Tracking on-orbit stability of the response versus scan angle for the S-NPP VIIRS reflective solar bands

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ABSTRACT

The Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP (National Polar-orbiting Partnership) satellite *(http://npp.gsfc.nasa.gov/viirs.html)* has been in operation for nearly five years. The on-board calibration of the VIIRS reflective solar bands (RSB) relies on a solar diffuser (SD) located at a fixed scan angle and a solar diffuser stability monitor (SDSM). The VIIRS response versus scan angle (RVS) was characterized prelaunch in ambient conditions and is currently used to determine the on-orbit response for all scan angles relative to the SD scan angle. Since the RVS is vitally important to the quality of calibrated level 1B products, it is important to monitor its on-orbit stability. In this study, the RVS stability is examined based on reflectance trends collected from 16-day repeatable orbits over pre-selected pseudo-invariant desert sites in Northern Africa. These trends nearly cover the entire Earth view scan range so that any systematic drifts in the scan angle direction would indicate a change in RVS. This study also compares VIIRS RVS on-orbit stability results with those from both Aqua and Terra MODIS over the first four years of mission for a few selected bands, which provides further information on potential VIIRS RVS on-orbit changes.

Keywords: VIIRS, Suomi NPP, calibration, on-orbit, reflective solar bands

1. INTRODUCTION

The Visible Infrared Imaging Radiometer Suite (VIIRS) [1-4], built on strong heritage of the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor, on the Suomi NPP (National Polar-orbiting Partnership) satellite (http://npp.gsfc.nasa.gov/viirs.html) has been in operation for nearly five years. It uses a constant-rate rotating telescope assembly (RTA) and a double sided half angle mirror (HAM) rotating at half the speed of the RTA. VIIRS has 22 bands with a spectral range from 0.4 to 12.0 µm (see Table 1). The Earth view swath covers a distance of ~3000 km over scan angles of ± 56.0^{o} off nadir. Observations by VIIRS cover the entire Earth's surface every one or two days and the derived products provide high quality environmental and climate information for land, ocean, and atmosphere.

The VIIRS on-board calibration components include a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) for the reflective solar bands (RSB), a V-grooved blackbody for the thermal emissive

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bands, and a space view (SV) port used to remove background signal from the raw response [5-8]. The SD and blackbody provide absolute calibration with standards traceable to those provided by the National Institute of Standards and Technology (NIST). Since both the SD and blackbody are located at fixed angles of incidence (AOI), the calibration at other AOIs requires an RVS correction that describes relative changes to those obtained at the on-board calibrator AOI. Thus, RVS characterization and on-orbit monitoring of its change is vitally important to ensure the quality of the calibrated radiance product.

The VIIRS RSB RVS was characterized at prelaunch in lab ambient conditions [9-11]. These tests were conducted at a number of different scan angles to ensure a good description of the RVS over the entire scan-angle range. Since there are certain radiometric requirements from prelaunch to on-orbit calibration, any changes in on-orbit RVS need to be accounted for in order to maintain the quality of the calibrated product. One major concern for the on-orbit RVS stability is the degradation of the scan mirror, which is mainly in the blue wavelength region due to the mirror-coating surface, as it is exposed to the UV light. The degradation of the scan mirror is AOI dependent and thus it affects the shape of RVS. For MODIS RSB, it is observed that the RVS for both mirror sides have been degrading throughout the mission [12-13]. In the case of VIIRS on-orbit RVS, the VIIRS design uses the four-mirror RTA in front of the HAM. Since the RTA absorbs most of the UV light before reaching the HAM surface, it is expected that the VIIRS on-orbit RVS is more stable than MODIS. Another advantage to the VIIRS optical design is that the HAM rotates at half the speed of the RTA. Thus, the Earth view (EV) range of AOI for VIIRS is between 28.6^o and 56.5^o, which is a 28^o change in AOI. This is corresponding to only about half the range of MODIS, although the corresponding scan angle range for both sensors is nearly the same. Currently, there is no adjustment to the VIIRS on-orbit RVS in the calibrated sensor data record (SDR) product. In comparison, the MODIS on-orbit RVS changes are characterized with a linear approximation in Collection-5 L1B using SD and lunar measurements acquired at two separate AOIs. In Collection-6, observations from a number of CEOS (Committee on Earth Observation Satellites) endorsed pseudo-invariant desert sites *(http://calvalportal.ceos.org/ceos-landnet-sites)*, in addition to the SD and lunar data, are used to describe the nonlinear changes in RVS.

The purpose of this study is to examine the stability of VIIRS RVS after four years of mission. It is expected that the VIIRS RVS performance is more stable than MODIS over the same four-year mission period due to an improved design in the optics. The top-of-atmosphere (TOA) reflectance trends over the CEOS endorsed pseudo-invariant desert sites from both VIIRS and MODIS are used to examine the temporal stability at a wide range of scan angle. To better illustrate on-orbit degradation problems in RVS, the TOA reflectance trends from MODIS are re-derived using only the prelaunch RVS and compared with the trends from VIIRS. This will help understand if there are possible degradations or potential future changes in VIIRS RVS.

Table 1. List of central wavelength (CW) and bandwidth (BW) for VIIRS/MODIS spectrally matched RSB in the visible and near-infrared wavelength region (units in nm)

VIIRS RSB			MODIS RSB		
Band	**CW (nm)**	**BW**	**Band**	**CW (nm)**	**BW**
M1	412	20	B8	412	15
M2	445	18	B9	443	10
M3	488	20	B10	488	10
M4	555	20	B4	555	20
M5	672	20	B1	645	50
M6	746	15	B15	748	10
M7	865	39	B2	858	35
M8	1240	20	B5	1240	20
M9	1378	15	B26	1375	30
M10	1610	60	B6	1640	24
M11	2250	50	B7	2130	50
I1	640	80	B1	645	50
I2	865	39	B2	858	35
I3	1610	60	B6	1640	24

Suomi NPP VIIRS

Scanning radiometer

22 bands between 0.4 and 12 µm

Afternoon polar orbit

Swath distance of 3000 km

Nadir resolutions: 0.37, 0.74 km

Launched Oct 28, 2011

Terra/Aqua MODIS

Scanning radiometer

36 bands between 0.4 and 14 µm

Morning/afternoon polar orbits

Swath distance of 2330 km

Nadir resolutions: 0.25, 0.5, 1.0 km

Launched Dec 1999 & May 2002

2. METHODOLOGY

The calibration of both VIIRS and MODIS RSB is performed using a sunlight illuminated SD to convert the instrument response to a radiometrically calibrated spectral radiance [5-7, 12]. The retrieval of the radiance from VIIRS is given by

$$L_{EV} = F\,(a_0 + a_1 dn_{EV} + a_2 dn_{EV}^2)/RVS_{EV} \qquad (1)$$

where L_{EV} is the spectral band radiance at the time of the EV measurement, the calibration coefficients a_0, a_1 and a_2 are determined prelaunch and corrected for any instrument temperature variation effect, dn_{EV} is the background subtracted EV digital response, and the scale factor F would be 1.0 if the instrument performs identically as in the prelaunch conditions. As the instrument's response changes onorbit, the value of F differs from 1.0.

MODIS level 1B RSB primary data product is the reflectance factor $\rho_{EV}cos(\theta_{EV})$, which is given by

$$\rho_{EV}cos(\theta_{EV}) = m_1 dn_{EV}(1 + k_{inst}\Delta T)\, d_{ES}^2/RVS_{EV} \qquad (2)$$

where θ is the solar zenith angle, m_1 is the calibration coefficient determined from the measured SD and SDSM signals, d_{ES} is the Earth-Sun distance in AU, k_{inst} represents the relative dependence of the digital response on the instrument temperature, ΔT is the difference of the instrument temperature relative to the reference temperature, and RVS is the response versus scan angle of EV normalized at the angle of incidence (AOI) of the SD.

The RVS term in both equations (1) and (2) can be further expressed as the following

$$RVS_{EV} = RVS_{PL} RVS_{OBT} \tag{3}$$

where RVS_{PL} is the RVS characterized prelaunch in lab ambient conditions and the RVS_{OBT} is the relative change on-orbit in RVS. If the RVS of the instrument does not show any on-orbit change, the value of RVS_{OBT} would be 1.0.

Currently, there is no on-orbit correction for the VIIRS RVS. Thus, the value of RVS_{OBT} is 1.0 for VIIRS. In the case of MODIS RVS, the correction for the on-orbit change starts from the beginning of mission. In order to identify potential on-orbit changes in VIIRS RVS, the TOA reflectance trends from the CEOS endorsed pseudo-invariant test sites, including the Libya-4 desert site (Figure 1), are used to examine their stability at various scan angles. The TOA reflectance trends from both Terra and Aqua MODIS over the first four-year mission are re-derived using the prelaunch-based RVS (i.e., set $RVS_{OBT} = 1$) and compared with those from VIIRS.

The TOA reflectances are collected from 16-day repeatable orbits and corrected by a site-specific bi-directional reflectance distribution function (BRDF) with coefficients derived using observations from the first year of the VIIRS mission and the first three years of both the Terra and Aqua missions. The BRDF model is developed based on the two-kernel driven functions [14-16]

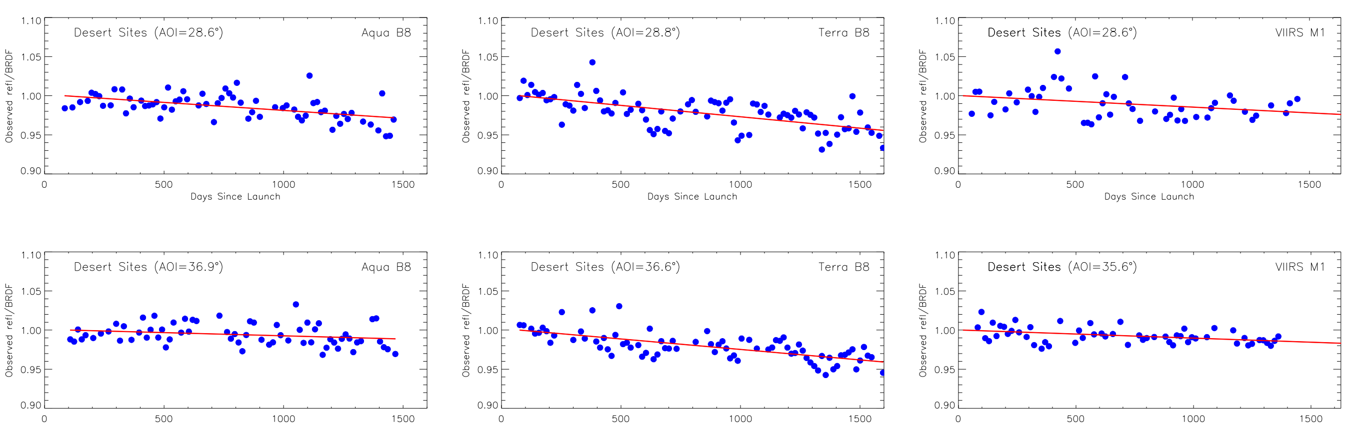
$$R^i(\theta,\varphi,\psi) = K_0^i + K_1^i f_1(\theta,\varphi,\psi) + K_2^i f_2(\theta,\varphi,\psi) \tag{4}$$

where R is the anisotropic reflectance factor defined as π times the ratio of radiance reflected into a particular direction to the reflected flux, θ, φ and ψ are the solar zenith, view zenith and relative azimuth angles, i is the index for the band wavelength, f_1 is derived from the volume scattering component, and f_2 is the component from surface scattering and geometric shadow casting theory. Coefficients K^i_0, K^i_1 and K^i_2 are given as functions of parameters related to the physical structure and optical properties of a reflecting surface in the original model. To the first approximation, it can be assumed that K^i_0, K^i_1 and K^i_2 are dependent on surface conditions.

Figure 1. A Google picture of the area surrounding the Libya-4 (28.55°N, 23.39°E) site and a zoomed picture of the site.

3. RESULTS

Figure 2 shows the stability of reflectance trends during the first four years of mission for both Aqua and Terra MODIS band 8 and NPP VIIRS M1 at three separate AOI angles of around 28°, 36° and 53°, respectively. As described in the methodology of this study, the trends for MODIS are derived using its prelaunch-based RVS to be consistent with the current use of the RVS in the VIIRS RSB calibration. Results at AOI of 28° (the first row of plots) indicate a downward drift for all three sensors with Terra being the most noticeable, while Aqua and VIIRS are comparable. At the near-nadir view angle AOI of 36° (the second row of plots), results are still trending downward but with a reduced slope, particularly for Aqua and VIIRS. At AOI of 53° (the last row of plots), both Terra and VIIRS show an upward trend, while Aqua is generally flat. These results indicate that there is an on-orbit RVS change for all three sensors and Terra MODIS shows the largest change. Between AOI of 28° and 53°, the relative change in the stability at the end of the four-year period is 3.0% for Aqua, 7.5% for Terra and 3.5% for VIIRS, respectively.



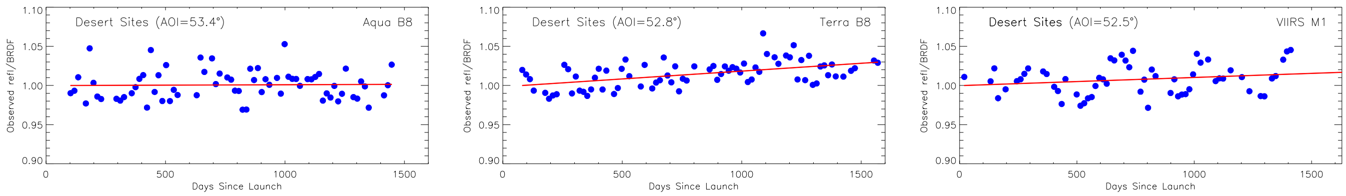


Figure 2. Trends of reflectance during the first four years of mission for Aqua and Terra MODIS band 8 and NPP VIIRS M1 at three separate AOI angles. The reflectances are collected from 16-day repeatable orbits over the CEOS endorsed pseudo-invariant desert sites and corrected by the site-specific BRDF.

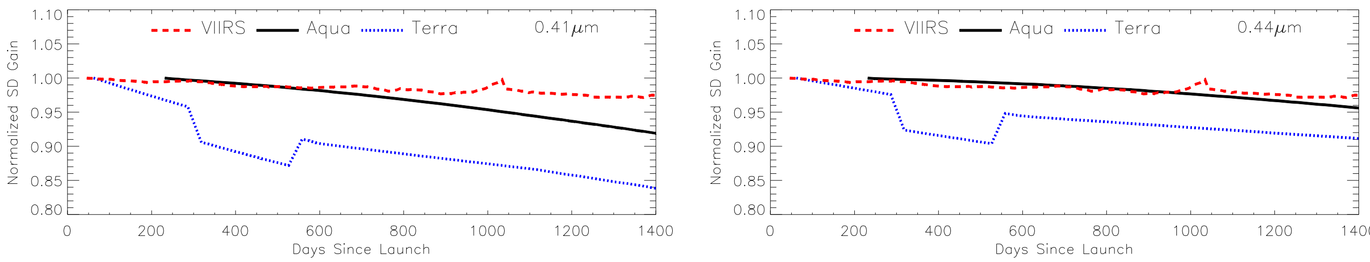


Figure 3. Trends of the normalized gain from the VIIRS, Aqua and Terra SD during the first four years of mission for the 0. 41 and 0.44μm bands. Note that Terra MODIS has electronic configuration changes on day 305 and day 550.

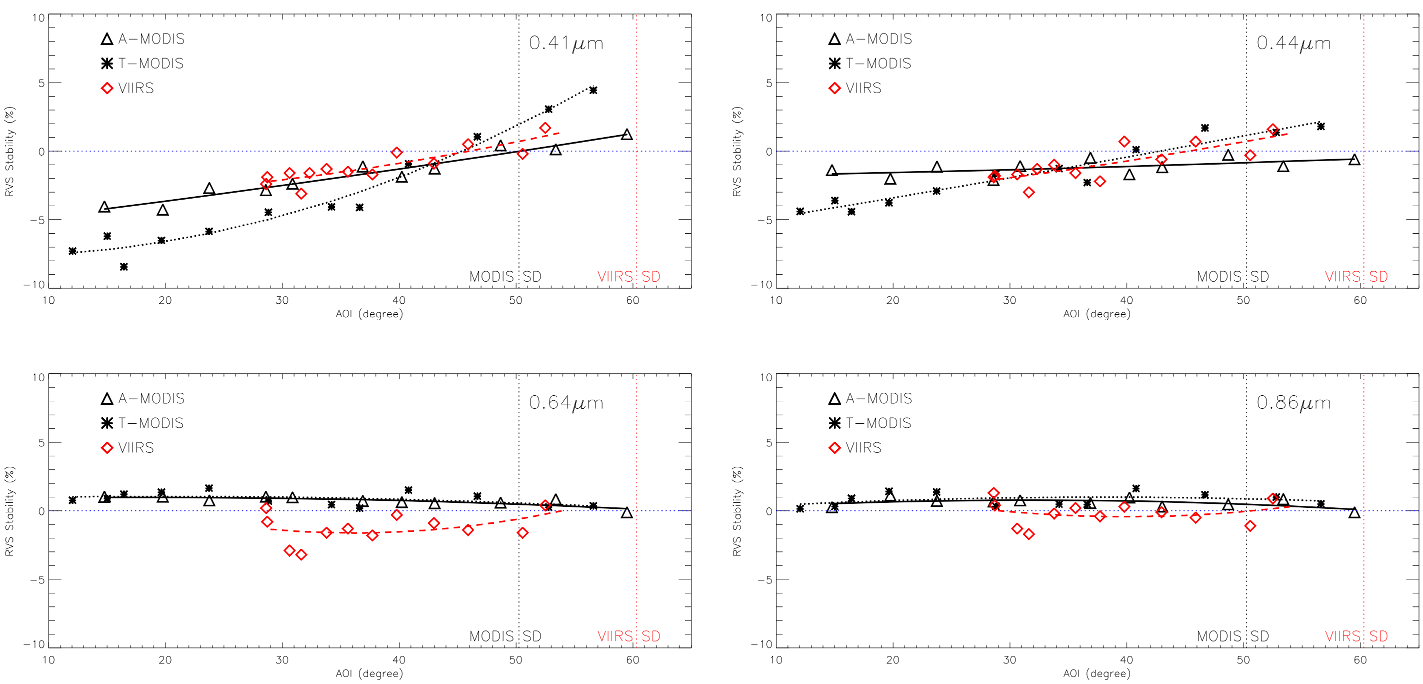
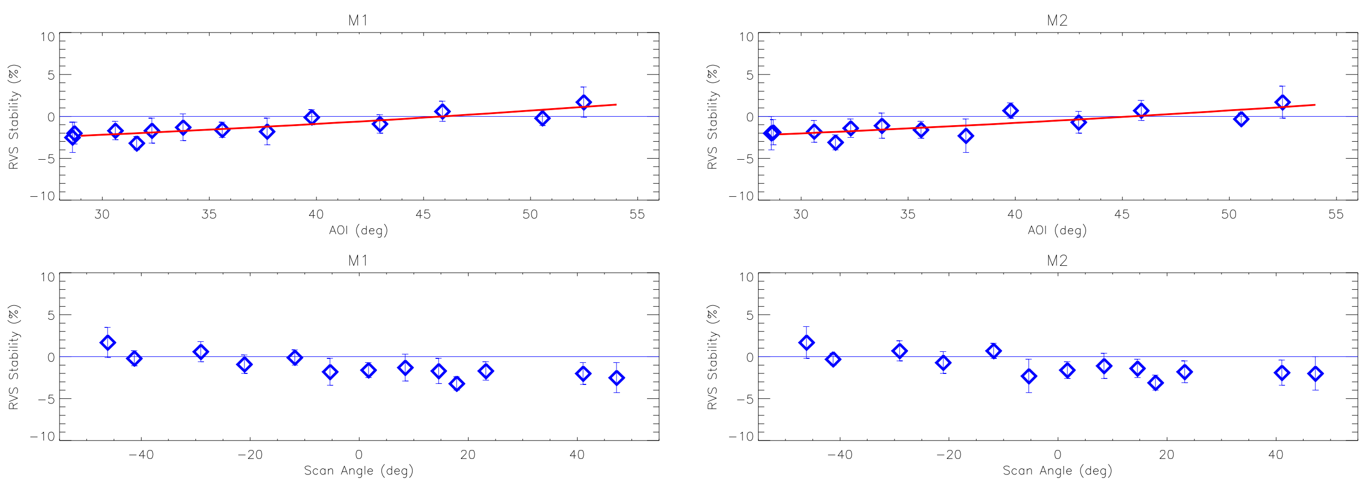


Figure 4. Comparison of the RVS stability among Aqua and Terra MODIS and NPP VIIRS after the first four years of mission for the 0. 41, 0.44, 0.64 and 0.86μm bands. The stability results are based on the linear fit to the data collected during the defined periods.

Comparison of on-orbit optics degradation among VIIRS, Aqua and Terra for the 0.41 and 0.44µm bands is shown in Figure 3. All three sensors show a downward drift in gain, with the most noticeable drift in Terra. Since the gain trends are derived based on the SD measurements at a fixed AOI of 50.3° for MODIS and 60.2° for VIIRS, they do not provide any information on the degradation dependent on AOI. However, if the VIIRS gain trends show a similar on-orbit performance with those from MODIS, it is likely that its RVS could have similar on-orbit issues as MODIS. To further compare the RVS stability among the three sensors, the stability results of the first four years of mission determined based on the linear fit are plotted versus AOI (Figure 4). The results are shown for four spectral bands at 0.41, 0.44, 0.64 and 0.86µm, corresponding to VIIRS M1, M2, I1 and I2, respectively. The reason that the Earth view range of AOI for VIIRS is about half of MODIS is due to its use of a HAM rotating at half the speed of the RTA. This allows the VIIRS scan mirror to rotate over an Earth view scan angle range between -55° and +55° for an AOI range from 28.6° to 56.5°, compared with an AOI range of 10.5° to 65.5° for MODIS. Figure 4 indicates that even with only half of the MODIS AOI range, the two shortest wavelength bands (M1 and M2) of VIIRS show an on-orbit RVS change of up to 3% after the four-year mission. In comparison with the stability results from MODIS over the same AOI range, VIIRS agrees well with Aqua MODIS at 0.41µm and Terra MODIS at 0.44µm, respectively. For the longer wavelength bands at 0.64 and 0.84µm, all three sensors do not show any noticeable drift in RVS.



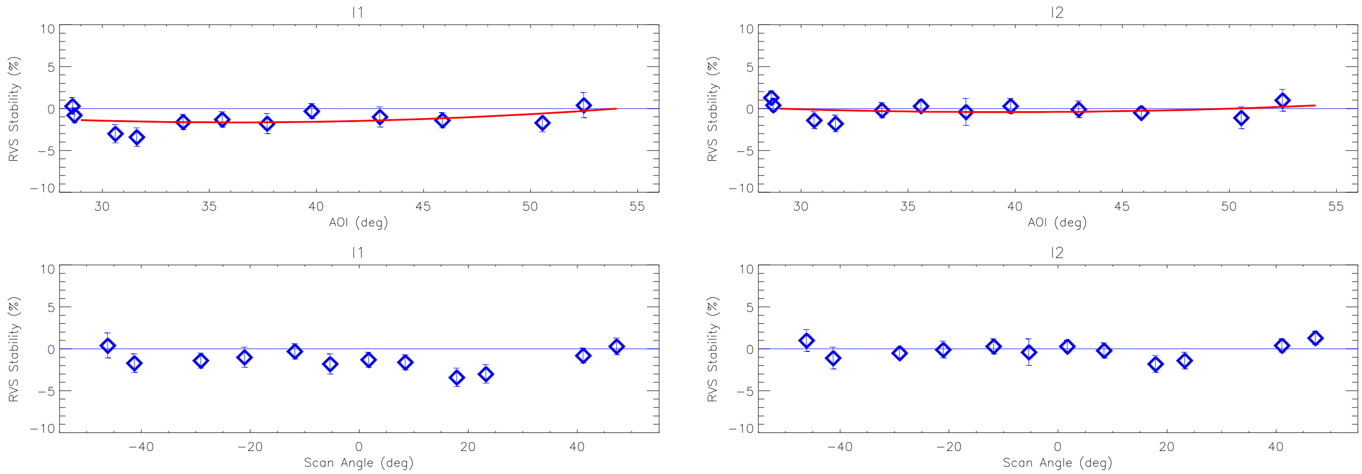


Figure 5. VIIRS RVS stability after the first four years of mission as a function of AOI and scan angle for M1, M2, I1 and I2.

Figure 5 shows the stability of VIIRS RVS for M1, M2, I1 and I2 after the first four years of mission plotted versus AOI and scan angle. Results indicate that data from near nadir is less affected by the RVS drift, while a comparison of data between the beginning and the end of the scan would reveal a more potential problem due to the RVS drift for M1 and M2, which is up to 3%. Examination of VIIRS RSB indicates that M1 to M3 may have the RVS drift and all other bands show no noticeable drifts. Compared with MODIS RVS performance during the first four years of mission, however, the RVS drifts are much smaller due to its use of a half angle mirror.

4. SUMMARY

RVS is an important calibration parameter to the quality of the VIIRS SDR product. The VIIRS RVS was characterized prelaunch in lab ambient conditions and is currently used to determine the on-orbit response for all scan angles relative to the SD scan angle. This study examines the VIIRS RVS on-orbit stability after its four-year mission based on reflectance trends collected from 16-day repeatable orbits at a wide range of scan angles over pseudo-invariant desert sites in Northern Africa. The trending results are compared with those from both Terra and Aqua MODIS over their first four-year missions, re-derived using the prelaunch RVS. The comparison among results from VIIRS, Terra and Aqua MODIS indicates that all three sensors show a similar on-orbit change in RVS at the shortest wavelengths. Within the AOI range of 28^{o} and 56^{o} that covers the entire Earth view swath for VIIRS, the largest relative change in the stability at the end of the four-year period is 3.0% for Aqua, 7.5% for Terra and 3.5% for VIIRS, respectively. Examination of all VIIRS RSB indicates that there is an RVS drift for M1 to M3, while all other bands show no noticeable drift. However, because of the use of a half angle mirror on VIIRS, the RVS drifts across the entire Earth view scan range is much smaller than that of both Terra and Aqua MODIS.

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