Stability of Narrow-Band Filter Radiometers in the Solar-Reflective Range

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ABSTRACT: We show that the calibration, with respect to a continuous-spectrum source, and the stability of radiometers using filters of about 10 nm full width, half maximum (FWHM) in the wavelength interval 0.4 to 1.0 μm, can change by several percent if the filters change in position by only a few nanometres. The cause is the shifts of the passbands of the filters into or out of Fraunhofer lines in the solar spectrum or water vapor or oxygen absorption bands in the Earth's atmosphere. These shifts can be due to ageing accompanied by the absorption of water vapor into the filter or temperature changes for field radiometers, or to outgassing and possibly high energy solar irradiation for space instruments such as the MODerate resolution Imaging Spectrometer - Nadir (MODIS-N) proposed for the Earth Observing System.

INTRODUCTION

It is well known that satellite multispectral sensor data in the visible and near infrared are acquired with spectral bandwidths from about 40 nm (System Probatoire d'Observation de la Terre (SPOT) band 2) and 70 nm (Thematic Mapper (TM) band 3) to about 200 and 400 nm (Multispectral Scanner System (MSS) band 4 and the Advanced High Resolution Radiometer (AVHRR) channel 2). It is not so well known that the transmittance profiles of the filters which define these bands can change with time and under vacuum conditions. For example, Markham and Barker (1985) noted a 9-nm shift in the long wavelength cut-off of the band-3 filters of the fourth Landsat MSS after storage at normal pressure, temperature, and humidity over an 18-month period. The cut-on at shorter wavelength was unchanged because it was mainly defined by a stable absorption filter. The cut-off was provided by an interference filter; thus, the full width at half maximum (FWHM) and therefore the total transmittance of the filter changed. The same effect was observed by Dinguirard *et al.* (1988) for the case of the multispectral filters on SPOT-1. A 27 percent change in transmittance was noted for the filter defining band 2 with a change from air to vacuum conditions. The broad panchromatic band, on the other hand, only exhibited a 3 percent change in transmittance.

These examples serve to remind us that interference filters should not be assumed to be stable. The effects of the shifts noted above, which resulted in a narrowing of the broad-band filters because the cut-on was defined by a stable absorption filter, have been studied by Suits *et al.* (1988). We investigate here the effect of the shift of the passband of narrow-band interference filters into or out of Fraunhofer absorption lines in the solar spectrum or water vapor or oxygen absorption bands in the Earth's atmosphere, when the passband width stays constant. This study was initiated to help define the filter specifications for the proposed MODerate resolution Imaging Spectrometer-Nadir (MODIS-N) on the Earth Observing System (1986). (MODIS-N is actually an imaging filter radiometer, not an imaging spectrometer.) The effect of filter shifts can be significant for other narrow-band filter systems used to measure solar radiant flux, for example, solar radiometers or instruments for determining ground reflectance or radiance.

SOLAR SPECTRUM

Though the sun is often assumed to radiate as a blackbody, its spectrum is filled with Fraunhofer absorption lines. Fraunhofer lines are helpful in providing information concerning the sun, but can lead to errors in moderate to high spectral resolution measurements of the Earth–atmosphere system if their effect is not taken into account. The concern is that the narrow-band filters in a radiometer may shift, causing them to move into or out of a region containing a Fraunhofer line, thereby causing a noticeable change in the radiometer output. In order to study the sensitivity to bandpass location and shift with respect to Fraunhofer lines, moderately high spectral resolution solar data (0.5 nm) are needed. Unfortunately, there is a large gap between the 2-nm resolution, absolutely calibrated data of Neckel and Labs (1984) and those relatively calibrated data presented in solar atlases with spectral resolutions of about 10^{-3} nm.

To conduct this study, we used high resolution solar spectral data compiled by Kurucz *et al.* (1984), available in both atlas and computer-compatible-tape form. A sliding average was used on the digital tape data to produce a smoothed spectrum with a resolution of 0.5 nm and a sampling interval of 0.1 nm. The resulting spectrum from 350 to 1000 nm is shown in Figure 1. (Note that, although the ordinate is indicated in spectral irradiance units, the absolute accuracy of the data is in question and the data are here only used in a relative sense.) Some of the more prominent lines have been identified by reference to the Utrecht solar atlas due to Minnaert *et al.* (1940). Several deep Fraunhofer lines can be easily seen which could obviously cause significant changes in radiometer output as a filter shifted to include or exclude them. The data compiled by Kurucz *et al.* also include certain telluric absorption features, for example, the oxygen absorption bands near 688 and 760 nm and the water vapor band at 940 nm.

DEFINITION OF CALIBRATION ERRORS AND SIMULATION OF FILTER PROFILES

An error in calibration is defined, for the purpose of this study, as the difference in radiant power received by a detector, with a filter passband centered at a specific wavelength λ to that received when the passband is centered at a shifted wavelength $\lambda + \Delta\lambda$. This can be expressed as a percentage as:

$$ERROR\ (\lambda, \Delta\lambda) = \frac{P(\lambda + \Delta\lambda) - P(\lambda)}{P(\lambda)} \times 100$$

where $P(\lambda)$ is the integral of the product of the filter profile, passband centered at λ, and the spectral solar irradiance shown in Figure 1. For example, in Figure 3, for a 10-nm rectangular filter centered at 520 nm, the detector would receive 0.6 percent

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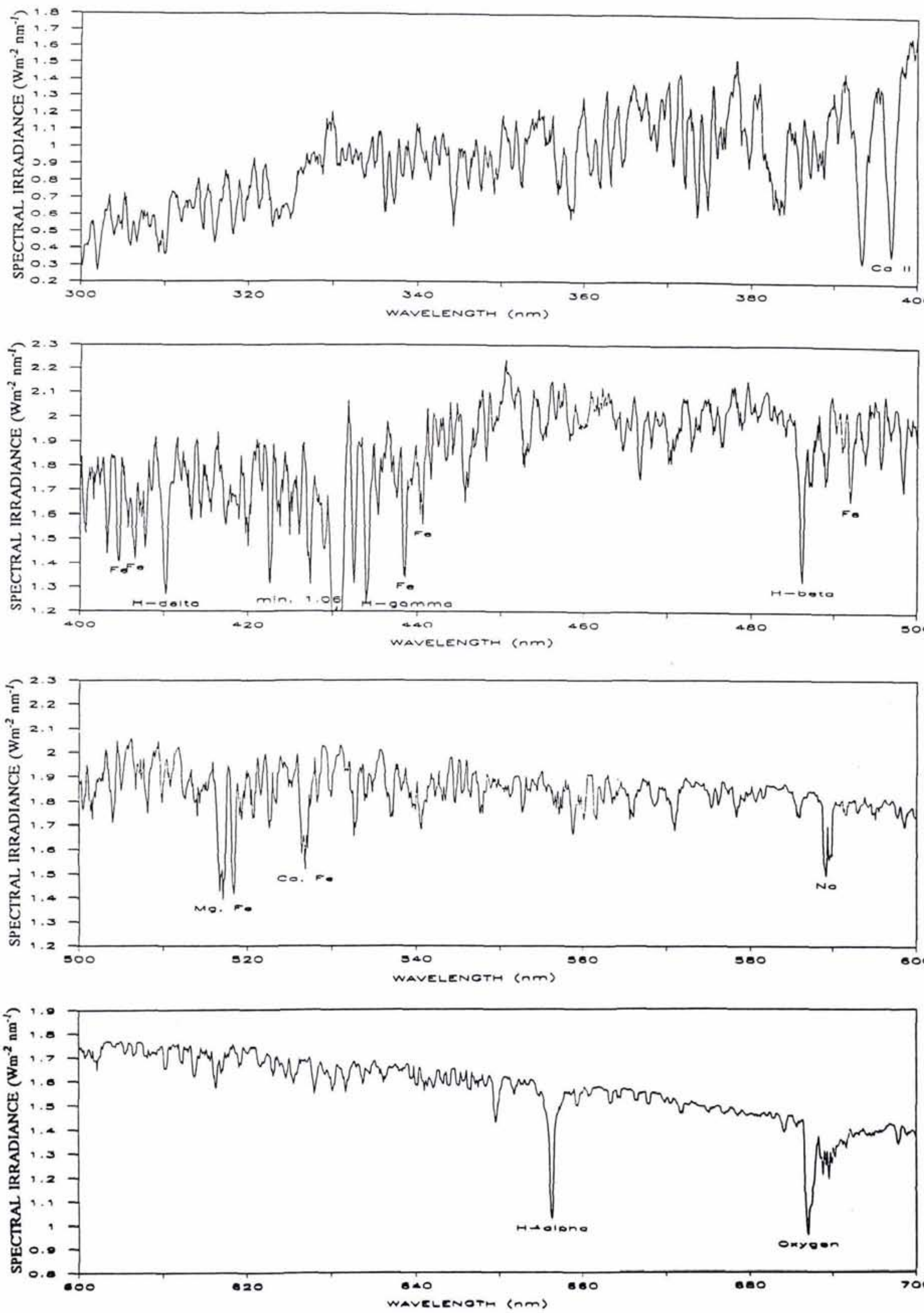

FIG. 1. Solar spectral irradiance at a resolution of 0.5 nm sampled at 0.1-nm intervals, obtained by smoothing the high resolution data of Kurucz *et al.* (1984).

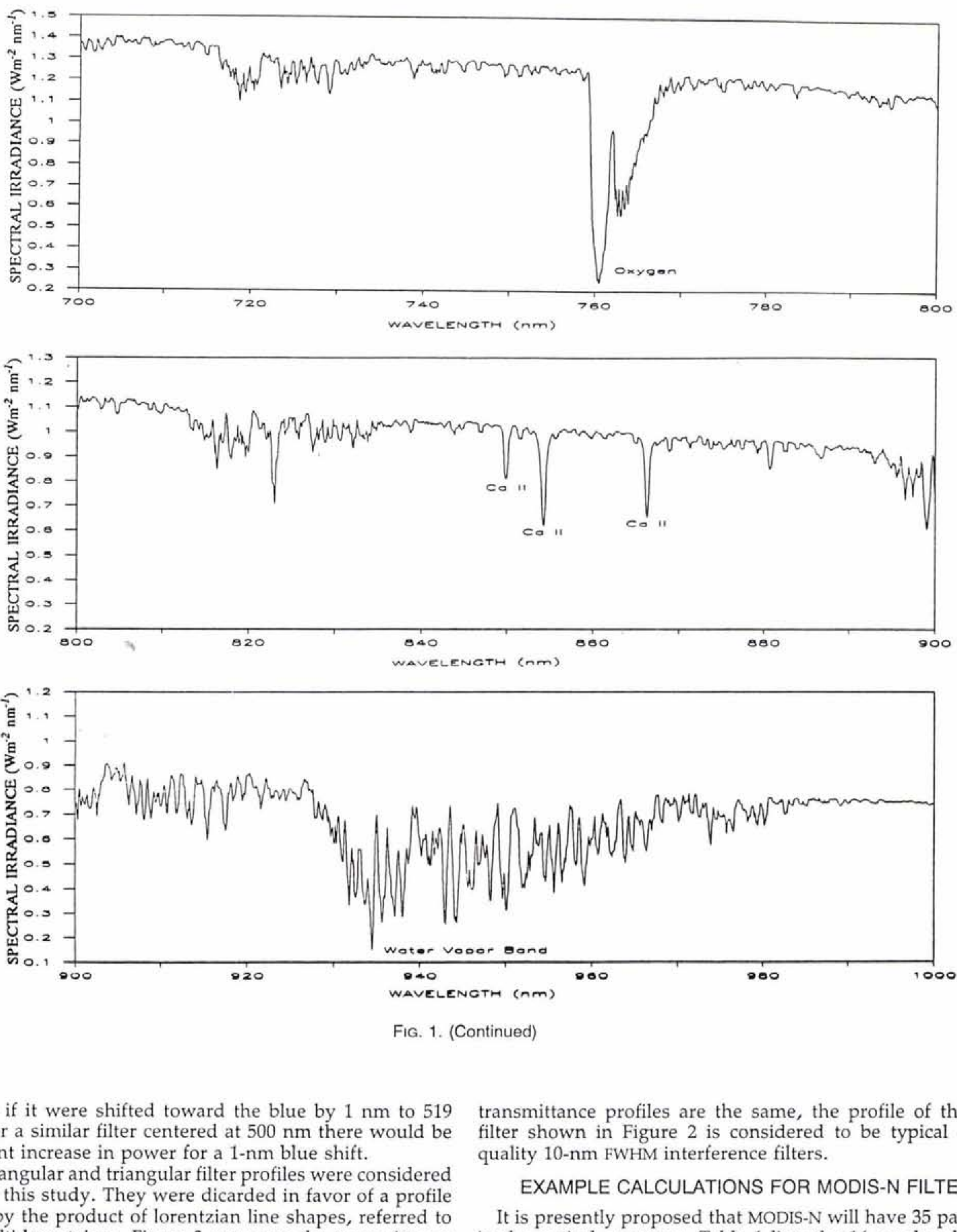

FIG. 1. (Continued)

less power if it were shifted toward the blue by 1 nm to 519 nm, and for a similar filter centered at 500 nm there would be a 0.7 percent increase in power for a 1-nm blue shift.

Both rectangular and triangular filter profiles were considered initially for this study. They were dicarded in favor of a profile simulated by the product of lorentzian line shapes, referred to here as multi-lorentzians. Figure 2 compares the transmittance profile for an actual 10-nm full-width-half-maximum (FWHM) passband filter and a multi-lorentzian. The multi-lorentzian is the product of three Lorentz line shapes, one with a 16-nm FWHM centered at the reference wavelength, and two with 6-nm FWHM shifted ± 4 nm from the center wavelength. For ease in computation, the transmittance of the multi-lorentzian is cut off at wavelengths where the transmittance is below 5.0 percent of the peak value. The errors in the zeroth, first, and second moments of the transmittance profiles for the actual and multi-lorentzian are no greater than 0.4 percent. Though not all filter transmittance profiles are the same, the profile of the actual filter shown in Figure 2 is considered to be typical of good quality 10-nm FWHM interference filters.

EXAMPLE CALCULATIONS FOR MODIS-N FILTERS

It is presently proposed that MODIS-N will have 35 passbands in the optical spectrum. Table 1 lists the 16 passbands in the range 413 nm to 950 nm, where there are many Fraunhofer lines in the solar output. The first attempt to analyze the filter-shift effect made use of rectangular filters for band 11 of MODIS-N. As can be seen in Figure 3, the result for the multi-lorentzian profile is smoother and of smaller amplitude than for the rectangular profile. The difference was considered significant enough that all further work was done employing profiles synthesized using multi-lorentzians.

The narrow-band profiles for the 10-, 15-, 20-, and 35-nm FWHM filters on MODIS-N were synthesized by combining three

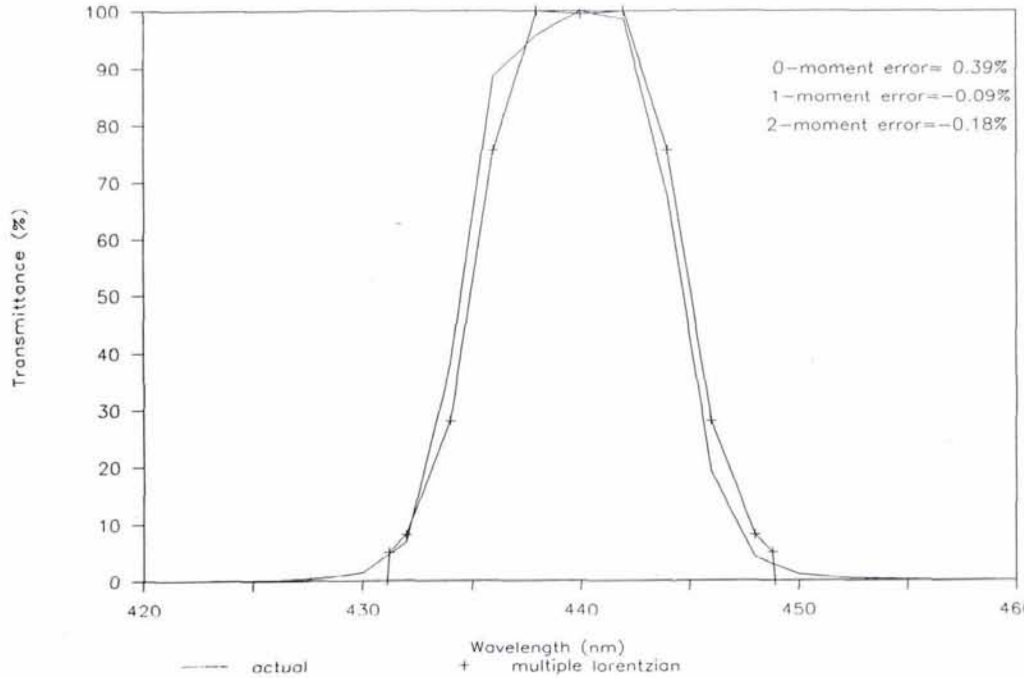

FIG. 2. Comparison between a multi-lorentzian passband simulation and an actual filter.

lorentzians as described earlier, but of wider FWHM and of greater displacement from their center wavelengths. It is interesting to note they all have band-edge slopes which meet NASA's preliminary phase C/D specification (1989) for the MODIS-N filters.

MODIS-N band 8 is chosen to demonstrate the filter shift problem and how it can be analyzed. Band 8 has a center wavelength at 413 nm and an FWHM of 15 nm. Looking at the solar spectrum in Figure 1, it is obvious the filter is located in a region where a slight shift in the center wavelength could cause a significant change in the radiometer output because of the presence of the calcium line at 396 nm, nearby iron lines at 406 nm, hydrogen-delta at 410 nm, and the Fraunhofer line at 431 nm due to many elements.

In Figures 4 and 5, the calibration error for a 15-nm multi-lorentzian filter at center wavelengths ranging from 400 nm to 450 nm is plotted for shifts of ±1 nm and ±5 nm, respectively. A 1-nm filter shift was chosen as being quite likely even under the best of conditions , as discussed in the next section, and a 5-nm shift was taken as a worst case. Near band 8 the calcium line at 396 nm poses the largest threat to calibration stability, because the closer the filter is positioned to the calcium line the greater is the possibility of a shift-induced error. For band 8, at 413 nm, there is only a 0.25 percent change in system response for a 1-nm shift in either direction from this center wavelength. However, a 5-nm shift toward the blue causes a 1.5 percent error, and a shift of the same distance toward the red produces a 0.3 percent error. This shows the dependence of the error upon the direction and size of the shift. Both red and blue shifts are considered in the following because it is not known in which direction the filters may shift.

If the actual filter for band 8 had a center wavelength of 411 nm, a 5-nm blue shift would produce a change in system response of over 3 percent demonstrating that a given filter might be at a wavelength that has relatively small calibration errors, but is near an unstable region. Because of this, error values of less than 0.5 percent for a 1-nm shift and less than 2 percent for a 5-nm shift were chosen as criteria for evaluating the MODIS-N system. Using these arbitrary criteria, a range of center wavelengths that includes the proposed center wavelength and satisfies these requirements for calibration error are shown in Table 1 for each MODIS-N band in the visible and near-IR. Some bands are acceptable according to one criterion but not the other, e.g., band 10, while others do not satisfy either criteria e.g., bands 9, 14, 17, 18, and 19 and are labeled not acceptable (NA). The last three of these bands are unstable due to the water vapor band starting near 900 nm. The columnar amount of water vapor present in the spectral data is not mentioned by Kurucz et al., but comparison with LOWTRAN 7 results shows that it was about 0.5 g cm^{-2}.

TABLE 1. LISTS OF THE TOLERABLE RANGES IN LOCATION OF THE CENTER WAVELENGTHS FOR THE VISIBLE AND NEAR-INFRARED FILTERS ON MODIS-N

Band	WL (nm)	BW (nm)	Range for ±1 nm shift <0.5% error	Range for ±5 nm shift <2.0% error	New center position & tolerance (nm)
1	470	20	451 - 674	455 - 644	470 ± 15
2	555	20	451 - 674	455 - 644	555 ± 99
3	665	20	451 - 674	650 - 670	665 ± 5
4	880	20	818 - 884	823 - 881	876 ± 15
8	413	15	409 - 420	412 - 417	415 ± 2
9	443	10	NA	NA	456 ± 2
10	490	10	NA	490 - 507	498 ± 5
11	520	10	516 - 521	NA	531 ± 2
12	565	10	521 - 584	529 - 582	565 ± 17
13	653	15	651 - 675	NA	665 ± 5
14	681	10	NA	NA	668 ± 2
15	750	10	722 - 750	NA	745 ± 2
16	865	15	819 - 886	852 - 883	865 ± 13
17	908	35	NA	NA	871 ± 5
18	936	10	NA	NA	917 ± 2
19	950	20	NA	NA	911 ± 3

From the ranges in Table 1, a new center wavelength and

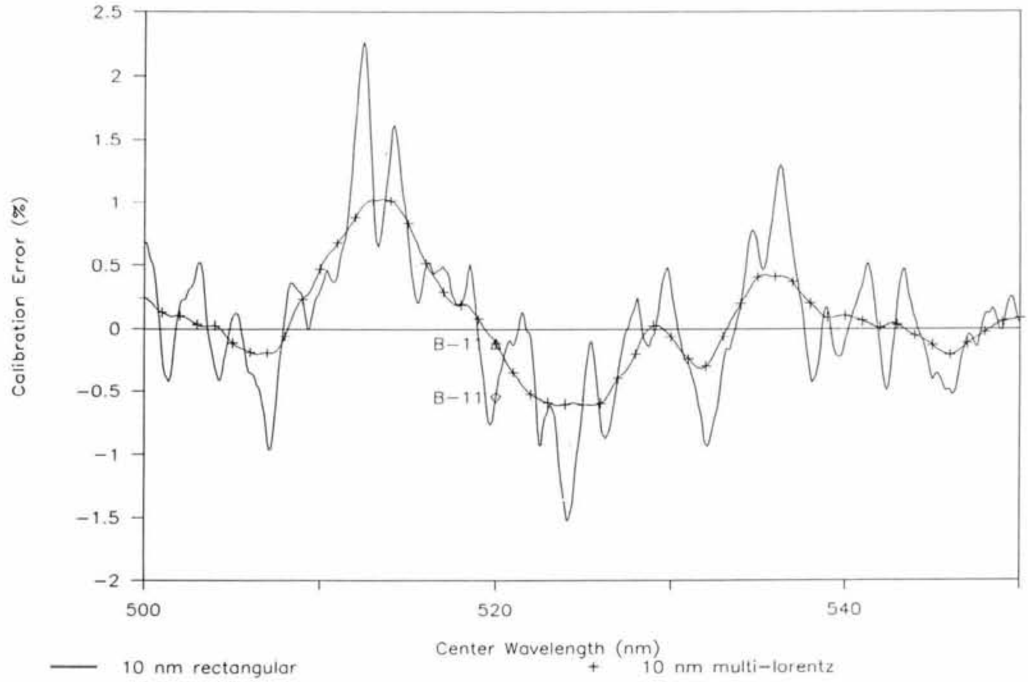

FIG. 3. A comparison between the calibration error with respect to a continuous source for a 10-nm FWHM rectangular and multi-lorentzian passband filter shifted through 1 nm. This filter corresponds to the band-11 filter on MODIS-N.

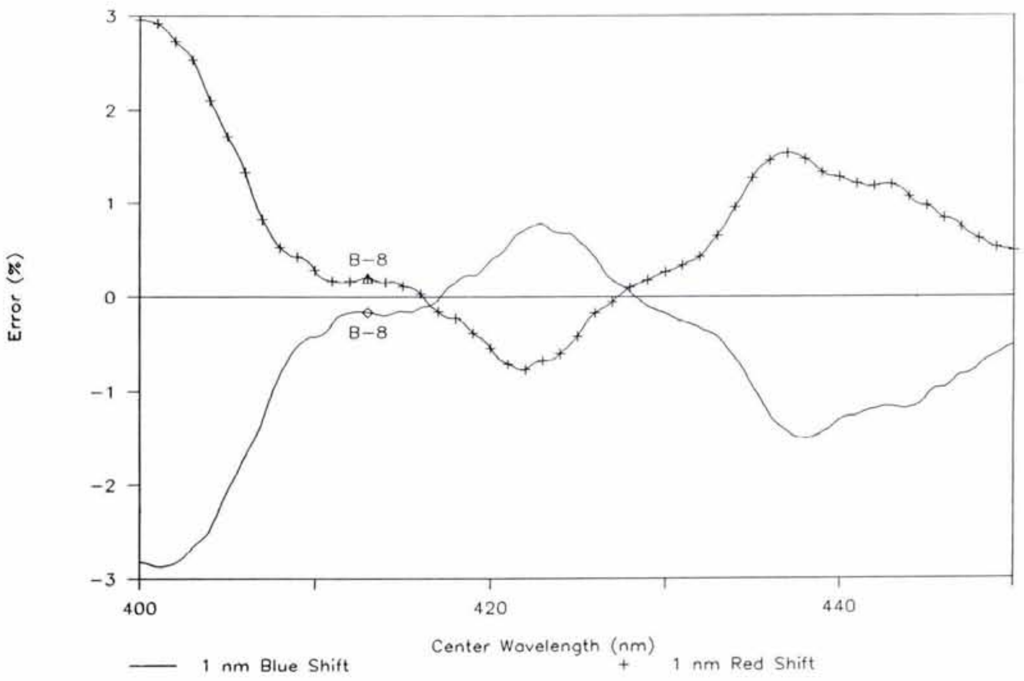

FIG. 4. The percentage error in calibration with respect to a tungsten-calibration lamp introduced by a 1-nm shift to the blue and red of the band-8 MODIS-N filter which has a 15-nm FWHM.

tolerance has been determined for each band which meets both calibration criteria mentioned above (see last column in Table 1). For example, it is suggested that band 8 be relocated at 415 nm to loosen the tolerance in the blue direction and also approximately equalize the positive and negative tolerances. The tolerances listed are reasonable manufacturing specifications for the narrow-band filters to be used for MODIS-N. In the repositioning of the bands, the scientific purpose for each band was not considered, this study being only concerned with identifying possible problems in calibration. Repositioning bands 13 and 14 and 16 and 17 results in redundancies, and repositioning band 19 results in it being in an ineffective location.

A solar-diffuser panel is proposed for the in-flight absolute calibration of MODIS-N. If such a panel is used, Earth-surface

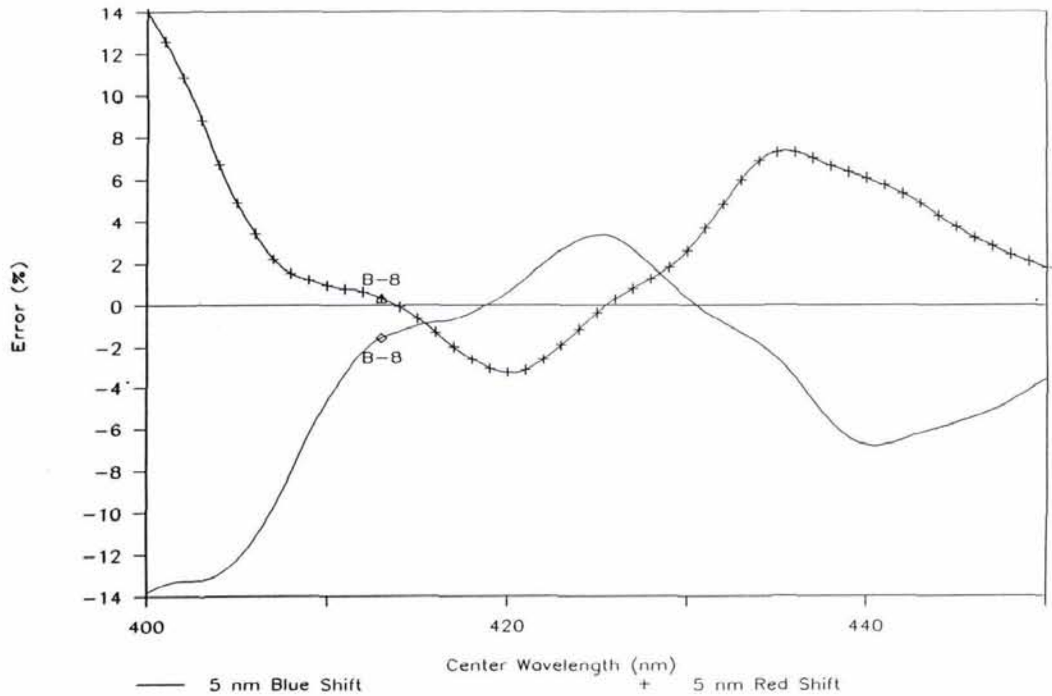

FIG. 5. As for Figure 4, but with a 5-nm shift to the blue and the red.

solar-reflectance measurements made by MODIS-N will be correctly calibrated because the spectral radiance of the panel will, of course, also include the presence of the solar Fraunhofer lines. However, if only a tungsten-lamp calibration is used, or if water vapor or oxygen band measurements are made, the results will be in error depending on the magnitude of any filter shift.

TEMPERATURE EFFECTS IN CONVENTIONAL RADIOMETERS

To determine possible changes in filter passband location with temperature for conventional ground-based radiometers, measurements were made of filters from three U.S. manufacturers. The temperature range explored was from 3 to 25°C, corresponding to early-morning and mid-day winter temperatures in the desert southwest of the United States at sites such as White Sands, New Mexico. The spectral transmittance measurements were made using a Cary 2415 UV-VIS-NIR spectrophotometer. Unfortunately, no cryogenic chamber is associated with the spectrophotometer so accurate thermal control of the filters was not possible. However, the time between removing the filter from the freezer and finishing a spectral scan was only about one minute.

The transmittance was first measured for each filter at the room temperature of 25°C. Then the filters were placed in a commercial freezer for several hours to reach thermal equilibrium at roughly 3°C, before they were quickly placed in the spectrophotometer. There was a problem with atmospheric water vapor condensing on the cooled filter surfaces. Because of this, the profiles were normalized independently to unity (see Figure 6). The condensation only affected the magnitude of the transmittance, not the shape of the profile.

A filter centered at 370 nm and having a bandpass of 10 nm showed the largest shift of 1.5 nm toward the blue when it was cooled from room temperature to near-freezing - a 22°C decrease. A filter at 937 nm from a second manufacturer showed a 0.5-nm red shift when cooled through the same range. Thus, a 1-nm shift in either direction seems possible for a field radiometer. The filter at 400 nm from the third manufacturer did not show a noticeable shift in passband with temperature and was judged to be stable to less than 0.1 nm over the temperature range explored.

With reference to Figure 4, we see that a 15-nm filter centered at 440 nm will give rise to a change in system response of 1.5 percent for just a 1-nm temperature-induced shift toward either the blue or red. The problem here is the relatively high concentration of Fraunhofer lines in this region -- Fe at 438, H-gamma at 434 nm, and multiple lines at 431 nm. As noted earlier, the atmospheric lines present in the solar spectral data used for calibration can also cause changes in system response. For example, 10-nm filter at 687 nm used to view the oxygen band, 686 to 688 nm, could cause a change in signal of 0.8 percent for a 1-nm shift toward the blue. The same problem is present when viewing the water vapor band starting near 900 nm, such as band 18 of MODIS-N. Here again a modest shift of 1 nm could cause a radiometer to view a different portion of the spectrum and thus change the received power and invalidate any conclusion drawn from the measurements.

It is also of interest to note that solar radiometers, which commonly use 10-nm filters, are often calibrated at high elevation mountain sites. The temperature of the non-temperature-controlled filters could then be substantially lower than under ordinary operating conditions and the radiometer may thus change in its calibration.

CONCLUSION

As remote sensing investigations require higher resolution spectral data, the possibility of measurement errors due to Fraunhofer and atmospheric absorption lines must be considered. We have shown that the calibration, with respect to a continuous-spectrum source, and the stability of radiometers, using filters of about 10-nm FWHM in the wavelength interval 0.4 to 1.0 μm, can change by several percent if the filters change in position by only a few nanometres. The cause is the shifts

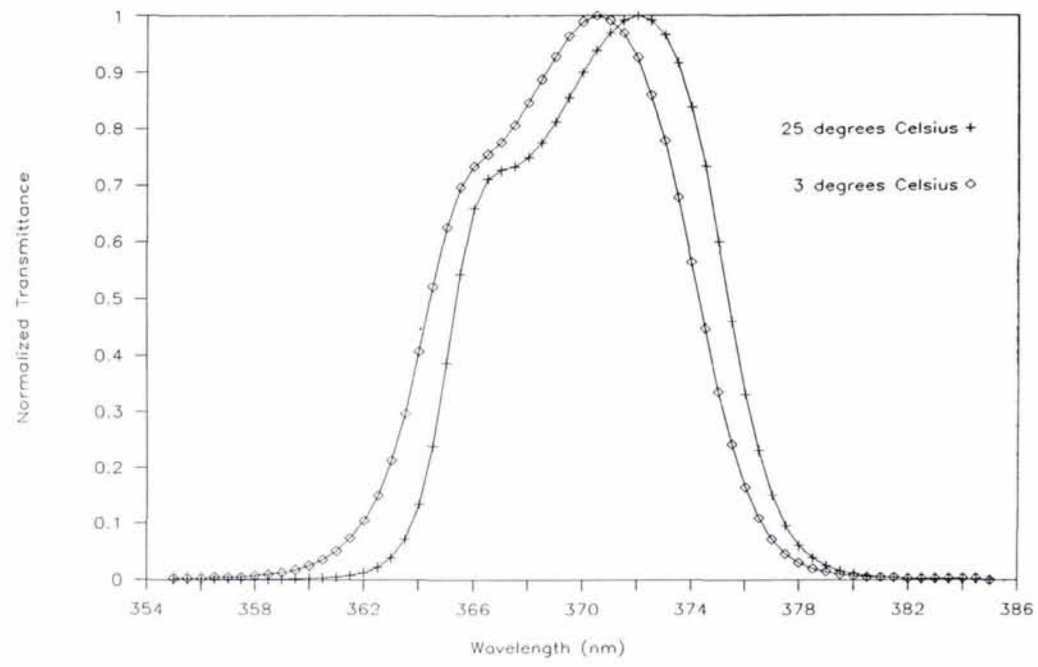

FIG. 6. The effect of temperature changes on the position of the passband of a commercial filter. Each passband profile has been normalized to unity.

of the passbands of the filters into or out of Fraunhofer lines in the solar spectrum or water vapor or oxygen absorption bands in the the Earth's atmosphere. These shifts can be due to ageing accompanied by the absorption of water vapor into the filter or temperature changes for field radiometers, or to outgassing and possibly high energy solar irradiation for space instruments such as the MODerate resolution Imaging Spectrometer - Nadir (MODIS-N) proposed for the Earth Observing System.

Although only filter radiometers have been considered here, a similar problem can arise in the case of imaging spectrometers if the spectral profile is not constant across the field of view of the instrument. A tungsten-source calibration will give rise to erroneous results that will be a function of field angle, and the results of measurements of water vapor or oxygen absorption will also vary with field angle. Fortunately, the extent of the spectrometer problem is known preflight and allowance can be made for the effect in the processing of the data. For the filter radiometer this is not the case and only an in-flight spectral scan of the filters can reveal the extent of filter shifts.

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