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POSSIBILITIES FOR SOUNDING THE ATMOSPHERE FROM A GEOSYNCHRONOUS SPACECRAFT

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This paper demonstrates that vertical temperature sounding of the atmosphere from geostationary altitude is feasible. It treats the meteorological and instrumental options which must be considered to obtain soundings from this great distance with the required accuracy in a reasonable period of time. Measurements from the geosynchronous ATS satellites are used to examine cloud conditions. Observations from experiments on Nimbus 3 are used to specify radiance levels to be measured. For a spin-scan system, like that planned for the SMS, an instantaneous field-of-view of 0.3–0.4 mrad (11–14 km) is recommended for the tropospheric sounding channels of 20 cm^{-1} bandwidth near the 15 μm region. Results indicate that it will be possible to sound the atmosphere to the earth's surface through openings in a 95% cloud cover in less than one hour.

1. Introduction

The measurement of infrared radiance from the earth's atmosphere well enough to infer the vertical temperature profile from geostationary altitude is difficult due to the low energy levels encountered. At 35800 kilometers random noise from the radiation detector is a large fraction of the signal from the atmosphere. Given a suitable optical system and very sensitive detector, we can overcome this energy deficiency by using multiple sampling in space, time or both. One must not use too long integration times, however, since the parameter of interest, atmospheric temperature, varies with time. One must also insure proper space sampling since temperature varies with space as well. Despite these difficulties, the effort will be well worth the trouble one must take because the atmosphere is a four-dimensional system (x, y, z, and t) and a continuous view adds the dimension time.

Such nearly continuous views of atmospheric conditions were first returned from experiments on the Applications Technology Satellites (ATS) 1 and 3, [1, 2]. These satellites are in equatorial orbits at geostationary altitude. They have carried high-resolution telescopic photometers to measure reflected solar radiance. Many of these measurements, formed line by line into a single frame, give an image of the earth–atmosphere system during a 20 to 30 minute period. Successive frames allow the measurement and study of the time variation of atmospheric conditions over a large portion of the earth's surface.

Very recently, spectrometer and interferometer experiments on Nimbus 3 [3, 4] and Nimbus 4 have successfully demonstrated the capability to infer atmospheric temperature profiles from radiation measurements. In addition, the operational value of such measurements (from the polar-orbiting Nimbus) has been shown [5]. It is the purpose of this paper to study the possibility of placing a vertical temperature profile experiment on a geostationary satellite. Our immediate requirement is the ability to infer temperature profiles with an rms error of less than 1° C.

One way to reduce the error is to restrict the observations to clear areas only. Thus only clear column radiances are used to reconstruct the temperature profile, and errors due to the presence of cloud are removed. The Nimbus 3 and 4 results are very impressive even including cloud in the field-of-view, but few would argue that the presence of cloud contributes to higher accuracy.

It is possible to reduce the field-of-view of the instrument in order to see through small openings in the clouds. A smaller field-of-view, however, decreases the signal-to-noise ratio of the measurement and more samples must be taken in order to improve the S/N ratio to acceptable levels. As one reduces the field-of-view are enough additional samples available to compensate for the poorer signal? A general answer to this question is not possible since the performance parameters of different instruments will yield different answers.

The central question of our study may be stated another way. Each radiance observation will be contaminated by detector noise and may be contaminated by "cloud noise". With a large instantaneous field-of-view (IFOV) it is not possible to separate the detector noise from the cloud noise. With a small IFOV, one can separate the "cloud noise" which is not random from the detector noise that is random. However, one can do this only at the price of a poorer signal-to-noise ratio. Are there enough additional clear column samples using a small IFOV to improve the S/N ratio to acceptable levels? The answer depends on the performance specifications of the instrument and on the natural occurrence of clouds.

2. Instrumental Options

The instrumental constraints used in this study are based on typical meteorological spacecraft configurations planned for the early 1970's. These include:

(i) a spin-scan instrument system (see Fig. 1)
(ii) 16 inch optics
(iii) spin rate of 100 rev min^{-1}
(iv) cooled HgCdTe infrared detectors (near 11 μm for imaging; sounding near 14 μm).

In addition to the high-resolution infrared imaging sensor (IFOV about 0.2 mrad) it is probable that an even higher resolution "visible" radiation sensor will share the same primary optical system with the infrared sounding channels.

Measurements from the Nimbus experiments have shown that the magnitude of infrared radiance near the 15 μm CO_2 band varies from 50 to 110 erg cm^{-2} s^{-1} sr^{-1} cm from band center to edge during clear sky conditions over most of the region viewed from a geostationary satellite. These same experiments obtained measurements with relative accuracies of about 0.25 erg cm^{-2} s^{-1} sr^{-1} cm. Vertical temperature profiles with an rms error of 1 °C were obtained from them. We shall use the observed radiance values to test our proposed experiment and adopt the same relative error value as our limit.

Several important instrument options remain. These include (a) IFOV α of the sounding channels (b) spectral location ν and width $\Delta\nu$ of the channels and (c) scan rate and time required to cover a finite area. These are all inter-related, each affects the relative accuracy of a radiance measurement and

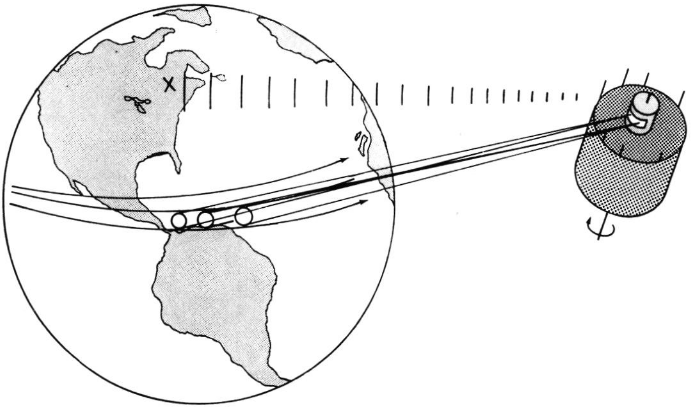

Fig. 1. Schematic depiction of a spin-scan sensor on a geostationary spacecraft.

each of these instrumental options also represents an important decision that will affect meteorological application of the measurements. Combinations of these parameters (as well as the general instrument characteristics mentioned above) were systematically varied in a set of standard instrumental relationships [6]. These include expressions for the power output from the detector, the noise equivalent power (NEP) and noise equivalent radiance (NER). The latter for any individual measurement is approximately:

$$\mathrm{NER} \sim 1/\alpha^2 \tag{1}$$

where α is the IFOV. The ground resolution spot size at nadir, D, is directly related to the IFOV, α. Over a finite grid mesh of area A (i.e. 400 km × 400 km as proposed for the Global Atmospheric Research Program) the possible number of discrete measurements N varies inversely with D^2. Furthermore, the NER due to random instrument noise for each discrete measurement may be reduced by $1/N^{1/2}$ when a representative radiance value over the grid is desired. Thus:

$$(\mathrm{NER})_\mathrm{A} = \frac{\mathrm{NER}}{N^{1/2}} \sim \frac{1}{N^{1/2}\,\alpha^2} \sim \frac{1}{N^{1/2}\,D^2} \sim \frac{1}{A^{1/2}\,D}\,. \tag{2}$$

Fig. 2 illustrates the relationship of the instrumental options for the geostationary sounder considered in this paper. Note that for a radiance error of 0.25 erg cm^{-2} s^{-1} sr^{-1} cm the required observable clear area increases rapidly as ground resolution improves. Two additional ordinate scales are provided. One demonstrates the percentage observable clear area required in a GARP grid mesh to acquire a sufficiently accurate radiance value with a sensor of given IFOV. It shows that the required accuracy is possible from *one scan pass* over a region 65–85% cloudy if the sensor's ground resolution D is 11–14 km.

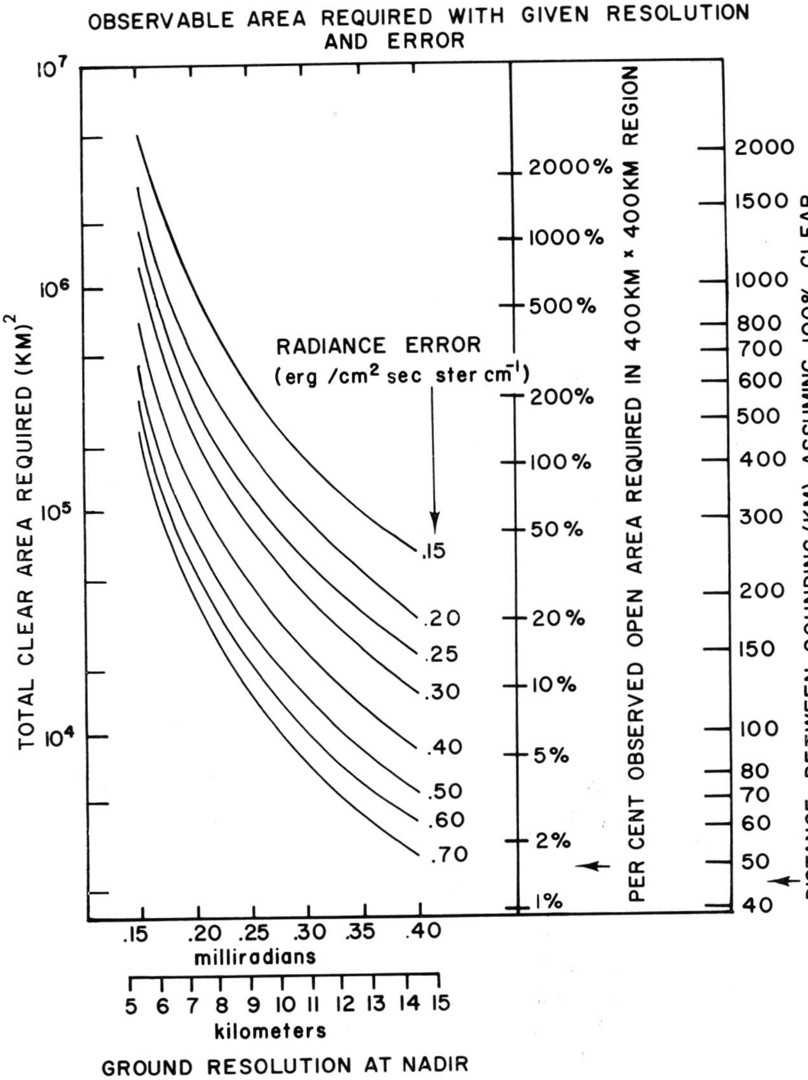

Fig. 2. Nomogram showing interrelation of instrumental options and their influence on meteorological temperature sounding requirements.

At 100 rev min^{-1}, one scan pass over a GARP grid near satellite subpoint would take about 20 seconds. For mesoscale applications over clear regions, the remaining scale shows that the geostationary sounder can acquire an accurate sounding every 150 km if $\alpha = 0.4$ mrad.

It is clear from the above that one observation in each sounding channel cannot be used to infer the temperature profile over the spot size ($D = 11$ to

14 km) on the earth enclosed in the narrow field-of-view. It may take more than a thousand discrete observations to improve the signal-to-noise ratio to the level needed to get a meaningful temperature profile *determination*. This will depend on the specified scan step and sampling frequency. Thus, for the sample instrument described here (with a scan step of 0.2 mrad) the minimum soundable area will be about 90 miles on a side, roughly one-tenth of a GARP grid.

3. Effect of Cloud Distribution

As mentioned earlier, cloud cover interferes with radiometric temperature sounding. To avoid clouds with a given instrument observing over a specified area, we must increase the time required to complete a sounding within our

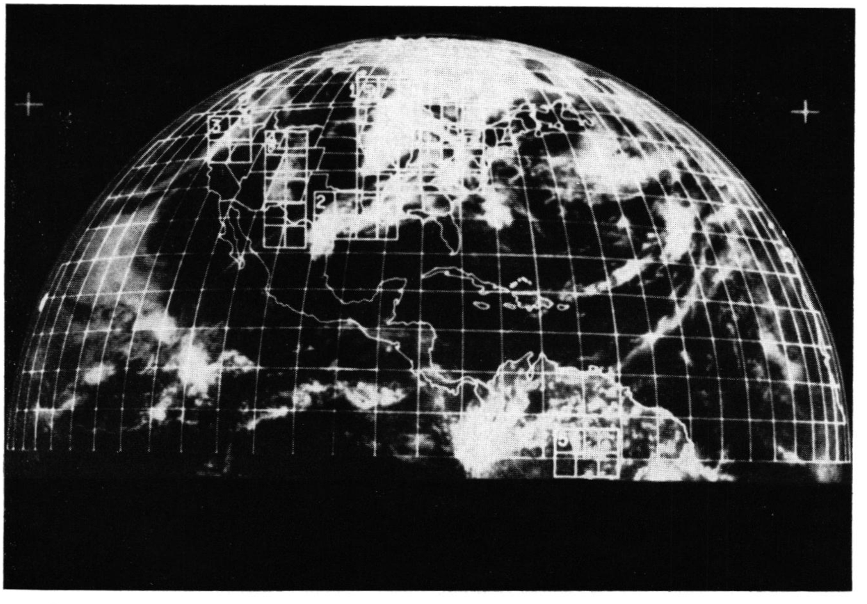

Fig. 3. ATS-3 picture of 23 April 1968 (1714Z) noting grid areas used in cloud distribution study [7].

relative accuracy limits. In order to separate cloud fields-of-view from clear observations, a higher resolution (but with a wider bandpass $\Delta\nu$) infrared imaging channel can be used.

Most meteorologically active (baroclinic) regions tend to be quite cloudy. Temperature soundings near these features of the circulation are particularly valuable. In order to test how well one can sample these areas, a special study [7] of cloud distribution was performed. It used data from ATS-1 and 3, thus simulating the view of the proposed sounder. The Spin Scan Camera on ATS 1 and 3 has an IFOV of only $\alpha = 0.1$ mrad. Thus it was possible to simulate the cloud statistics of a radiometer having a larger IFOV.

Some of the regions studied (e.g. Fig. 3) were completely cloud-covered. Others (in the intertropical convergence zone, over areas of dense broken cloud cover near extratropical fronts and within active convective cloud regions over South America) can be represented by the traces labeled Case 1, 2 and 3

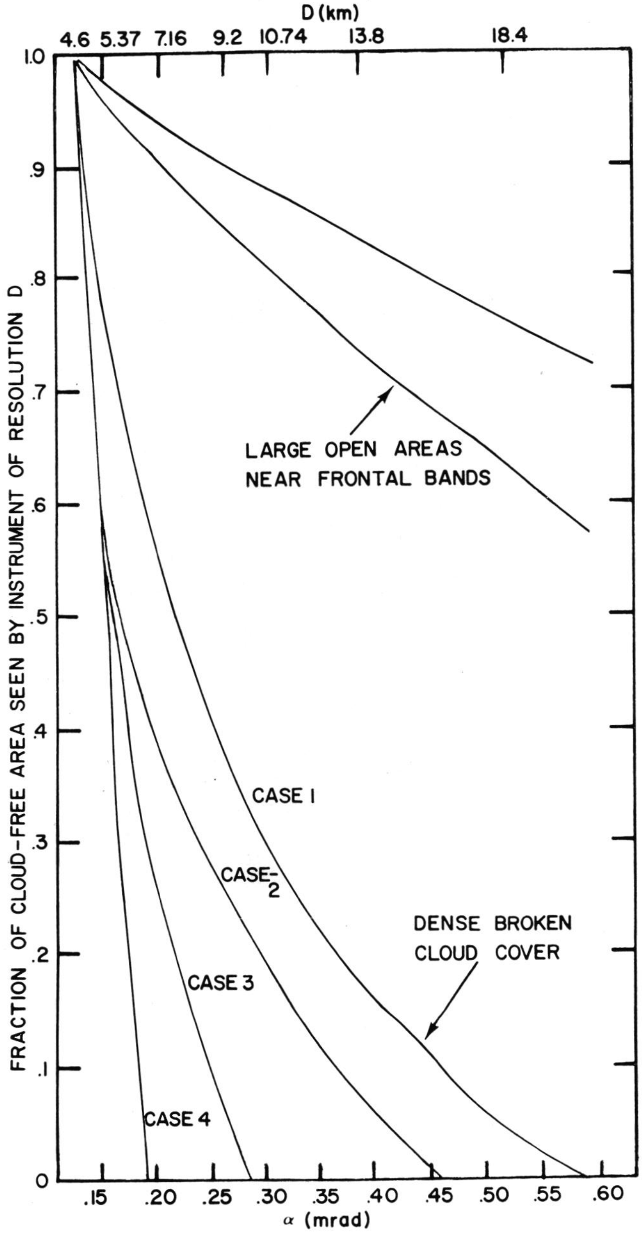

Fig. 4. Fraction of "open" or cloud-free area seen over a GARP-size grid by instrument of angular resolution α (normalized to 100% of 4.6 km ground resolution).

in Fig. 4. These show the reduction in the total area of clear fields-of-view as a function of sensor ground resolution. The values are normalized to the percentage clear area seen by a sensor with ground resolution of 4.6 km. Case 4 in the figure is a rather special case with all clear areas smaller than 7 km. Other, less cloudy, conditions are shown to have less rapid reduction of observable clear area with increasing α or D.

In order to optimize the engineering choices to typical cloud distributions we must specify the scan-step size mentioned earlier. Since a high-resolution infrared imager is likely to be included along with the sounder, a scan step about 0.2 mrad is probable. We shall use this value and thus a typical frame of the entire earth would require 15 to 20 minutes.

Table 1
Temperature sounding time required for various cloud conditions
($A = 160000$ km^2, $(\mathrm{NER})_A = 0.25$ erg cm^{-2} s^{-1} sr^{-1} cm, $\alpha = 0.4$ mrad, $\nu = 690$ cm^{-1}, $\Delta\nu = 20$ cm^{-1})

% Open area	Number of complete frames	Time for sounding (hr.)
100	1	0.26
50	1	0.26
10	2	0.52
5	3	0.79
1	11	2.88

Table 1 shows the time required to obtain a vertical temperature sounding over a GARP grid for various cloud conditions using the above scan step with our sample instrument. Note that while 0.2 mrad stepping was used the sounding channel had an IFOV of 0.4 mrad. The surface temperature is 300 °K; a relative radiance error of 0.25 erg cm^{-2} s^{-1} sr^{-1} cm will be obtained over the grid mesh. Note that even in a region of 95% cloud cover an accurate sounding is possible in under one hour.

It is evident from our balancing between relative accuracy, field-of-view and area/time that there is an optimum set of parameters for a specific spacecraft and basic instrument. The observing system considered here is similar to the proposed GeoSynchronous Meteorological Satellite (SMS). For such a system we are apparently instrument-noise limited for small IFOV's and cloud-noise limited at larger IFOV's. Fig. 5 shows this very well in terms of relative sounding time required over a GARP grid. Each trace refers to a cloud situation shown in Fig. 4. For a given case the valley curves indicate a preferred resolution to minimize the sounding time. This effect is demonstrated by [7] who considered 18 grids near frontal zones over the US and over convective cloud regions of the Amazon basin (see Fig. 3). Four of these regions are more than 99% cloud covered and cannot be sounded at $\alpha = 0.3$–0.4 in a reasonable time period. Of the remaining 14, nine may be sounded with desired accuracy in less than one hour with IFOV of 0.3–0.4 mrad and five would require from 2 to 6 hours. At higher and lower ground resolution the results were less favorable.

In general, the region of $\alpha = 0.3$–0.4 mrad looks best even though we are viewing only 10 to 30% of the cloud-free area which would be viewed by a sensor with smaller α. Since the curves in Fig. 5 have rather flat minima, it may be best to make a final IFOV selection closer to 0.4 mrad to gain signal-to-noise ratio as noted by equation (1). This applies especially to the low and mid-tropospheric channels: those where cloud effects are most severe.

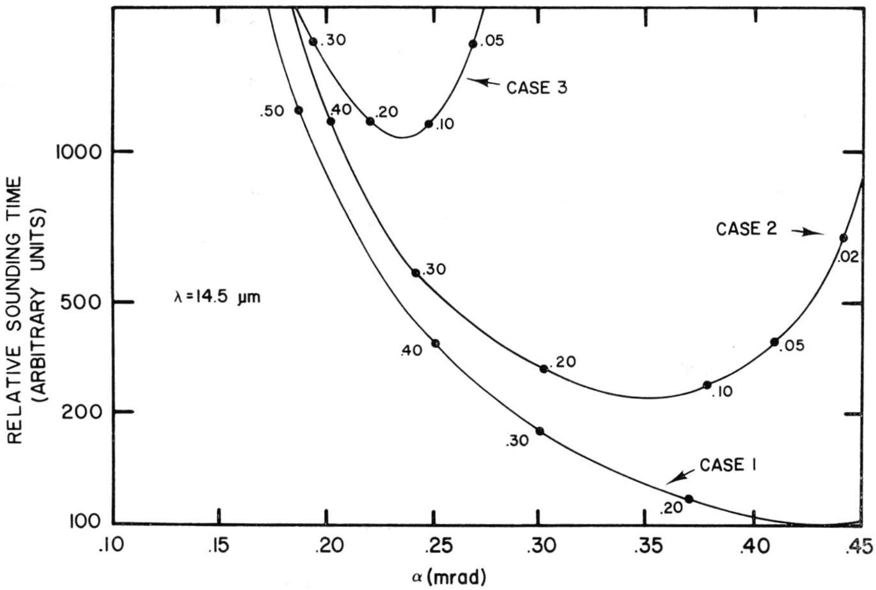

Fig. 5. Relative sounding time required as a function of the rate of change of measured "open" area (Fig. 3) with angular resolution. Values at the dots show fraction of the cloud-free area seen by sensor with specific α.

4. Summary

Our studies show that the opportunity for sounding the atmosphere from geosynchronous orbit looks very attractive. These studies have shown that even with typical cloud distribution near meteorologically active regions a sounding is possible over a 400 km × 400 km grid mesh within a reasonable time interval.

A recent paper [8] shows that when soundings from geostationary altitude are added to those obtained from two polar orbiting satellites, the numerical model's predicted wind error is reduced by 35%. In addition, they demonstrate that a geostationary sounder can serve as a powerful backup to a two-satellite polar orbiting sounding system. Their results show that a combination of geostationary satellites and one polar orbiting satellite gives wind values at least as good as two polar orbiting satellites alone if the data are inserted at intervals of twelve hours. They also find that if the geostationary data are inserted more frequently than every 12 hours there is an improvement over results obtained from polar orbiting satellites. In view of the fact that the incremental cost of including infrared sounders on geostationary satellites is relatively modest and that even in the worst conditions one can obtain soundings every two hours, this feature should be added to the global observing system.

COSPAR Working Group 6 Report [9] states that "If the results of such studies show that infrared soundings will be feasible from geostationary satellites, such observations in combination with those obtained from near-polar satellites would form an almost ideal complementary combination." The present study shows that the infrared sounding from geostationary altitude is indeed feasible and the observing system simulation study [8] shows these observations to be very valuable.

Acknowledgments

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References

[1] V. Suomi and R. Parent, Bull. Am. Met. Soc. **49**, 74 (1968).
[2] V. Suomi and T. Vonder Haar, J. Spacecraft and Rockets **6**, 342 (1969).
[3] D. O. Wark and D. T. Hilleary, Science **165**, 1256 (1969).
[4] R. Hanel and B. Conrath, Science **165**, 1260 (1969).
[5] W. Smith, H. Woolf and M. Jacob, Mon. Weath. Rev. **98** (1970).
[6] R. Krauss, Special Report under Contract NAS5-11542, SSEC, University of Wisconsin (1970).
[7] A. Stamm and T. Vonder Haar, J. Appl. Met. **9** (1970).
[8] R. Jastrow and M. Halem, Bull. Am. Met. Soc. **51** (1970).
[9] COSPAR Working Group 6 Report to JOC, Second Draft (1968).