2.1 SPECIFYING SATELLITE ORBITS FOR HIGH ACCURACY CLIMATE MONITORING

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I. Introduction

A crucial shortcoming of modern climate research is the lack of long-term benchmarks against which to test the rate of change of key climate indices. As part of an effort to design a system of small satellites to make benchmark observations of spectrally resolved infrared radiation emitted by the earth, we explore the impact of imperfect sampling on the ability of a suite of low earth orbiting satellites to reproduce mean radiance on a variety of spatial and temporal scales. Our aim is find those orbits which maximize the temporal and spatial resolution at which mean radiance can be measured to an accuracy of 0.1 K or better in brightness temperature. This level of accuracy is chosen to agree with the expected magnitude of decadal trends in temperature forced by changes in greenhouse gas concentration.

Our approach follows that of Salby and Callaghan (1997), who showed that significant errors in climate properties arise when polar orbiting satellites are used to construct short term averages of brightness temperature. They used geostationary satellite data as a proxy for the true brightness temperature, and simulated the sampling of polar orbiting satellites. They found that very large errors (in excess of 10 K) arose from sampling error of brightness temperature. We extend their work by defining the extent of spatial and temporal averaging necessary to overcome sparse sampling, and obtain highly accurate mean brightness temperatures.

Leroy (2001) considered the aliasing of the diurnal cycle onto satellite retrievals of annual mean surface temperature. He showed that for a diurnal temperature cycle with a peak-to-peak amplitude of 10 K, a single sun-synchronous nadir-sampling orbiter will have a bias of nearly 3 K in the retrieved global mean temperature. In extension of this work, we will consider the effect of diurnal biasing for retrieved brightness temperatures, and will show that, because the diurnal component of variations of brightness temperature is small compared to the surface temperature cycle, the bias in mean temperature by diurnal aliasing is smaller than in the case of surface temperature retrieval.

We model the sampling error of various potential satellite orbits and orbit combinations using the Salby Global Cloud Imagery (GCI) 11 micron brightness temperature data set to simulate real variations in radiance. We compare averages over space and time of the GCI data, and of the same data sampled along the paths traversed by a downlooking satellite footprint for each potential orbit, including the role of anticipated instrument error properties. We vary the inclination and altitude of orbits, to see how these affect retrieval accuracy. Maps of retrieval accuracy are formed for monthly mean and annual mean radiance. We show that for a suite of six sun-synchronous satellites, an accuracy of 0.1 K in brightness temperature can be achieved world-wide at a horizontal resolution of $22.5^\circ \times 22^\circ$. For three such satellites (the NPOESS configuration), 0.1 K accuracy can be achieved in most such grid squares, and in zonal means taken over 22.5 degree-wide bands.

II. Method

We consider the retrieval of brightness temperature by a highly accurate nadir-looking satellite with a field-of-view of 0.05 radians. Our method is to calculate the location of the sub-orbital point over the course of one year, and to use archived satellite brightness temperatures to simulate the brightness temperature retrieved by our simulated orbiter at each time. These brightness temperatures are grouped by location, and averaged together over the year, and then compared with the average of all the brightness temperatures in the archived data for that location. For our archive, we use the Salby Global Cloud Imagery data set (Salby et al., 1984), a re-gridded compilation of 11 μm brightness temperatures retrieved from geostationary and polar orbiting satellites. It has a spatial resolution of .35 degrees Latitude and 0.70 degrees Longitude, for a total of 512 X 512 grid points, and a temporal resolution of 3 hours. The 11 μm band has the advantage, for our purposes, of being one of the most highly variable bands in the terrestrial spectrum. Being minimally affected by water vapor or carbon dioxide, this band essentially measures the temperature of the highest cloud layer, or of the surface, in the absence of clouds. Other bands, which mostly represent emission by water vapor or carbon dioxide high in the atmosphere, have variances approximately three times smaller. Thus our estimates of sampling error represent the worst case over the terrestrial band, and a satellite or set of satellites that can accurately retrieve 11 μm brightness temperature can certainly retrieve other bands to higher accuracy.

A satellite orbiting about the earth remains in a plane fixed with respect to the stars, except to the extent that this orbital plane is perturbed by such things as atmospheric drag, radiation pressure of sunlight, and the the earth's departures from perfect sphericity. We consider only the perturbation due to the first zonal harmonic perturbation to the earth's shape, J_2. Assuming a circular orbit, this perturbation will affect only the angular orientation of the satellite's plane of orbit with respect to the stars (Heiskanen and Moritz, 1967):

$$\Omega' = \frac{3na_e^2}{2a^2}\cos i \tag{1}$$

, where Ω' is the rate of change of the angular orientation of the satellite's plane of orbit, n is the angular speed of the satellite along its orbit, where $n = (\frac{GM}{a^3})^{1/2}$, a_e is the earth's radius, a is the radius of the satellite's orbit, G is the gravitational constant, and M is the mass of the earth, and i is the inclination of the satellite's orbit with respect to the equator.

Once the satellite's orbital plane and its initial position is known, we can locate the region at surface sampled at any instant:

$$\phi = \arcsin(\sin i \cos d + \cos i \sin d) \tag{2}$$

$$\lambda = \lambda_1 - \arctan(\frac{\sin d \cos i}{\cos d - \sin\phi \sin i}) + t * (\Omega - \Omega') \tag{3}$$

where ϕ is the latitude, λ is the longitude, λ_1 is the initial longitude, and Ω is the earth's angular rotation rate, equal to 7.292 s^{-1}. The initial position is assumed to be at $\phi = i$, $\lambda = \lambda_1$, and the initial motion to be purely zonal.

Our assumed field-of-view of 50 mrad gives a footprint of 40 km for an orbit altitude of 800 km. This is close to the 0.35 degree latitude, 0.7 degree longitude resolution of the GCI brightness temperature data. Thus, for simplicity, we assume that each satellite view combines all those grid points through which the suborbital point passes, during an assumed averaging period of 10 seconds. These satellite views are summed together on the same 512 by 512 grid used by the GCI data. We can then average adjoining grid point retrievals together over a larger region. This can reduce the sampling error if the adjoining points' brightness temperatures are correlated with one another, since in that case the number of samples increases faster than the number of independent data points to be sampled.

III. Results and Discussion

The sampling errors resulting from several simulated satellite orbital configurations are shown in Figures 2–4. Errors for single satellites in three different orbits are compared in Figure 2. We see that a polar orbiter has small errors at high latitudes, but relatively large errors in low latitudes. A low-latitude orbiter, with an inclination of 33° has small errors in the tropics, but no coverage outside the tropics. These orbital configurations have two important distinctions. The first is the obvious one: observations are concentrated in different regions. The polar orbiter visits each pole some 14 times each day, while the low-latitude orbiter never sees the poles, and has higher frequency of observations at any given location in the tropics. The second distinction is that, while the polar orbiter's plane of orbit remains fixed with respect to the stars (and thus results in a single annual cycle in the time of day of observations at any given location, the low-latitude orbiter's plane of

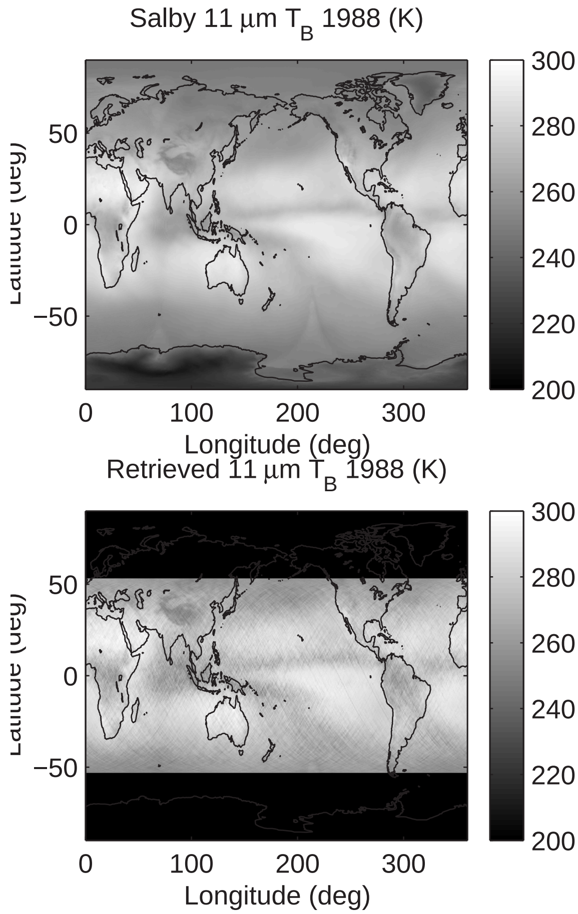

Figure 1: Top: Annual mean 11 μm brightness temperature for the year 1988 from the Salby GCI data. Bottom: Sample retrieval of this brightness temperature by a simulated precessing orbiter with an inclination of 53°.

orbit precesses six times about the earth in a period of a year. Further simulations show that a single annual cycle in the time of day of observations is in general a poor choice, especially for tropical regions. It turns out that a sun-synchronous orbit is a represents a good compromise between broad latitude coverage and accuracy in the tropical belt. Errors for a sun-synchronous orbit are shown in the bottom panel of Figure 2.

Although a single sun-synchronous orbiter can obtain brightness temperature retrievals that are reasonably accurate, it clearly does not attain a global accuracy of 0.1 K at 22.5° resolution. To reach this goal of 0.1 K accuracy, we can add more satellites. Figure 3 shows retrieval errors for a suite of three equally spaced sun-synchronous orbiters. The top panel, for the year 1988, shows that brightness temperature is retrieved with 0.1 K accuracy over a majority of the earth. However, comparison with the bottom panel (1987) shows that the locations of 0.1K accuracy (denoted by *'s) are not the same from one year to the next.

Figure 4 shows two ways to obtain consistent accuracy over the whole earth. Addition of three satellites (for a total of six) allows 0.1 K accuracy at 22.5° resolution over the great majority of the globe. Alternatively, one may compromise spatial resolution, and seek to measure zonal mean brightness temperatures. The bottom panel shows that accuracy of 0.1 K or better can be achieved by a suite of three sun-synchronous satellites, by a single low-latitude satellite, or by a single sun-synchronous satellite over a large portion of its latitude range. Similar regions of high-accuracy coverage are obtained for 1987.

IV. Conclusion

Our study has demonstrated that 0.1 K accuracy in the retrieval of zonal mean brightness temperature is attainable in the 11 μm band by a suite of 3 sun-synchronous satellites; that a suite of 6 sun-synchronous satellites can achieve this level of accuracy in each grid square of a $22.5° \times 22.5°$ longitude-latitude grid, and that a single polar orbiting satellite can obtain zonal mean brightness temperature in this band with an accuracy (accounting for sampling errors alone) of 0.2 K.

References

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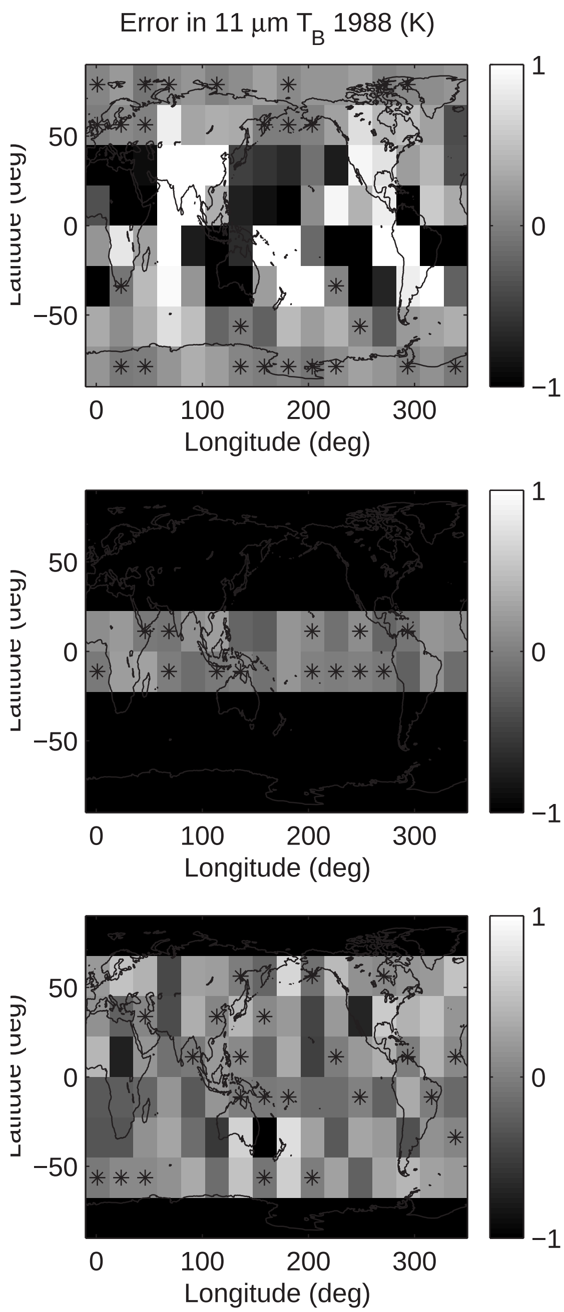

Figure 2: Top: Retrieval error of annual mean brightness temperature in the year 1988 due to sampling for a single polar orbiting satellite. Retrieved brightness temperatures are averaged over $22.5° \times 22.5°$ grid boxes. Those grid boxes where the sampling error is smaller than 0.1 K are marked by an asterisk ('*'). Middle: as in top, for a single precessing orbiter with an inclination of $33°$. Bottom: as in top, for a single sun-synchronous orbiter.

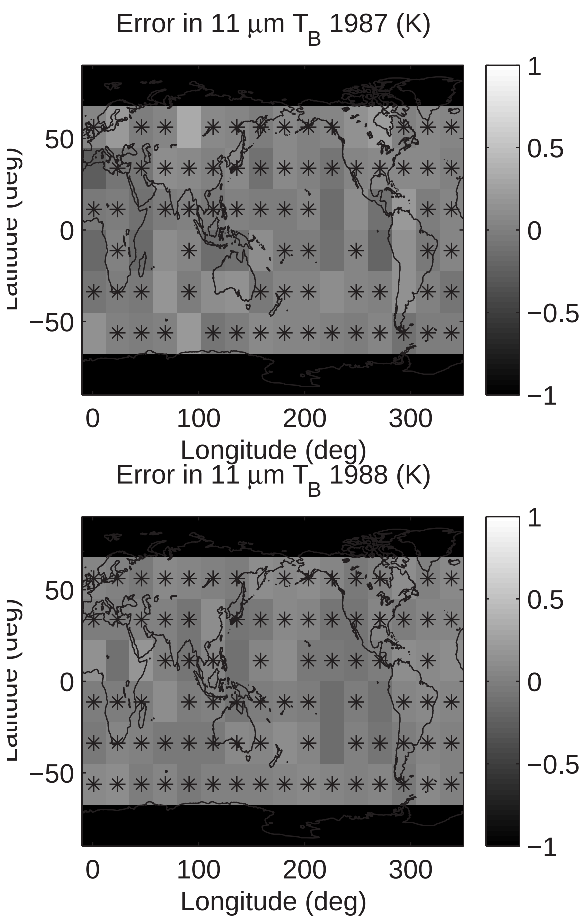

Figure 3: As in figure 2. Top: suite of three sun-synchronous orbiters, spaced equally in longitude around the earth, with inclinations of $98.765\,°$, for the year 1988. Bottom: same configuration, for the year 1987.

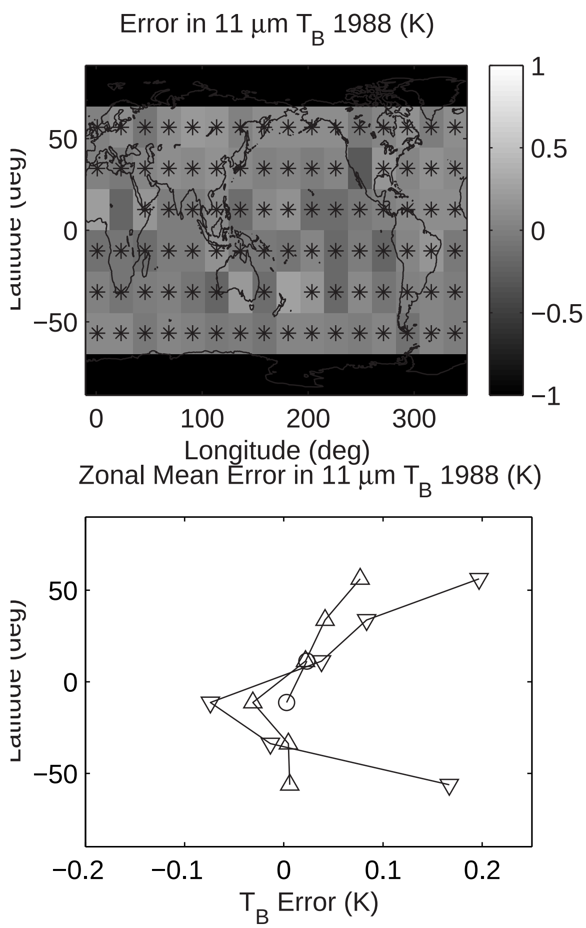

Figure 4: Top: As in figure 2, for a suite of six equally spaced sun-synchronous orbiters, for the year 1988. Bottom: Error of retrieved zonal mean brightness temperature for 1988 for three orbital configurations. Upward-pointing triangles: three sun-synchronous orbiters; downward-pointing triangles: a single sun-synchronous orbiter; circles: a single low-latitude (incl. $33\,°$) orbiter.

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