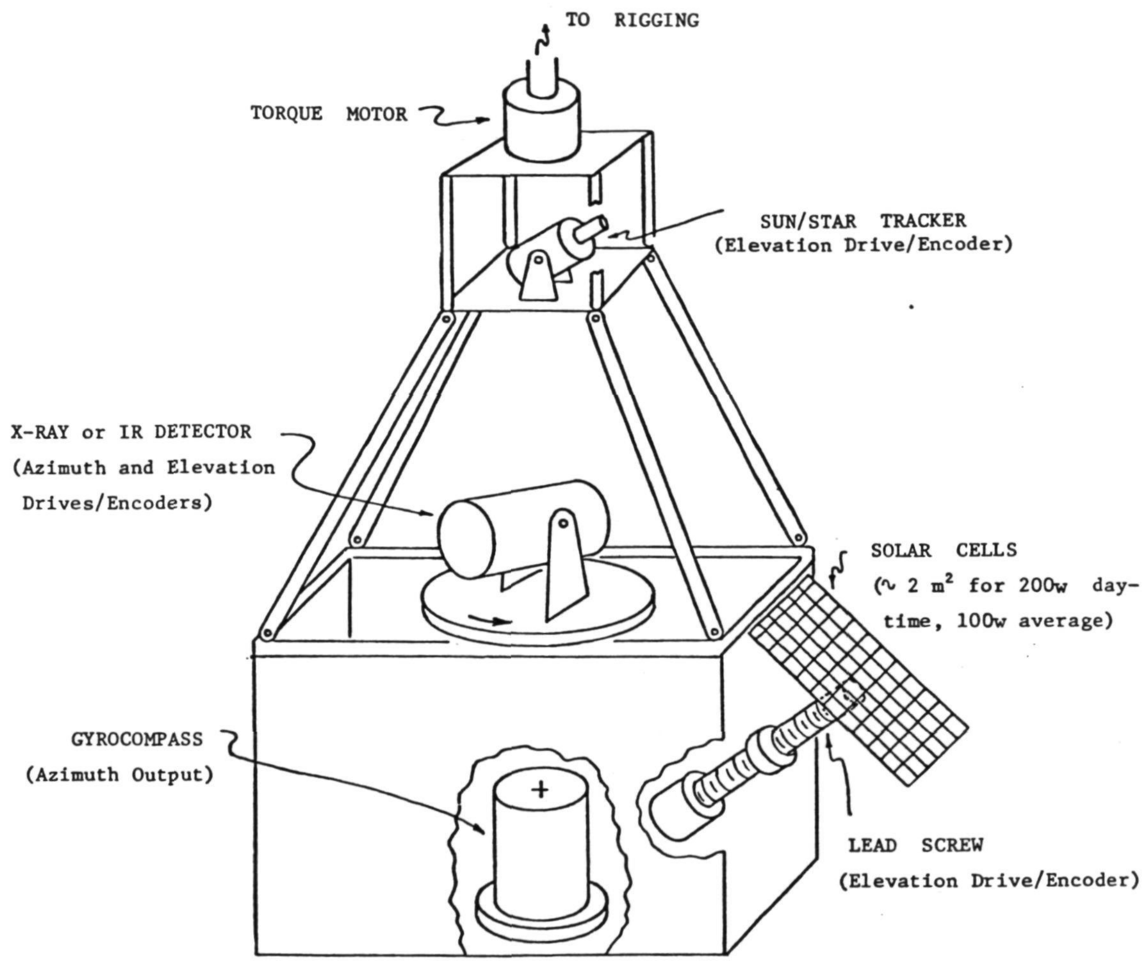


Figure 1. Around-The-World Gondola (Daytime Mode)

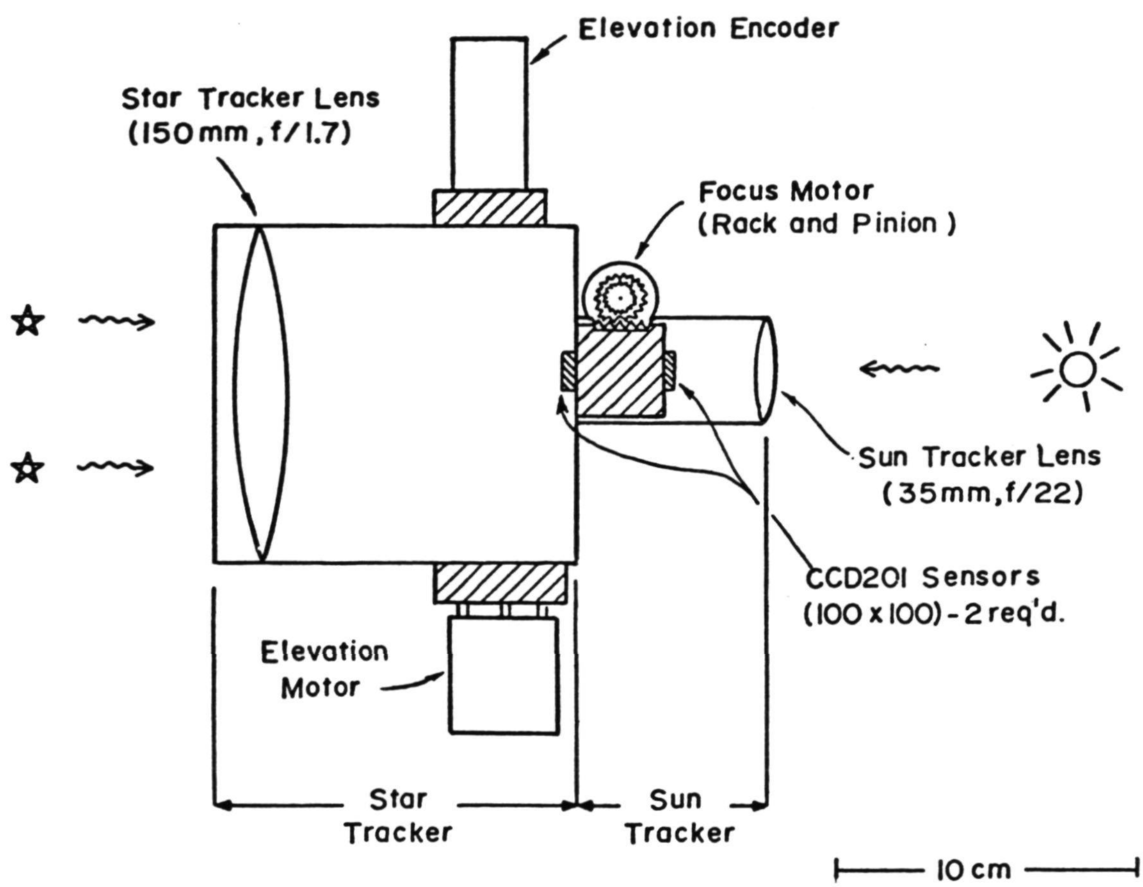


Figure 2. Sun/Star Tracker (Top View)

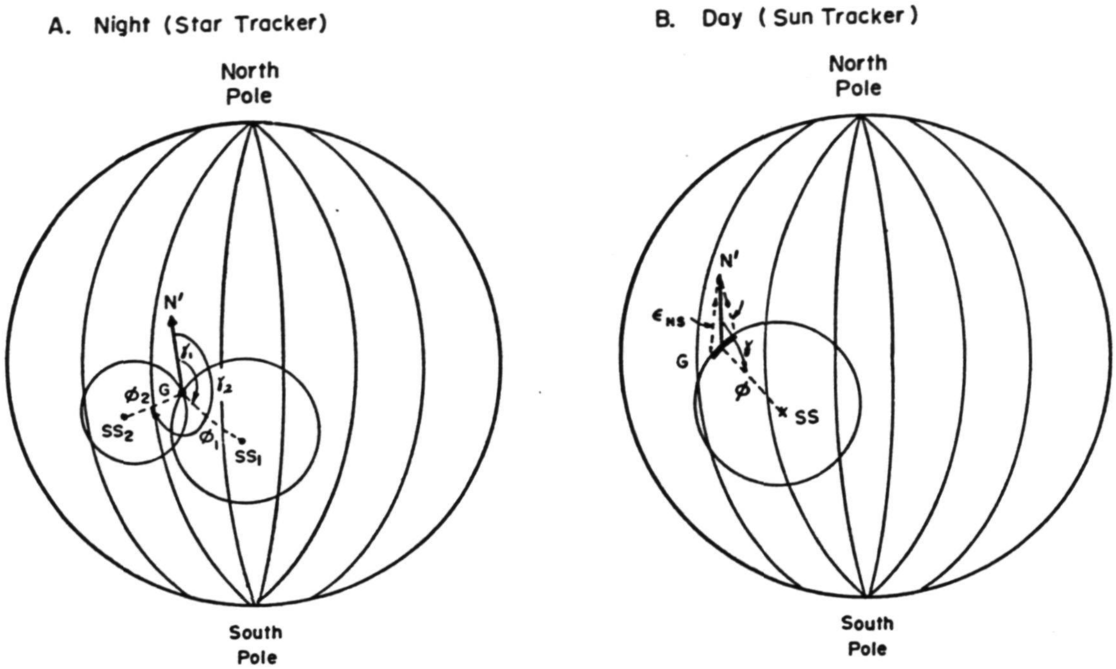
Next, we consider how the overall system (tracker plus gyrocompass plus computer) would be used to determine the longitude and latitude for the gondola during the night and during the day. Figures 3A and 3B depict the earth during the night and day, respectively. The gondola is over point G on the earth's surface. The vector $\vec{GN}'$ is apparent north determined by the gyrocompass. At night, the star tracker is then used to measure the zenith angle, ϕ, and the azimuth, γ, relative to the gyrocompass azimuth (in the gondola frame) for two stars. The substellar points on the earth for these two stars are SS_1 and SS_2. The two small circles are the loci of points on the earth's surface at which the stars are observed at the measured zenith angle. From these measurements and the Universal time, we can determine the longitude and latitude of the gondola at night, after the computer has identified the two stars; this will be a rather straightforward operation as we will only use bright stars. We can also determine our gyrocompass error ε_{NS} from this same data. Obviously, the on board computer is vital for all these determinations in order to perform the required coordinate transformations.

In the daytime, we have only one star to work with - the sun. Therefore, we must rely on our gyrocompass to narrow down the arc along the small circle of constant solar zenith angle where we might be. We are limited in our ability to do this by the gyrocompass error, ε_{NS}. This error is composed of several position-, velocity-, and acceleration-dependent components, all of which are systematic (and hence correctable) except for a small random drift. The magnitude of this small random drift is such that it could accumulate to $\sim$ 10 arc minutes between a sunrise and a sunset ($\sim$ 12 hours). At night, we do not allow it to accumulate because of repeated star sightings, but during the day we must accept it as an irreducible error; there is only one sun.

Figure 4 is a block diagram for the entire system. The central role of the computer is immediately evident from its origination. The computer that we are planning to use would be based on an Intel 8080 microprocessor with an instruction cycle time of < 2 µsec. This is an 8 bit machine, and we would probably require $\sim$ 8 kbytes of memory to run our system.

The main telescope (x-ray or IR) would input its data to the computer, and would receive azimuth and elevation commands from the computer. The roll and pitch tiltmeters would tell the computer whether the gondola were out of level (DC-wise). The torque motor servo would have an offsettable azimuth null under computer control. The gyrocompass is a Gyrosystems Model 800, which is a 2 axis gimballed system with a full 360° azimuth range. Its basic resolution would be 1.3 arc minutes (14 bits). Its weight is approximately 4 kg, and it requires 20 watts of power. The sun/star tracker has already been discussed. Data from the computer would be recorded on board and a selection from it telemetered to earth continuously on an HF radio link. This data would be of lesser quality than could be obtained from a VHF/UHF line of sight link which would be used when and if the gondola happened to pass over a suitable ground station. A data uplink (through the command receiver) could also be used to modify the observing program or restart the computer system or digital clock in the event of a power loss of other temporary malfunction.

The on board computer can provide a number of functions in addition to those discussed above. These roles can be, somewhat arbitrarily, subdivided into <u>cogitative</u> and <u>incogitative</u> categories. The incogitative roles are the rather straightforward tasks which, regardless of the system, the computer



<u>Define:</u> $\gamma_1 = \measuredangle N' - G - SS_1$
= Gyrocompass azimuth to Star 1.

$\gamma_2 = \measuredangle N' - G - SS_2$
= Gyrocompass azimuth to Star 2

<u>Nighttime Calculations:</u>

Gondola Longitude, Latitude --

$$(\lambda, \beta)_G \sim f\ [(\lambda, \beta)_{SS_1}, \phi_1, (\lambda, \beta)_{SS_2}, \phi_2, \gamma_1, \gamma_2; UT]$$

$$\sim f\ (\phi_1, \phi_2, \gamma_1 - \gamma_2, UT; \alpha_1, \delta_1, \alpha_2, \delta_2)$$

Gyrocompass Error --

$$\epsilon_{NS} \sim F\ (\gamma_1 \text{ or } \gamma_2)$$

$$\sim F\ [(\lambda, \beta)_G, (\lambda, \beta)_{SS_1 \text{ or } SS_2}, \gamma_1 \text{ or } \gamma_2]$$

<u>Daytime Calculations:</u>

$$(\lambda, \beta)_G \sim f'\ [\phi, \gamma, \epsilon_{NS}, UT; \sigma_{\odot}(UT), \delta_{\odot}(UT)]$$

Figure 3. Longitude/Latitude Determination

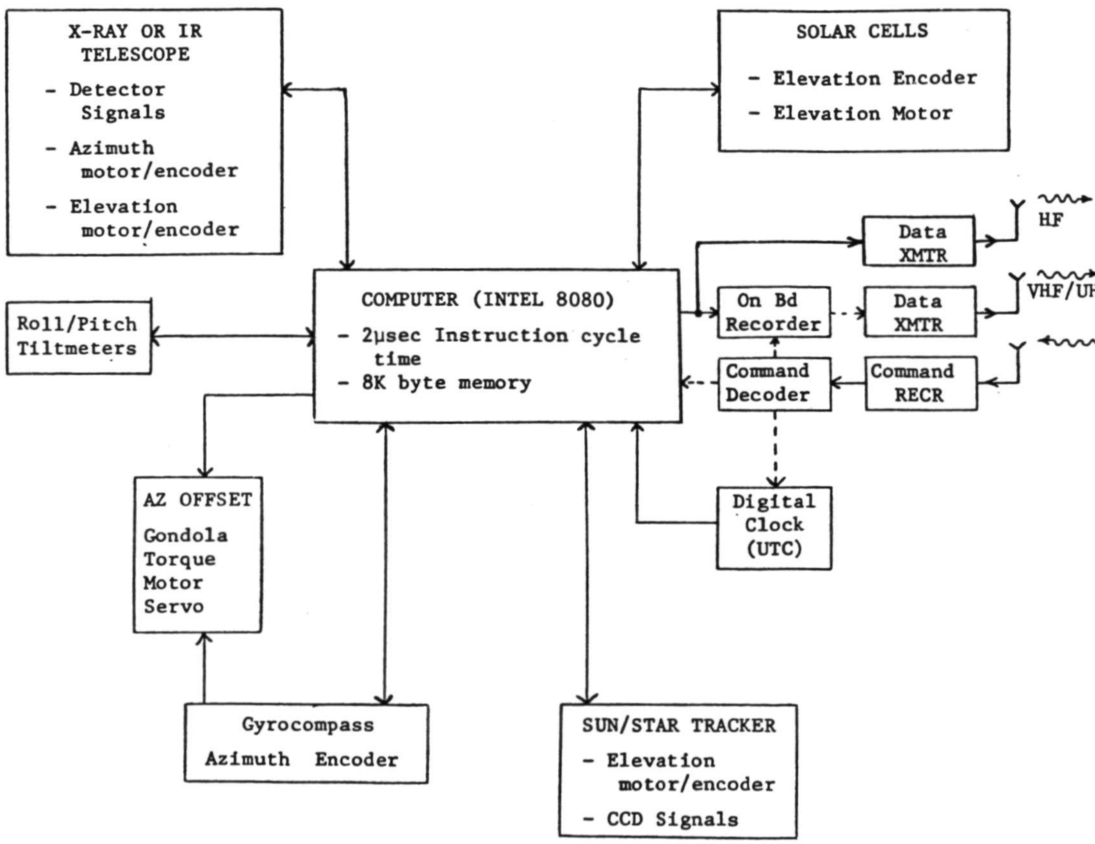


Figure 4. Aspect/Data System

would have to perform. The cogitative roles are more sophisticated ones which would be limited by memory size and computing speed. First, the incogitative:

INCOGITATIVE ROLES FOR FLIGHT COMPUTER

1. Gyrocompass corrections (ε_{NS} - Azimuth error; "north steaming error" - velocity, acceleration dependent)
2. Source list look up and coordinate transformation:

   $[(\alpha, \delta) \rightarrow (Az, El)]$

   - Sun
     - Coarse: Solar Cell Panel
     - Fine: Sun Tracker
   - Bright Stars
   - X-Ray or IR Sources
3. Data compression (for on-board recorder)
4. "Flywheel" for day/night transition
5. Inflight gondola re-leveling (tiltmeter sensors)
6. Sun/star tracker focusing
7. Star tracker protection (shutter activation)
8. Mode switching (instrument calibration, operational checks, etc.)

For the cogitative roles, one can think of a "computer soliloquy" after the fashion of an experienced human observer using a ground-based telescope. Among the questions such a computer-observer might ask itself are the following (where "I" = The Computer):

COGITATIVE ROLES FOR FLIGHT COMPUTER

1. Observing Program Selection
   a) What sources are potentially visible now (i.e., sufficiently above the horizon but not behind the balloon)? Of these, which have the highest pre-flight priority?
   b) What sources have I not looked at recently? Of these, which did I detect the last time I looked at them? Of the candidates not examined recently, which should I look at again?
   c) If I am observing a given source, am I detecting a positive flux? If not, how much longer should I continue trying to see it? If I am detecting it, is it behaving in such an "interesting" manner (e.g., time or spectral variability) that I should continue taking data on it?
2. Data Dump Decision (VHF or UHF Link)
   a) Am I within range of a receiving station?
   b) How long has it been since I last made a dump?

c) Is the wind velocity such that I will have time for a complete dump?

3. Cutdown Decision

a) Have I been in "orbit" long enough?
b) Am I over a suitable recovery area?
c) Is it daylight?
d) Have I turned on my tracking beacons and lights?
e) Have I received an override command from a ground station?

The practical number and effectiveness of the algorithms for these computer decisions will be largely determined by the skill and creativity of the human programmer. Implementing all of the options listed here would likely require a very large computer memory; but with the steady decrease in price/bit and the increase in bits/chip for low power C/MOS memory elements, this is not likely to pose a significant problem.

In summary, the system described here should be able to achieve the high degree of flexibility and pointing accuracy which balloonists have come to expect from ground-controlled gondolas, without requiring a telemetry command "umbilical", a link which could be very tenuous for around-the-world flights.

DISCUSSION SUMMARY — PAPER 2.2

In response to questions about progress on this system, the speaker said that the star tracker and the computer have been started.

It was suggested that the star tracker could be used for the same purpose as the 20-watt two-gimbal gyrocompass and therefore save power. The conclusion of the MIT Group is that at $5,000 and eight pounds per gyrocompass that they represent a less expensive trade-off. These units are expected to have ten arcminutes of drift per 12-hour period. It is expected that in the future gyrocompasses will be available for $10,000 to $20,000 with absolute accuracy of ±2 arcminutes for indefinite time periods.

The computer planned for this system is inexpensive, lightweight, uses less than a watt of power and uses a CMOS-type memory.

Some of the advantages of the CCD detector planned for the star tracker were mentioned. These are: no mechanical chopping required, location of spatial elements known very well and high quantum efficiency. The cost is about $500 to $1000 per unit. This star tracker is expected to have a signal to noise ratio of ten for a third magnitude G star using a 1/30-second integration time.