JPSS-1/NOAA-20 VIIRS early on-orbit geometric performance

Guoqing Lin, Robert E. Wolfe, James C. Tilton, Ping Zhang, John J. Dellomo, et al.

Guoqing Lin, Robert E. Wolfe, James C. Tilton, Ping Zhang, John J. Dellomo, Bin Tan, "JPSS-1/NOAA-20 VIIRS early on-orbit geometric performance," Proc. SPIE 10764, Earth Observing Systems XXIII, 107641H (7 September 2018); doi: 10.1117/12.2320767

Event: SPIE Optical Engineering + Applications, 2018, San Diego, California, United States

JPSS-1/NOAA-20 VIIRS early on-orbit geometric performance

Guoqing (Gary) Lin*[a,b], Robert E. Wolfe[b], James C. Tilton[b], Ping Zhang[a,b], John J. Dellomo[c,b], Bin Tan[a,b]

[a]Science Systems and Applications, Inc., 10210 Greenbelt Road, Lanham, MD 20706, USA;
[b]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA;
[c]Global Science & Technology, Inc., 7855 Walker Drive, Greenbelt, MD 20770, USA

ABSTRACT

The first NOAA/NASA Join Polar Satellite System (JPSS-1) satellite was successfully launched on November 18, 2017, becoming NOAA-20. Instruments on-board the NOAA-20 satellite include the Visible Infrared Imaging Radiometer Suite (VIIRS). This instrument is the second build of VIIRS, with the first flight instrument on-board NASA/NOAA Suomi National Polar-orbiting Partnership (SNPP) satellite operating since October 2011. The purpose of these VIIRS instruments is to continue the long-term measurements of biogeophysical variables for multiple applications including weather forecasting, rapid response and climate research. The geometric performance of VIIRS is essential to retrieving accurate biogeophysical variables. This paper describes the early on-orbit geometric performance of the JPSS-1/NOAA-20 VIIRS. It first discusses the on-orbit orbit and attitude performance, a key input needed for accurate geolocation. It then discusses the on-orbit geometric characterization and calibration of VIIRS and an initial assessment of the geometric accuracy. It follows with a discussion of an improvement in the instrument geometric model that corrects small geometrical artifacts that appear in the along-scan direction. Finally, this paper discusses on-orbit measurements of the focal length and the impact of this on the scan-to-scan underlap/overlap.

Keywords: JPSS-1, NOAA-20, SNPP, VIIRS, pointing, geolocation, DNB, focal length

1. INTRODUCTION

The NASA/NOAA Visible Infrared Imaging Radiometer Suite (VIIRS) instrument onboard the Suomi National Polar-orbiting Partnership (SNPP) satellite has performed well on-orbit[1,2,3,4] since it was launched in October 2011. A second VIIRS instrument onboard the first Joint Polar Satellite System (JPSS-1, J01 or J1) spacecraft was launched on November 18, 2017, that became NOAA-20 (or N20), the latest addition to the NOAA Polar Orbiting Environmental Satellite (POES) fleet. The nominal design of this second instrument is the same as the first one onboard the SNPP spacecraft, with some minor differences in the as-built parameters[5]. These missions are expect to produce reliable and accurate geolocated and calibrated sensor data records (SDRs) for retrieving accurate geophysical variables for both the long-term monitoring and operational communities. This paper describes the geometric performance of the VIIRS instrument in early on-orbit checkout and post-launch test (PLT), part of the commissioning phase, as well as the early on-orbit performance. Section 2 discusses the on-orbit orbit and attitude data performance, a key input needed for accurate geolocation. Section 3 then discusses the on-orbit geometric characterization and calibration of VIIRS geometry and an initial assessment of the geometric accuracy. This section includes a discussion of an improvement in the geometric model that corrects small geometrical artifacts that appear in the along-scan direction. Section 4 discusses on-orbit measurements of the focal length and the impact of this on the scan-to-scan underlap/overlap. Lastly, section 5 is the conclusion and discussion of possible future work.

----
*Gary.Lin@nasa.gov; glin@ssaihq.com; phone 301-614-5451; fax 301-614-5269; www.ssai.org

Earth Observing Systems XXIII, edited by James J. Butler, Xiaoxiong (Jack) Xiong, Xingfa Gu, Proc. of SPIE Vol. 10764, 107641H · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2320767

2. SPACECRAFT ORBIT AND ATTITUDE VERIFICATION

The spacecraft orbit position, velocity, and attitude are fundamental in establishing the VIIRS line-of-sight and calculating the earth location (geolocation) of every observation. We first checked these as they were downlinked the very first time on 21 November 2017 using an off-line tool we developed and have been using for SNPP. The first complete orbit in the dataset was on 20 November 2017, two days after its launch on 18 November 2017, 9:47 UTC. The calculated altitude and attitude for this orbit are shown in Figure 1. The altitude was about 8 km below its nominal value of 839 km (Figure 2a). This was because J1 (NOAA-20 or N20) spacecraft was planned to be in the same orbital plane as the SNPP spacecraft in the inertial frame of reference and a half orbit or 50.75 minutes ahead of SNPP. J1 was initially inserted into the orbit below and behind SNPP. As the velocity of J1 was faster at the beginning, it gradually caught up with SNPP and flew ahead until about 50 days later when they had near-constant separation and in the same orbit configuration, including altitude and velocity (Figure 2). In that process, functional tests of the spacecraft and instruments were performed, in addition to orbit configuration adjustments in inclination and altitude. The final orbit altitude adjustment was performed on Day 49 (from the first day of launch), 6 January 2018 (Figure 2), which was very small compared to the one before that on Day 38, 26 December 2017.

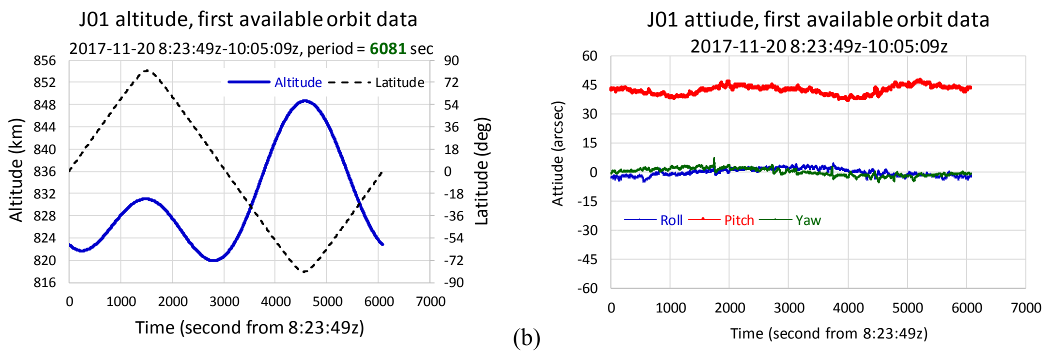

Fig. 1. Altitude of J1 in the first orbit (a) and attitude calculated using an off-line tool used in SNPP (b).

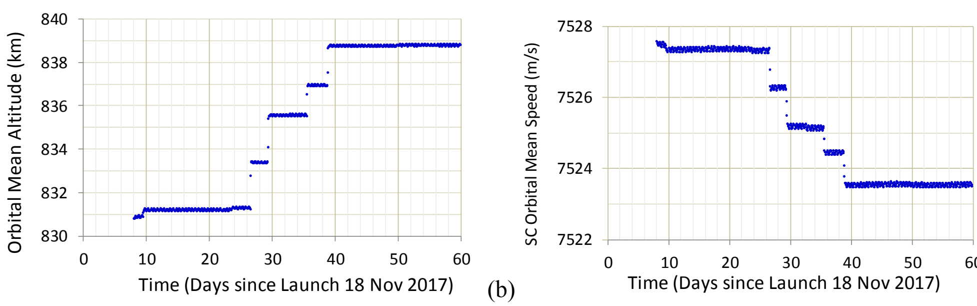

Fig. 2. Orbit mean altitude (a) and velocity (b) in the first 60 days after J1 launch.

The attitude calculated using the off-line tool showed an offset in pitch of about 40 arcsec. Examination of the time tags in the spacecraft diary data revealed that there was a 0.1-second time difference in the ephemeris (orbit) data and quaternion (attitude) data as shown at Points a and b in Figure 3. SNPP spacecraft data did not have such a difference and so the off-line tool assumed that the time tags had the same value. We then changed the off-line tool, using the time tag for the quaternion to interpolate the ephemeris data to Point c and recalculate attitude as shown in Figure 4a. This was the same as was done in the ground operational processing system, the JPSS Interface Data Processing Segment (IDPS). After the fix, the pitch offset became about 20 arc-seconds. Communications with the spacecraft vendor revealed that the flight software (FSW) used ephemeris data at Point d to control and command the attitude 0.1 second later at Point a. That 0.1-second time difference is equivalent to 21.3 arc-seconds on average, the inertial pitch-rate needed for the spacecraft to point to nadir as it circles the earth. So, a spacecraft lookup-table was uploaded on 7 February 2018 to change the control frame of reference that results in near-zero attitude values as computed by the ground software by referencing ephemeris data at the interpolated Point c (Figure 4b). The correction changed the appearance of attitude performance with an insignificant impact on geolocation (see Figure 7 where no discontinuity exists before and after 7 February 2018, Year 18.10 after year 2000).

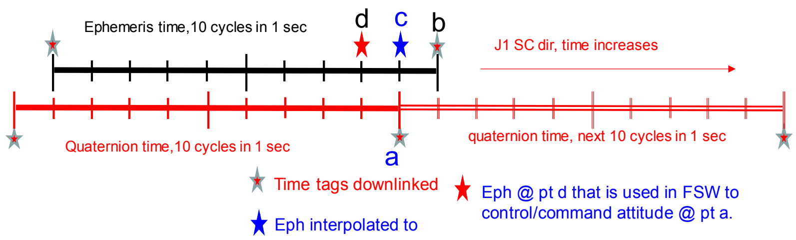

Figure 3. Illustration of time tags and other possible moment of time used in attitude control and calculation.

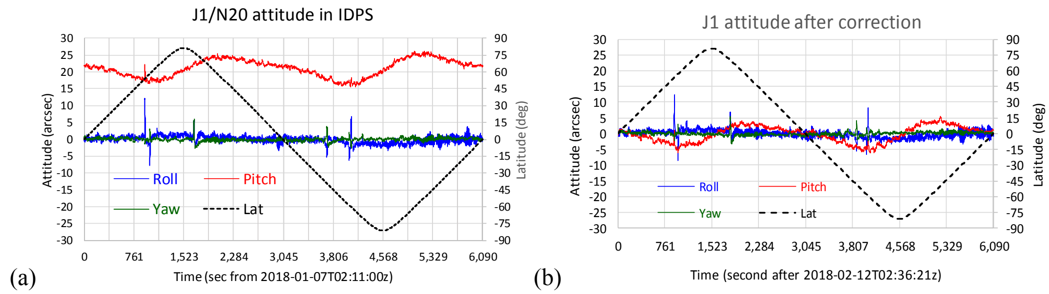

Figure 4. Attitude calculated by ground SW before (a) and after (b) a correction in the FSW.

3. EARLY ON-ORBIT GEOLOCATION CALIBRATION

The nadir door of the VIIRS instrument was open on 13 December 2017, seeing the first light from the visible and near-infrared (VisNIR) bands of I1, I2 and M1 to M7. Datasets were processed using coefficients in look-up tables (LUTs) from pre-launch measurements and tests. Band I1 radiometric and geolocation datasets were used to assess geolocation accuracy through a control point matching (CPM) program that has been used for SNPP VIIRS geolocation error characterization and correction[1,2]. The CPM program was originally developed to accurately measure MODIS geolocation errors and bias corrections[6] using a library of globally distributed ground control point (GCP) chips of Landsat red band 30 m resolution 800 by 800-pixel clear sub-scenes. It was modified for use to measure VIIRS geolocation errors and bias corrections using the same library of control points. Before the launch of J1, the VIIRS CPM program was improved so that there were more match-ups. The main improvement was in handling the boundaries between the scans in the track direction and between the aggregation zones in the scan direction. The effect of this improvement for SNPP is shown in Figure 5b, where the number of matches increases as the absolute values of scan angles increases. In contrast, the prior version of the VIIRS CPM program missed many matches where the absolute values of scan angle is greater than 45^o.

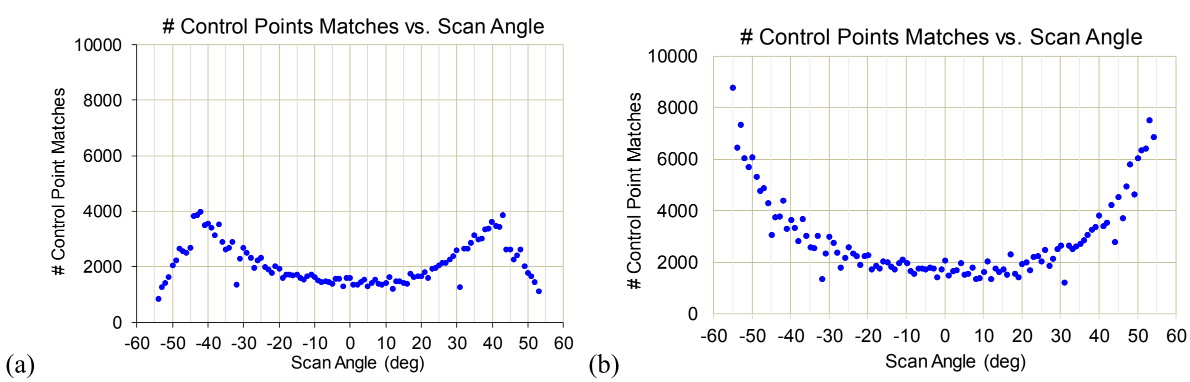

Fig. 5. Control point matches as a function of scan angle. (a) Matches from the original VIIRS CPM code for about 6 years from the beginning of the SNPP VIIRS mission up to October 2016. (b) Matches from the improved CPM code for about 7 years up to May 2018

This improved CPM code was used to measure the NOAA-20 VIIRS geolocation errors. Also, the CPM step size was increased from nominal 0.05 I1 sampling intervals to 0.2 sampling intervals at the beginning of the on-orbit operations, in anticipation of possible large geolocation errors right after launch. The CPM program uses a search area 50 steps in all four directions. Combined with the 0.2 step size, it can measure geolocation errors up to 3750 m nadir equivalent in the positive and negative scan and track directions. The measurements from the first data-day did indicate that there were large geolocation errors, -897 m in the track direction and 1710 m in the scan direction (Figure 6)

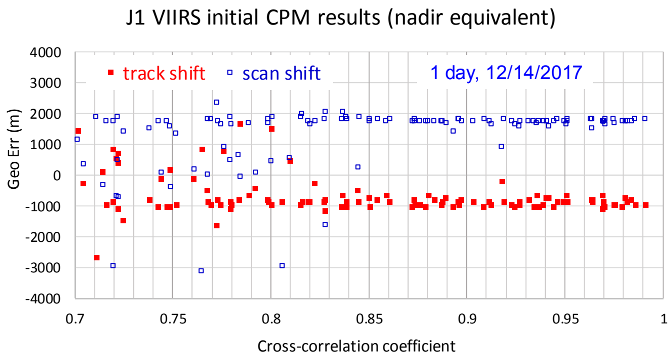

Fig. 6. J1 VIIRS geolocation error measurement results for a single day after the first light.

The above results were obtained from the VIIRS CPM program executed at NASA's VIIRS Land Science Investigator-led Processing System (SIPS). This program is also run at NOAA/JPSS Government Resources for Algorithm Verification Independent Test and Evaluation (GRAVITE) and by NOAA Center for Satellite Applications and Research (STAR) colleagues at their facility. All three results were similar. Corrections for the geolocation biases were made in both Land SIPS and IDPS by updating values in geolocation parameter lookup-tables (LUTs). After the first revision of the LUTs, the CPM step size was returned to nominal 0.05 I1 sampling intervals to enable measurements at a finer resolution. Our NOAA colleagues also used point sources to measure the VIIRS Day-Night Band (DNB) geolocation errors and made additional corrections to the LUTs. Two revisions of the LUTs have been made so far, both in the IDPS and Land SIPS.

The Land SIPS team has helped us reprocess geolocation in two revisions, r1 and r2 as listed in Table 1. Roll, pitch and yaw are the instrument-to-spacecraft mounting rotation angles. Alpha, beta and gamma are the VIIRS Half-angle Mirror (HAM) wedge angles and HAM motor axis angle. DNB Focal Plane Assembly (FPA) x-offset corresponds to best estimate in the scan direction. Readers may find better explanation of these parameters in VIITS Geolocation Algorithm Theoretical Basis Document (ATBD)[7]. The "At-launch" values represent the best estimates of these parameters before launch. NOAA STAR colleagues made the first revision (r1) for the value of the DNB offset using point source, while we refined that value in the second revision using Landsat 8 data in image matching (see Section 4 below).

Table 1 also lists a test case of the VIIRS Instrument Geometric Model Update (VIGMU). Re-analysis of VIIRS pre-launch geometric test data and in-depth analysis of SNPP VIIRS geolocation error pattern indicate the need to update the VIIRS instrument geometric model. More details will be described later. However, this test led to some change in the instrument-to-spacecraft mounting rotation angles, mainly in the roll (scan) direction, as we can see from the values in the fourth and fifth columns in Table 1.

Table 2 lists the geolocation errors statistic. As we can see, the geolocation errors were greatly reduced after the first revision, from the order of 1000s of meters to biases of 10s of meters and uncertainties (root-mean-square errors, or RMSEs) of not more than 80 meters. In the second revision, the uncertainties were reduced to about 60 meters, but the overall biases increased, because of slowly varying VIIRS line-of-sight pointing (see Figure 8). The VIGMU tested geolocation for 32 data-days had the best performance.

Table 1. Original and revised values of J1 VIIRS geolocation parameters used in various LUTs.

Parameters	**At-launch**	**Land SIPS r1** 2018-01-03*	**Land SIPS r2** 2018-03-14*	**VIGMU** tested	**Deltas: "VIGMU" minus "At-launch"**
Roll (")	0.9	-423.5	-422.9	-363.6	-364.5
Pitch (")	51.1	300.5	298.5	295.4	244.3
Yaw (")	80.5	99.4	111.4	112.6	32.1
Alpha (")	3.9	3.9	-4.4	9.2	5.3
Beta (")	9.5	9.5	9.5	-15.9	-25.4
Gamma (")	-6.0	-6.0	1.0	-2.6	3.4
DNB FPA x-offset (m)	0.00000	-0.00380	-0.00403	-0.00403	-0.00403

*NASA Land SIPS re-processed all data using the revised r1 and r2 geolocation parameter LUTs up to the points when the new LUTs were implemented in the forward-processing data stream.

Table 2. J1 VIIRS geolocation errors statistics (nadir equivalent).

Parameters	**At-launch**	**Land SIPS r1** 2018-01-03*	**Land SIPS r2** 2018-03-14*	**VIGMU** tested
Scan mean error (m)	1710	-3.4	-26.2	0.4
Track mean error (m)	-897	14.3	6.7	-0.9
Scan RMSE (m)		53.8	60.0	52.7
Track RMSE (m)		79.5	61.0	59.5
Data-span (days)	1	70	234	32
DNB geolocation accuracy (m)#	~5000	~300	~100	~100

*NASA Land SIPS re-processed all data using the revised r1 and r2 geolocation parameter LUTs up to the points when the new LUTs were implemented in the forward-processing data stream.
Spot checking only for DNB geolocation.

The longest time series so far for the J1 VIIRS geolocation error measurements is from revision r2. Figure 7 shows the daily means and standard deviations of the geolocation errors in the track and scan directions in nadir equivalent units. The daily geolocation uncertainty (standard deviation plus or minus mean for the corresponding day) are mostly within 125 m, meeting the requirement of 375 m 99.73% of the time (3σ). However, there are drifts of the daily means up to about 50 m in both track and scan directions. These drifts can be traced back to the pointing variations of the VIIRS instrument. Figure 8 shows the rotation angles that would be needed to correct the pointing variation at the instrument to spacecraft mounting interface. These values are calculated every four days based on 16 days of data. A correction that will remove most of this variation is planned for a future re-processing. The magnitude of the fluctuation is about 60 m, peak-to-peak for about 8 months of the J1 VIIRS mission so far.

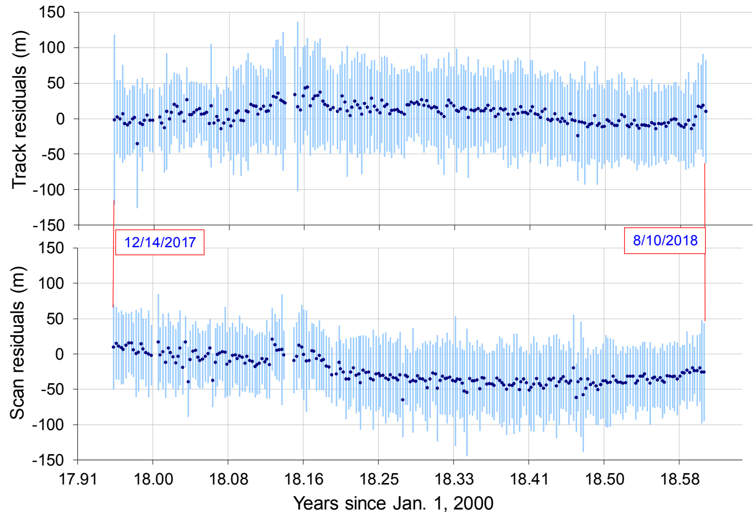

Fig. 7. Trends of J1 VIIRS geolocation errors (nadir equivalent daily mean and standard deviation) up to mid-August 2018.

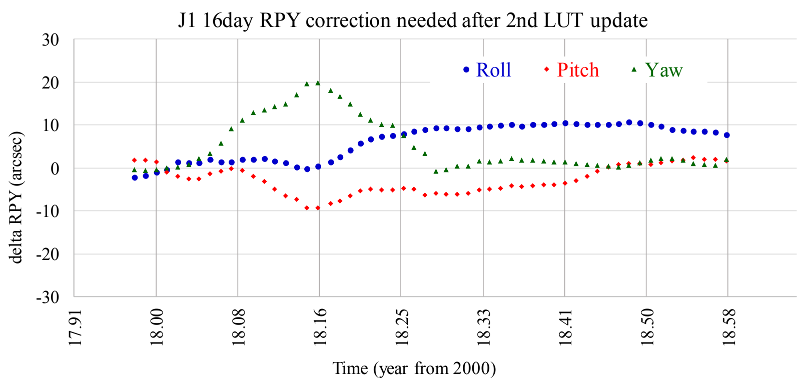

Fig. 8. J1 VIIRS pointing variation as measured by the VIIRS CPM program

Table 1 also lists corrections for the HAM wedge angles alpha and beta and HAM motor axis angle gamma. These angles affect geolocation accuracies in the daily means and standard deviations. They also affect geolocation accuracies across the scan angle. Figure 9 shows such dependencies in the revision r2 dataset. In addition to the overall biases reflected in the intercepts of the best-fit curves, there are differences in the different HAM sides and "slopes" as functions of scan angle. In the scan direction, there are fluctuations as functions of scan angle that have peaks about every 22°.

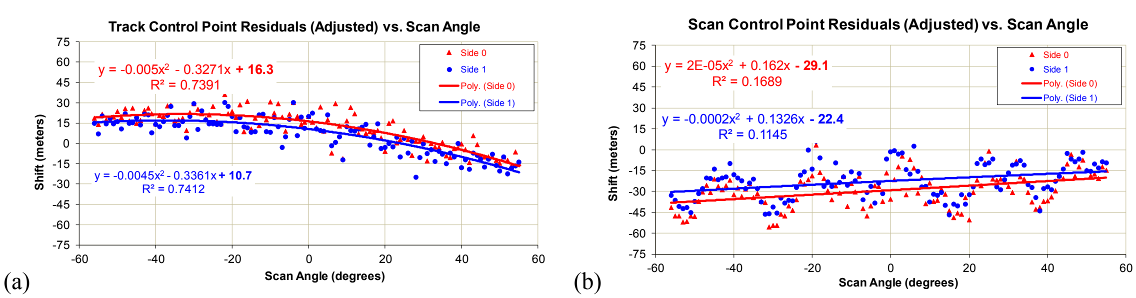

Fig. 9. J1 VIIRS scan angle dependence of the geolocation errors (nadir equivalent). Statistics for the two sides of the HAM are shown seperately.

The pattern of fluctuation in geolocation errors with respect to the scan angle is clearer in the SNPP VIIRS (Figure 10) with the same phase as in J1 VIIRS. The magnitude of the fluctuation is about 40 m, peak-to-peak, for 7 years of the SNPP VIIRS mission. This pattern is found to be out-of-phase (180 degrees) from the pattern of non-linearity of HAM encoders or timestamps (there is non-linearity in RTA encoders but the magnitude is about an order of magnitude smaller). The magnitude of non-linearity of the HAM encoders is about 20 arc-seconds peak-to-peak.

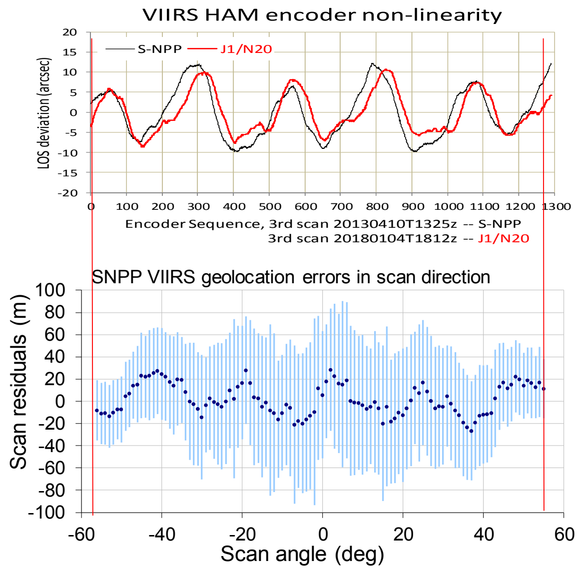

Fig. 10. SNPP VIIRS geolocation error pattern versus scan angle (bottom) and HAM encoder non-linearity (top).

The ground geolocation software makes full use of encoders in the scan pointing knowledge equation, so this fluctuation pattern should not have appeared in the geolocation errors.

We recognized such a fluctuation pattern a few years into the SNPP mission. Re-analysis of pre-launch test data and documents revealed that images entering the Rotating Telescope Assembly (RTA) flip before they are reflected by the HAM and enter the aft-optics assembly. This effectively changes the sign of magnification, currently +4.0, used in the ground software. We confirmed with the instrument vendor that the magnification should be -4.0. We tested this VIIRS instrument geometric model update (VIGMU) for the data days from 7 April 2018 to 8 May 2018, along with a few parameter changes as listed under the “VIGMU” column in Table 1. The results are shown in Figure 11 and under the “VIGMU” column in Table 2. The residuals now show a near-ideal performance (Figure 11) with no fluctuation pattern in the scan geolocation errors. Note that the changes for the on-orbit instrument-to-spacecraft mounting rotation angles from those measured before launch under the “At-launch” column in Table 1 are smaller with VIGMU by about 50 arc-seconds in the roll direction. We are in the process of implementing this VIGMU in the Land SIPS and IDPS in forward processing, and in re-processing in Land SIPS.

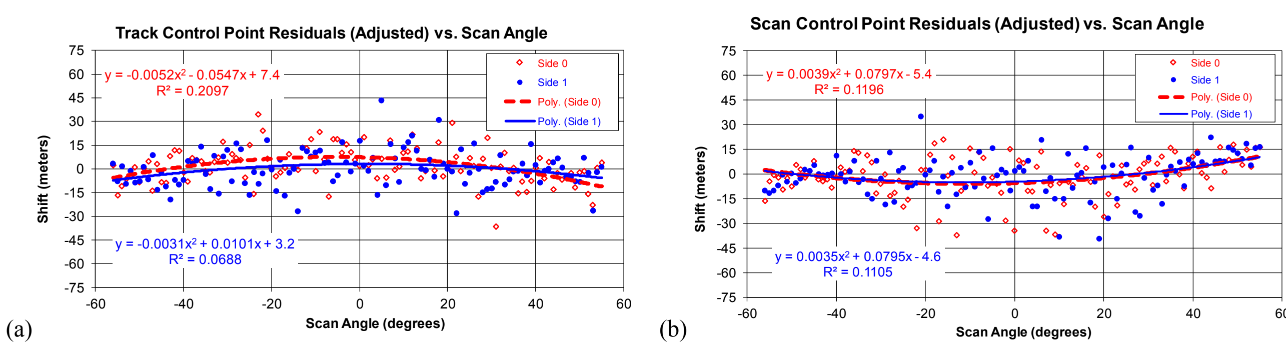

Fig. 11. VIIRS scan angle dependencies of geolocation errors from a 32-day VIGMU test.

In Tables 1 and 2, we also list the changes for the DNB LUT value and performance, respectively. Our NOAA STAR colleagues measured the DNB geolocation bias by using point sources and corrected it in revision r1. We performed a double-check using a method originally intended for measuring VIIRS instrument effective focal length. The method is very similar to control point matching (CPM) program, with addition of off-line VIIRS geolocation production by varying focal length and with selection of Landsat 8 Operational Land Imager (OLI) band B2 (0.452-0.512 µm band pass), B3 (0.533-0.590 µm), B4 (0.636-0.673 µm) and B5 (0.851-0.879 µm) to simulate the VIIRS DNB (0.500 – 0.900 µm)[8]. To increase robustness of the results, cloud-free and high contrast Landsat images were used to match VIIRS images on the same day. One product of this method is the relative registration of the DNB sub-images relative to Landsat-8 OLI images. Since the OLI bands selected here have nominal ground resolution of 30m and accuracy of better than 10 m (1σ)[9], we regard OLI geolocation as ground truth. The results of double-checking the DNB correction in revision r1 are shown in Figure 12 (left). Mis-registration of DNB in this revision is only -170 m in nadir equivalent units. On the focal plane, that required another -0.23 mm on top of the -3.8 mm correction in revision r1. We tested this total correction of -4.03 mm, implemented it in Land SIPS revision r2 and verified that the DNB geolocation bias became very small (~3m nadir equivalent) as shown in Figure 12 (right) for the data on 6, 8, and 9 January 2018.

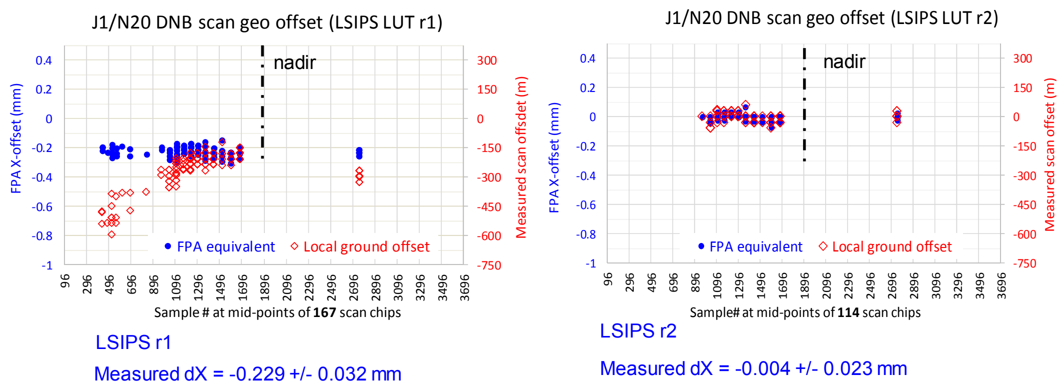

Fig. 12. DNB geolocation error measurements (left), and bias correction and verification (right).

4. EFFECTIVE FOCAL LENGTH AND SCAN-TO-SCAN OVERLAPS/UNDERLAPS

After discovering that VIIRS scan-to-scan underlap existed in SNPP VIIRS[5,10], we developed a method to measure the VIIRS effective focal length[8], which plays a key role in scan-to-scan overlap or underlap at nadir. The first step is to co-register the VIIRS images with Landsat images, as described at the end of the section above. The corresponding results in measured effective focal length are shown in Figure 13a. More datasets from 29 & 30 April and 28 May 2018 were used to measure the focal length not only for DNB but also for bands M7, I2, I3 and I5 (Figure 13b). As we can see, the J1 VIIRS effective focal length does not vary from nominal value significantly (less than 0.1%), except for band I5 on the long-wave IR FPA (more than 0.2%). We will make more measurements for these bands and for other bands, especially those on the LWIR FPA.

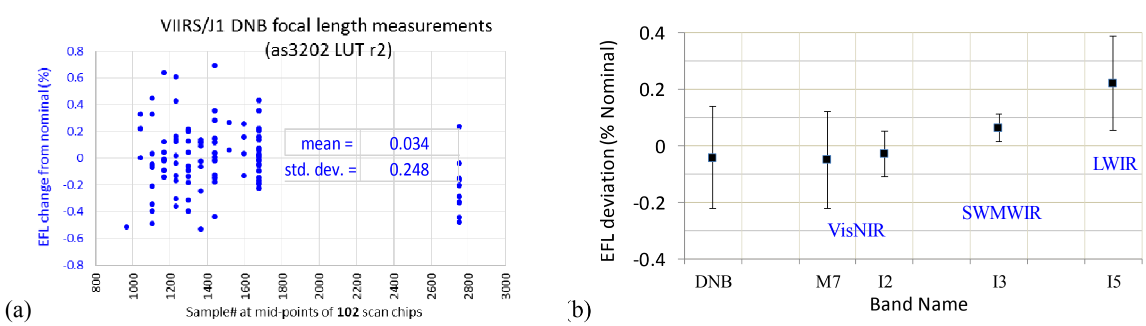

Fig. 13. Results of J1 VIIRS focal length measurements. (a) DNB only from datasets on January 6, 8 and 9, 2018; (b) DNB, M7, I2, I3 and I5 from datasets on 29 & 30 April and 28 May 2018.

The effective focal length, F, plays a role in the nadir scan-to-scan overlap (or underlap when the overlap becomes negative) as expressed in the following equation,

$$Overlap = n\frac{p}{F}h - [V_{ECI} - V_{earth0}\cos i]T$$

where F = effective focal length = Mag x aft optic focal length, p = detector "pitch" interval in the track direction, n = # detectors, h = altitude, T = RTA rotation scan period, i=inclination angle (in ECI) = nominal 98.7^o for JPSS satellites including J1, V_{ECI} = spacecraft ground speed in the inertial frame, V_{earth0} = speed of earth rotation at equator, Overlap < 0 indicates underlap.

Since longer focal length F also results in longer RTA rotation scan period T for meeting band-to-band co-registration requirements, the amount of change in F has doubling effect in scan-to-scan underlap. Reference [10] has some experiments to explain this effect.

For J1 VIIRS, we checked scan-to-scan overlaps/underlaps on ascending orbit on 6 May 2018 using the VIGMU test data stream, which has more accurate geolocation including the HAM side parity (Figure 11). The results are shown in Figure 14, which are consistent with the predictions in reference [10]. The widest underlaps occur at nadir near 15^{o}N at about 70 m in this case. The underlap narrows as J1 goes north or south due to increasing altitude. The underlap also closes at off nadir angles (at about 10^o, not shown here) due to bowtie effects. Terrain height also has an effect on scan-to-scan underlaps because it effectively reduces the satellite altitude from the earth surface as expressed in the equation above, and reduces the footprint size. High terrain widens the underlap where it already exists, and may open it up where underlap would not exist on the ellipsoidal earth surface.

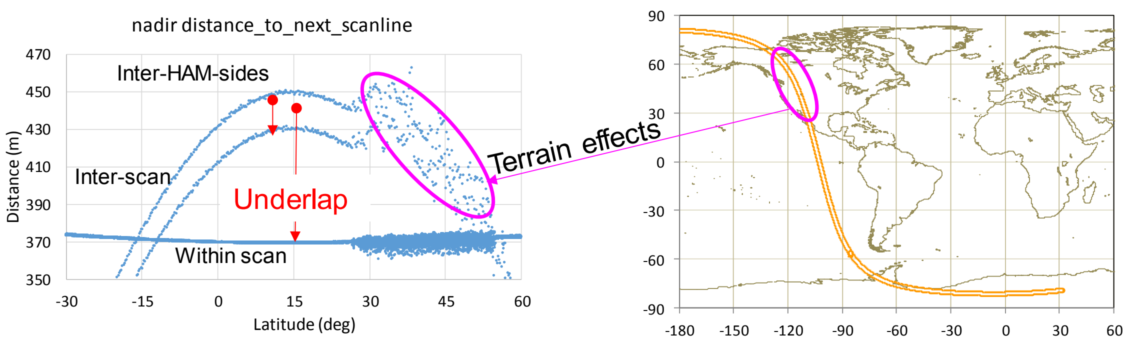

Fig. 14. J1 VIIRS scan-to-scan underlaps in an ascending orbit over the western US tht includes a terrain effect

For SNPP VIIRS, underlaps are less of an issue because of its shorter focal length and scan period (~0.4%). For JPSS-2 VIIRS, we are likely to see a wider underlap near 15^{o}N around nadir due to its slightly longer focal length. But for the JPSS-3 and JPSS-4 VIIRS builds, measures have been taken to shorten the focal length by about 0.8%. So we will not likely to see any scan-to-scan underlaps from JPSS-3 and JPSS-4 VIIRS builds.

5. CONCLUDING REMARKS AND PATHS FORWARD

The NOAA/NASA JPSS-1 satellite was successfully launched on 18 November 2017 to become NOAA-20. After a three-month post-launch test (PLT) campaign, VIIRS on-orbit geolocation was very well calibrated and characterized. The overall geolocation performance is good. The accuracy is within 70 m uncertainty (root-mean-squared-errors, 1σ), well within the specified requirement of 125 m, 1σ, including DNB geolocation. The effective focal length was measured for a few bands, indicating little to no variation from the nominal value. Scan-to-scan underlaps near nadir over the 15^{o}N regions were calculated and have a maximum of about 80 m (at nadir) as expected based on pre-launch tests and analysis.

Long-term geometric monitoring is on-going, as well as other improvements to the geolocation performance. J1 VIIRS pointing as measured by ground control point matching program exhibits larger variations than anticipated, up to 20 arc-seconds in yaw. Investigation is on-going while we are in the process of implementing correction for pointing variation to improve geolocation performance through a time series of the mounting matrixes in the LUTs. An update to the VIIRS instrument geometry model (VIGMU) was tested that removes a oscillating pattern in the geolocation errors versus scan angle. This update will be implemented in forward processing as well as in re-processing in Land SIPS.

ACKNOWLEDGEMENTS

The authors acknowledge the sponsorship of this work by the NASA JPSS Project Science Office and NOAA Center for Satellite Applications and Research (STAR), and the cooperation and assistance from many colleagues from Raytheon Company, The Aerospace Corporation, the NASA VIIRS Land SIPS, the VIIRS Characterization Support Team (VCST) Radiometric Group, the JPSS Program Office, the JPSS-1 Mission Operation Support Team (MOST) and the JPSS Flight Project.

REFERENCES

[1] Wolfe, R.E., G. Lin, M.Nishihama, K.P. Tewari, E. Montano (2012), "NPP VIIRS Early On-Orbit Geometric Performance", Earth Observing Systems XVII, edited by J. J. Butler, X. Xiong, X. Gu, *Proc. of SPIE* Vol. 8510, 851013, doi: 10.1117/12.929925.

[2] Wolfe, R.E., G. Lin, M. Nishihama, K. P. Tewari, J. C. Tilton, A. R. Isaacman (2013), "Suomi NPP VIIRS prelaunch and on-orbit geometric calibration and characterization", *Journal of Geophysical Research – Atmospheres*, VOL. 118, 11,508–11,521, doi:10.1002/jgrd.50873.

[3] Cao, C., F. DeLuccia, X. Xiong, R. Wolfe, F. Weng (2014), "Early On-orbit Performance of the Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) Satellite," *IEEE Trans. Geosci. Remote Sens.*, vol. 52, no. 2, pp. 1142–1156, DOI:10,1109/TGRS.2013.2247768.

[4] Tilton, J. C, G. Lin, and B. Tan (2016), "Measurement of the Band-to-Band Registration of the SNPP VIIRS Imaging System From On-Orbit Data", *Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, Vol. 10, No.3, March 2017, pp. 1056-1067; DOI: 10.1109/JSTARS.2016.2601561.

[5] Lin, G., and R. E. Wolfe (2016), "JPSS-1 VIIRS at-launch geometric performance." Earth Observing Systems XXI, edited by J. J. Butler, X. Xiong, X. Gu, *Proc. of SPIE* Vol. 9972, 99721L, doi: 10.1117/12.2238804.

[6] Wolfe, R.E. and M. Nishihama, (2011) "Accurate MODIS global geolocation through automated ground control image matching," in *Image Registration for Remote Sensing*, J. Le Moigne, N. S. Netanyahu and R. D. Eastman (eds.), Cambridge Univ. Press, New York, pp. 437-455, 2011, doi: 10.1017/cbo9780511777684.022.

[7] NASA Joint Polar Satellite System (JPSS) Ground Project, "Joint Polar Satellite System (JPPS) VIIRS Geolocation Algorithm Theoretical Basis Document (ATBD)", document No. 474-00053, Goddard Space Flight Center, Greenbelt, Maryland, July 31, 2011.

[8] Tilton, J. C., R. E. Wolfe, G. Lin, and Z. Yin (2017), "On-orbit measurement of the focal length of the SNPP VIIRS instrument," in *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium*, Fort Worth, TX, USA, pp. 4056-4059, July 23-28, 2017, doi: 10.1109/IGARSS.2017.8127890.

[9] Storey, J.C., M.J. Choate, K. Lee (2014), "Landsat 8 Operational Land Imager on-orbit geometric calibration and performance." *Remote Sens*. 6, 11127–11152.

[10] Lin, G., R. E. Wolfe, J. C. Tilton (2016), "Trending of SNPP ephemeris and its implications on VIIRS geometric performance", Earth Observing Systems XXI, edited by J. J. Butler, X. Xiong, X. Gu, *Proc. of SPIE* Vol. 9972, 99721K, doi: 10.1117/12.2239043.