Insolation During STREX

1. Comparisons Between Surface Measurements and Satellite Estimates

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Comparison between measurements of insolation from pyranometers mounted on ships and estimates from satellite visible measurements during STREX are presented. In general for both hourly and daily insolation values the comparison is quite favorable. The root mean square (rms) difference between the two measurements of daily insolation was about 13 W m\(^{-2}\). From a detailed analysis of the errors and measurement discrepancies it was found that a large part of the difference between the two estimates of insolation could be due to inaccuracies in the surface measurements, interpolation during periods of radio interference, and ship motion. Comparisons between time-averaged insolation values over periods of about 10 days and limited statistical analysis of the pyranometric time series suggest that, on that time scale, the accuracy of the satellite estimates is of the order of 4 W m\(^{-2}\). Large-scale insolation fields derived from satellite during STREX will be presented in the companion paper (C. Gautier and S. Masse, manuscript in preparation, 1984).

1. INTRODUCTION

The Storm Transfer and Response Experiment (STREX), which took place in November and December of 1980 in the northeastern part of the Pacific Ocean has been described by Fleagle et al. [1982]. One of the objectives of STREX was to study the magnitudes and spatial scales of the fluxes occurring across the air-sea interface during cyclonic storms -- the eventual goal being to develop a model of a "composite" mid-latitude cyclone and the response of the upper ocean to its passage.

Two ships, the Canadian weather ship Vancouver (Station P) and the American research vessel Oceanographer (Station P') were located at 50°N, 145°W, and 50°N, 140°W, respectively, for most of the two phases (day 314 to day 325 and day 335 to day 346) of the experiment, and various atmospheric and oceanographic variables were measured. Data sets of research quality were acquired over a 45 day period (30 days of observation) in an oceanic area of the world where few measurements are available, particularly during late fall. Shortwave irradiance at the surface (insolation) was measured continuously from the two ships. Measurements of reflected shortwave radiation from a geostationary satellite (GOES-3) (Figure 1) have been collected and archived at the University of Wisconsin. The purpose of this paper is to demonstrate the importance of the surface data for in situ validation of satellite measurements and algorithms. The satellite and in situ measurements also provide valuable redundancy checks, one for the other, and allow us to close data gaps in the time series.

This is a two-part study dealing with insolation during the STREX experiment. In this first paper we describe the measurements of insolation made on board ships and the estimates made from geostationary satellite data and compare the two types of estimates for both hourly and daily averages. In the second paper (C. Gautier and S. Masse, manuscript in preparation, 1984), the spatial variability of insolation, as derived from the satellite measurements, is presented and discussed.

In section two of this paper we describe the in situ measurements, and in section three the method used to derive insolation from visible geostationary satellite measurements is described. In the fourth section we present a comparison of satellite estimates with pyranometer measurements. In section five we discuss the major sources of error within the two estimation systems and the possible sources of discrepancy between the two kinds of estimations. Finally, in the last section the results are summarized, and some conclusions are drawn.

2. INSOLATION MEASUREMENTS FROM SHIPS

During STREX, insolation measurements were made continuously from both ships. At Station P the measurements were made as part of the meteorological surface network using a KIPP model CM6 pyranometer. At Station P' the data were obtained expressly for the STREX program, also with a KIPP model CM6 pyranometer. Hourly and daily measurements for Station P are published by the Canadian government [Monthly Radiation Summary and Supplement, 1980] while other meteorological measurements and the hourly and daily measurements for Station P' are reported (R. Lind and K. Katsaros, manuscript in preparation, 1984).

The Vancouver measurements were made from a gimbaled mount on a boom near mid-ship, while the Oceanographer measurements were made from a gimbaled mount near the bridge. The main difficulty with the in situ data at Station P' was due to the electrical interference by radio transmissions. Examples of a relatively uncontaminated and a contaminated time series are found in Figure 2(a,b).
Fig. 1. GOES 3 visible image on Julian day 315 (November 5) at 2145 GMT (1145 local time at 145°W) and eightfold reduced resolution (i.e., 8 km at the satellite subpoint and about 16 km at 50°N).

A redundant estimate of the insolation was obtained by additional measurements of the total irradiance (solar plus terrestrial) with a Schulze pyradiatorometer at Station P'. The terrestrial irradiance was also measured independently with an Eppley pyrgeometer, which makes it possible to obtain insolation from the Schulze measurements by subtraction (R. Lind and K. Katsaros, manuscript in preparation, 1984). Since difficulties were experienced with the pyrgeometer in STREX, this method was not used. However, during a period when all three instruments were functional, the agreement in shortwave irradiance is 4%.

3. SATELLITE ESTIMATIONS OF INSOLATION

We have developed [Gautier et al., 1980] and tested [Gautier, 1982; Diak et al., 1982] a model to derive hourly and daily insolation from a combination of calibrated high-resolution visible brightness measurements obtained from a NOAA geostationary satellite.

Since an absolute calibration of the sensor (VISSR, Visible Infrared Spin Scan Radiometer) is neither performed before the satellite launch nor provided by NOAA after launch, we perform our own calibration of the VISSR. In the case of the GOES-West (or GOES 3), which was in place during the STREX experiment, we have made a cross calibration with GOES-East (or GOES 2), previously calibrated by us using the technique of Norton et al. [1980] during the STREX time period for a region where the fields of view of the two satellites overlap. A region of high albedo (White Sands, New Mexico) has been chosen for the high end, and black space has been used for the low end of the calibration. The appendix describes the method used for this cross calibration and Figure A1 the resulting calibration curve together with the GOES-East calibration curve. Such a calibration is not absolute and will obviously be a source of error in estimating the insolation from brightness measurements.

For this study we derived insolation for an area corresponding to a square consisting of 64 (eight by eight) pixels. The choice of eight pixels in the north-south direction results from the configuration of the VISSR, which is composed of an array of eight sensors. In this way it is not necessary to derive a calibration for each individual sensor, and an averaged calibration is sufficient. The choice of eight pixels in the east-west direction is for symmetry of the processing but is not necessary. The resolution of the input brightness data was 4 km at satellite subpoint. At the latitude of the two ships during STREX the resolution of these data is about 8 km. We have com-
Computed insolation over a square composed of four such brightness values (which in this case represents approximately a 16 by 16 km area). The sun and satellite angles required for the model calculations of the insolation were those corresponding to the center of the 16 by 16 km square.

The total insolation for 1 day was calculated by integrating over time, applying the trapezoidal method on the hourly insolation estimates for the 16 by 16 km square. Although it would be preferable to estimate insolation half hourly, economic reasons prevented us from choosing this solution, since it would have doubled the already large costs of data acquisition and processing. The sunrise and sunset times required for this integration were calculated from the navigation information contained in the heading of each GOES digital image file and again are those corresponding to the center of the square.

Fig. 2. Insolation measured at ship P on two days, the thick curve in the lower part of the figure in each case. The solid line is the data trace, the thin line gives the interpolated insolation (see text). The upper curve in each figure indicates when the data were contaminated by radio transmission: (a) Julian day 346—a day with little radio interference around midday; (b) Julian day 318—a day with considerable interference.

Fig. 3. Comparison between hourly insolation on Julian day 322 measured at ship P and estimated from satellite data averaged over two different resolutions: 1 x 1 pixel and 8 x 8 pixels; 1 x 1 pixel means that the satellite-estimated insolation has been calculated for a 16 x 16 km area; 8 x 8 pixels means that it has been estimated by averaging over a 128 x 128 km area. Before 815 GMT and after 2300 GMT the satellite estimates for the 8 x 8 pixels resolution has been extrapolated to sunset and sunrise.

4. Comparison between Satellite Estimates and Ship Measurements

Comparisons between satellite estimates and pyranometer measurements of hourly insolation at ship P for a 6-hour time period are shown on Figures 3 and 4 for day 322 and 337, respectively. Only the first 6 hours have been used because they correspond to only 1 Greenwich Mean Time (GMT) day. Our image manipulation software would have had to be extensively modified to take into account the few remaining daylight hours that fell on the following GMT day to compute daily insolation. This results from the configuration of our software, whereby hourly and daily insolation are all computed in the same job stream. This should result in an error smaller than the errors resulting from other sources (see below). Figures 3 and 4 illustrate that the satellite estimations vary with spatial averaging. Using only one insolation estimate over a 16 by 16 km area for the comparisons would require an accurate knowledge of the geographical position of the area; additionally, spatial averaging reduces the effect of the positioning uncertainty. We have used an average of eight by eight pixels to estimate insolation and have found...
Daily Insolation (140°W)

![Graph of daily insolation with ship and satellite data]

Fig. 5. Time-series of daily total insolation averaged over 24 hours: (a) Ship (solid line) and satellite estimates (dashed line) at Station P (145°W); (b) Difference between ship and satellite estimates of upper panel.

Note the good general agreement (Figures 3 and 4) in terms of the evolution of the hourly mean insolation over the day. From these results one can expect that daily insolation values, which are integrals of these curves, will show improved accuracy over those obtained for hourly values.

Comparisons between the satellite estimates and the pyranometer measurements of daily insolation for Station P and P' are presented in Figures 5 and 6, respectively. These figures present the satellite and ship time series plotted on the same graph, and also a corresponding plot of the difference, to facilitate the interpretation. The first characteristic to note on Figure 5 (Station P) is a general good agreement between the two time series for the period extending from day 317 to day 338. After day 338 the Vancouver ship of Station P was no longer on station, and the comparison is discontinued thereafter. Day 315 stands out as a very poor satellite estimate. The conditions for that day are illustrated on Figure 1. The cloudiness for the region in the vicinity of the two ships is quite complicated. It is very patchy over a large part of the area but with a thicker cloud system in the west. Under these conditions, a mispositioning of the ship on the satellite image introduced by an uncertainty in the satellite navigation could cause the observed discrepancy in insolation. An even larger discrepancy exists at Station P' on that same day, as shown on Figure 6. The satellite estimates appear slightly larger overall than measurements at ship P', particularly during phase one of the experiment. There is better agreement between the satellite estimates and the pyranometer's measurements after day 335.

The bias calculated from each of the two time series are 6.7 W m⁻² for ship P for the period shown on Figure 5 and 8.7 W m⁻² for ship P' for the period shown on Figure 6. From these results it can be concluded that the satellite estimates are consistently high by about 8 W m⁻². Independent results [Gautier, 1982] have also shown a tendency for the satellite method to overestimate the daily insolation by comparison to pyranometer measurements.

The accuracy of satellite estimates are calculated from the standard deviation of the difference between the bias corrected satellite time series and the surface measurements. Such a calculation gives a value of 13.1 W m⁻² for ship P and 12.2 W m⁻² for ship P'. Because ship P' is a research ship, it could be expected that its measurements would be of higher quality. However, the slightly better result found in the comparison between the satellite estimates and ship P' measurements is not sufficiently marked to favor one set of surface measurements over the other at this point. We will show later that ship measurements...
**Daily Insolation (145°W)**

**Ship**

**Satellite**

![Graph](image)

**Fig. 6.** Same as Figure 5 but for Station P' (140°W).

contain a large error and that consequently the number provided by the intercomparison is more like an upper limit for the satellite estimation accuracy.

A scatter diagram for the uncorrected satellite estimates versus the two sets of pyranometer measurements is shown on Figure 7. The correlations between the ship measurements and the satellite estimates have been found to be 0.73 for ship P and 0.72 for ship P'. Despite the similar correlation values for the two intercomparison data sets, if we compute a linear regression between the ship measurements and the satellite estimates at each ship position, we find that the slope of the regression line is closer to 1 for ship P' (0.87), with a zero crossing at 13.5 W m\(^{-2}\), and the slope for ship P is 0.55, with a zero crossing at 25.4 W m\(^{-2}\). These differences occur because the ship measurements and the satellite estimates have a much wider range for ship P'. The dates of the outlying points have been marked on Figure 7. The values for day 315 stand out on this diagram for both ships, suggesting that the problem most likely stems from the satellite estimates.

A summary of the results just discussed is presented in Table 1. The average insolation for the entire period of the comparisons have been calculated for both satellite and ships, and comparisons of the results are also presented in Table 1.

It is useful for many purposes to know the typical value of the daily averaged insolation over a certain time period and its accuracy. From our results it is difficult to predict the reduction of uncertainty that can be expected from averaging procedures for the satellite estimates, but the ultimate accuracy of the time-averaged daily value will certainly be better than that found for an individual day. Correlation functions have been calculated for the daily insolation time series at Station P', and near zero values were obtained at 1-day lag and beyond. Therefore, individual daily samples can be considered as independent from each other, and the error reduction introduced by averaging over n days will be close to the square root of n. In the case of a 10-day average the anticipated error reduction would then be about 3. From this limited data set, indications are that the standard deviation of the difference of the time averaged (n = 11−14 days) insolation between satellite estimates and the two ship measurements is about 4 W m\(^{-2}\). This is approximately a factor of 3 reduction from the standard deviation of 13 W m\(^{-2}\) found for daily comparisons.

5. **Sources of Uncertainty**

5a. **Ship Measurement Errors**

One of the major problems we generally face in comparing satellite estimates with in situ measurements is the accuracy of the in situ observations, which is usually taken as the standard. First, the calibration error of regular
Insolation... *Satellite vs. Ship* (Watts/Meter²)

![Graph](image)

**Fig. 7.** Scatter plot for total daily insolation averaged over 24 hours. Satellite estimates vs ship measurements corresponding to both Stations P and P'.

Pyranometers is about 4—5%, according to the manufacturer [Latimer, 1972]. In addition the signal has to be amplified, and some variability in the gain of the amplifier may occur because of changes in temperature of the environment. Further, the signal is recorded and usually digitally integrated over 1 hour, and there can be some inaccuracy linked to the recording procedure [Hay and Wardle, 1982]. There is always some obstruction of the hemispheric sky dome for instruments not mounted on top of a mast. Finally, measurements made on board a ship are affected by the motions of the ship and they do not average out in general [Katsaros and DeVault, 1983]. Therefore we removed most of the motion-caused errors by gimbaling the sensor. When adding all these potential sources of error, an 8% accuracy can probably be achieved in carefully controlled conditions [Hanson, 1974], but for the difficult environment of STREX an accuracy of about 10% is estimated.

Because of the frequent damaging interference on the data recordings at Station P' from radio transmission, there are large gaps. These gaps were closed by applying an interpolation scheme as follows. For several data points before the gaps, but excluding the last one, an average atmospheric transmittance \( \tau \) was calculated. (Transmittance is defined as the ratio of the received irradiance to the irradiance at the top of the atmosphere, which we can calculate [e.g., Patridge and Platt, 1976].) Using this mean transmittance, half of the data gap was closed by calculating the surface irradiance from the irradiance at the top of the atmosphere. Similarly, a mean transmittance was found for the other side of the gap, and it was applied to the calculations for the second half of the gap. The appearance of these interpolated periods is illustrated by Figure 2b. The interpolation error was then estimated by differencing the interpolated value from the satellite estimation. This approach has been chosen because we did not have enough data to simulate gaps in a statistically significant manner and then calculate the differences between the interpolated data and the original record. A mean interpolation error of 4.2 W m⁻² was estimated from these calculations.

**TABLE 1. Averaged Insolation Estimates From Satellite and Pyranometers**

<table>
<thead>
<tr>
<th></th>
<th>Station P</th>
<th>Station P'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship mean</td>
<td>41.3</td>
<td>36.5</td>
</tr>
<tr>
<td>ship s.d.</td>
<td>19.3</td>
<td>14.3</td>
</tr>
<tr>
<td>Satellite mean</td>
<td>48.0</td>
<td>45.2</td>
</tr>
<tr>
<td>Satellite s.d.</td>
<td>14.4</td>
<td>17.3</td>
</tr>
<tr>
<td>Mean difference</td>
<td>6.7</td>
<td>8.7</td>
</tr>
<tr>
<td>rms difference</td>
<td>13.1</td>
<td>12.2</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.73</td>
<td>0.72</td>
</tr>
</tbody>
</table>
5b. Satellite Measurements Errors

The satellite estimates contain their own errors associated with (1) the calibration of the VISSR, (2) the algorithm to calculate the hourly insolation from the measurements of visible reflected radiance, and (3) the time integration procedure. The error caused by the calibration has been recently estimated [Gautier, et al., 1984] to about 5%. The errors in the radiative transfer approximation are more difficult to estimate, but other results suggest that the sum of the calibration and the algorithm error is less than 9% [Gautier et al., 1980]. (The value of 9% represents the rms of the difference between the satellite estimates and the surface measurements and therefore contains the surface measurement error.) The error from the extrapolation in time (it only takes into account the daylight hours until 2315 UT) can be estimated by comparison to the contribution this part of the day has to the total insolation measured by the ship. Following this procedure we find a mean integration error of about 3 W m\(^{-2}\). If the first (last) satellite estimate of the day is in error, then the extrapolation to sunrise and sunset contains some additional error not quantified here. Another source of error stems from the possible mislocation of the ship on the satellite image. This is partly compensated by the spatial averaging of the satellite estimates, but in other studies we have encountered satellite navigation (registration) errors of up to 100 km. We usually correct for these misalignments by visually estimating the shift (on an image processing system) and taking it into account in the insolation calculations, but in the case of STREX it was not possible to align the images on specific clear landmarks because there was not enough clear regions over land. We have had to rely upon the routine navigation performed by NOAA-NESS. The anticipated error resulting from misregistration is at least 10% of the mean, i.e., 5 W m\(^{-2}\). Furthermore, during the STREX experiment, the conditions for estimating insolation from a geostationary satellite are particularly difficult. For a latitude of 50°N the satellite viewing is poor. Under these conditions, we have also found a tendency for an overestimation from the satellite data, and our model may require further work for these cases. However, it is important to note that conditions of low insolation are rarely encountered in the regions where insolation is important for the heat budget, and the exact magnitude of these values may not be necessary for budget calculations, since the magnitude of the insolation itself is close to the error of the net heat budget.

5c. Discrepancy Between the Two Measurement Systems

In addition to the intrinsic errors of the in situ and satellite measurements there is a discrepancy to be expected in the comparison deriving from differences in the two types of measurements. A pyranometer measures the total incoming radiation over the entire solar spectrum and a 2 \(\pi\) solid angle. The satellite estimates are made from a limited viewing angle instrument in the visible band (0.55–0.75 \(\mu\)m) of the solar spectrum, from which we calculate broadband cloud bulk radiative properties. Results from Welch et al. [1980] show that the spectral reflectance corresponding to the VISSR wavelengths is within a few percent of the broadband reflectance for most cloud types. Also, the satellite estimates are based on quasi-instantaneous measurements which are averaged over space. Another few percent inaccuracy can be expected from this mismatch in averaging procedures.

Furthermore, the ship is considered as fixed in our comparisons, but we have found instances during which a “fixed ship” had moved by no less than 65 km during the day. We have attempted to estimate the range of the discrepancy to be anticipated as a result of ship motion (or equivalently of mislocation) within a highly variable insolation field. The mean value of satellite-computed spatial variance was about 5 W m\(^{-2}\) for scales of 100 km. First, we have estimated the anticipated maximum error (\(\Delta l_{\text{max}}\)) that could be expected by calculating the difference between the maximum and the minimum values for the satellite-derived insolation in a square of 128 by 128 km. The rationale for this is that in some instances the ship could have moved in the direction of the maximum insolation gradient over the day. The mean value for this maximum possible error is 22.4 W m\(^{-2}\). Another way to estimate the order of magnitude of the error caused by the ship motion (or mislocation) is to examine the mean spatial variance for the 128 by 128 km square. This is equivalent to moving the ship by ±65 km. The mean value thus found is 4.9 W m\(^{-2}\).

From these two estimates of the effects of the ship motion together with the possible sources of error in the ship data discussed above we have obtained an estimated order of magnitude of the total mean uncertainty and of the anticipated maximum uncertainty. These values are 10.6 W m\(^{-2}\) and 22.4 W m\(^{-2}\). From these values we can see that a good part of the 12 or 13 W m\(^{-2}\) mean difference between the satellite estimates and the ship measurements found in section 4 could be due to the inaccuracies in the ship measurements or improper ship location. However, when using land-based measurements with accurately registered satellite images, the error in daily values is still around 9%. Thus some of the rms difference results from calibration and algorithm errors.

Table 2 shows the estimated values for the various sources of uncertainties in the comparisons between the satellite estimates and the ship measurements.

Obviously one would expect \(\delta_{\text{ corr}}\) to at least fall within the maximum uncertainty range calculated. However, there are a few days for which \(\delta_{\text{ corr}}\) is very close to or at the limits of this range, and these days are 319 and 338.

6. SUMMARY AND CONCLUSIONS

We have presented a detailed comparison between measurements of insolation from pyranometers mounted on ships and estimates of insolation from satellite visible brightness measurements. Comparison of daily insolation estimates obtained by the two techniques yielded an rms value of the difference of about 12–13 W m\(^{-2}\). From a thorough analysis of the errors and measurement discrepancies we have shown that a large part of the difference between the two estimates of insolation could be due to inaccuracies in the surface measurements, interpolation during periods of radio interferences, and ship motion (or mislocation on the satellite image). The cumulative mean uncertainty (mean of \(\epsilon_{\text{ corr}}\)) between the
two compared measurements is within a range of 10--20 W m$^{-2}$. Comparisons between averaged insolation values over 7--10 days and limited statistical analysis suggest that the accuracy of the satellite estimates on that time scale may be of the order of 4 W m$^{-2}$. These results are quite encouraging, particularly for estimating insolation over large areas from satellite measurements and especially considering the difficult conditions during STREX for the geostationary satellite estimates (high latitude, winter, and over an ocean with few visible landmarks). Large-scale insolation fields derived from satellite will be presented and discussed in the companion paper (C. Gautier and S. Masse manuscript in preparation, 1984). We have found a tendency for an overestimation from the satellite measurements when the daily insolation value is less than 30 W m$^{-2}$. Such low mean daily insolation conditions are, however, mainly found in high latitudes in the winter.

### APPENDIX: CALIBRATION

**Background**

The Visible Infrared Spin Scan Radiometer (VISSR) on board the U.S geostationary satellites allows high resolution (1 km at satellite subpoint), narrow spectral band (0.55--75 μm) and small solid angle measurements of reflected solar radiation from the top of the atmosphere. The determination of the insolation at the surface from the VISSR measurements requires its calibration. The VISSR is poorly calibrated before launch and not calibrated after. Therefore in-flight calibration must be performed. In the following paragraphs we describe the instrument and its rudimentary prelaunch calibration in order to facilitate the understanding of the rationale for our calibration strategy.

The response of the visible detector to a source of incoming light is known to be linear, the digitizing scale is not (linear) but is purposefully adjusted to keep the signal to noise ratio (S/N) linear with respect to counts, i.e., S/N is proportional to the square root of the irradiance. Thus knowing the functional relationship between S/N and the irradiance, only one calibration point is theoretically needed. However, the instrument has some unknown zero offset that needs to be determined. Consequently, two calibration points are required.

Several techniques are available to obtain these two reference points, and we describe below the two methods we have applied, i.e., cross-calibration with a calibrated instrument and calibration with an object (the sun) of known brightness. The VISSR is actually made of an array of eight detectors having similar response properties and near-equivalent spectral characteristics. Consequently, a mean calibration for the eight sensors is adequate.

#### Cross-calibration

Cross-calibration is achieved by determining a linear relationship between a set of collated (space and time) radiation measurements from two instruments, and if the characteristics of the instruments are equivalent, no correction is needed. This is, for instance, the case for cross-calibration of two VISSR’s or of a VISSR and a spectral radiometer having the same spectral characteristics as

### TABLE 2. Estimated Magnitudes of the Anticipated Uncertainties In the Insolation Values From Ships

| $|\delta_{corr}|$ | $\epsilon_{meas}$ | $\epsilon_{mea}$ | $\Delta I_{max}$ | $(\sigma_T)^2 = s_f$ | $\epsilon_{max}$ | $\epsilon_{rms}$ |
|-----------------|----------------|----------------|-----------------|-------------------|----------------|-------------|
| 314             | 11.2          | ±4.2           | -4.4            | 45.3              | ±9.3           | 53.9        | 11.0        |
| 315             | 26.9          | ±3.2           | -3.1            | 29.2              | ±6.7           | 35.5        | 8.0         |
| 318             | 12.6          | ±5.7           | -6.8            | 34.2              | ±6.0           | 47.7        | 10.7        |
| 319             | 22.1          | ±2.9           | -3.0            | 17.0              | ±4.4           | 22.9        | 6.1         |
| 320             | 2.6           | ±2.1           | -3.8            | 11.3              | ±2.6           | 19.2        | 5.1         |
| 321             | 1.8           | ±4.6           | +5.5            | 25.1              | ±5.6           | 38.7        | 11.4        |
| 322             | 6.4           | ±5.0           | +8.6            | 23.0              | ±5.0           | 29.1        | 8.4         |
| 323             | 1.2           | ±6.1           | +2.8            | 11.8              | ±2.9           | 18.0        | 5.4         |
| 324             | 5.3           | ±3.3           | +4.9            | 35.7              | ±8.1           | 46.4        | 10.8        |
| 325             | 0.3           | ±3.7           | +0.8            | 44.3              | ±10.2          | 48.0        | 10.9        |
| 326             | 14.3          | ±2.9           | 0.0             | 17.0              | ±3.9           | 19.9        | 4.9         |
| 327             | 9.8           | ±2.9           | +1.5            | 21.7              | ±4.4           | 24.6        | 5.5         |
| 328             | 22.8          | ±3.5           | +9.1            | 11.7              | ±2.9           | 24.3        | 10.2        |
| 341             | 7.5           | ±1.6           | 0.0             | 9.8               | ±2.2           | 11.4        | 2.7         |
| 342             | 6.6           | ±2.0           | 0.0             | 11.3              | ±2.5           | 13.3        | 3.2         |
| 343             | 8.3           | ±4.2           | +1.6            | 27.9              | ±6.4           | 35.0        | 7.8         |
| 344             | 2.5           | ±1.8           | +3.1            | 11.3              | ±2.5           | 13.1        | 4.4         |
| 345             | 7.7           | ±0.8           | 0.0             | 11.8              | ±2.7           | 12.6        | 2.8         |

- $|\delta_{corr}|$, corrected absolute value of the difference between ship measurements and satellite estimates corrected for a high bias of 8 W m$^{-2}$.
- $\epsilon_{meas}$, error in ship measurements, i.e., 10% of measured value (W m$^{-2}$).
- $\epsilon_{mea}$, error in daily estimates from ship as a result of interpolation. Satellite estimates used corrected for high bias of 8 W m$^{-2}$.
- $\Delta I_{max}$, difference between maximum and minimum value of insolation from satellite estimation over area of 128 x 128 km (W m$^{-2}$).
- $(\sigma_T)^2 = s_f$, spatial standard deviation of satellite-derived insolation over area of 128 x 128 km (W m$^{-2}$).
- $\epsilon_{max}$, maximum anticipated error, i.e., $\epsilon_{meas} + \epsilon_{int} + \Delta I_{max}$ (W m$^{-2}$).
- $\epsilon_{rms}$, rms anticipated error, i.e., $\sqrt{\epsilon_{meas}^2 + \epsilon_{int}^2 + (\sigma_T)^2}$ (W m$^{-2}$).
The VISSR. We have used these two types of instruments to calibrate GOES-West and GOES-Indian Ocean during STREX and the First GARP Global Experiment, respectively. In the case of STREX we have cross-calibrated GOES-West and GOES-East for the fall 1980. This was possible because GOES-East had been previously calibrated using the sun as a reference (see later and Norton et al. [1980]). The low-end reference point was taken as the radiance measured from space (black). The high-end point had to be a target of known and high albedo in a region of overlap of the two fields of view of the satellites. The chosen region was the area of White Sands in New Mexico, where surface composition is well known, in this case the surface albedo in clear atmospheric conditions can be determined quite precisely.

Calibration Using the Sun

The other approach consists of taking advantage of certain earth-sun configurations in which the sun appears within the field of view of the satellite, i.e., the sun appears very close to the earth on the recorded image. A deintensifying side-looking prism then allows direct solar observations. Although this type of measurement would provide an excellent means of monitoring the visible sensor, there are some problems associated with this technique. First, the required earth-sun configuration is relatively rare, and therefore sun observations are usually not recorded. Second, the optical properties of the prism and the exact path of the received solar beam are not well known. Finally, the aperture for the solar beam does not correspond to the aperture of a normal terrestrial measurement, and this introduces some bias. This technique has, however, been used by Norton et al. [1980] and Gautier et al. [1980] to calibrate GOES-East (GOES 2) in 1979, and these calibrations compare quite favorably with that obtained by E. A. Smith and D. Loranger [unpublished manuscript, 1977] for SMS-1 using a cross-calibration technique with the NOAA-2 scanning radiometer.

Calibration Verification

One time calibration of the VISSR does not insure that the calibration is continuously applicable. Consequently, it is necessary to monitor the possible drift of the sensor. If it is assumed that the instrument gain remains stable, then only one single reference need be monitored for offset drift. In-flight and surface based reference measurements need to be accumulated in order to diagnose possible long-term drifts. The data bases require measurements over a known surface and under ideal sky conditions. The STREX experiment was short enough that a few verifications of the calibration were sufficient.

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REFERENCES


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