Mathematical Aspects in Meteorological Processing of Infrared Spectral Measurements from the GOES Sounder. Part II: Analysis of Spatial and Temporal Continuity of Spectral Measurements from the GOES-8 Sounder

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ABSTRACT

The spatial and temporal continuity of the infrared measurements from the Geostationary Operational Environmental Satellite (GOES)-8 sounder data are investigated, and an experimental processing approach is presented. Spatial filtering and cloud detection are performed in a joint algorithm: the preparation of the data for sounding analysis starts with spatial smoothing, followed by cloud detection, followed by averaging the clear-sky (cloud free) subsamples. Analysis of the sounder images reveals the presence of coherent noise on large spatial scales in some of the spectral bands. Analysis of a temporal sequence of spatially smoothed sounder images reveals regions of unphysical hourly change likely induced by instrument noise. A nonlinear temporal–spatial filtering algorithm is presented and tested that improves the noise filtering for the sounder spectral measurements and the thermodynamical spatial and temporal consistency of the sounding retrievals in the troposphere.

1. Introduction

A temporal–spatial analysis of the Geostationary Operational Environmental Satellite (GOES)-8 sounder spectral measurements is undertaken in order to improve atmospheric and surface parameter retrieval. Application of spatial averaging that differs from one spectral band to another was discussed in Plokhenko and Menzel (2001). In this work, temporal analysis supplements spatial analysis to further improve the spectral measurements.

Accurate depiction of the error structure in the infrared (IR) spectral measurements is important for deriving a meaningful solution to the atmospheric remote sensing inverse problem for several reasons.

• Errors in the measurements, reinforced by the instability of the inverse problem, can substantially reduce the accuracy of the retrievals.

• Forecast model-derived first-guess temperature–moisture profiles are already very accurate, and so GOES measurements must be of high quality to add new information.

• The signal-to-noise ratio (SNR) of the GOES measurements signal with respect to the existing back-ground first-guess noise can be improved by filtering the spatial and temporal structure of the GOES measurement errors.

GOES sounder measurements contain noise that varies substantially from one spectral band to another. The spectral measurements are related to the surface emissivity, surface temperature, and atmospheric vertical profiles of moisture and temperature. These parameters exhibit different spatial variability. Surface properties of land can vary drastically from one field of view (FOV) to the next. Atmospheric moisture and especially temperature fields are substantially smoother; moreover,
they become smoother with increasing height. Each GOES sounder spectral radiance measurement describes a specific atmospheric layer (sometimes in combination with the surface) and will have the corresponding spatial properties. Spectral bands sensitive to upper-tropospheric and stratospheric layers, where there are no cloud or surface signals, exhibit large-scale spatial uniformity, and their noise is characterized by spatial variations on small scales by comparison. The differences between spatial scales of measurement noise and spatial scales of the associated meteorological parameters can be effectively used to suppress the noise. Adding temporal smoothing to spatial smoothing improves the noise detection and filtering and, thus, the quality of the spectral information.

In section 2, the basic characteristics of the GOES-8 sounder data gathering are presented. In section 3, a joint procedure of noise filtering and cloud detection is discussed; results of spatial–spectral analysis of spectral measurements are reviewed. Then, in section 4, results of temporal analysis are added, unphysical radiance changes from one time to the next are discussed, and the presence of large-scale coherent noise in the temporal spectral measurements is shown. In section 5, statistical analysis of the temporal variability of the sounder spectral measurements is discussed, an algorithm for filtering the large-scale coherent noise is presented, and results after filtering are shown. Conclusions are offered in section 6. Appendices detail the mathematical formulation of the spatial and temporal filtering.

2. Characteristics of the GOES-8 sounder

Descriptions of the GOES-8 sounder can be found in Menzel and Purdom (1994) and Menzel et al. (1998). The GOES-8 sounder spectral channels along with the earth–atmosphere layer sensed by each channel and the associated parameter(s) are presented in Table 1. A field of radiance measurements (that can be displayed as an image) is acquired via a step-and-settle process, wherein the mirror first steps to a location to observe the radiation within a FOV of the earth–atmosphere system and then waits for the mirror-pointing errors to “settle” (Space Systems-Loral 1998). The 18 infrared channels are sensed with a rotating filter wheel that consists of three concentric rings—the inner, middle, and outer rings contain the midwave (8–12), shortwave (13–18), and longwave (1–7) bands, respectively. At any given time, one channel (or band) from each ring is being sensed. The filters within a ring are arranged so that measurements in bands peaking higher in the atmosphere are followed by bands peaking near or at the radiating surface. Thus, the first bands sensed are less susceptible to any pointing error due to the settling that occurs after moving the mirror. Four FOVs of a spectral band are sampled simultaneously via an array of four detectors; each ring has such an array. The detectors have a resolution of approximately 8.7 km [an instantaneous geometric field of view (IGFOV) of 242 μrad] at the subsatellite point (i.e., 0° latitude and 75°W longitude for GOES-8). However, the samples are spaced 10 km (280 μrad) apart at nadir view. The FOV becomes larger at larger satellite viewing angles. Sounding samples can be integrated over three different dwell times; the default time of 0.075 s is most often employed. After completion of an east–west swath, the mirror is directed south to begin another set of four scan lines. The swath directions alternate between west-to-east and east-to-west. Routine sounder coverage over the continental United States consists of 196 lines (north–south) by 324 detectors, each detector generating its own scan line. The system absolute accuracy specification for each detector–band combination is 1 K. The line-to-line, detector-to-detector, and band-to-band relative accuracies are specified to be better than 0.25, 0.4, and 0.29 K, respectively. The band-to-band coregistration parameters are specified in two ways: 1) all bands must be within ±36 μrad (or 25% of one FOV) of the longwave infrared window (28 μrad equate to 1 km), and 2) any band on a ring must be within ±22 μrad to the reference window band of that ring. There are noticeable spatial differences in the “physical” locations of the FOVs within each ring. Measurements in the atmospheric window bands are especially sensitive to coregistration because they sense surface thermal gradients. Instrument noise values (converted into brightness temperature val-

<table>
<thead>
<tr>
<th>Channel</th>
<th>Central wavelength (μm)</th>
<th>Purpose: T (temperature), Q (moisture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.69</td>
<td>Stratosphere T</td>
</tr>
<tr>
<td>2</td>
<td>14.37</td>
<td>Tropopause T</td>
</tr>
<tr>
<td>3</td>
<td>14.05</td>
<td>Upper-level T</td>
</tr>
<tr>
<td>4</td>
<td>13.65</td>
<td>Midlevel T</td>
</tr>
<tr>
<td>5</td>
<td>13.38</td>
<td>Low-level T</td>
</tr>
<tr>
<td>6</td>
<td>12.65</td>
<td>Surface T; Q</td>
</tr>
<tr>
<td>7</td>
<td>12.06</td>
<td>Surface T; Q</td>
</tr>
<tr>
<td>8</td>
<td>11.03</td>
<td>Total ozone</td>
</tr>
<tr>
<td>9</td>
<td>9.71</td>
<td>Low-level Q</td>
</tr>
<tr>
<td>10</td>
<td>7.47</td>
<td>Midlevel Q</td>
</tr>
<tr>
<td>11</td>
<td>7.03</td>
<td>Upper-level Q</td>
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<tr>
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<td>4.58</td>
<td>Low-level T</td>
</tr>
<tr>
<td>14</td>
<td>4.53</td>
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<tr>
<td>15</td>
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</tr>
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<td>16</td>
<td>4.13</td>
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</tr>
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<td>17</td>
<td>3.98</td>
<td>Surface T</td>
</tr>
<tr>
<td>18</td>
<td>3.75</td>
<td>Surface T; Q</td>
</tr>
</tbody>
</table>
ues for each spectral band observing a typical meteorological scene) exhibit significant variations from one spectral band to another (see Fig. 1).

The sounder band measurements can be characterized as follows (see Table 1).

- Surface reflection increases appreciably in the shortwave (SW) going from channel 13 to 18 and increases in the longwave (LW) going from channel 1 to 8.
- Radiation absorption by cloud ice particles is substantially larger in the LW than the SW channels.
- Atmospheric moisture affects measurements in the SW channels much less than measurements in the LW channels, including the “atmospheric windows.”

Temperature weighting functions, moisture sensitivities, and atmospheric transmittances are shown in Fig. 2; these are consistent with the characterizations in Table 1. Figure 2 suggests that there are many similarities in the vertical distribution of the contributions to measurements in pairs of LW and SW spectral bands; for example, channels 3 and 15 (in Fig. 2a), channels 5 and 14 (in Fig. 2a), and channels 6 and 16 (in Fig. 2b) have very similar weighting functions. These similarities in the different spectral measurements are used to assist with noise filtering and detection of clouds.

3. Spatial smoothing and cloud detection

Spatial smoothing often improves the retrieval of atmospheric parameters from remote sensing measurements. The physical model of a spectral measurement is based upon the radiative transfer equation (RTE). The corresponding inverse problem of retrieving atmospheric profiles from spectral measurements is ill posed (Tikhonov and Arsenin 1977); there is no one-to-one relationship between spectral measurements and meteorological parameters. Because the solution of the problem is unstable, a small variation in a measurement and/or in the physical model of a measurement can cause a significant change in the solution. The RTE is nonlinear with respect to all parameters; these include surface emissivity and temperature, as well as atmospheric temperature and moisture profiles (Plokhenko and Menzel 2000). To stabilize the solution of the RTE and to reduce the uncertainty, a priori information about the “earth-atmosphere” system is necessary. A forecast of temperature-moisture profiles from the Eta Model (Black 1994; Rogers et al. 1996) is used as a first guess. Thus, the GOES-8 retrievals are evaluated against the first-guess accuracy. If the first guess is accurate, then the GOES sounder measurement signal-to-noise ratio must be large in order to improve upon the first-guess profile. Figure 3 demonstrates the change in the GOES-8 sounder measurements (converted to brightness temperatures), corresponding to the uncertainty in the first guess from the Eta Model (as indicated by differences in moisture and temperature between validating raobs and Eta first guess). The GOES sounder signal noise is also indicated in Fig. 3; it is obvious that the sounder noise must be reduced by spatial averaging (especially in the LW channels 1–4 and SW channels 12, 14, and 15) in order to increase the information content of the measurement. This can be accomplished as long as the radiance mea-
measurement in a given spectral band is treated as an element of a spatial field and a priori information about its spatial structure is used. Because the fields of spectral radiation (brightness temperature) from the earth-atmosphere system and fields of sounder measurement noise have substantially different spatial structures, they can be easily discriminated.

In Plokhenko and Menzel (2001), spatial averaging is used in all spectral channels (a moving average of a square box whose size varies as a function of the spectral band). After spatial averaging, cloudy FOVs are identified with tests of spatial smoothness (second differential), and spectral smoothness [differences between LW and SW channels (14, 5), (16, 6), (17, 8)]. A second spatial smoothing averages only the cloud-free FOVs within the averaging square box. Final estimates on the subsample of spatially smoothed cloud-free FOVs are presented in Table 2. Additionally, a triangle filter is applied to reduce the residual effect of the scan line to scan line striping. Details are found in appendix A.

Table 2 shows that this spatial smoothing produces uniform accuracy in the averaged clear-sky measurements in all spectral channels. The procedure is especially effective in stratospheric and upper-tropospheric channels (1, 2, 3, 4, 15). For those channels we can estimate the error variance; for other channels, the error variance estimate contains some contribution from the spatial variability in the scene. Table 2 describes the results of filtering only the spatial shortwave component of the instrument signal errors. The measurement errors of the GOES-8 sounder are much more complicated temporally and spatially; they depend on all the factors of the instrument instability described earlier.

The spectral signature for cloud-free conditions from the GOES sounder measurements can be explained by the refraction index of cloud particles. The imaginary part of the refraction index describes radiation absorption by a particle. Figure 4 shows that the imaginary part of the refraction index of the cloud particle increases with increasing wavelength from 4 to 13 \( \mu m \) (Downing and Williams 1975; Warren 1984), corre-
than warmer sea surfaces, and dark areas correspond to cloud cover. Figure 6a demonstrates the SW minus LW spectral signatures difference produced by different kinds of surfaces and clouds; dark red areas (positive differences up to 20 K) correspond to upper-tropospheric ice clouds, while dark blue areas correspond to low-tropospheric clouds. Figure 6b shows the spatial distribution of the results from the different cloud tests; black areas designate FOVs that do not satisfy the spatial smoothness test, light gray areas correspond to the FOVs that do not pass the LW and SW spectral consistency test, and white areas correspond to brightness temperatures that are outside of the clear-air surface temperature threshold. Figure 6b demonstrates that the spatial smoothness, spectral consistency, and temperature threshold requirements complement each other spatially.

To demonstrate how spatial smoothing affects the spatial features of the measured spectral fields, Figs. 7a and 7b show (a) the initial and (b) the resulting fields in channel 5. Channel 5 is sensitive to low-tropospheric moisture (see Fig. 2c), and the first-guess temperature for the corresponding atmospheric layer is very accurate (see Fig. 3); thus, channel-5 temperature–moisture measurements must be of very good quality that can only be achieved with successful SNR enhancement via spatial smoothing. The observed channel-5 thermal field in Fig. 7a displays obvious measurement errors, especially the effects of striping. After smoothing, the thermal field in Figure 7b is smooth and the apparent striping is not observed. Figures 8a and 8b show differences in K of (a) 14.4 – 14.7 μm (channel 2 – channel 1) and (b) 4.45 – 4.1 μm (channel 15 – channel 3) at 2000 UTC 1 June 2000. Measurements in channels 1, 2 and 3, 15 describe lower-stratospheric and upper-tropospheric thermal fields, respectively (see Fig. 2a), and are not affected by atmospheric moisture fluctuations. The corresponding atmospheric layer thermal fields are spatially smooth, and we expect that the channel differences should be spatially smooth. But Fig. 8 shows the difference fields are very rough, with geometric and periodic structures that cannot be attributed to the thermal fields; Fig. 8a has an oscillation propagating along the scan line direction and Fig. 8b also has an unusual “cell” structure. Those structures indicate that perhaps we are observing effects of some spurious signal propagating into the optical system of the sounder.

4. Temporal analysis

Spatial smoothing removed some of the smaller spatial oscillations (those with short wavelengths) from the image. Spectral differences of the smoothed images revealed the presence of spurious signals that require further consideration. The physical signal of the measured thermal field is presented in a scan line by a scan-element coordinate system, which is roughly equivalent to
Fig. 6. (a) Window difference (4–11 μm) in kelvins and (b) identification of measurement quality using spatial–spectral smoothness and temperature threshold tests of measurements at 1000 UTC 1 Jun 2000. Black areas correspond to FOVs that did not pass the spatial smoothness test, light gray areas designate FOVs that did not pass the spectral variation test, and white areas correspond to FOVs that did not pass the temperature threshold test.

a latitude-by-longitude coordinate system. Instrument effects are best described in a coordinate system dependent on the satellite clock time that relates to the changes in the sounder operation. Separating the instrument noise from the signal requires temporal analysis in addition to spatial analyses.

GOES sounder data from 18 September 2000 demonstrate the advantage of temporal plus spatial analysis. The meteorological characteristics of the atmosphere at 1000 UTC 18 September 2000 are evident in Figs. 9a and 9b, which present brightness temperature differences (K) of spectral measurements 4.13–12.65 μm (channel 16 – channel 6) and 4–11 μm (channel 17 – channel 8). Spectral difference images distinguish the clear and cloudy areas. In the lower left, the Gulf of Mexico coastline is evident; in the upper right, the contours of the Great Lakes are visible. Areas of red correspond to upper-tropospheric clouds, dark blue areas in Fig. 9b correspond to lower-tropospheric clouds. Figures 10a–d show the temporal differences of the spatially smoothed spectral measurements for 1000–0900 UTC in channel 1 (14.7 μm), channel 2 (14.4 μm), channel 6 (11.0 μm), and channel 15 (4.45 μm). The window channel differences in Fig. 10c appear to be reasonable and show the displacement of clouds over the hour; thermal gradients at water/land interfaces caused by spatial displacements in FOVs are also evident [signal variations from the range (−1, 1) (K) are shown]. Figures 10a, 10b, and 10d are very different; the presence of striping and cell structures are recognizable, as well as a strong similarity with the images of spectral differences shown in Figs. 8a and 8b. This further suggests that the spectral measurements are affected by a spurious signal that has a complicated temporal structure. It has both a short time component (oscillation about 25–30 FOVs, propagating along scanning
lines and generating the cell structure) and a long time component (scan line packets, propagating in the direction of scan lines and generating the striping structure).

Temporal differences can be attributed to a variety of causes such as filter wheel motion, switching detectors, electronic impulse response functions, detector-to-detector cross talk, scene changes (such as cloud motions), and other physical mechanisms. For example, the along scan line smearing can be explained by detector recovery.

5. Temporal smoothing

The statistics of hourly temporal variations for 1000 – 0900 and 1100 – 1000 UTC of spatially smoothed “clear” measurements (FOV by FOV) for 7 days on 18–28 September 2000 are presented in Figs. 11a–d: average and standard deviations of temporal variation in the 18 channels are presented, and 18 September 2000 results are highlighted. The number of samples varies from 13 000 to 19 000, depending on cloud cover. Biases (Figs. 11a,b) describe the physical heating/cooling of the atmospheric layers and the earth surface. Lower-tropospheric and window channels (6, 7, 8, 16, 17, 18) indicate surface cooling at night; midtropospheric channels 4 and 14 indicate atmospheric warming at night. Because temporal gradients do not substantially change in 1 h, standard deviations (Figs. 11c,d) must be attributed to measurement errors, perhaps including calibration fluctuations. These deviations are considered statistically significant given the number of samples (~15 000). Temporal fluctuations around zero in channels 1–3, and 15 are evident. Temporal changes in water vapor channels 10–12 are not so clear because a spatial shift of moisture occurs.

Figure 11 shows that temporal filtering will probably be effective because the spectral images have good linear properties in the temporal dimension, and temporal variations are small. Figure 10 shows that the temporal disturbances have a distinctive spatial pattern. To develop a temporal–spatial analysis, we use the following approach:
1) estimate the mean temporal gradient in a given spectral channel for the whole scene for all times;
2) remove the average change (temporal gradient) from the images;
3) identify those temporal disturbances that exceed an acceptable level;
4) interpolate from nearby areas of acceptable temporal change to infer new values within areas of unacceptable temporal change;
5) identify outliers within the temporal disturbance (differences between the interpolated value and the measurement exceed an acceptable level); and
6) minimize the temporal disturbance by replacing outliers (defined in step 5) with the interpolated value (defined in step 4).

Details of the algorithm are found in appendix B.

An example of temporal adjustment with spatial smoothing is shown in Fig. 12; measurements in channel 2 at 0900, 1000, and 1100 UTC 18 September 2000 for element 125 of the images are shown in cross section (orientation from north to south along ordinate axis). Results of temporal adjustment for the elements at 0900–1000 UTC (shown by open circles) and at 1000–1100 UTC (shown by open triangles) are indicated. First, it should be noted that the observed temporal oscillations with amplitude 0.5 K are significant in channel 2, because the signal range is less than 2 K. Second, the procedure correctly identifies and effectively smooths the spatial disturbances. And third, the procedure effectively assimilates the temporal sequence of the images, substantially improving the measurement estimate at 1100 UTC. To assess the effect of the temporal smoothing on the temperature profile retrievals, we inspect the second spatial derivative (Laplace operator) describing the spatial “roughness” of the retrieved temperature and moisture fields at various levels in the troposphere. The variance of the roughness of an atmospheric parameter estimate is a measure of the accuracy of the retrieved estimate; the less variance, the more accurate the estimate. The standard deviation of
the second spatial derivative of the retrieved temperature profile before and after temporal filtering is shown in Fig. 13; the retrieved solution after temporal filtering is smoother and, hence, more correct than the retrieved solution before temporal smoothing. The reduction of spatial roughness is especially important in the upper troposphere and the stratosphere, where thermal fields are very smooth; in a thermodynamical sense, a spatially smoother solution better satisfies the equation of continuity.

Figures 14 and 15 show the effect of the localized temporal discontinuities ("thermal blobs" in Fig. 10) on the atmospheric temperature profile estimates. Figure 14 shows the temperature profile estimates with and without temporal filtering at (a) 400 and (b) 500 hPa at 1000 and 1100 UTC 18 September 2000 for element 125 in cross section from Fig. 10. The localized temporal discontinuities of the measured thermal fields generate an unrealistic spatial–temporal pattern in the retrievals. It is especially obvious for the estimates at 400 hPa where the field should have a small spatial–temporal variability. The temporal filtering produces retrievals that are more spatially and temporally stable. Figure 15 shows the average and standard deviation of the temporal gradient of temperature profile estimates with and without measurement temporal filtering at 1000–1100 UTC 18 September 2000. Statistics of the temporal gradient of the temperature profile first guess are shown as well; the first-guess fields are spatially and temporally very smooth. In Fig. 15a the observed measurement errors produce a noticeable warming in the 300–650-hPa layer, and cooling in the 50–250-hPa layer; this drastically differs from the vertical structure of temporal gradient derived from first-guess fields. Positive measurement error contributions in some channels emanating primarily from one atmospheric layer are being compensated by the negative changes in another atmospheric layer to balance the RTE. Temporal filtering is not affecting the vertical structure of the retrieval and keeps it closer to the initial field characteristics. Figure 15b shows that temporal filtering substantially improves the temporal stability of the profile retrieval.
6. Conclusions

An experimental processing approach for retrieving temperature and moisture profiles from GOES-8 sounder infrared measurements is presented. To improve the quality of the spectral information and to enhance the accuracy of the retrieval results, a temporal–spatial–spectral analysis is performed.

Noise reduction is accomplished with spatial filtering (smoothing) that averages clear-sky measurements within a square box whose size depends on the spectral channel and triangular average filtering that reduces the residual effect of the scan line to scan line striping. The spatial smoothing and cloud detection is performed in combination; initial spatial smoothing is followed by cloud detection and then followed by averaging the clear-sky (cloud free) subsamples. Cloud detection is accomplished with tests for spatial smoothness (second differential) and spectral consistency [differences between LW (11 - 13.4 \(\mu m\)) and SW (3.7 - 4.6 \(\mu m\)) bands].

The GOES-8 sounder measurements from about 40 days from May, June, and September 2000 were analyzed. The results of the spatial smoothing demonstrate noticeable improvement in the image and information quality. Signal-to-noise ratios are increased, but residual noise remains in the spatially smoothed images.

Temporal variation in the spectral measurements in clear skies in the spatially smoothed data reveals measurement errors with a complicated temporal–spatial–spectral structure. The measurement noise exhibits both small- and large-scale spatial components. The small-scale spatial component is associated with “fast” temporal variations in the instrument optical system and the large-scale component is associated with “slow” temporal variations. It is likely that these are effects related to a spurious signal propagating through the sounder optical system.

Spatial smoothing filters out the small-scale spatial component of measurement errors. To filter out the large-scale component of the measurement error, an algorithm for nonlinear temporal–spatial filtering is developed. The algorithm uses statistical detection of temporal–spatial discontinuities in a temporal sequence of the measurements. Removing outliers (with respect to signals interpolated into the spatial domain of the temporal disturbance), the temporal–spatial discontinuities are minimized and a priori requirements (based on the quality of the first guess) are better satisfied. The retrieved temperature and moisture profile fields exhibit smoother horizontal and, hence, more physical behavior.

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APPENDIX A

Algorithm for Spatial and Cloud Filtering

Spatial filtering of the noise is based on a linear estimation. The measurements are described by

$$\tilde{f}(x, y) = f(x, y) + \xi(x, y),$$  \hspace{1cm} (A1)

where $f(x, y)$ is a true value of a function at a coordinate point $(x, y)$, and $\tilde{f}(x, y)$ is a measurement contaminated by random noise $\xi(x, y)$. The objective is to construct a function $F[\tilde{f}]$ that provides a measurement estimate $\hat{f} = F[\tilde{f}]$ with the desired spatial characteristics. We define $F[f]$ as spatial averaging over the rectangular domain

$$\hat{f}(x, y) = F[\tilde{f}](x, y)$$

$$= (2\Delta)^{-2} \int_{y-\Delta}^{y+\Delta} \int_{x-\Delta}^{x+\Delta} [\tilde{f}(x, y) + \xi(x, y)] \, dx' \, dy', \hspace{1cm} (A2)$$

where the variable parameter $\Delta$ is the size of the spatial averaging. If $f(x, y)$ has “good” linear characteristics, then by varying $\Delta$ we can obtain a more accurate field $\hat{f} = F[\tilde{f}]$ with the desired spatial characteristics. To characterize the field $\hat{f}$ we use

$$\sigma^2(\hat{\xi}) = \frac{\sigma^2(\xi)}{4\Delta^2},$$  \hspace{1cm} (A3)

where $\sigma^2(\hat{\xi})$ designates the variance of the error $\hat{\xi} = F[\xi]$ and $\sigma^2(\xi)$ is the variance of the initial error $\xi$.

$$\sigma^2(\delta L[\hat{f}]) \leq \frac{1}{4\Delta^2} \sigma^2(\xi),$$  \hspace{1cm} (A4)

where the variance differential of the Laplace operator is $\delta L[\hat{f}] = (\partial^2 \hat{f}/\partial x^2)(\delta x)^2 + (\partial^2 \hat{f}/\partial y^2)(\delta y)^2$, from which it follows that

$$\sigma^2(\hat{\xi}) \leq \Delta \sigma^2(\delta L[\hat{f}]).$$  \hspace{1cm} (A5)

In the data processing, $\Delta$ is a vector parameter whose components correspond to the 18 GOES sounder spectral channels. Use of spatial smoothing (A2) in atmospheric remote sensing is justified by the physical properties of the atmosphere. Temperature and moisture fields, that generate the outgoing IR radiation, are smooth fields especially in and above the upper troposphere. A spectral measurement describes a specific atmospheric layer (sometimes in combination with the
Fig. 12. Measurements in channel 2 at 0900, 1000, and 1100 UTC 18 Sep 2000 for element 125 in the image cross section from Fig. 11a (orientation from north to south along ordinate axis). They are results of temporal adjustment for the elements at 0900–1000 UTC (open circles) and at 1000–1100 UTC (open triangles).

Fig. 13. The std dev of the spatial differential $(\partial^2 \delta T/\partial x^2)(\delta x)^2 + (\partial^2 \delta T/\partial y^2)(\delta y)^2$ of the temperature profile estimate before and after temporal filtering. Corresponding characteristics of the first-guess thermal fields are also shown.
The temperature profile estimates with and without temporal filtering of temporal discontinuities in the measurement fields (see Fig. 10) at (a) 400 and (b) 500 hPa at 1000 and 1100 UTC 18 Sep 2000 for element 125 in the image cross section from Fig. 10 (orientation is from north to south along ordinate axis). Results without temporal filtering are shown at 1000 (open circles) and 1100 UTC (open diamonds). Results at 1100 UTC after temporal filtering are shown by solid triangles.

The temperature profile estimates (with and without temporal filtering of temporal discontinuities) from measurement fields (see Fig. 10) at 1000–1100 UTC 18 Sep 2000. Statistics of temporal gradient of temperature profile first guess are shown as well.

The parameters for spatial smoothing and the characteristics of the resulting fields for each spectral band are given in Table 2. A linear smoothing filter is used on those spectral bands where the associated brightness temperature field is smooth; a median filter is used otherwise. The table presents the dimensions of the spatial filter $\Delta$, an estimate of the spatial roughness $\sigma^2(\Delta L[\hat{f}])$ (K$^2$) and the approximation accuracy $\sigma^2(\hat{\xi})$ (K$^2$) for the 18 spectral channels of the GOES-8 sounder. Differences between the results from Table 2 and the corresponding results from Plokhenko and Menzel (2001) are explained by the following new features in the data analysis:

1. We apply spatial smoothing to LW channels 6, 7, and 8 to mitigate the effects of the spatial misalignment between the LW and SW window channels (see section 1).

2. The statistic $\sigma^2(\Delta L[\hat{f}])$, $\Delta L[\hat{f}(i, j)] = 1/2(\hat{f}(i + 1, j) + \hat{f}(i - 1, j) + \hat{f}(i, j + 1) + \hat{f}(i, j - 1) - 4\hat{f}(i, j))$ is estimated on a spatially smooth subsample of estimates $\hat{f}$. We perform the spatial smoothing in stages:
   - construct the field $\hat{f}$ using a linear or median estimate [see Table 2, as developed in Plokhenko and Menzel (2001)];
   - remove elements $[\hat{f}(i + 1, j) - \hat{f}(i, j) > 5 \text{ K}]$, $[\hat{f}(i, j + 1) - \hat{f}(i, j) > 5 \text{ K}]$;
   - calculate $\sigma^2(\Delta L[\hat{f}])$ and remove elements $[\Delta L[\hat{f}(i, j)] > 3 \sigma(\Delta L[\hat{f}])]$;
   - keep the remaining elements that define the spatially smooth subsample;
   - identify and remove cloudy elements (explained later); and
   - calculate the variance $\sigma^2(\hat{f} - \hat{f})$ and reconstruct the field $\hat{f}$ using a spatial linear estimate on elements $[\Delta L[\hat{f}(i, j)] > 3 \sigma(\Delta L[\hat{f}])]$ from the subsample of spatially smooth cloud-free elements.

As a last step, a triangular filter $\hat{f}'(i, j) = \frac{1}{6}(2\hat{f}(i, j) + \hat{f}(i, j + 1) + \hat{f}(i, j - 1))$ is applied to reduce the residual effect of the scan line to scan line striping in $\hat{f}$.

Cloud identification is accomplished by multispectral tests against a priori thresholds. We estimate the thresholds to be...
The increase in threshold of 0.5–1.0 K over water with respect to land is due to the increased surface emissivity for water surfaces. The more negative differences account for water clouds in the lower troposphere, and more positive differences account for ice clouds in the upper troposphere. Additionally, we use a priori information about air surface temperature $T_s'$ and require $(\hat{f}_8, \hat{f}_9, \hat{f}_{17}, \hat{f}_{18} > T_s' - 5.0)$ (K) over land and $(\hat{f}_8, \hat{f}_{17}, \hat{f}_{18} > T_s' - 7.5)$ (K) over water. It should be noted that these threshold values are based on nighttime measurements.

**APPENDIX B**

**Algorithm for Temporal Filtering**

The temporal gradient is estimated from three consecutive images (see Fig. 11); there are three estimates of the temporal gradient $\hat{f}(t) - \hat{f}(t - 1), \hat{f}(t + 1) - \hat{f}(t)$, and $[\hat{f}(t + 1) - \hat{f}(t - 1)]/2$, where $\hat{f}(t)$ is a clear-sky spatial average of the signal at time $t$. The estimate $f_i'$, of the temporal gradient is defined as the minimum absolute value. Using $f_i'$, we adjust the images to the common time $t$.

The temporal disturbance is identified as a sequence of $n_i$ lines $\{x_i\}_{i=1}^{n_i}$ or $n_j$ elements $\{y_j\}_{j=1}^{n_j}$ for which

$$-2.5 < \hat{f}_{17} - \hat{f}_8 < 2.0$$

$$-4.0 < \hat{f}_{16} - \hat{f}_6 < 2.0$$

$$\hat{f}_{14} - \hat{f}_5 < -0.5$$

$$-1.5 < \hat{f}_{17} - \hat{f}_8 < 3.0$$

$$-3.5 < \hat{f}_{16} - \hat{f}_6 < 2.5$$

$$\hat{f}_{14} - \hat{f}_5 < 0.0$$

(K) over land and

$$\hat{f}(x, y, t) - \hat{f}(x, y, t - 1) > \sigma_t$$

$$\hat{f}(x, y, t) - \hat{f}(x, y, t - 1) > \sigma_t$$

$$\sigma_t = \sigma(\hat{f}_{t-1}, \hat{f}_t) = [\hat{f}(x, y, t) - \hat{f}(x, y, t - 1)]$$

where the absolute temporal difference $\sigma_t$ is averaged over the spatial domain. To simplify, we consider data analysis for the coordinate $x$ under a fixed $y$. The interpolated signal within domain $\{x_i\}_{i=1}^{n_i}$ is the cubic polynomial $\varphi(x) = \Sigma_i x^{i-1}$ (spline) defined by the signals at the time $t - 1$ at the boundaries $[\varphi_{t-1}(x_i) = \hat{f}(x_i, t - 1), \varphi_{t-1}(x_{i-1}) = \hat{f}(x_{i+1}, t - 1)]$ and the temporally averaged spatial derivative at the boundaries

$$\frac{d\varphi_{t-1}}{dx}(x_i) = \frac{x}{2} \left[ \frac{\partial^2 \hat{f}}{\partial x^2}(t) + \frac{\partial^2 \hat{f}}{\partial x^2}(t - 1) \right](x_i)$$

$$\frac{d\varphi_{t-1}}{dx}(x_{i+1}) = \frac{x}{2} \left[ \frac{\partial^2 \hat{f}}{\partial x^2}(t) + \frac{\partial^2 \hat{f}}{\partial x^2}(t - 1) \right](x_{i+1})$$

where parameter $\alpha$ ($0 \leq \alpha \leq 1$) provides stability to the derivative in the following sense:

$$\frac{d^2 \varphi}{dx^2} = \left[ \frac{2a_2}{2a_3 + 3a_3(x_{i+1} - x_i)} \right] \leq 2\sigma(\frac{d^2 \hat{f}}{dx^2})$$

and $\sigma(d^2 \hat{f}/dx^2) = |(d^2 \hat{f}/dx^2)(x, y)|$ is the second derivative averaged over spatial domain (examples of $d^2 \hat{f}/dx^2$ and $d^2 \hat{f}/dy^2$ are presented in Table 2). The cubic polynomial $\varphi(x)$ has four parameters that are defined by four boundary conditions. The approximation parameters $a_2$ and $a_3$ depend linearly on $\alpha$; thus, $\alpha$ is explicitly derived from (B3). Using the temporally averaged spatial derivatives corresponds to suggesting that temporal changes in the images must be linear.

Temporal adjustments of the measurements at times $t - 1$ and $t$ are accomplished with

and the spatial smoothing operation

$$\hat{f}(x, t') = \hat{f}(x, t') + \eta[\varphi_t(x) - \hat{f}(x, t')]$$

where $0 < \eta < 1$. Outliers in the signal $\hat{f}$ (with respect to the interpolated signal $\varphi$) are identified in (B4); smoothing with (B5) reduces temporal variation in the measurements [see the right-hand side conditions in (B4)].

The filtering accomplished by (B1)–(B5) reduces statistically significant temporal differences, smoothes spatial outliers, reconstructs the image using spatially smooth elements from two consecutive images, and retains spatial derivatives. The definition (B1) of the temporal–spatial disturbance and the definition (B4) of the outliers show that the filter (B5) affects image elements with differences larger than $2\sigma_t$. To construct the smoothed time-referenced image, we allow linear time changes and constant spatial smoothness, which are provided by the derivatives (B2) and (B3), and the filters (B4) and (B5). Designating in (B1)–(B5) $\hat{f}^{(o)} = \hat{f}$ and
\( \hat{f}^{(k+1)} = \hat{f} \), where \((k) \) is the iteration cycle number, we define an iteration procedure for nonlinear temporal–spatial smoothing, sequentially applied

\[
\begin{align*}
x &\Rightarrow y \\ &\Rightarrow t,
\end{align*}
\]

where \( K \) is a number of the iteration cycle in \((B1)-(B5)\). The parameter \( \eta \) is used to provide smoothing in both directions \( x, y \). At time \( t+1 \) the filtering depends on the image at time \( t+1 \) and the filtering from time \( t \).

Experiments show that smoothing disturbances with amplitudes \( \sim 0.5 \) K requires \( \sigma^{(k)} \sim 0.07 \) K. With \( \eta = 0.7 \), about \( K \sim 5 \) iterations are needed for channels 1–5, 10–12, 14, and 15.

REFERENCES


