Ground control points refresh for MODIS and VIIRS geolocation monitoring

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ABSTRACT

The Control Point Matching (CPM) program and a set of over 1200 globally distributed ground control points (GCPs) have been successfully used to develop more than 20 years of MODIS geolocation products. In this research, we refresh current GCP library with more than 2500 new GCPs using the latest Landsat 8 Collection 2 images. The refreshed GCPs are distributed from 56 S to 80 N latitude, with more than 2000 shoreline and 500 inland GCP chips. The size of these GCPs are extended from 800*800 to 1400*1400 Landsat pixels and the CPM program correspondingly increases the searching distance from 0.8 pixels to 2.5 pixels, which also extends the geolocation error measurement from +/-45 to the edge of scan at +/-55 degree in scan angle. This will allow the algorithm to catch geolocation errors that are larger than one MODIS pixel. The geolocation errors measured with the refreshed GCP library are comparable to the previous results, yet with 2-3 more times of matched GCPs. The daytime Aqua ascending orbits and Terra descending orbits enable us to identify a few GCP outliers which might be due to the quality of the original Landsat images. Most importantly, the refreshed GCP library will include images from both Landsat band 4 to match with VIIRS I1, and Landsat band 6 to match with VIIRS I3. This will allow us to measure and correct on orbit band-to-band registration at both track and scan directions, which will help understanding and improving future JPSS mission's prelaunch geometric performance.

Keywords: VIIRS, MODIS, geolocation monitor, ground control points, Landsat 8, refresh, accuracy,

1. INTRODUCTION

On-orbit geolocation errors are measured using a ground Control Point Matching (CPM) program for both Moderate Resolution Imaging Spectroradiometer (MODIS) and Visible Infrared Imaging Radiometer Suite (VIIRS) instruments. Currently, the CPM program runs over 1200 globally distributed ground control point (GCP) images of Landsat red band 30 m resolution with a size of 800 by 800-pixel. These chips are used to simulate images of MODIS Band 1 (250 m nadir resolution) and VIIRS band I1 (375 m nadir resolution) with their corresponding projection of ideal line spread functions (LSFs) in triangular or trapezoidal shape in the scan direction and square shape in the track direction. An area-based correlation is computed between the MODIS/VIIRS images and the Landsat simulated images [1]. The shift in a MODIS/VIIRS location at the maximum cross-correlation with the simulated Landsat image is the control point residual. These residuals are defined in MODIS/VIIRS along-scan and along-track angular space. These residuals are analyzed for corrections of various sensor parameters stored in the geolocation algorithm lookup table (LUT). Currently, the CPM program only co-registers the MODIS Band1 and VIIRS I1 to the Landsat red band, the geolocation of all other bands are tied to Band1/I1 through band-to-band co-registration.

The SNPP and NOAA-20 VIIRS sensors have been successfully operated on orbit for more than 9 years and 3 years, respectively. Geolocation accuracy for both sensors are within 10% I-band pixels in terms of daily mean geolocation shifts, and within 20% pixels in terms of standard deviations [2]. The MODIS geolocation products have been re-processed through Collections 5, 6 and 6.1. Forward processing of C6 and C6.1 is on-going with combined data streams in 40+ years (21+ years for Terra MODIS and 19+ years for Aqua MODIS). For the latest collection C6.1, the overall measured geolocation accuracy in terms of nadir equivalent root-mean-square errors (RMSEs) is 43 m in the track direction and 45 m in the scan direction for Terra MODIS, and 46 m and 53 m for Aqua MODIS [3].

In this paper, we discuss the performance of current GCP library in Section 2. Section 3 characterizes the refreshed new GCPs. Section 4 compares the current and refreshed GCP libraries using VIIRS data. Section 5 demonstrates the capability of the new GCP library to calculate on-orbit band-to-band registration and Section 6 concludes the research.

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2. PERFORMANCE OF CURRENT GCP LIBRARY

The current GCP library has over 1200 image chips acquired around year 2000 from Landsat-5 and Landsat-7 images. It has been successfully detecting and monitoring MODIS and VIIRS geolocation errors with the control point matching (CPM) program.

Figure 1 shows the trending of the daily number of matched GCP chips from current library for MODIS Terra and Aqua reprocessing C6.1 data. A negative linear relationship is found between the time and the average daily matched chips that has a cross-correlation coefficient equal to or larger than 0.6. This threshold is chosen to filter out inaccurate, out-of-date GCPs, and GCPs contaminated by cloud and aerosols [1]. In general, in the early 2000s, MODIS Terra CPM program returns more than 270 GCP matches every day to calculate the geolocation errors. By contrast, CPM program returns about 230 GCP matches every day in 2020. On average, the number of matched GCPs is decreased by roughly two every year. This linear coefficient could explain 92% of the variance in the daily matches over the past 20 years. Similar results are found for Aqua reprocessing C6.1: about 230 GCP matches in early 2000s and less than 210 GCP matches most recently. On average, the CPM program find 2 chips less per day each year and this linear fit could explain 88% of the variance in Aqua C6.1 daily matches.

Figure 2 shows the total number of matches for each individual current GCPs during the Terra mission up to May, 2021. From February, 2020 to May, 2021, about 7% of GCPs have less than 100 matches, 29% of the GCPs have 100 to 1000 matches, 26% of the GCPs have 1000 to 2000 matches, 18% have 2000 to 3000 matches, 15% have 3000 to 4000 matches, and 5% GCPs have more than 4000 matches. In general, GCPs with less matches are located along equator in South America, Africa, and South East Asia where cloud covers the ground most time of the year. Some GCPs located at high latitude also have less matches, which might be due to the ice and seasonal variations. The GCPs with high number of matches are found in the areas of arid and semi-arid climate, such as south-west U.S, north-west Africa, and west Australia.

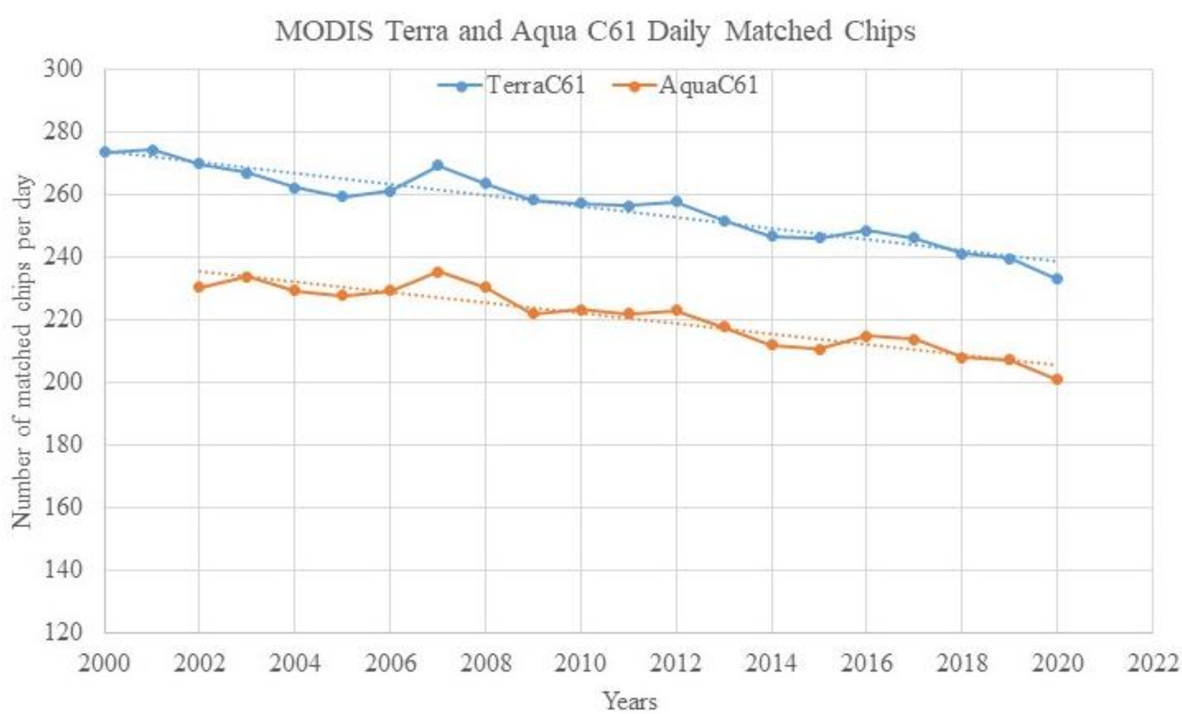


Figure 1. Long term trending of daily matches for current GCP library using MODIS Terra and Aqua reprocessing C6.1 data from early 2000s to 2020.

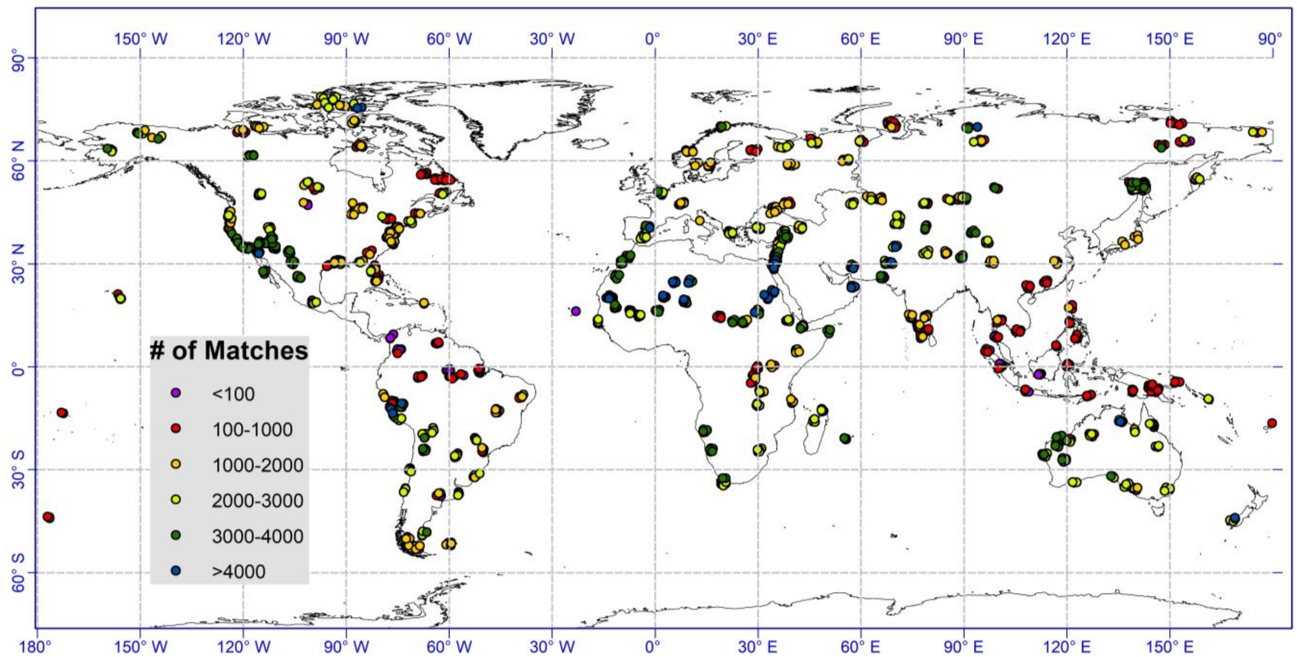


Figure 2. Total number of matches for each current GCP chips using MODIS Terra reprocessing C6.1 data from 2000 to 2021.

3. CHARACTERIZATION OF THE REFRESHED CHIPS LIBRARY

We obtained almost 1000 Landsat8 Collection 2 images from 2013 to 2020 to generate the updated the GCP chips library. These Landsat Collection 2 images have been substantially improved in the following aspects. First, the absolute geolocation accuracy of the global ground reference dataset has been refined to improve interoperability of the Landsat images through time [4]. Second, Collection 2 also includes updates in global digital elevation models and calibration and validation processing [5].

We generated more than 2500 new GCPs that are distributed from 56 S to 80 N latitude, with more than 2000 shoreline and 500 inland GCP chips. The size of these GCPs are extended from 800*800 to 1400*1400 Landsat pixels. Figure 3 shows the number of chips distributed over time. About half of the GCP chips (>1190) are generated from 2014 and 2017 Landsat8 images and about 80 chips are derived from 2019 and 2020 images.

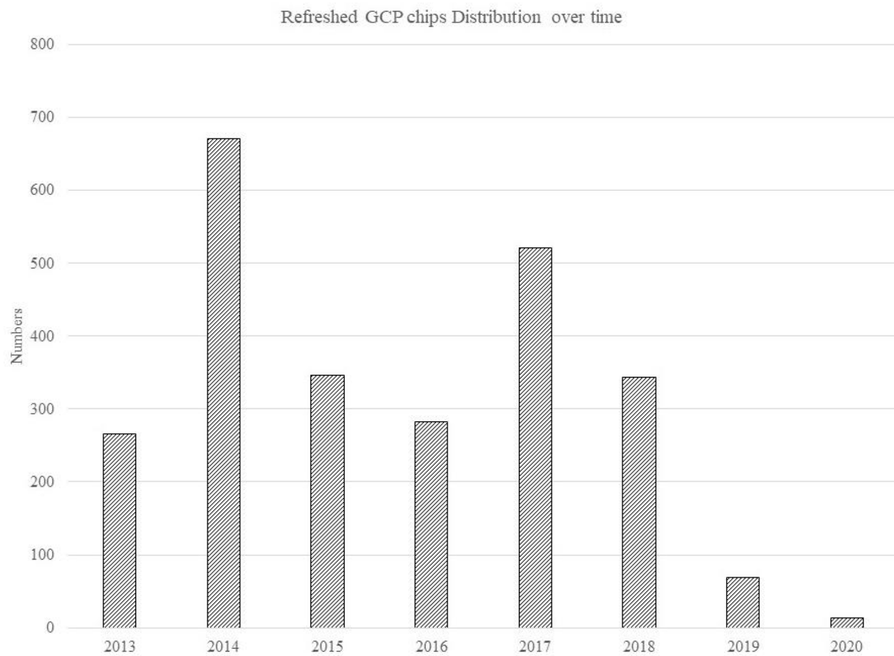
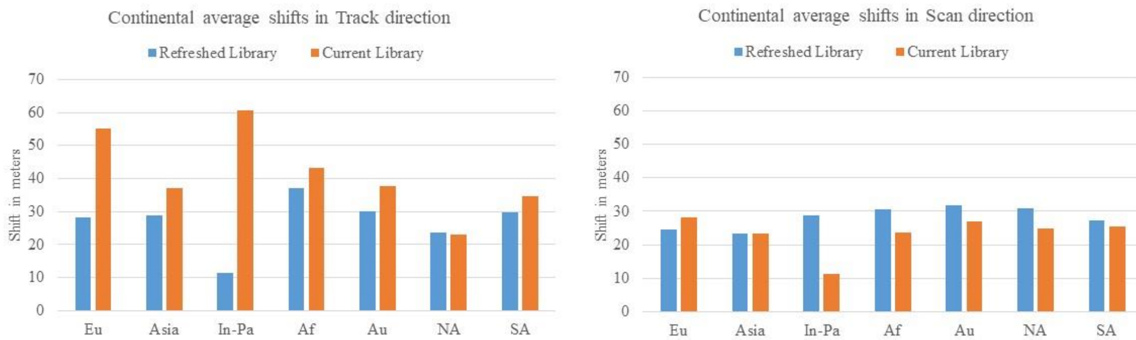


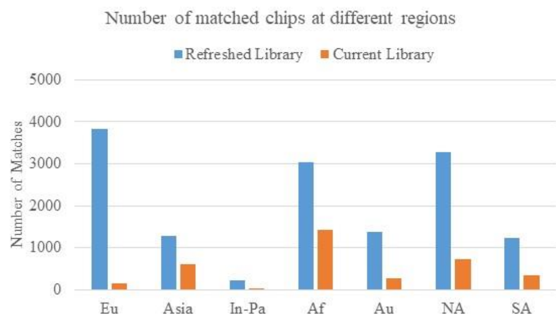
Figure 3. The refreshed GCP chips distribution over time.

3.1 Characterization of Chip Libraries with SNPP VIIRS Data

We ran a 16-day test of the refreshed chip library through the SNPP VIIRS data. The test run used existing geolocation and Level-1B radiometric products from Collection-1 (C1) [2]. This was to gain some understanding of the similarities and possible differences between the existing chip library and the refreshed library in different regions around the world.

Figure 4 shows the comparison of continental geolocation errors between the refreshed GCP and current GCP chips using SNPP VIIRS on-orbit data from September 5th to 20th 2019. In general, the nadir-adjusted geolocation shifts along scan direction are comparable when using these two GCP libraries. The along-track geolocation shifts has been reduced about 5-10 meters in Asia, Africa, Australia, North America, and South America. The along-track shift has been reduced 20-50 meters when using the refreshed GCP chips in Europe and Indian-Pacific Islands. The number of matches in all regions are increased with the refreshed GCP library, especially in Europe and North America, mainly due to the high-density chips distribution at these two regions.





ID	Region	Latitude	Longitude
Eu	Europe	>30N	30W-30E
Asia	Asia	>30N	30E-180E
In-Pa	India-Pacific Islands	0-30N	>=60E
Af	Africa	<30N	30W-60E
Au	Australia	<0	90E-180E
NA	North America	>=15N	180W-30W
SA	South America	<15N	180W-30W

Figure 4. Continental comparisons between refreshed GCP library and current library using SNPP data from September 5th 2019 to September 20th 2019.

3.2 Characterization of Chip Libraries with MODIS Data

We then ran a two-year test of the refreshed chip library using both Terra and Aqua MODIS latest C6.1 datasets. Years 2003 and 2015 are chosen to represent both the early and recent mission periods. Note that with the size of chips increased from 800x800 to 1400x1400 Landsat pixels, the MODIS CPM program was updated by increasing the error searching distance from +/-0.8 pixels to +/-2.5 pixels. We also extend the geolocation error measurements from +/-45 to the edge of scan at +/-55 degree in scan angle. This will allow the algorithm to detect geolocation errors that are larger than one MODIS pixel in the entire scan range. The updated error searching area and the extended scan angle range are now the same as used in VIIRS CPM program with either the current or the refreshed chip library.

The results of the test run show that with different minimum cross-correlation coefficient value (CCV), the nadir-adjusted geolocation errors along track direction are consistently around 8-10 meters larger with the refreshed GCP chips [Figure 5]. Similarly, the geolocation errors along scan are consistently 7-9 meters shifted away from the nadir in the negative direction with the refreshed library. Figure 5 also shows with the refreshed chips library, the standard deviation of the geolocation errors in both track and scan directions reduced from larger than 80 meters with a minimum cross-correlation of 0.6 to less than 40 meters when the minimum cross-correlation equals 0.95. When the minimum CCV is equal or larger than 0.85, the standard deviation of the geolocation shifts with refreshed library is comparable to the results with current library, in which the error searching distance is +/-0.8 pixels and the minimum CCV to retain detected errors is 0.6.

Figure 6 shows the consistent geolocation shift along track direction with refreshed GCP library is around 10 meters across the entire scan extends (-55 to 55 degrees). At the same time, the number of matched GCP chips increases from the nadir to the edge of the scans. By contrast, the number of matches decrease beyond 45 degree scan angle with current GCP library, which is mainly caused by the smaller size of the current GCP chips. Similar results are found in the tests with MODIS Aqua data (not shown here).

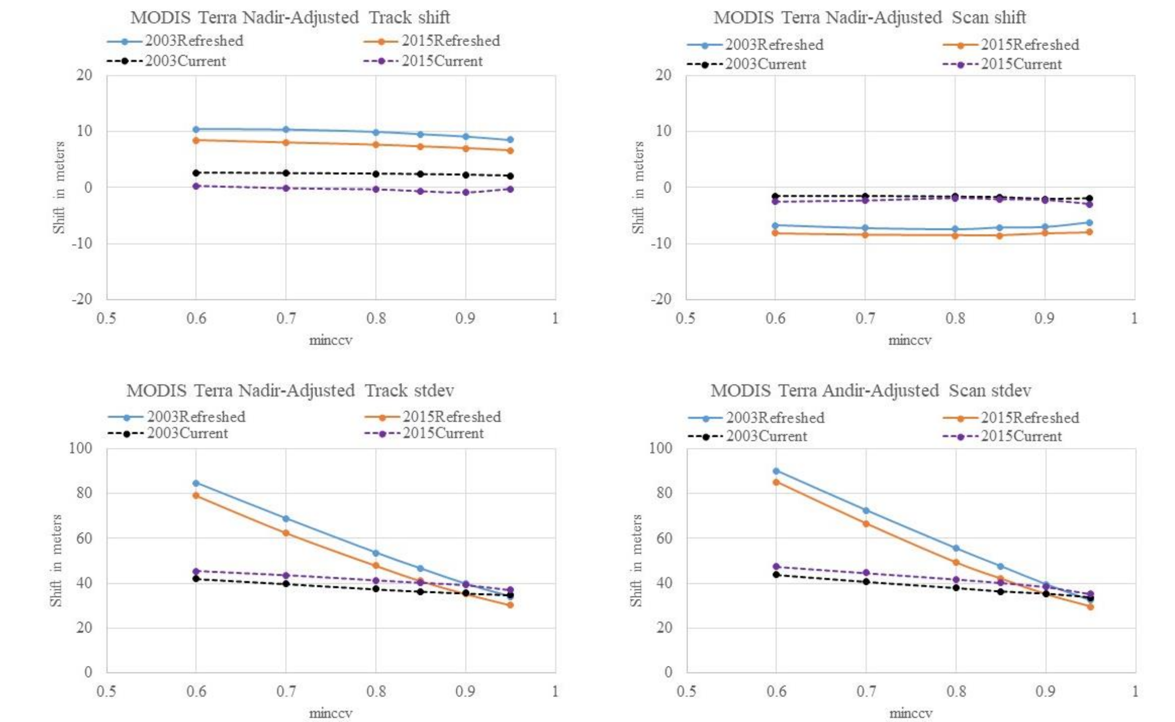


Figure 5. Comparisons between refreshed GCP library and current library using MODIS Terra data from 2003 and 2015.

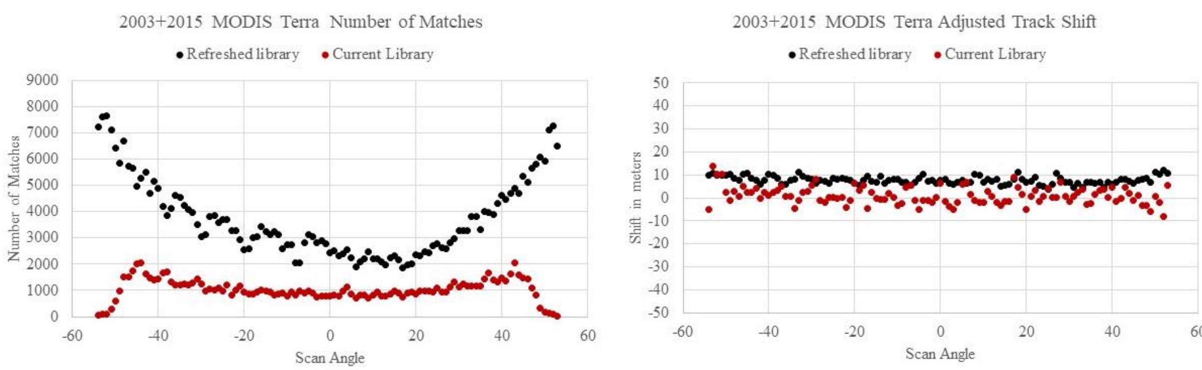


Figure 6. Scan profile comparisons between refreshed GCP library and current library using MODIS Terra data from 2003 and 2015.

3.3 Quality Check of the Refreshed GCP Library

Taking advantage of the daytime Aqua ascending orbits and Terra descending orbits, we are able to identify about 20 refreshed GCP chips that measured consistent large geolocation shifts during these two years. We calculated the statistics of measured errors for each chip that has CCV equal or larger than 0.85. We use the following preliminary criteria to select the GCPs that need extra quality check: i) number of matches is more than 20; ii) circular mean shift (= sqrt((track mean)^2 + (scan mean)^2)) is larger than 100 m; iii) the measured mean shift values in track or scan direction are in opposite directions from Terra and Aqua results; iv) ratio of circular_mean to circular_standard_deviation is larger than 1.0. Using these criteria, we are able to identify 22 chips that have constantly large mis-registration (shown in Table 1). They were marked and checked for qualities and geolocation accuracy and are removed later from the refreshed library due to either cloud coverage or mis-registration of the original Landat8 images.

Table 1. Preliminary identification of low quality control points.

	Terra						Aqua					
CP_ID	# Matches	Track mean (m)	Scan mean (m)	Track stdev (m)	Scan stdev (m)	Ratio (cir_mean /cir_stdv)	# Matches	Track mean (m)	Scan mean (m)	Track stdev (m)	Scan stdev (m)	Ratio (cir_mean /cir_stdv)
10069	63	17	138	33	80	1.60	95	45	-143	34	74	1.85
10073	68	83	74	53	85	1.11	49	-25	-106	39	79	1.24
10441	86	29	228	66	211	1.04	83	48	-241	86	195	1.15
10699	61	2	134	47	100	1.22	72	57	-147	34	98	1.52
10991	269	-25	105	37	91	1.10	217	75	-83	48	89	1.11
10993	229	3	117	36	77	1.38	198	66	-116	47	89	1.33
11076	135	167	35	131	65	1.16	280	-128	-94	104	98	1.11
11295	261	70	-121	39	50	2.21	236	-107	58	48	65	1.51
11319	144	248	236	198	203	1.21	102	-59	-327	104	253	1.21
11445	100	98	72	53	100	1.08	106	-36	-135	41	112	1.18
11615	228	36	-165	36	116	1.39	237	-98	134	74	101	1.33
11657	96	71	-204	53	100	1.90	84	-135	100	78	86	1.45
11773	36	119	-6	51	39	1.84	35	-77	-196	53	109	1.73
11774	40	93	-62	56	61	1.35	30	-101	-95	63	72	1.45
11840	171	64	-340	94	193	1.62	150	-225	284	131	165	1.72
11885	126	14	-118	24	84	1.36	67	-34	108	33	103	1.04
12011	108	17	-162	26	84	1.86	114	-58	94	30	58	1.68
12163	448	0	102	42	80	1.14	477	47	-120	36	82	1.44
20023	66	55	-137	75	121	1.04	29	-204	317	254	148	1.28
20095	176	-12	-163	33	140	1.14	94	-45	247	53	169	1.42
20217	50	126	371	170	309	1.11	95	-36	-376	90	183	1.85
20417	451	191	-266	68	121	2.35	430	-263	121	98	100	2.06

3.4 Long-term Tending of Refreshed GCP Library

The two-year test with refreshed chip library and MODIS data is slightly better in geolocation accuracy as shown in Section 3.2. The "new" geolocation biases need to be corrected through updated look-up tables (LUTs) in future Collection of MODIS products (i.e., C7) that is planned to start in later 2021. We extended the MODIS test to the whole mission and archived the reprocessing data as Collection 6.2. We are able to generate the trending of daily matches of the refreshed GCP library using MODIS Terra C6.2 data from 2000 to 2020 [Figure 7]. A significant positive linear relationship is found over the past 21 years between the daily matches and time. In early 2000s, the CPM program with refreshed library returns about 540 matches every day. The daily matches increase to more than 590 in 2020. Over all, the daily matches with refreshed GCP library is more than those with the current GCP library. On average, the CPM program will return 3 more chips per day each year and this linear fit could explain 85% of the variance of Terra reprocessing daily matches.

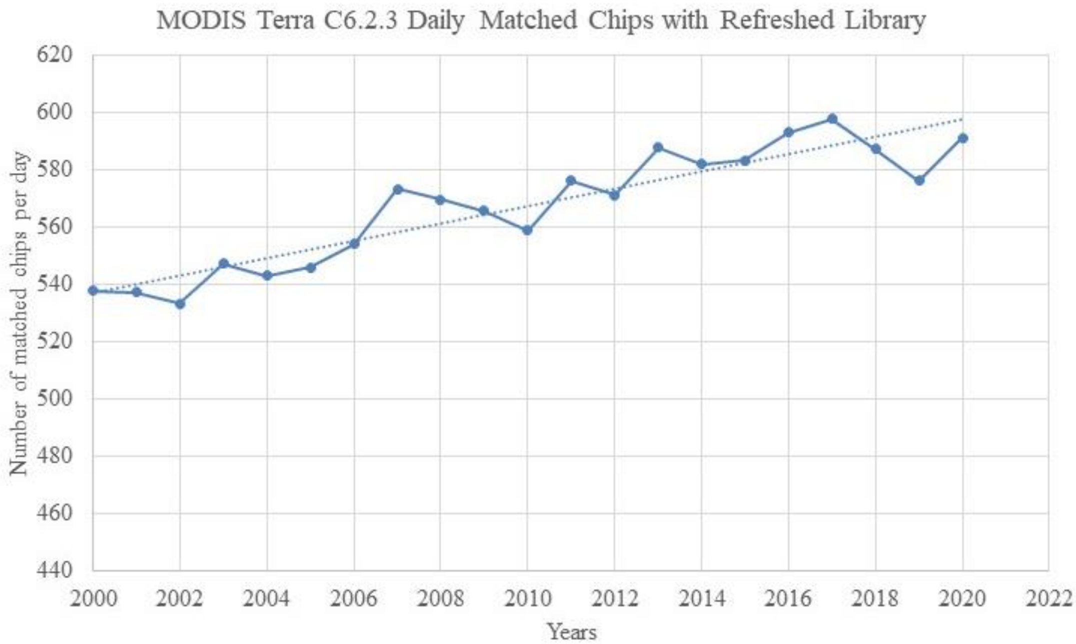


Figure 7. Long term trending of daily matches for refreshed GCP library using MODIS Terra reprocessing C6.2.3 data from 2000 to 2020.

4. COMPARISON BETWEEN CURRENT AND REFRESHED LIBRARY

We started recently reprocessing VIIRS products using the refreshed GCP library. To better understand the difference between these two GCP libraries, we compared the NOAA20 (J1) processed C2 and C2.1 data in which C2 uses current GCP library and C2.1 uses the refreshed GCP library. From 2nd February 2021, J1 C2 and C2.1 data applied the same LUTs and algorithms in the processing and the only difference between these two products in control point residuals is the GCP library.

Figure 8 shows the 16 days average shift along track and scan directions for J1 data using both the current (C2) and refreshed (C2.1) libraries. Instead of grouping the results into northern hemisphere and southern hemisphere, we use the sun angle relative to the orbit to separate the global results into morning orbit and afternoon orbit. This will allow us to analyze the satellite on-orbit thermal effect on geolocation errors through seasons. In general, J1 morning orbit roughly corresponds to Southern hemisphere but with seasonal variations from almost 23.5º S in winter to 23.5º N in summer. J1 afternoon orbit roughly corresponds to Northern hemisphere again with seasonal variations. In general, geolocation biases in the Morning and Afternoon hemisphere become closer with the refreshed GCP library along both track and scan directions. In specific, the geolocation errors between these two hemispheres are around 20 meters along track direction with current GCP library. By comparison, the geolocation shift difference is about 10 meters with refreshed library. Similarly, along scan direction, the geolocation errors between these two hemispheres are about 10 meters with current library, but reduced to 0-5 meters with the refreshed library. The 16 days total number of matched GCP chips has increased from around 3000 to almost 15000 in the refreshed GCP library.

With the reprocessing of C2.1 data from 2018, Figure 9 demonstrates the number of matches for each refreshed GCP chips. Similar to the current chips, the refreshed GCP chips located in tropical forests and subarctic climate zones tend to have less matches, for instance most chips in Nunavut Canada have less than 200 matches for the last 3.5 years. By contrast, refreshed chips located in the Mediterranean climate zones (e.g., west coast of North America, west Australia, and the Mediterranean sea basin) have more than 800 matches.

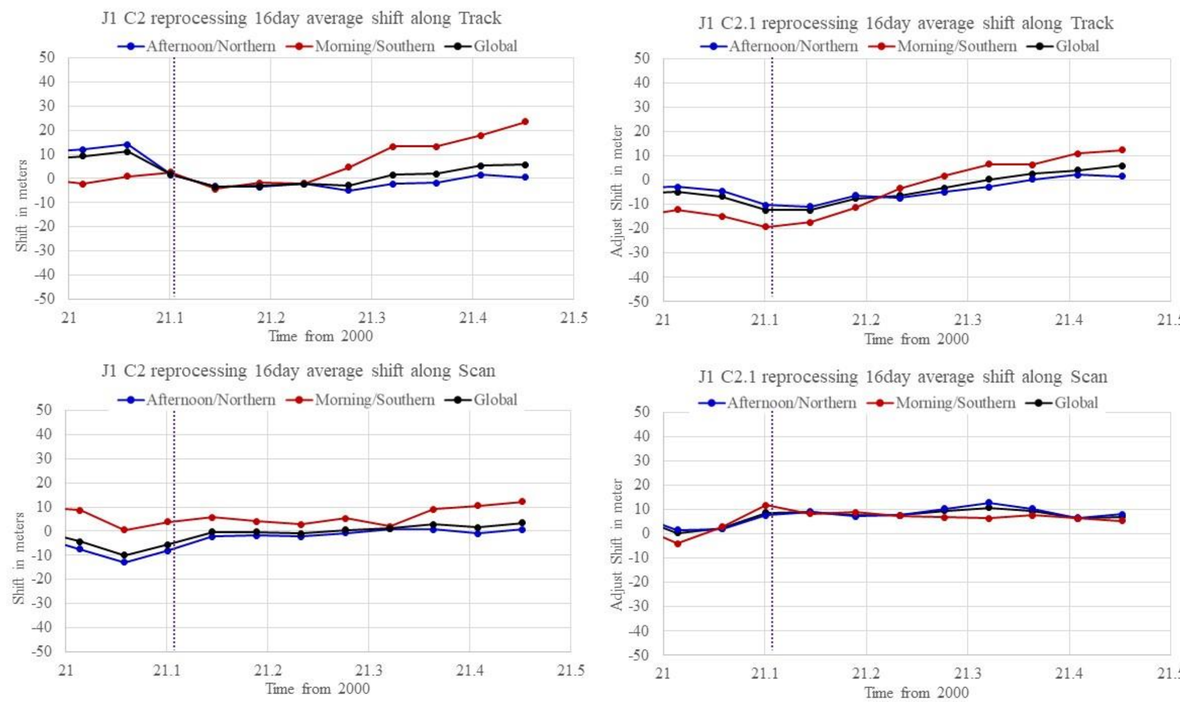


Figure 8. 16 days average shift along track and scan directions for J1 using current (C2) and refreshed (C2.1) libraries. The purple dotted line shows the start of the 16 days when the same LUTs are installed for C2 and C2.1.

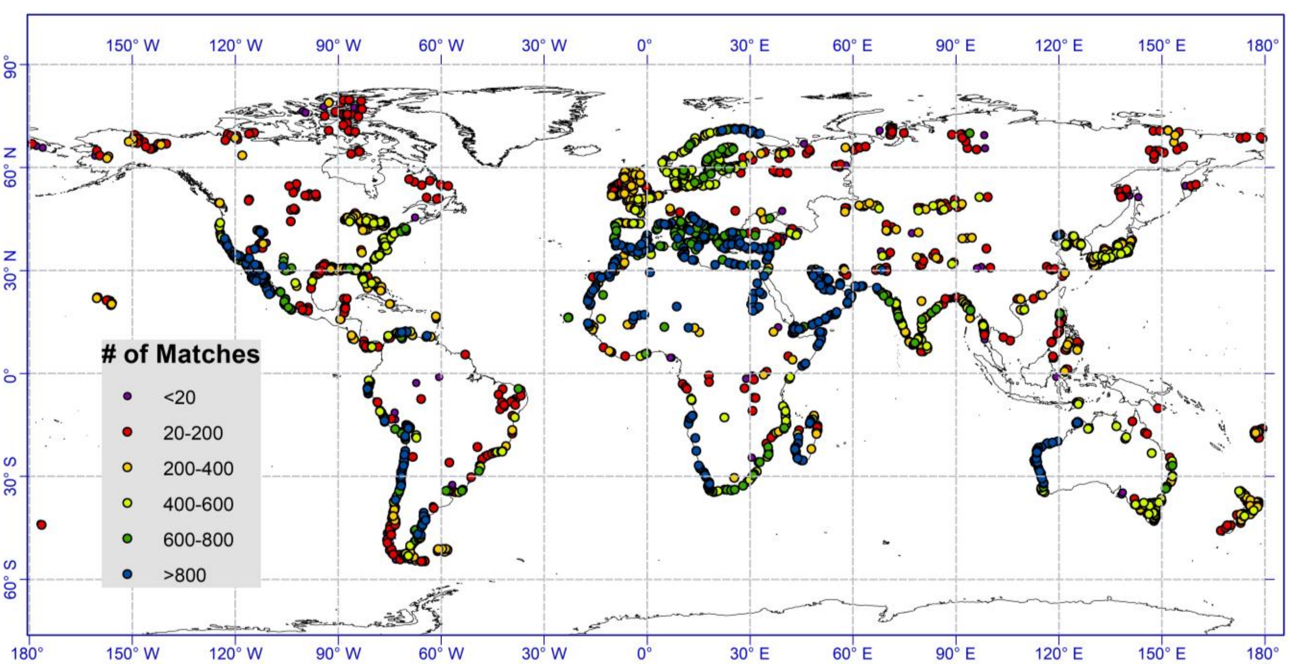


Figure 9. Total number of matches for each refreshed GCP chips using NOAA20 (J1) C2.1 data from 2018 to 2021.

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5. ON-ORBIT BBR USING MULTIBAND REFRESHED GCP LIBRARY

The refreshed library contains more than 2500 multiband GCP chips to simulate VIIRS. Given the similar wavelength between VIIRS and Landsat8, Landsat8 band 4 is used to generate the GCPs for VIIRS band I1, and Landsat8 band 6 is used to generate the GCPs for VIIRS band I3. These multiband chips will allow us to calculate on-orbit band-to-band registration for VIIRS. By moving the Landsat simulated images over VIIRS images, the geolocation offsets between the Landsat simulated images and VIIRS images at the maximum cross-correlation are used to determine geolocation offsets of the VIIRS products. The geolocation offsets of VIIRS Band I1 and I3 will give us the on-orbit BBR between these two bands based on the assumption that Landsat8 band 4 and band 6 are well aligned.

Figure 10 shows the global average along-track geolocation shift between Landsat8 band 4 and VIIRS band I1 (blue dots), as well as Landsat8 band 6 and VIIRS band I3 (orange dots). These along-track geolocation shifts between each pair of Landsat and VIIRS images are converted to nadir-equivalent distance for comparison. In general, NOAA 20 (JPSS-1) VIIRS band I1 are well aligned with Landsat8 band 4 along-track direction. The nadir equivalent geolocation shift between these two bands are -6 meters. By comparison, the nadir equivalent along-track shifts between VIIRS band I3 and Landsat B6 are -91 meters for these sampled days in 2019. With the assumption that the Landsat8 band 4 and band 6 are well co-registered, the on-orbit BBR between NOAA 20 (J1) band I1 and I3 are about 85 meters, which agrees well with Tilton's [6] earlier findings of 80-100 meter. According to the NOAA 20 (J1) VIIRS pre-launch tests, the along-track BBR between band I1 and I3 at TVac nominal performance is 7% M-band ASI, or about 50 meters [7]. The BBR results of the on-orbit and lab-tests are comparable and the difference might be caused by temperature difference and possible post launch shifts. In addition, Landsat8 images have about 4 meters of band-to-band registration accuracy and about 7 meters of multi-temporal image-to-image registration accuracy [8]. Both of these will also affect the VIIRS on-orbit BBR results.

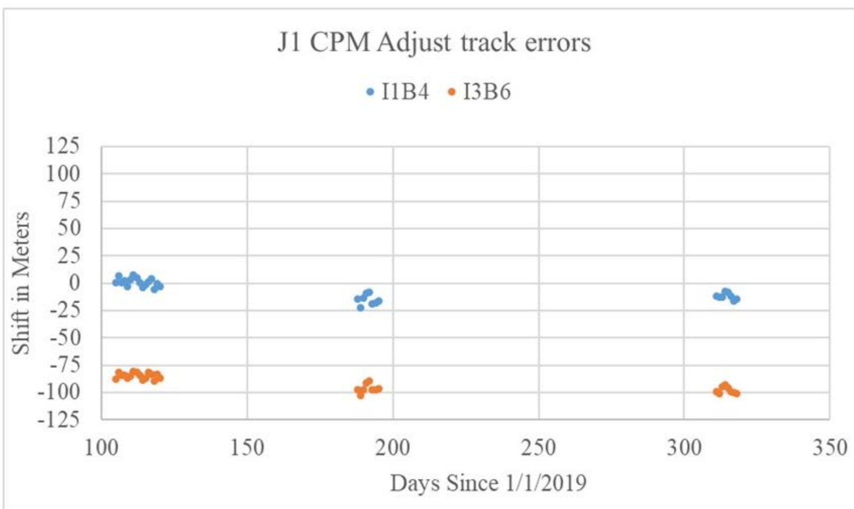

Figure 10. Global average on-orbit geolocation shift along tracking direction between Landsat8 band 4 and VIIRS band I1 (I1B4 in blue dots), as well as Landsat8 band 6 and VIIRS band I3 (I3B6 in orange dots) for NOAA 20 (J1).

6. CONCLUDING REMARKS

We refresh current GCP library with about 2500 new GCPs including more than 2000 located along shorelines and 500 inlands. These GCP chips are generated using the latest Landsat8 Collection 2 images from 2013 to 2020. The size of the refreshed GCPs are extended to 1400*1400 Landsat pixels and the CPM program for MODIS geolocation correspondingly increases the searching distance and extends the geolocation error measurement to the edge of scan. From 2000 to 2020, the daily matched GCP chips with current library is around 250/day and decreases about 2 chips per day each year. By contrast, the refreshed GCP library generated about 580 daily matches each day and increased 3 chips per day every year.

Overall, the geolocation errors measured with the refreshed GCP library are comparable to the previous results, yet with 2-3 more times of matched GCPs, which improved geolocation errors at different continental regions. Across the entire scan, the refreshed GCP chips generate more chips at the edge of the scan. The updated CPM algorithm for MODIS will detect larger geolocation errors due to increased searching distance and measurements close to the edge of the scan. The standard variations of detected geolocation errors retained by CCV of 0.85 or above are comparable with those detected by current chip library and retained by CCV of 0.60 or above. Our analysis indicate that using the refreshed GCP library, there are additional geolocation biases that are more accurate and will be corrected with updated LUTs in an upcoming new Collection (C7) of MODIS data products.

The refreshed GCP library also includes images from both Landsat8 band 4 to match with VIIRS I1, and Landsat8 band 6 to match with VIIRS I3 images. This will allow us to measure and correct on orbit band-to-band registration at both track and scan directions, which will help understanding and improving future JPSS mission's prelaunch geometric performance.

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