Characterization of two spectrometers in support of the Landsat Data Continuity Mission

B. Carol Johnson[a*], Robert D. Saunders[a], Zhigang Li[a], Abra Fein[a], Lawrence Ong[b], Milton G. Hom[c], Robert A. Barnes[d], Brian L Markham[e]

[a]National Institute of Standards and Technology, Gaithersburg, MD 20899
[b]Science Systems and Applications, Inc., Lanham, MD 20706
[c]Sigma Space Corporation, Lanham, MD 20706
[d]Science Applications International Corporation, Beltsville, MD 20705
[e]NASA Goddard Space Flight Center, Greenbelt, MD 20771

ABSTRACT

The Landsat Data Continuity Mission (LDCM) project at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) is supervising the manufacture and calibration of the Operational Land Imager (OLI) satellite instrument by Ball Aerospace in Boulder, Colorado. As part of that oversight function, the project is preparing a set of radiometers to monitor long-term changes (if any) in the radiance from the integrating sphere used for the radiance calibration of the OLI instrument. That sphere, calibrated at the National Institute of Standards and Technology (NIST), serves as an artifact for establishing traceability of the OLI radiance calibration to SI units, that is, to the radiance scale at NIST. This paper addresses the characterization of two Analytic Spectral Devices (ASD) Fieldspec spectrometers that are part of the NASA/NIST program to validate radiometric reference standards in the LDCM project. In particular, we report on a series of measurements at NIST to determine the ASD spectrometers' long-term stability. Along with other radiometers, the ASDs will be used in the monitoring of changes in the OLI reference sphere from its calibration at NIST to its use in the calibration of the OLI satellite instrument. The ASD stability measurements will continue through the conclusion of the calibration of OLI.

Keywords: LDCM, OLI, radiance, prelaunch calibration

1. INTRODUCTION

The Landsat Data Continuity Mission, carrying the Operational Land Imager, is on target for a December 2012 launch[1]. The OLI is a follow-on for the ETM+ instrument[2], currently operating onboard the Landsat-7 satellite. The OLI is a nine-band, push-broom filter radiometer with 13800 detectors for the panchromatic band and 6900 detectors for each of the other eight. The nominal spectral responses for the OLI bands are shown in Fig. 1, and a brief summary of the OLI design can be found in Ref. 1. Ball Aerospace is performing the design, construction, and calibration of OLI .

The on-orbit radiometric measurements from the OLI will be traceable to national reference standards of spectral radiance values. The establishment of traceability for the OLI is via a 28 cm diameter transfer sphere that was calibrated by NIST in February 2010 Facility for Spectroradiometeric Calibration (FASCAL)[3]. Immediately following this calibration, the radiance of the Ball sphere was measured by a set of transfer radiometers in the Remote Sensing Laboratory (RSL) at NIST. In the future, at Ball, the radiance calibration of the 28 cm sphere will be transferred to a large aperture integrating sphere for the calibration of OLI. Currently, this is scheduled for the fall 2010. Before the transfer process at Ball, the output of the 28 cm sphere will be re-measured by the set of transfer radiometers to check for changes in the sphere radiances since the FASCAL calibration. Ball Aerospace has placed a value of 0.5%[4] for changes in the reference sphere radiance values from the time of the FASCAL calibration to the transfer to the OLI sphere (~9 months) into its uncertainty budget for the calibration of OLI. In order to determine any changes in the reference transfer sphere by monitoring with radiometers, they must be stable to at least 0.5% over the time interval required. This is the goal for the stability of the radiometers provided by NASA and NIST as part of the OLI calibration. In addition, the spectrometers will be used with a NIST-provided integrating sphere to check the radiance from the OLI transfer sphere at Ball Aerospace. We also investigate the short-term stabilities of the spectrometers for their part in that sphere comparison.

*(BCJ, contact author) cjohnson@nist.gov; phone (301) 975-2322; fax (301) 869-5700; Optical Technology Division, NIST, Gaithersburg, MD 20899.

Earth Observing Systems XV, edited by James J. Butler, Xiaoxiong Xiong, Xingfa Gu,
Proc. of SPIE Vol. 7807, 780708 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.862056

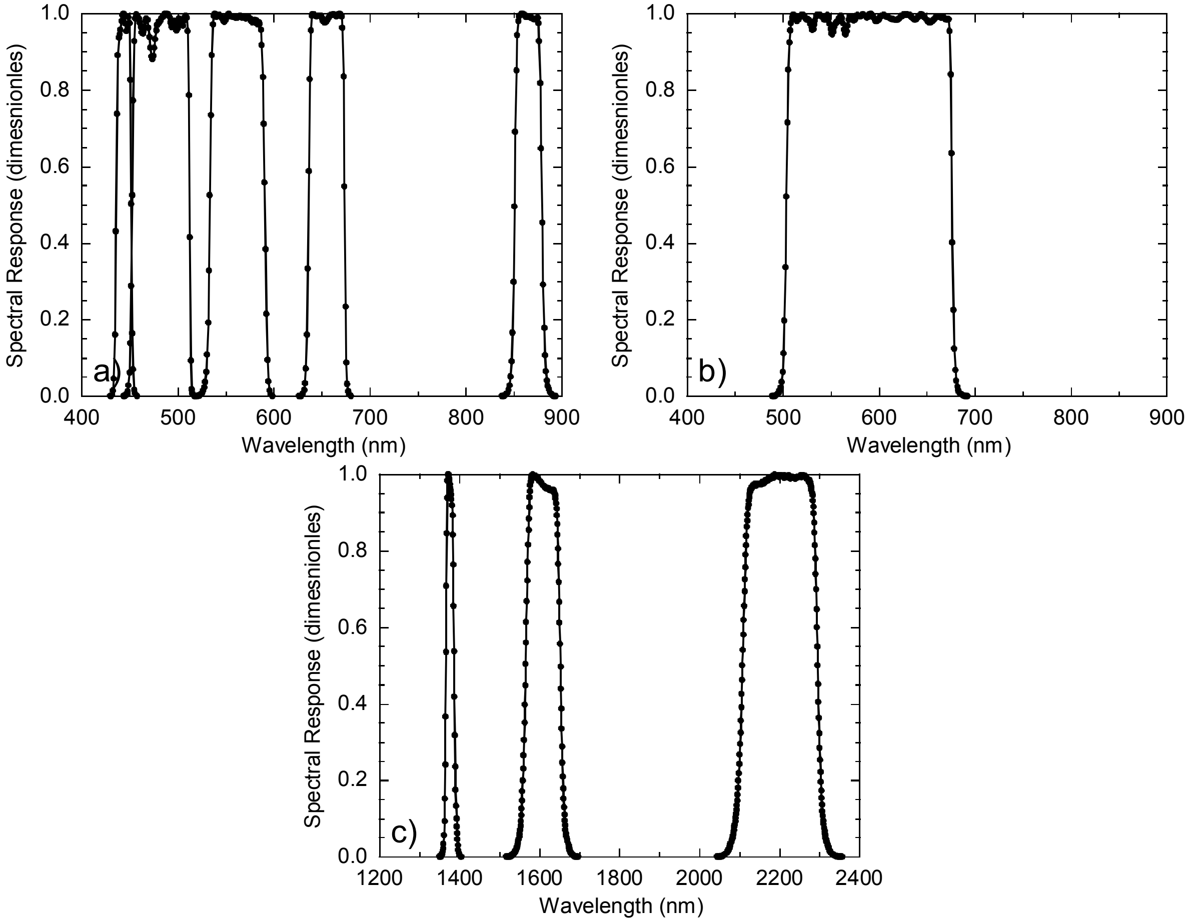

Figure 1. Nominal spectral responses for the Operational Land Imager, normalized to maximum values of unity.

a) Visible/near-infrared (VNIR) bands: coastal aerosol (443 nm center wavelength); blue (483 nm); green (562 nm); red (665 nm); and near-infrared (865 nm).

b) Visible/near-infrared bands: panchromatic (590 nm). The response for the panchromatic band covers those for the red, green, and part of the blue bands.

c) Short-wave infrared (SWIR) bands: cirrus (1375 nm center wavelength); SWIR1 (1611 nm); and SWIR2 (2201 nm).

For NASA and NIST, the radiometer measurements in the RSL in February 2010 were made by a set of visible/near-infrared (VNIR) transfer radiometers. Two of the radiometers, the Landsat Transfer Radiometer (LXR) and the EOS Visible Transfer Radiometer (VXR), had participated in previous validation campaigns at the facilities for satellite instrument builders[5,6]. However, short-wave infrared (SWIR) transfer radiometers from previous campaigns[6] were not available for the February 2010 comparison campaign. This limited the ability of NASA and NIST to monitor the Ball transfer sphere over the wavelength intervals for the OLI SWIR bands (1375 nm, 1611 nm, and 2201 nm, see Fig. 1).

2. ANALYTICAL SPECTRAL DEVICES FIELDSPEC SPECTROMETERS

The absence of SWIR transfer radiometers was filled through the use of two Analytical Spectral Devices FieldSpec spectrophotometers (www.asdi.com) (ASDs)[7]. The first, number 16058, is located in the RSL at NIST and is used for various laboratory and field measurements. Here it is called the NIST ASD. The second, number 6172, is used by the LDCM project at GSFC and is referred to as the GSFC ASD. The ASD is a field spectrometer measuring over wavelengths from 350 nm to 2500 nm. Light is fed into the spectrometer by a fiber optic bundle that is 1.2 m in length. Physically, the ASD contains three spectrometers, one in the visible/near-infrared (350 nm to 1000 nm) and two in the SWIR (1000 nm to 2500 nm). The bandpass is about 3.3 nm in the VNIR and approximately 10 nm in the SWIR. The standard instrument readout reports values at a spacing of 1 nm, oversampling the bandwidth. The outputs from the three spectrometers are merged into a single spectrum by the ASD software installed on the computer that operates the instrument.

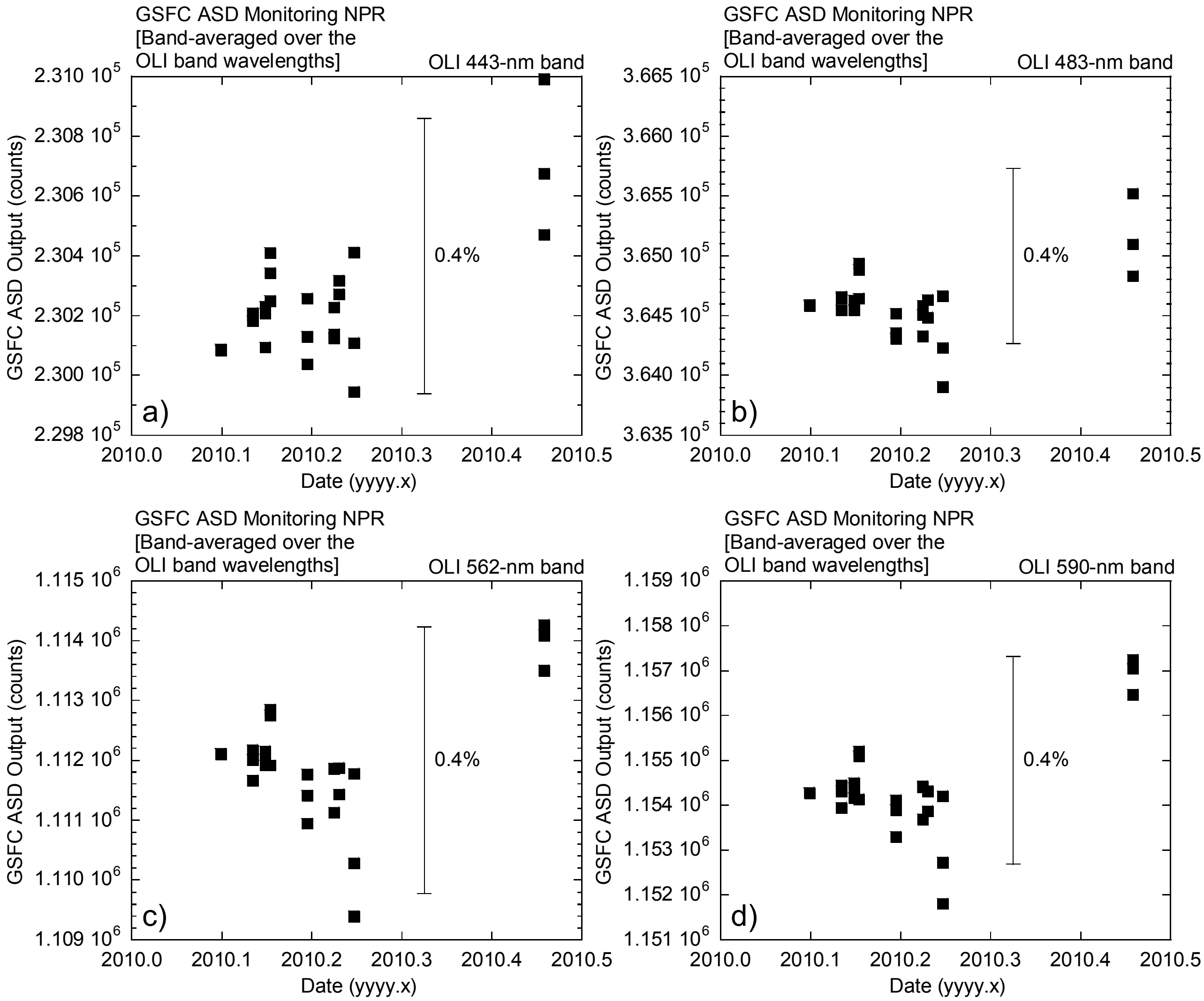

Figure 2a. Measurements of NPR by the GSFC ASD in the first-half of 2010. The measurements have been band-averaged using the nominal OLI spectral responses. There are multiple measurements on each day. The vertical bar in each panel acts as an aid to scale the changes. It is 0.4 % from top to bottom.

a) Measurements averaged over the 443 nm band.
b) Measurements averaged over the 483 nm band.
c) Measurements averaged over the 562 nm band.
d) Measurements averaged over the 590 nm band.

Different fore optics can be coupled to the end of the fiber optic bundle, including lenses with fields-of-view (FOVs) of up to 18° or Gershun tubes.

For the measurements presented here, the GSFC ASD used a 1° FOV fore optic and was mounted on an optical table 28 cm away from the 10 cm aperture of the reference integrating sphere in the RSL at NIST. The ASD was horizontally and vertically aligned to the center of the opening of the sphere. Before data collection, the sphere and ASD were turned on for a minimum of 30 minutes. The thermal electric cooler for the GSFC ASD's VNIR detector array was turned on at the same time as the sphere and the spectrometer. For the NIST ASD, the fore optic was a Gershun tube that limited the FOV to 5°, and the spectrometer's VNIR detector array was not equipped with temperature stabilization. Otherwise, the setup of the NIST ASD was the same as the GSFC spectrometer.

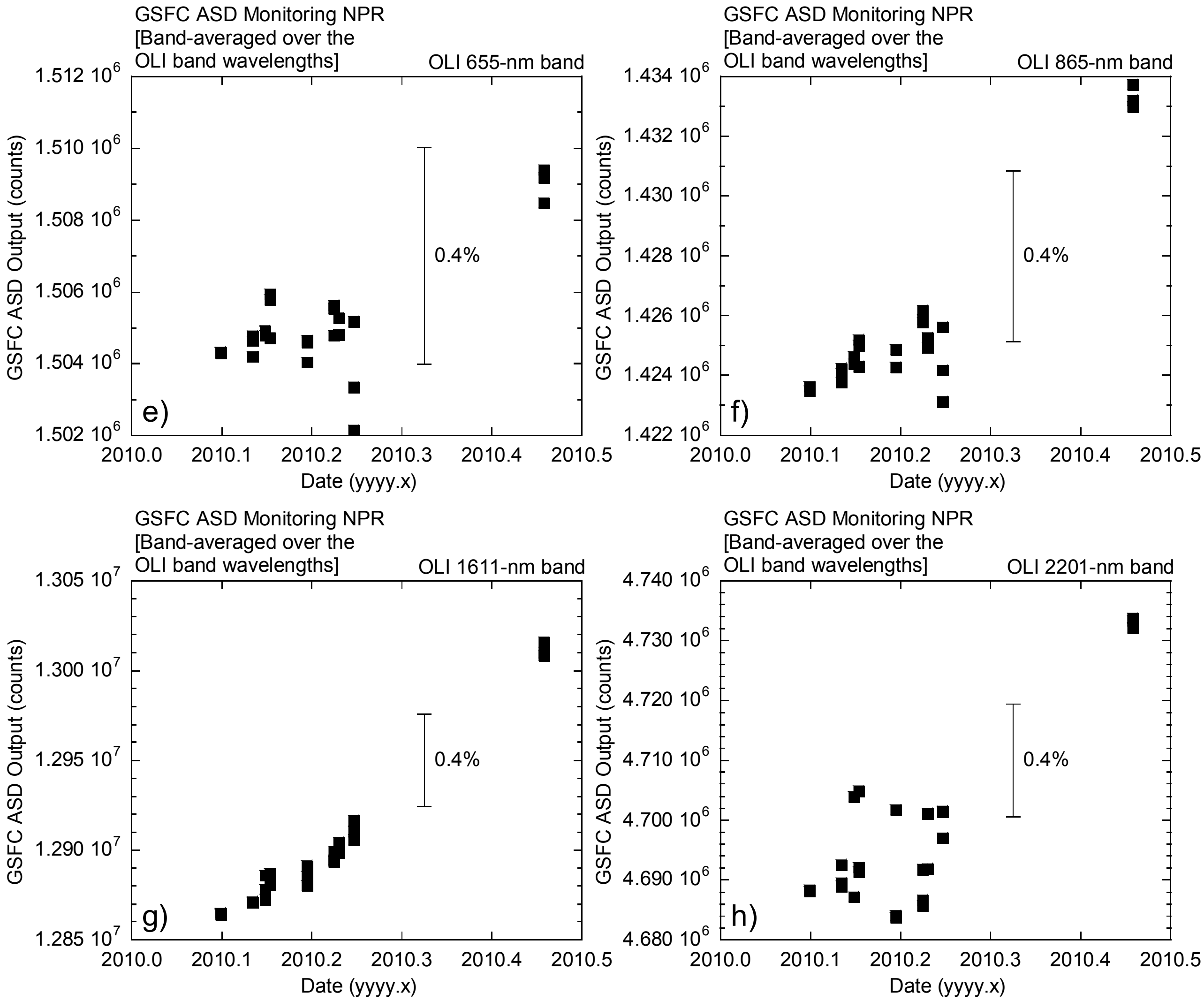

Figure 2b. Measurements of NPR by the GSFC ASD in the first-half of 2010. The measurements have been band-averaged using the nominal OLI spectral responses. There are multiple measurements on each day. The vertical bar in each panel acts as an aid to scale the changes. It is 0.4 % from top to bottom.

e) Measurements averaged over the 665 nm band.
f) Measurements averaged over the 865 nm band.
g) Measurements averaged over the 1611 nm band.
h) Measurements averaged over the 2201 nm band.

Each ASD spectrum includes values at over 2100 wavelengths. This creates data sets that are very large and contain more information than we need to evaluate the stability at the OLI bands. The results presented here have been simplified through the process of band-averaging, using the nominal OLI spectral responses in Fig. 1. A band-average is a weighted mean,

$$X_b = \frac{\int X_\lambda R_\lambda d\lambda}{\int R_\lambda d\lambda} , \qquad (1)$$

where X is the value that is averaged, R is the spectral response, and λ is the wavelength. Here X_λ are the counts from the ASD at 1 nm intervals, and X_b is the band-averaged result, also in counts. For the use of Eq. 1, the scaled value for R_λ is unimportant, so long as it is used consistently in the numerator and denominator.

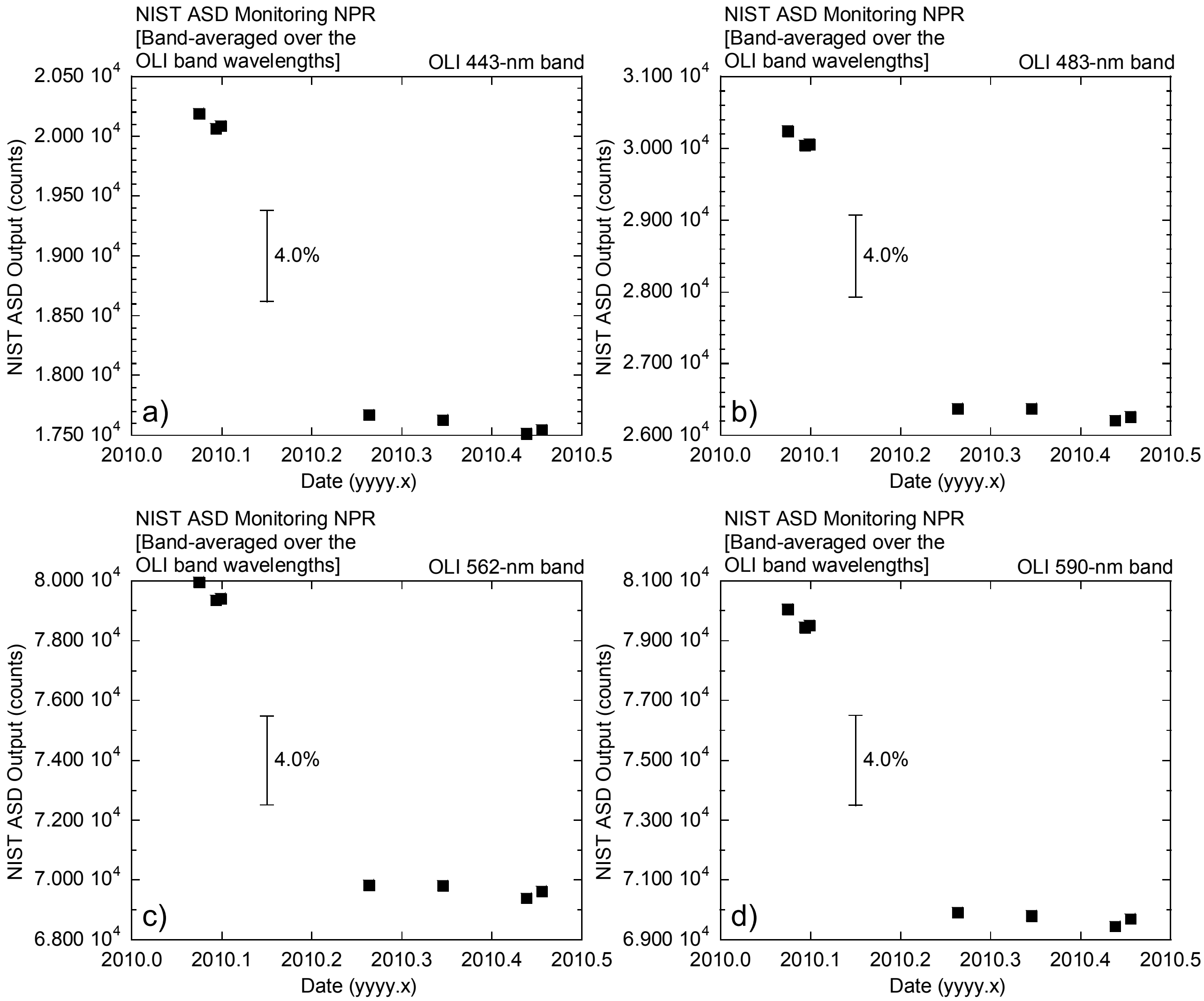

Figure 3a. Measurements of NPR by the NIST ASD in the first-half of 2010. The measurements have been band-averaged using the nominal OLI spectral responses. The vertical bar in each panel acts as an aid to scale the changes. It is 4 % from top to bottom.

a) Measurements averaged over the 443 nm band.
b) Measurements averaged over the 483 nm band.
c) Measurements averaged over the 562 nm band.
d) Measurements averaged over the 590 nm band.

3. LONG-TERM TRENDING MEASUREMENTS

The first study was an examination of the set of NPR measurements by the ASDs from 2006 through 2009. The counts in the time series for both the NIST and GSFC showed changes up to 10 %, and the measurement sets were sparse. From the records, we found that the instruments were used for field programs with a variety of operators. It is possible the fore optics were different. Also, one of the ASDs had been repaired by the manufacturer. More importantly, we learned that the laboratory measurements were calibrations of the spectrometers with the NPR for use with short-term projects. For periods of a few days to a few weeks, the ASD outputs, that is, the derived radiances from the NPR calibrations, were constant at the few percent level. Basically, the ASDs were not used in a manner consistent with our purposes. Based on this information, protocols were set up for the operation of each spectrometer, and the ASDs were kept in the RSL for use with the LDCM project only.

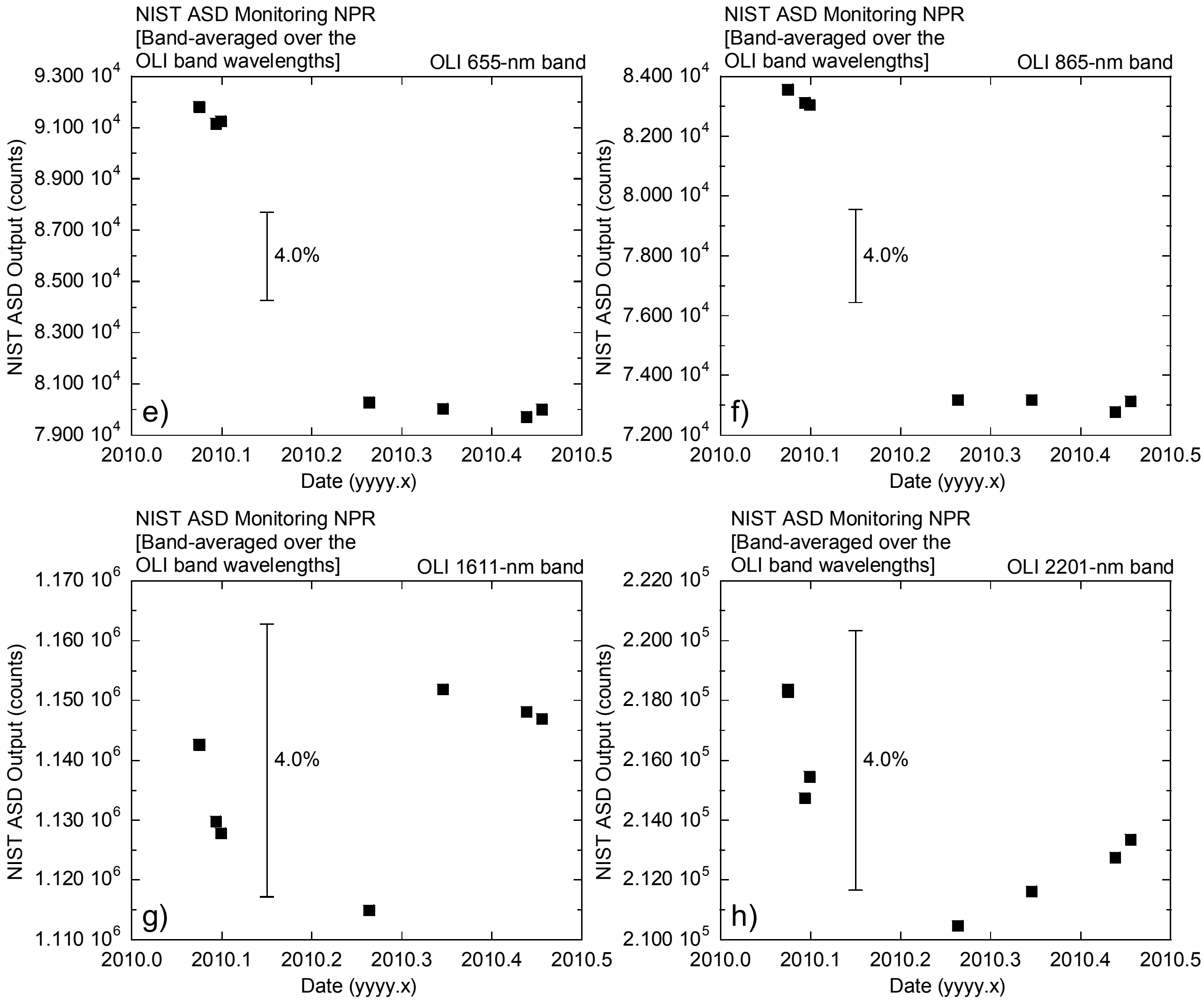

Figure 3b. Measurements of NPR by the NIST ASD in the first-half of 2010. The measurements have been band-averaged using the nominal OLI spectral responses. The vertical bar in each panel acts as an aid to scale the changes. It is 4 % from top to bottom.
e) Measurements averaged over the 655 nm band.
f) Measurements averaged over the 865 nm band.
g) Measurements averaged over the 1611 nm band.
h) Measurements averaged over the 2201 nm band.

The measurements of the NPR by the GSFC ASD during the first half of 2010 are shown in Fig. 2. The values are band-averages of the 1 nm outputs (in counts) from the spectrometer. Panels a, b, c, and d in Fig 2a are band-averages over the 443 nm, 483 nm, 562 nm, and 590 nm band responses of OLI. The spectral responses for those OLI bands are shown in Fig. 1. In the same manner, panels e, f, g, and h in Fig. 2b are band-averages over the 655 nm, 865 nm, 1611 nm, and 2201 nm OLI band responses. The OLI 1375 nm band is not represented in Fig. 2, since it sits on a strong water vapor absorption feature. This feature has the capacity to generate a variability for which we cannot quantify, since the humidity in the laboratory was not monitored during the measurements. And for our purpose, the 1611 and 2201 nm values in panels g) and h) give an adequate representation of the stability of the ASD outputs in the SWIR. Each of the panels in Fig 2 also contains a vertical bar that extends 0.4 % from top to bottom. The vertical bars give references for the magnitude of the changes in the ASD outputs. The measurements cover nine days during the period from early February to mid-June 2010. For the first day in the time series there are two NPR measurements by the ASD,

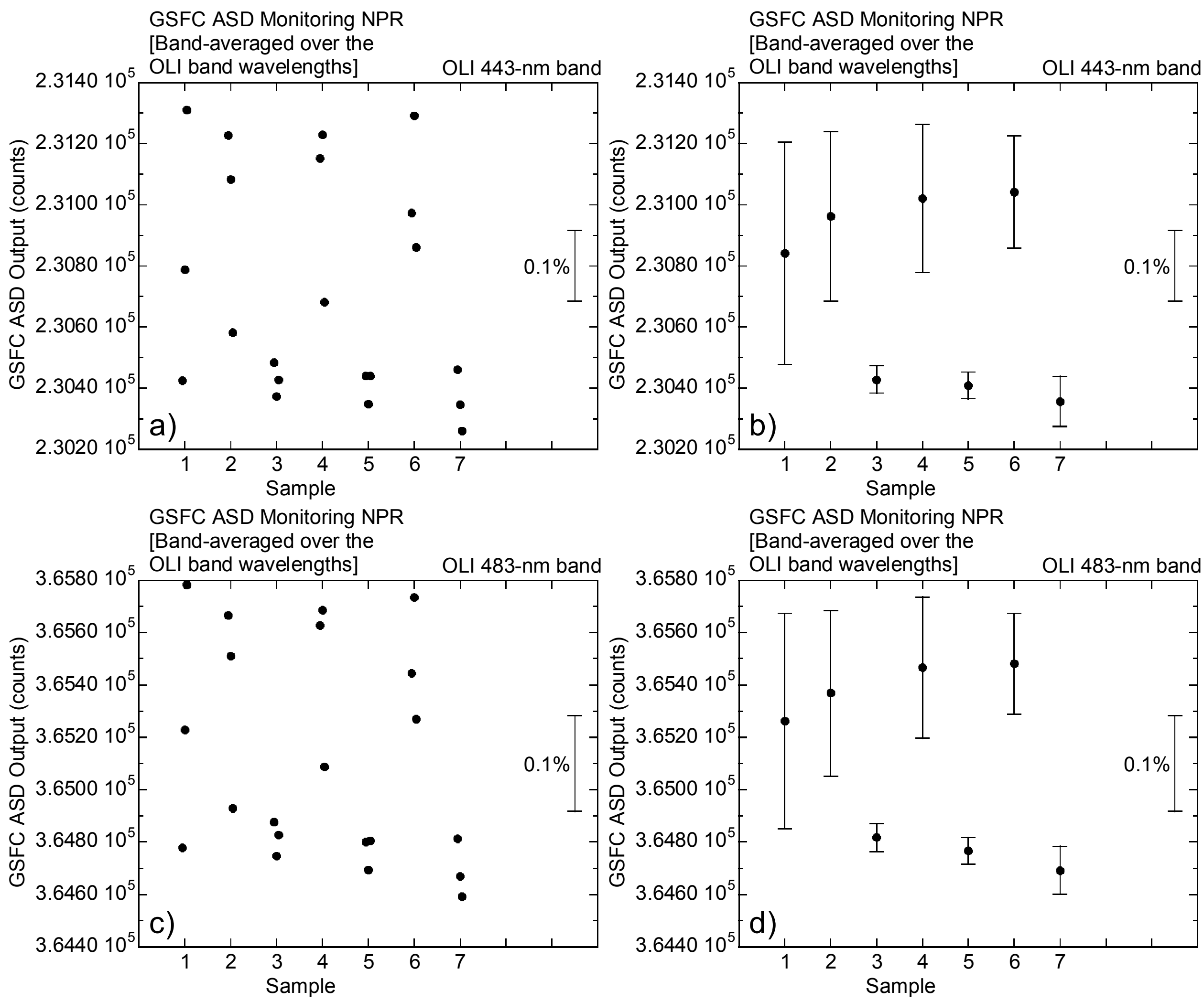

Figure 4a. Twenty-one measurements of NPR by the GSFC ASD on 16 June 2010. The measurements are separated into seven samples with three measurements per sample. The left-hand panels show all of the measurements; the right-hand panels show the measurements for each sample combined in a mean and standard deviation. The vertical bar at the far right of each panel is 0.1 % from top to bottom.

a) and b) Measurements averaged over the OLI 443 nm band.

c) and d) Measurements averaged over the OLI 483 nm band.

and for the remaining days there are three measurements per day. There is a cluster of measurements in February and March with a break before the measurement in mid-June. Measurements on a regular basis resumed in July and will continue until the sphere and spectrometers are moved to Ball Aerospace for measurements of the OLI sphere.

For GSFC ASD measurements in the visible (blue to red, 443 nm to 655 nm), the full set of measurements fall within 0.4 % of each other. There is some concern about the differences of the June measurements from those in February/March. However, the continuation of the measurement through the summer and into the fall should give a resolution to the concern, one way or the other. For the near-infrared (NIR) band (865 nm, panel f) and the SWIR bands (1611 and 2201 nm, panels g and h), the differences are a factor of two to a factor of three times larger than the 0.4 % vertical bar. Although the measurement program is not complete, there is an indication that the long-term stability of the GSFC ASD is better in the visible. Still, the principal purpose of the spectrometers is to monitor long-term changes of the OLI sphere at the 0.5 % level in the SWIR. Several factors effecting the SWIR stability are being considered, including the temperature stability of the SWIR detectors, the measurement characteristics at the wavelength limits for the operation of

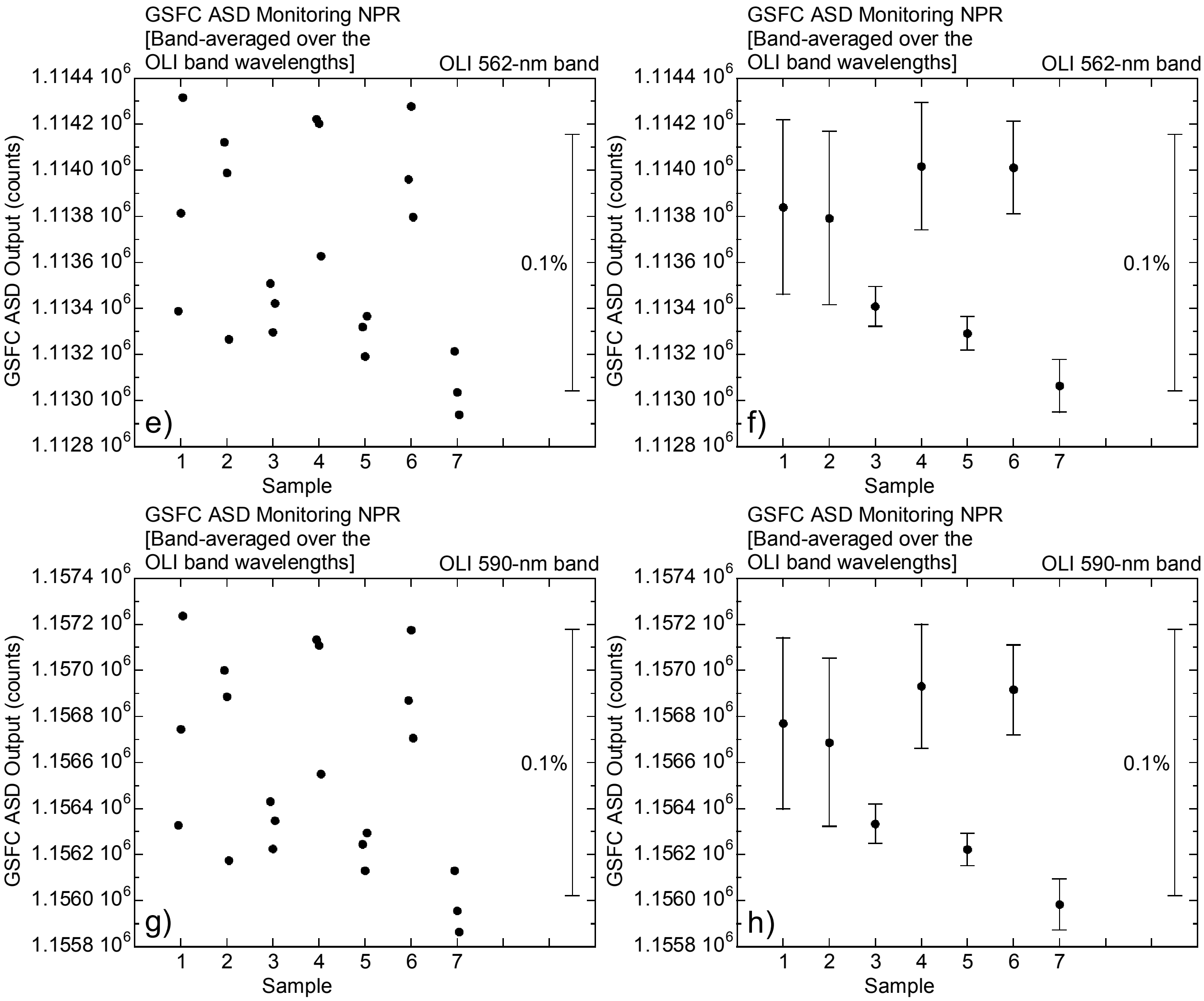

Figure 4b. Twenty-one measurements of NPR by the GSFC ASD on 16 June 2010. The measurements are separated into seven samples with three measurements per sample. The left-hand panels show all of the measurements; the right-hand panels show the measurements for each sample combined in a mean and standard deviation. The vertical bar at the far right of each panel is 0.1 % from top to bottom.

e) and f) Measurements averaged over the OLI 562 nm band.

g) and h) Measurements averaged over the OLI 590 nm band.

the two SWIR detectors, and atmospheric trace gas transmittance effects in the SWIR, particularly by water vapor. Studies of these factors are now underway.

The measurements of the NPR by the NIST ASD during the first half of 2010 are shown in Fig. 3. The layout of the panels in Fig. 3 are the same as the corresponding panels in Fig. 2. This includes the vertical reference bars in Fig. 3 that extend 4 % from top to bottom, a factor of ten times greater than those in Fig. 2. In addition, there are only seven measurements of the NPR in the NIST ASD data set. In February 2010, just after the first cluster of measurements in the panels, the SWIR detector for the spectrometer failed, and the instrument was sent to Analytical Spectral Devices for repair. When the spectrometer was returned in April 2010, the outputs of the NIST ASD had changed by about 12 % in the VNIR, in other words, the responsivity had changed. It is possible that the assumption of a constant NPR output can be used to bridge the differences caused by the repair of the NIST ASD. If this is done, then the long-term stability of the measurements becomes dependent on the long-term stability of the NPR. This removes the independence of the NIST ASD as a monitor for changes in the OLI sphere. Also troubling is the scatter in the SWIR measurements from

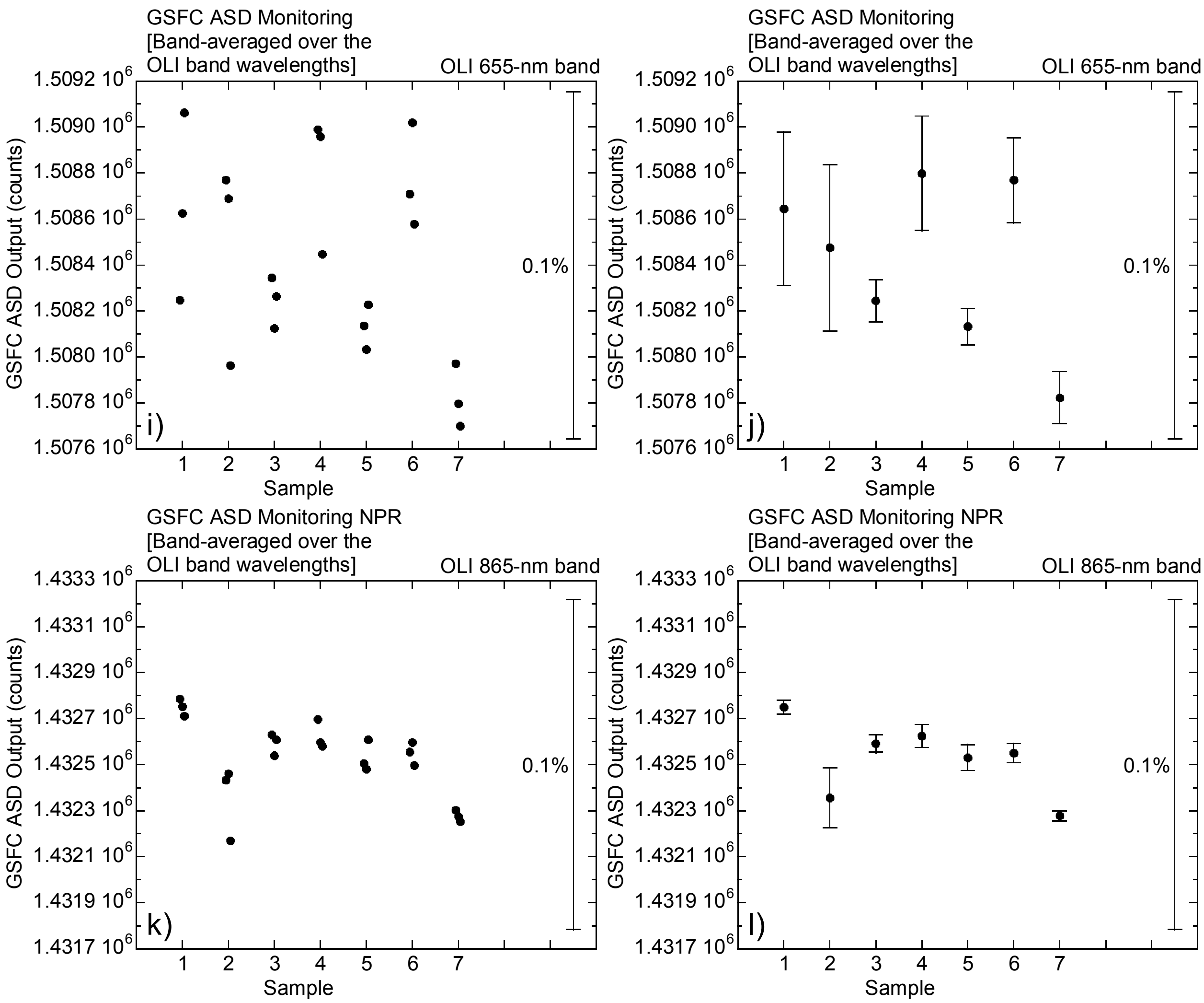

Figure 4c. Twenty-one measurements of NPR by the GSFC ASD on 16 June 2010. The measurements are separated into seven samples with three measurements per sample. The left-hand panels show all of the measurements; the right-hand panels show the measurements for each sample combined in a mean and standard deviation. The vertical bar at the far right of each panel is 0.1 % from top to bottom.
i) and j) Measurements averaged over the OLI 655 nm band.
k) and l) Measurements averaged over the OLI 865 nm band.

this ASD in panels g and h of Fig. 3b. These are in the wavelength region where the ASD is to be used. Even after the ASD's return from repair, the scatter in the SWIR measurements ranges from about 1 % to about 3 %. Unfortunately, this is significantly greater than the 0.5 % stability goal for validation of the OLI sphere.

4. SHORT-TERM STABILITY MEASUREMENTS

On June 16, a set of short-term stability measurements of the two ASDs was made. The purpose was to see if the ASDs could perform transfers of the radiance between two spheres. If so, then the radiance spectrum from the NPR could be compared with that from the OLI sphere during the measurement campaign at Ball, providing an additional check of the OLI sphere. Without a transfer radiometer with adequate short-term stability, a comparison between the NPR and Ball spheres is not possible.

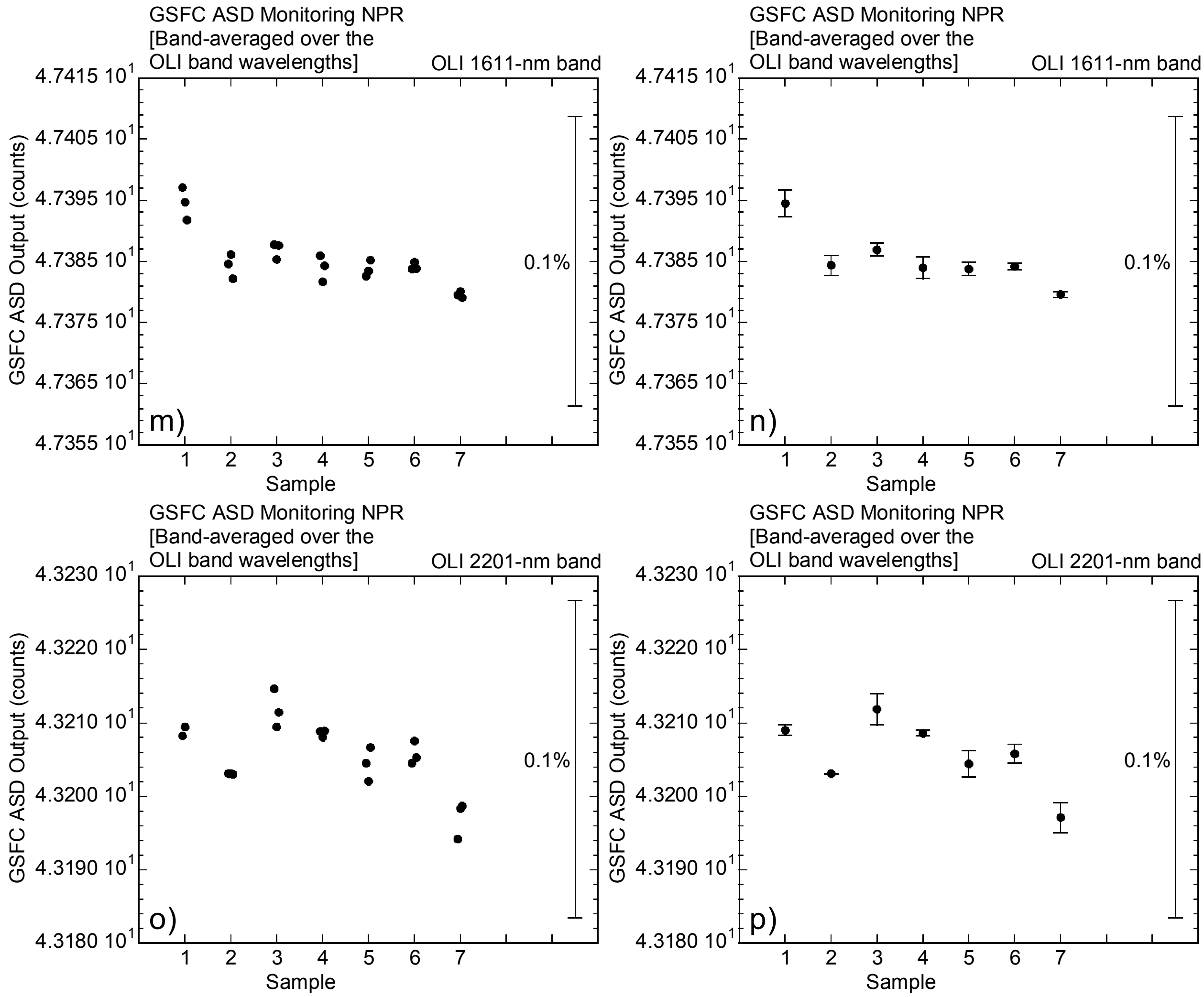

Figure 4d. Twenty-one measurements of NPR by the GSFC ASD on 16 June 2010. The measurements are separated into seven samples with three measurements per sample. The left-hand panels show all of the measurements; the right-hand panels show the measurements for each sample combined in a mean and standard deviation. The vertical bar at the far right of each panel is 0.1 % from top to bottom.

m) and n) Measurements averaged over the OLI 1611 nm band.

o) and p) Measurements averaged over the OLI 2201 nm band.

The measurements were made in the form of seven samples with three measurements for each sample. Between each sample, the ASD's fiber optic cable was moved away from the aperture of the NPR and then moved back. This simulated the movements expected during alternating measurements of two spheres. We know of anecdotal evidence of problems with the fiber optics, particularly their susceptibility to damage, leading to their replacement by Analytical Spectral Devices. As a result, we wished to investigate the possibility of problems with the fiber optics for the GSFC and NIST ASDs. Thus, the basic pattern for the measurements was three readings by the ASD over the period of half a minute, followed by a few minutes to move and realign the fiber optic. The entire process took about an hour.

The Jun 16 measurements were made with a sequence of A-B-A, where the B measurement is the sample to be tested and the average of the two A measurements forms the baseline. This sequence helps minimize the effects of a drift in the transfer instrument. At Ball, the A measurement would be of the NPR and the B measurement would be of the OLI sphere. The set of seven samples gives three A-B-A pairs. In the seven sample sequence used here, samples 2, 4, and 6

Table 1. Short-term stabilities for GSFC ASD measurements of the NPR. The results are calculated results for Eq. 2. The rightmost columns give the means and standard deviations for the differences. An outlier in the data set for the 2201 nm band has been removed from the calculation.

OLI Band	Diff($Sample_2$) (%)	Diff($Sample_4$) (%)	Diff($Sample_6$) (%)	Mean (%)	Std Dev (%)
443	0.143	0.262	0.286	0.230	0.063
483	0.090	0.185	0.206	0.160	0.051
562	0.015	0.060	0.075	0.050	0.025
590	0.012	0.056	0.070	0.046	0.025
655	0.002	0.040	0.052	0.032	0.022
865	-0.022	0.004	0.010	-0.002	0.014
1375	-0.023	0.009	0.008	-0.002	0.015
1611	-0.013	-0.003	0.005	-0.004	0.008
2201	-0.017	0.001	0.012	-0.001	0.012

Table 2. Short-term stabilities for NIST ASD measurements of the NPR. The results are calculated results for Eq. 2. The rightmost columns give the means and standard deviations for the differences. The data for these calculations are not shown in the body of the paper. An outlier in the data set for the 2201 nm band has been removed from the calculation.

OLI Band	Diff($Sample_2$) (%)	Diff($Sample_4$) (%)	Diff($Sample_6$) (%)	Mean (%)	Std Dev (%)
443	-0.075	-0.156	-0.263	-0.165	0.077
483	-0.076	-0.149	-0.272	-0.165	0.081
562	-0.069	-0.133	-0.269	-0.157	0.083
590	-0.059	-0.106	-0.241	-0.135	0.077
655	-0.053	-0.089	-0.195	-0.112	0.060
865	-0.058	-0.064	-0.199	-0.107	0.065
1375	-0.771	-0.819	-0.493	-0.695	0.144
1611	-0.643	-0.750	-0.310	-0.568	0.187
2201	-0.121	-0.061	-0.445	-0.209	0.169

are B measurements, and samples 1, 3, 5, and 7 are A measurements. Using this terminology, the percent difference of sample n (where n is 2, 4, or 6) from the baseline is

$$Diff\left(Sample_n\right) = 100\left(\frac{2Sample_n}{Sample_{n-1} + Sample_{n+1}} - 1\right) , \tag{2}$$

where the differences is given in percent. For the measurements presented here, all of the samples come from measurements of the NPR, so the ideal solution to Eq. 2 in this case is zero percent.

The short-term measurement of the NPR by the GSFC ASD are shown in Fig. 4. The left-hand panels show the twenty-one measurements with three measurements per sample. The right-hand panels show the means and standard deviations for each sample. On the far right-hand side of each panel is a vertical bar that extends 0.1 % from top to bottom. Each vertical bar gives a visual reference for the magnitude of the differences in the ASD counts. For the ASD measurements band-averaged over the OLI 443 nm band response, the results are given in panels a and b of Fig. 4a. The results for the OLI 483 nm band are given in panels c and d of Fig. 4b. The ASD results band-averaged for the other OLI bands are presented using this pattern in the other panels of Fig. 4. As with Figs. 2 and 3, the results for the 1375 nm cirrus band are not shown. There was no effort to determine the causes of the sample-to-sample patterns in Fig. 4, nor the differences in the standard deviations for the different bands. The purpose of these measurements was to provide an estimate of the stability of the spectrometers during the transfer of the calibration between the NPR and the OLI transfer sphere. The causes of the measurement artifacts remain unknown to us.

Table 1 summarizes the stability results for the GSFC ASD in terms of the calculated results for Eq. 2. As shown by the average difference for each band, the GSFC ASD is stable at better than the 0.25% level for this type of transfer between spheres. For the SWIR bands, which are of the most interest for the ASDs, the GSFC ASD is stable at better than the 0.05 % level. This is an indication of the contribution of the ASD stability to the uncertainty budget for a cross-calibration of the NPR and the OLI transfer sphere. The uncertainty budget for such a transfer is currently unknown to us as is the stability requirement. In addition, the effects on short-term stability caused by transporting the GSFC ASD to Ball Aerospace are unknown. Thus, the short-term stability results presented here should be treated as a proof-of-concept only.

Table 2 summarizes the stability results for the NIST ASD in the same manner as for the GSFC ASD in Table 1. The data behind Table 2 are not shown in this paper. In general, the NIST ASD is stable at the 0.25% level except for two of the SWIR bands. However, the stability of the NIST ASD SWIR bands is definitely inferior to that for the GSFC ASD. We have concluded that each ASD has its own performance characteristics, and that the characteristics for these spectrometers may not be representative of others. However, for both ASDs there was an outlying measurement in the 2201 nm region for sample 1 of their measurement sets. As a result, we plan to repeat the short-term stability measurements to look for a reoccurrence of this test artifact. In addition, these measurements will be used to examine the inconsistencies in the sample-to-sample measurements in Fig. 4. Although these consistencies are small, at the 0.1 % level, the cause for this feature in the measurements remains puzzling.

5. CONCLUDING REMARKS

Both the GSFC and NIST ASDs, along with other radiometers, participated in the initial measurements of the OLI transfer sphere immediately following its calibration at NIST in February 2010. A second set of measurements of the sphere is scheduled for the time of the calibration of OLI at Ball Aerospace. These radiometer measurements will be used to assess the drift in the OLI sphere during the intervening interval. The uncertainty budget for the calibration of OLI has a term of 0.5 % to cover this change in the sphere. A series of measurements of the NIST Portable Radiance source (NPR) by the two ASDs has been undertaken to check the long-term stability of the spectrometers assuming the NPR radiance was constant in time. Shortly after the initial measurements in February, the SWIR detector of the NIST ASD failed, requiring repair by its manufacturer. This eliminated the ability of the NIST ASD to track the changes in the OLI sphere independently. For the GSFC ASD, intermediate results from the series of NPR measurements have shown the ASD's variability for visible wavelengths to be less than 0.4 %. For the near- and shortwave-infrared, the ASDs variability ranges from about 1 % to 3 %. This is outside of the 0.5 % requirement from the OLI uncertainty budget. There is cause for concern, since NASA and NIST have no other radiometers in the SWIR. However, ASD measurements of the NPR will continue until the time of the set of radiometer measurements at Ball.

On June 16, 2010 a set of measurements was made of the NPR to approximate the conditions of a transfer of calibration between two integrating spheres, using the ASDs as transfer instruments. This transfer allows a comparison of the radiance from the NPR and the OLI sphere as an added check of the OLI sphere. The short-term stability of the instruments is a component in the uncertainty budget for the calibration of the OLI. The uncertainty budget for such a transfer at Ball is currently unknown, as is the stability requirement. However, the results of the June 16 measurements show the GSFC ASD to be stable in the transfer at better than the 0.25 % level and better than 0.04 % in the SWIR. In general the NIST ASD is also stable at better than the 0.25 % level except for two of the SWIR bands. Effects on short-term stability caused by transporting the ASDs to Ball Aerospace is also unknown, so the short-term stability results presented here should be considered as a proof-of-concept only.

REFERENCES

[1] Markham, B. L., Dabney, P. W., Murphy-Morris, J. E., Pedelty, J. A., Knight, E. J., Kvaran, G., and Barsi, J. A., "The Landsat Data Continuity Mission Operational Land Imager (OLI) radiometric calibration," IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Jul 25-30, Honolulu HI, 2010.

[2] Markham, B. L., Barker, J. L., Barsi, J. A., Kaita, E., Thome, K. J., Helder, D. L., Palluconi, F. D., Schott, J. R., and Scaramuzza, P., "Landsat-7 ETM+ radiometric stability and absolute calibration," Proc. SPIE, 4881, 308-318, 2003.

[3] Walker, J. H., Saunders, R. D., and Hattenburg, A. T., "Spectral Radiance Calibrations. NBS Special Publication SP250-1, U.S. Government Printing Office, Washington, DC, 1987.

[4] G. Kvaran, Ball Aerospace Corporation, private communication, 2010.

[5] Butler, J. J., Johnson, B. C., Brown, S. W., Saunders, R. D., Biggar, S. F., Zalweski, E. F., Markham, B. L., Gracey, P. N., Young, J. B., and Barnes, R. A., "Radiometric measurement comparison on the integrating sphere source used to calibrate the Moderate Imaging Spectroradiometer (MODIS) and the Landsat 7 Enhanced Thematic Mapper (ETM+)," J. Res. Natl. Inst. Stand. Technol, 108, 199-228, 2003.

[6] Butler, J. J., Johnson, B. C., Rice, J. P., Brown, S. W., and Barnes, R. A., "Validation of radiometric standards for the laboratory calibration of reflected-solar Earth observing satellite instruments," Proc. SPIE, 6677, 667707, 2007.

[7] Identification of commercial equipment does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

[8] Brown, S. W. and Johnson, B. C., "Development of a portable integrating sphere source for the Earth Observing System's calibration validation programme," Int. J. Remote. Sens., 24, 215-224, 2003.