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POSITION DETERMINATION METHODS USED TO TRACK SUPERPRESSURE BALLOONS

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ABSTRACT

The method that has been used in the past to determine the position of superpressure balloons employed in long-term meteorological and technological experiments—projects GHOST (Global Horizontal Sounding Technique), EOLE (French, God of the Winds), SOMEX (Solar Monitoring Experiment), etc.—was to measure the solar elevation during the daylight hours and then compute the balloon position at local noon: latitude by the noon solar altitude and longitude by the time of balloon noon. This method has disadvantages: it requires a lengthy series of measurements during the day and has degraded accuracy when the maximum solar angle approaches 90° . Another method was therefore devised in which the solar angle data are complemented by data that indicate the local geomagnetic rigidity; the correlation of the two data yields an improved position determination algorithm. This method was applied to the trajectory determination of the SOMEX balloons with considerable success.

1. BALLOON LOCATION BY MEASUREMENT OF SOLAR ELEVATION

The classic method of nautical navigation is based upon measurements of the angular altitude of heavenly bodies above the horizon. Each such measurement yields a locus of possible positions having the form of a circle on the terrestrial globe whose center is the substellar or subsolar point and whose angular radius is the complement of the measured stellar (solar) elevation.

The position of a ship is determined either by quasi-simultaneous "shooting" of several heavenly bodies or by shooting a single body at given intervals as it moves across the sky. The intersection of the resulting minor circles yields the ship's position.

Figure 1 illustrates this concept as used to provide tracking data for the superpressure balloon test flights. A simple solar angle sensor was incorporated in each payload, allowing the instantaneous solar elevation to be telemetered. Since only a single heavenly target was used, these measurements had to be made repeatedly during the daylight hours. This inherent limitation led to the following dilemma:

1. If measurements were too close together in time, the intersection of the loci were nearly parallel resulting in large uncertainty in position determination.

2. If the measurements were too widely spaced in time, the geographical displacement of the balloon (up to 1000 km between sunrise and sunset) caused erroneous intersection of the loci.

This paper discusses the methods adopted by the authors to improve location accuracy for the SOMEX II (Solar Monitoring Experiment) flights (Blamont et al. 1969). That flight series included three balloons that were launched to the 100-mb level from Pretoria, Republic of South Africa, in May–June 1968 and flew for 4 to 6 mo. These lengthy flights provided a data base for the evaluation of the navigational techniques to be discussed below.

This paper will show how the measurements were made, the method by which the data was transformed into estimates of balloon position, and the probable errors. Possible improvements of this navigational system through the execution of other simple measurements will then be discussed.

SOMEX II SUN MEASUREMENT INSTRUMENTATION

The sensor used was a GHOST (Global Horizontal Sounding Technique) solar altitude detector furnished by V. Lally of NCAR (National Center for Atmospheric Research) at Boulder, Colo. (Lichfield and Frykman 1967). As shown in figure 2, a photoconductive cell is mounted into an opaque cylindrical structure. A filter is placed in

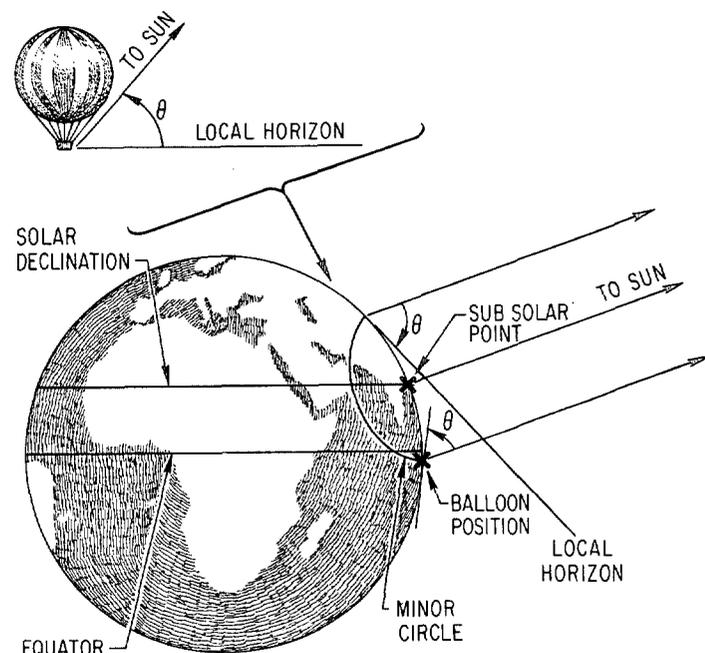


FIGURE 1.—Solar angle method of balloon position determination.

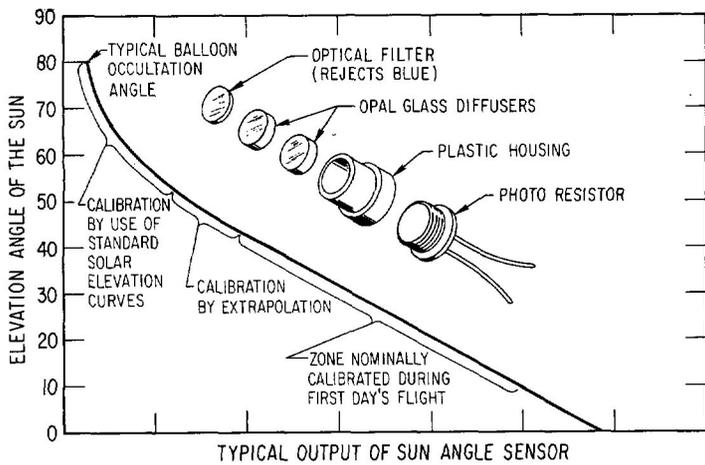


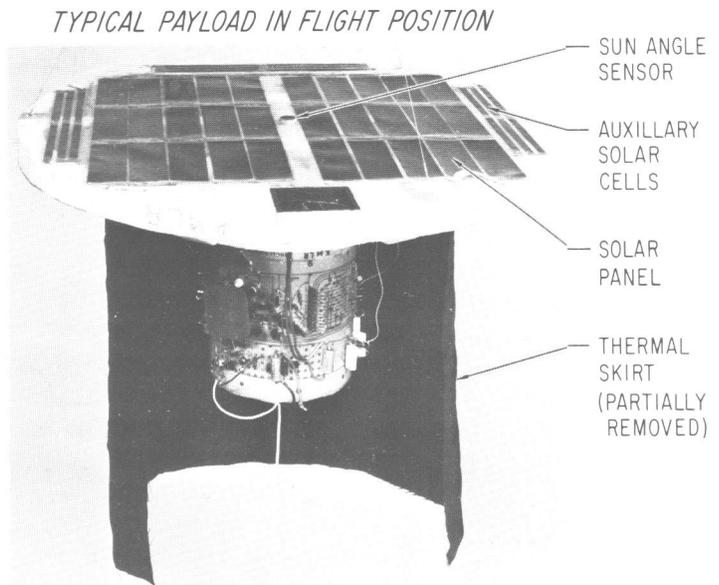
FIGURE 2.—Exploded view of NCAR sun elevation sensor.

the optical path to restrict optical sensitivity to the 6600 to 7500 Å band. Three opal glass diffusers inserted between the filter and the photoconductive cell compensate for the inherent anisotropic response of the photocell, eliminating sensitivity to solar azimuth angle. The restricted neck of the instrument improves sensitivity of the detector at high sun angles. The detector is therefore measuring the incident solar illumination impinging upon the horizontal surface of the filter. This illumination varies as the sine of the solar elevation angle.

PAYLOAD CONFIGURATION

The detector (Heinsheimer and Pommereau 1968) was mounted into the SOMEX nacelle (fig. 3) so that its axis was within $\pm 0.5^\circ$ of the vertical with the nacelle suspended as in flight. Except for the occasional shadows impinging upon the detector from the supporting tripod, or from the balloon itself (which occult the detector at very high solar angles), the detector has a continuous view of the sun during daylight hours. As the solar cell power supply provides sufficient power to drive the transmitter when the solar elevation is above 3° to 5° , sun angle data are transmitted continuously for nearly the entire day.

Each balloon is equipped with a payload whose design is based upon the NCAR payloads used for the GHOST program. The payloads process onboard measurements in the following manner. The measuring sensor (solar elevation detector, for example) controls the frequency of an oscillator (fig. 4). The oscillator frequency feeds a Morse code letter forming circuit, such that the repetition rate of the Morse code letter being formed is a monotonic function of the input frequency. This signal is then used to key a HF transmitter (generating 100 to 1000 mW RF power). Since four independent measurements are made in these flights, an onboard programmer sequences the sensors so that each is monitored continuously for 30 sec. Each balloon is identified by its particular group of code



BOTTOM VIEW (WITH SKIRT REMOVED)

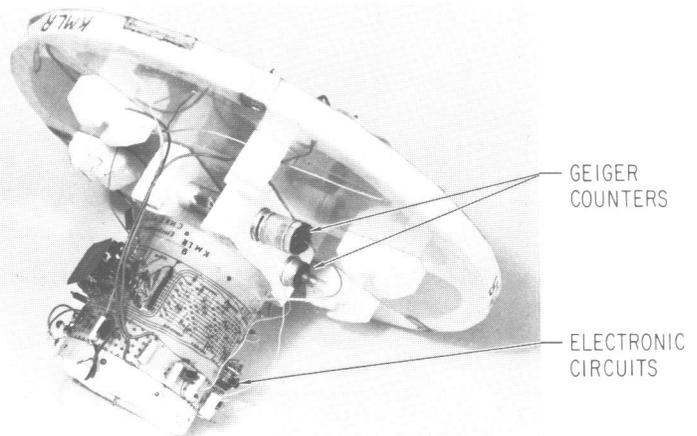


FIGURE 3.—SOMEX nacelle.

letters. For the three SOMEX II balloons mentioned above, the identifying groups were

VMWR, ZMXX, and ZMYR

where the first letter of each series represented the solar elevation, the second and fourth letters (*M* and *R*) represented two Geiger counters, and the third letter identified the measurement of atmospheric temperature.

DATA HANDLING

The signals are received at stations of the French and NCAR balloon tracking networks (fig. 5). There, each received signal is processed manually; an operator identifies a balloon by its code letters and measures the rate of letter transmission with a stopwatch. This process is continuously repeated as long as there are balloon signals being received. The tracking range of an individual station

varies from 3,000 to 12,000 mi, depending upon station equipment, operator acuity, and HF reception conditions.

The data are manually recorded on standard forms and transmitted to the data reduction center in Paris.

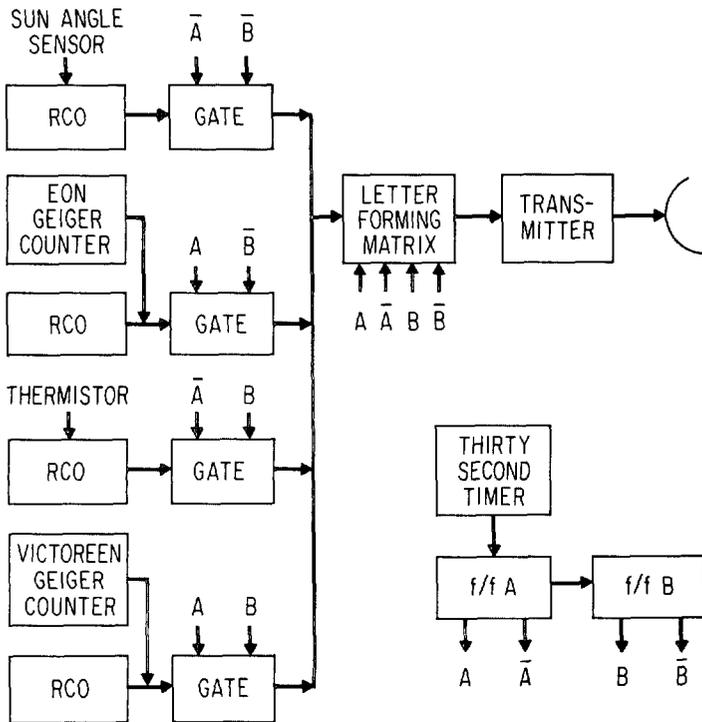


FIGURE 4.—Logic block diagram of SOMEX II payload (based on NCAR design).

There, the data are plotted (fig. 6) and, after bad points are rejected, the calculation of balloon position is accomplished.

As a single position per day is sufficient to define the balloon's trajectory, the simplest technique is to determine that position at balloon "noon." This can be done either manually or automatically (Solot 1968). In either case, for a balloon experiencing no significant acceleration and no large north-south velocity component, the noon position is determined by the axis of symmetry of the day's solar elevation curve. The GMT time associated with that axis yields the balloon longitude, and the measured solar altitude at that time determines latitude.

Should the balloon have either a significant north-south velocity component or an acceleration during the day, the solar elevation curve will be skewed. Although this error can be partially compensated for by a sophisticated data-processing technique, the procedure is inherently iterative and of limited value.

Positional accuracy (whether automatically or manually determined) is limited by the quality of the data judged by three criteria.

1. Is the distribution of a day's data sufficiently extensive to permit tracing of the entire day's solar curve and thereby to determine the noon solar position?
2. Is the scatter of data points small enough to preclude gross errors?
3. Is the knowledge of the calibration curve of the detector sufficient over all portions of the day's solar curve?

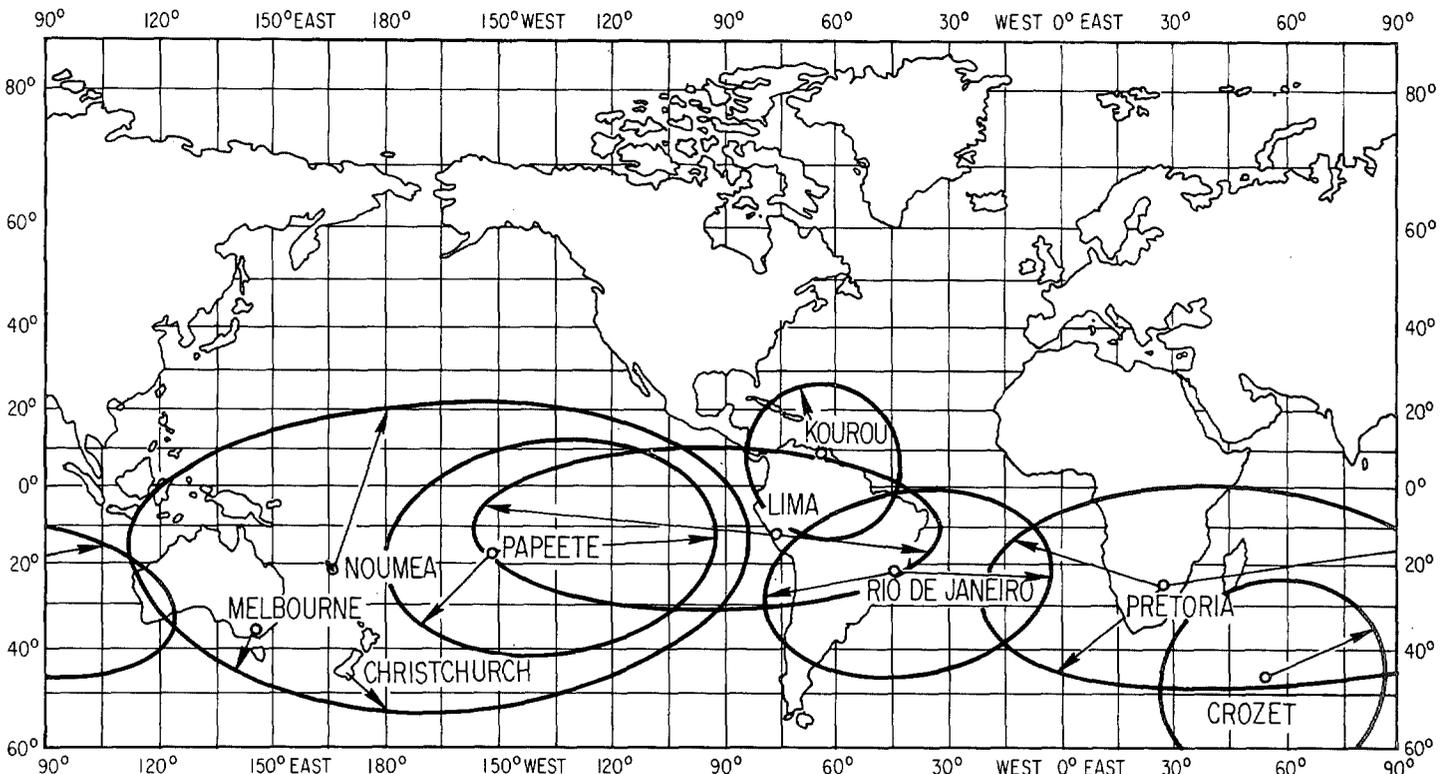


FIGURE 5.—Tracking stations participating in SOMEX II (ellipses indicate nominal coverage).

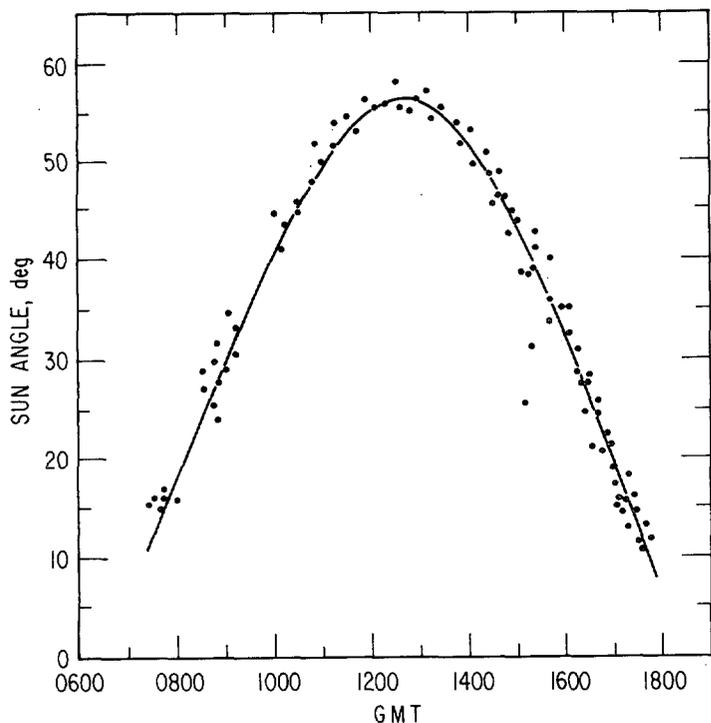


FIGURE 6.—Typical sun angle curve.

Experience has shown that factors (1) and (2) are well in hand and do not usually contribute serious errors. The precision of the calibration curve (3) is generally found to be the greatest source of error.

SUN ELEVATION SENSOR CALIBRATION

The calibration curve of a given balloon is primarily a function of the solar angle, and a lesser function of balloon altitude (atmospheric filtering), payload temperature (thermal drift of detector and electronics), season (solar distance), and flight duration (sensor aging).

Because these error-producing factors are difficult to simulate, it is necessary to calibrate the sensor in flight. The balloon is launched so that it arrives at ceiling altitude in the early morning. It is thereby able to transmit its observations of the entire day's sun angle data. These data are compared with the actual sun angle seen by the balloon as determined by either radar observation of balloon motion or trajectory predictions based on quasi-simultaneous radiosonde wind measurements. Comparison of the actual sun angle data with measurements made by the balloon establishes a calibration curve of sun angle measurements over the range of sun angles seen during the first day's flight. This range is bounded at the top by the maximum sun angle seen during the day (near 45° for the SOMEX balloon flown from Pretoria in May) and at the bottom by the sun angle at loss of signal (typically 5° to 10°).

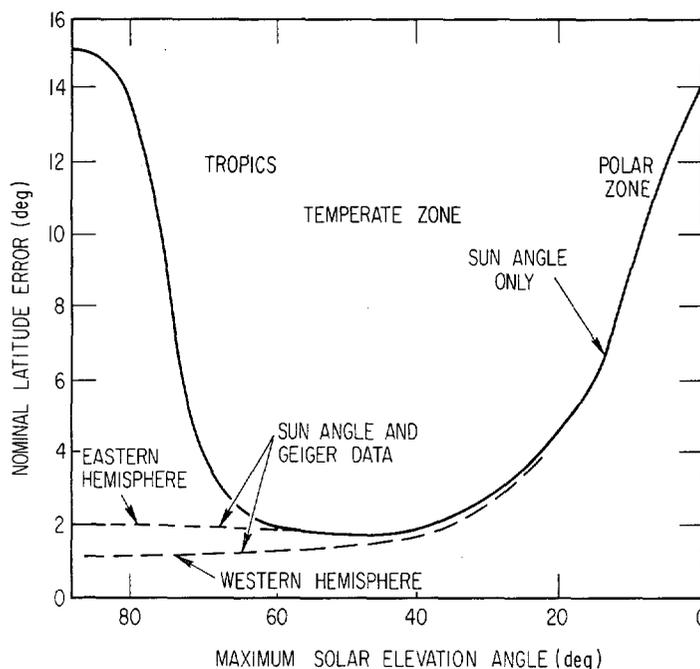


FIGURE 7.—Nominal latitude errors associated with position determination.

Further extension of the calibration curve can be implemented on subsequent days by using computer-derived standard solar elevation curves. This process is extremely sensitive to balloon velocity which distorts the solar angle curve. As a result, effective calibration is only maintained in the range of sun angles seen during the first day and in the linear region immediately adjacent to it (fig. 2). An additional calibration point is available for extremely high solar elevation angles. This is the angle at which the sun angle sensor begins to be occulted by the balloon. Occultation is clearly visible in the data as a sudden decrease in the apparent solar elevation angle. The angle is clearly a function of the geometry of the balloon ensemble (balloon diameter, payload-to-balloon distance) and is typically of the order of 80°.

ACCURACY OF POSITION DETERMINATION

Given the method previously described, one can determine the position of the balloon to a certain level of accuracy. The nominal errors associated with position determination are shown in figure 7. Note that there are essentially three zones—those in which the maximum solar angle is high (tropical zone), intermediate (temperate zone), and low (polar zone). The exact geographical location of these zones is a function of the season, or more exactly of the solar declination.

The curve shows the typical errors associated with the determination of a single day's position as a function of the maximum solar elevation seen on that day. In some cases, much better accuracy is achieved, particularly if extensive data is available on days immediately preceding

and following. The curve is meant to indicate the trend in accuracy variation with solar angle rather than to give an absolute value of attainable accuracy.

In the polar zone, accuracy is limited by three factors: (1) the solar angle varies very slowly during the day, making the determination of balloon noon difficult; (2) the calibration for very low sun angles may be poor; and (3) the strength of the signals received from the balloon may be too weak to permit reliable tracking. Weak signal strength is a result of the low solar angle impinging upon the horizontal solar panel. This problem is circumvented on some of the NCAR flights through the use of nearly vertical panels containing supplementary solar cells. As the SOMEX balloons were not expected to fly in the polar region, the horizontal solar cell array was deemed sufficient.

In the intermediate zone where the calibration is good and the data reception is extensive, position accuracy is at its best. In the case of a balloon for which extensive data are available over many continuous days, accuracies of better than 1° in both latitude and longitude are possible.

In the tropical zone, longitude is accurate to within 1°, but three factors combine to limit the accuracy of latitude determination. These factors are:

1. Poor calibration accuracy (as mentioned above).
2. Insensitivity of the sensor output to variation of the solar angle above 75° (due to the relative insensitivity of the cosine of the solar angle in that range). Note that this problem can be partially overcome by use of the balloon occultation data.
3. The ambiguity of measurements made by balloons nearly under the sun. A balloon found 10° north of the sun will transmit essentially the same solar elevation data as a balloon found 10° south of the sun. It is therefore possible to make gross errors in position determination (tens of degrees). Such errors occur when in the course of its flight the balloon comes close to the latitude corresponding to the solar declination. Subsequent days spent within ≈10° of that latitude are subject to this error. If the balloon subsequently diverges from this area, the errors can be corrected by measurement of the day's duration (which is radically different 30° north of the sun than it is 30° south). For experiments in the Tropics, where the balloon does not subsequently diverge from this area, or where it may cross "under the sun" several times, this factor is a serious limitation.

2. IMPROVED NAVIGATIONAL METHODS

The positioning of balloons will be improved by up to two orders of magnitude when the balloon-satellite relays (Fourrier et al. 1966) such as EOLE (French, God of the Winds) and Nimbus are flying. Even without a satellite, however, some improvements are possible.

For eliminating the need for exhaustive data collection and processing now necessary to arrive at a single balloon position, two independent measurands could be sampled simultaneously, and the resulting intersection of loci could be used to give the instantaneous balloon position with an accuracy limited by instrument error and the

orthogonality of intersection of the two loci. Such pairs of measurements could, for example, combine solar elevation with magnetic dip angle, or solar azimuth. An instrument for effecting the magnetic measurement has been developed by Lally (1969) for the GHOST flights. Another instrument that measures the solar azimuth (with respect to the local magnetic north) was developed by one of the authors.

The SOMEX II data showed, however, that an improvement could be accomplished without suffering the complexity (and weight) of an additional instrument and associated electronics. It was found that the sensors carried to fulfill the scientific objectives of the mission could also serve to improve the navigational accuracy.

POSITION DETERMINING BY MEASUREMENT OF SECONDARY COSMIC RADIATION

Each of the SOMEX II flights was equipped with two Geiger counters to perform a scientific mission that required monitoring of secondary radiation at an altitude of 55,000 ft. This experiment was primarily designed to permit detection of radiation increases associated with solar flares. The data served well, however, in reducing the position errors. For using the data appropriately, the geographical dependence of the steady-state radiation level (cosmic secondaries) must be well known, and errors due to the major perturbing phenomena must be eliminated. It will be shown below that these two conditions were satisfied.

The radiation level at the 100-mb level is a steady-state function of the earth's magnetic field and of the mass of air above that level. The magnetic field influences the local radiation level by tending to deflect the incoming charged particles toward the geomagnetic poles. To describe quantitatively the relative deflection experienced by such particles, one may conveniently define the particles' "rigidity" (P) given by the formula

$$P = \frac{1}{e} (E^2 + 2m_0c^2E)^{1/2}$$

where e is the electron charge, m_0 the particle rest mass, E the particle kinetic energy, and c the velocity of light.

An evaluation can then be made of the rigidity required of a particle to reach a given spot over the earth's surface (above the atmosphere). This leads to the determination of a "geomagnetic cutoff" value that is, for each location on earth, the minimum rigidity required of a charged particle (incident from a given direction) to reach that location.

Quantitative evaluation of the geomagnetic cutoff was first done by Stormer using a magnetic dipole model of the earth's field and improved by Quenby and Wenk (1962) who added non-dipole terms. Figure 8 shows the resulting values of the geomagnetic cutoff for vertically incident particles as a function of geographical position. Note that the relative symmetry of the lines of "isorigidity" in the southern regions is distorted by the geomagnetic anomaly in the South Atlantic.

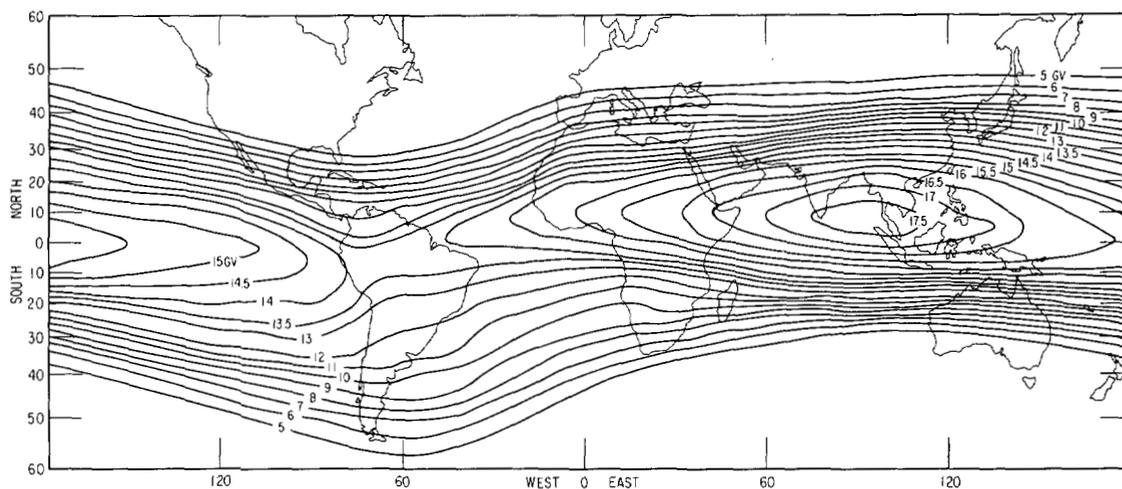


FIGURE 8.—Nominal values of vertical rigidity (in GV).

The other fundamental parameter mentioned above, which influences the steady-state radiation level, is the airmass above the level at which the measurements are made. At the top of the atmosphere, the radiation level is due to incident cosmic primaries. Descending through the atmosphere, the primaries are filtered out by collision, but the overall radiation level increases due to the augmented quantity of secondary particles. A maximum intensity level is reached, the "Pfozter maximum," below which the radiation level decreases rapidly. This maximum is found at the 80-mb level (17500 m) in the polar areas and at 160 mb (13300 m) in the Tropics (Bethery and Legrand 1965). The descent of the maximum level toward the lower latitudes (areas of high rigidity) is due to the increased rigidity of primary particles impacting in the equatorial region and the resulting greater depth of their atmospheric penetration.

It is seen therefore that both the geomagnetic cutoff and the atmospheric absorption effects depend primarily on the particle rigidity. For balloon flights at constant pressure altitude, the rigidity determines the steady-state radiation level. Although a superpressure balloon floats at a constant density level rather than constant pressure, this discrepancy results in an error that, if corrected by using the standard atmospheric tables, becomes negligible.

The steady-state radiation level has superimposed upon it numerous perturbations. This paper will not discuss the geophysical and astrophysical phenomena involved, but will indicate the quantitative effects of position determination. Discussion of the phenomena may be found in the work of Dorman (1963) and Hofmann and Sauer (1968). These authors show that all perturbations (whether cyclical or occasional), except solar eruptions and geomagnetic storms, have an impact on the steady-state radiation level of less than 2 percent.

The two major perturbations are both associated with solar flares. Within a few minutes (or hours) of the beginning of a major flare, a proton shower may be detected. Such showers of protons having energies

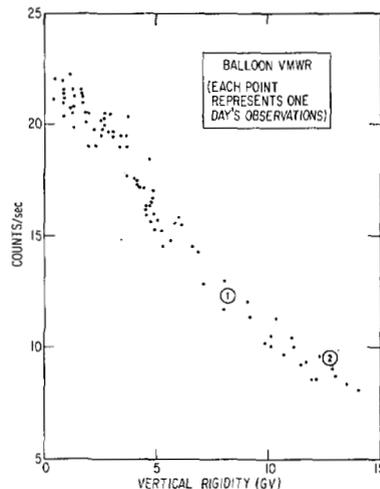


FIGURE 9.—Typical Geiger count rate versus rigidity (calibration curve).

<400 MeV (million electron volts) last only a few hours and influence radiation intensity only at high geomagnetic latitudes. This will rarely affect the balloon-borne measurements. Subsequently, magnetic storms may be experienced when the plasma ejected from the flare reaches the earth (1 to 2 days after flare commencement). For our purposes, the importance of such a storm is measured by the resulting reduction in cosmic radiation (Forbush effect) as monitored by a network of ground-level neutron counters. A 5-percent reduction in the neutron count rate is considered sufficient to invalidate a day's balloon-borne measurement of steady-state radiation. This occurs not more frequently than 1 or 2 days per month.

TRAJECTORY DETERMINATION PROCEDURE

The first steps in the trajectory analysis are aimed at establishing a pair of accurate calibration curves, the

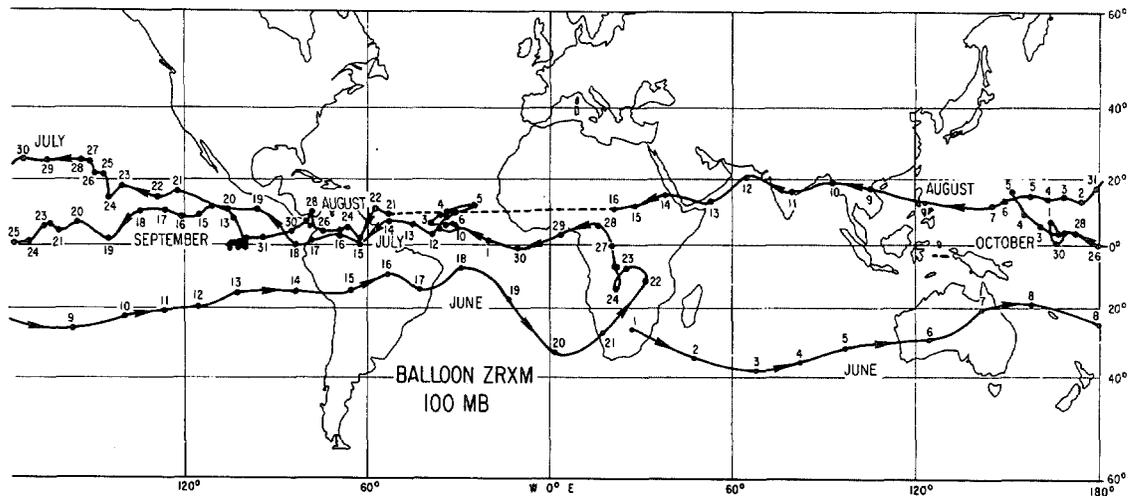


FIGURE 10.—Trajectory for balloon ZRXM.

first yielding the response of the solar angle sensor to solar elevation and the second yielding the Geiger counting rate as a function of vertical rigidity. This is accomplished as follows: on the first flight day, the solar sensor is calibrated using the procedure described earlier (fig. 2).

Also measured on the first day of flight is a single point on the Geiger counter calibration curve (point 1 of fig. 9). In the case of a launch from Pretoria, this point would fall at a vertical rigidity of ≈ 8.5 GV (gigavolts), see figure 8. The errors associated with this point are due to scattering of the Geiger counter measurements and uncertainty of balloon position.

After establishing the initial calibration points on both curves, the procedure is then aimed at both expanding these curves to their respective limits and on continuously reducing the calibration errors. On a subsequent day, when the balloon is found at a latitude such that its noon sun angle is within the calibrated range of sun angles, another calibration point is determined on the Geiger counter curve. For example, if on a given day the solar data showed a position of 30° S., 120° W., the corresponding vertical rigidity is found (from fig. 8) to be 12.5. Geiger counter data observed during the interval of noon ± 1 hr are then used to give a calibration point for a rigidity of 12.5 (point 2 of fig. 9).

Note that due to the unsymmetrical nature of the isoridity lines, the range of rigidities that can be calibrated by a balloon at 30° S. ranges widely, from a rigidity of 4.5 to 13.1. This asymmetry is critical to the procedure. Having extended the Geiger calibration curve through use of the solar angle curve, the reverse process can then be accomplished. On a subsequent day when the balloon is found to be at a position such that the solar angle exceeds the calibrated range and the Geiger counter rate is within its calibrated range (between points 1 and 2), the position can be determined by the intersection of the two known loci; that is, the relevant isoridity curve (fig. 8) and the meridional line indicated by the axis of symmetry of the day's solar curve. This position permits computation of a

new point on the solar calibration curve. This iterative procedure is then continued indefinitely, allowing extension and refinement of both calibration curves as well as determination of daily balloon position. In the case of long flights, the continuous reprocessing of positions as the calibration curves are improved will further upgrade the accuracy of the trajectory. This also guards against sudden calibration shifts due to instrumentation or processing problems that might otherwise go undetected.

ACCURACY OF POSITION DETERMINATION

Determination of balloon position using the sun angle and Geiger counter data results in significant accuracy improvements (fig. 7). The improvement will be discussed below for the three latitudinal zones previously discussed:

1. In the polar region, the Geiger counter method is not very sensitive to variations in latitude. It does, however, alleviate the necessity of precisely determining the time of balloon noon as would be required if sun angle only were employed. It thereby allows the measurement of balloon position with only a sparse amount of data. As data reception from balloons in the polar regions is often sporadic (due both to weak transmitter power and poor coverage of the polar region by the ground stations), the method would permit more frequent positioning of polar balloons.

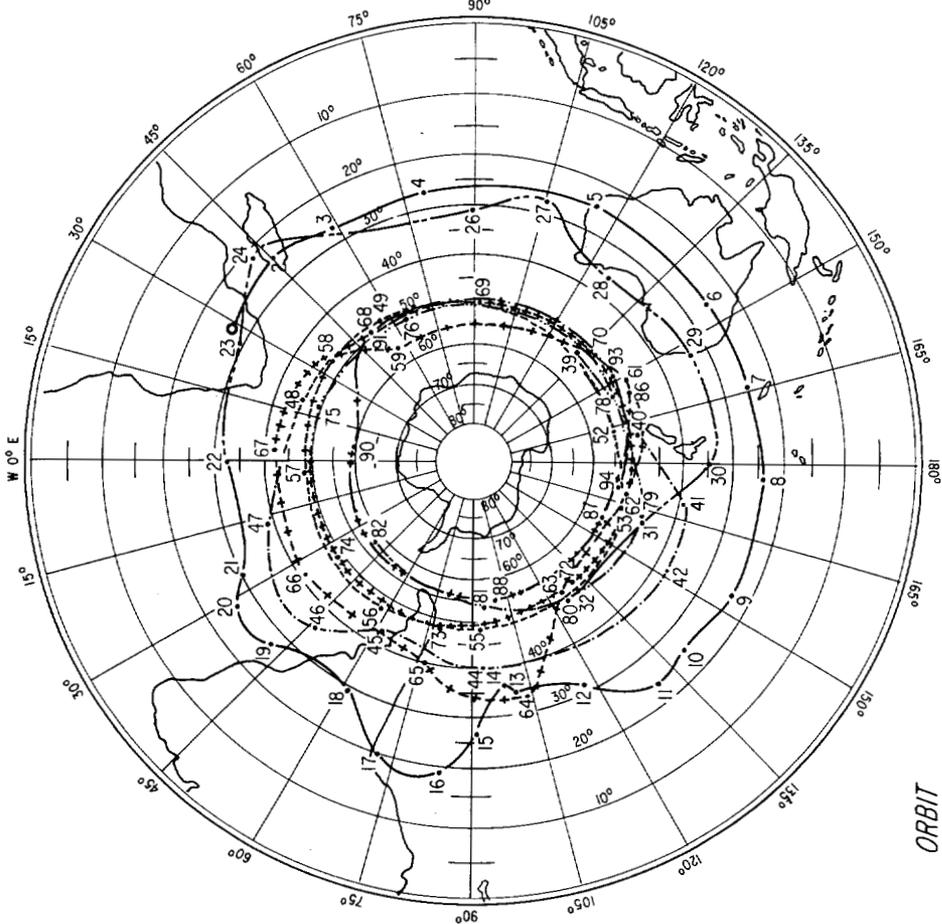
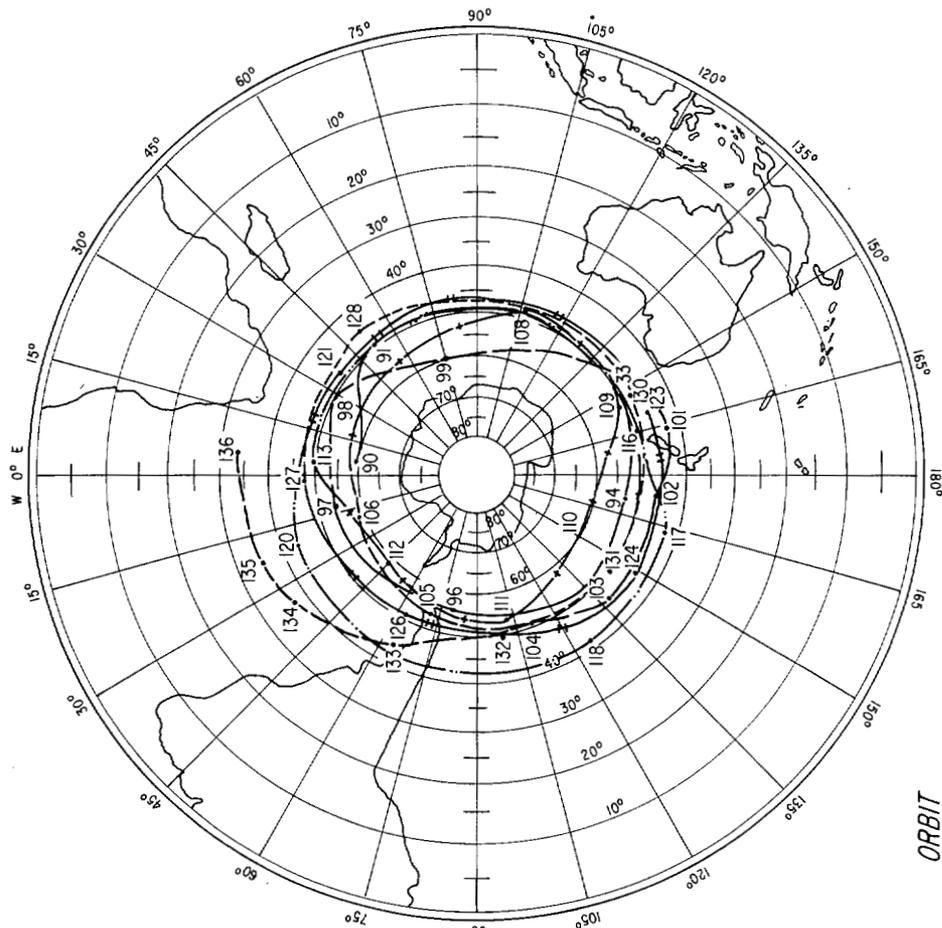
2. In the temperate region, the use of solar angle data alone is usually sufficient. The Geiger counter data is of value for the detection of unexpected shifts in the solar angle calibration curves (due to electronic difficulties). The method thereby adds to the credibility of the computed trajectories of these balloons.

3. In the tropical region, the method of position determination using both types of data is of fundamental importance. As seen from figure 8, the variation of the Geiger counting rate is most extreme in areas close to the Equator (where the solar angle sensor is least sensitive). The method therefore allows a dramatic increase in posi-

(THE NUMBERS ARE FLIGHT DAYS FROM DATE OF LAUNCH)

(THE NUMBERS ARE FLIGHT DAYS FROM DATE OF LAUNCH)

LAUNCHED 29 MAY, 1968



ORBIT

- 9 ————
- 12 - - - -
- 10 - - - -
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- 14 - - - -

ORBIT

- 1 ————
- 6 + + + +
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FIGURE 11.—Trajectory for balloon VMWR.

tional accuracy for the tropical balloons. In addition, the use of the Geiger data removes the ambiguity in position determination of balloons nearly under the sun. Balloons 10° on either side of the solar declination would have nearly equivalent solar angle curves (as indicated previously), but the Geiger count rate would be considerably different.

RESULTS

The described technique was used to determine the trajectories of the SOMEX II balloons. Two typical cases are shown, balloon *ZRXM* (fig. 10) that flew in the Tropics and balloon *VMWR* (fig. 11) that flew in the temperate zone. The meteorological data accumulated by such balloons flying extensively over ocean areas where meteorological data is sparse is of considerable interest.

ACKNOWLEDGMENT

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