MTSAT-1R Visible Imager Point Spread Function Correction, Part II: Theory

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Abstract—An image processing methodology is presented to recover the quality of the Multifunctional Transport Satellite (MTSAT)-1R visible channel data affected by spatial crosstalk. The slight blurring of the visible optical path is attributed to an imperfection in the mirror surface caused either by flawed polishing or a dust contaminant. The methodology assumes that the dispersed portion of the signal is small and distributed randomly around the optical axis, which allows the image to be deconvolved using an inverted point spread function (PSF). The PSF is described by four parameters, which are solved using a maximum-likelihood estimator using coincident collocated MTSAT-2 images as truth. A subpixel image matching technique is used to align the MTSAT-2 pixels into the MTSAT-1R projection and to correct for navigation errors and cloud displacement due to the time and viewing geometry differences between the two satellite observations. An optimal set of the PSF parameters is derived by an iterative routine based on the 4-D Powell’s conjugate direction method that minimizes the difference between the PSF-corrected MTSAT-1R and the collocated MTSAT-2 images. The PSF parameters were found to be consistent over the 5 days of available daytime coincident and MTSAT-1R and MTSAT-2 images. After applying the PSF parameters, the visible sensor response is nearly linear, and the space count is close to zero. The overall linear regression standard error was reduced by 52%. Users can easily apply the PSF parameter coefficients to the MTSAT-1R imager level counts to restore the original quality of the entire MTSAT-1R record.

Index Terms—Calibration, deconvolution, image restoration, multi-functional transport satellite (MTSAT-1R), point spread function (PSF).

I. INTRODUCTION

THE Clouds and the Earth’s Radiant Energy System (CERES) [1] incorporates 3-hourly geostationary (GEO) derived broadband fluxes to determine the diurnal variation of flux in between the CERES measured fluxes onboard the Terra and Aqua sun-synchronous satellites [2]. The Terra and Aqua satellites have a local equator crossing time of 10:30 A.M. and 1:30 P.M. The CERES project as of June 2013 has ingested imagery from 16 individual GEO satellites across five contiguous GEO domains since March 2000. In order to derive uniform fluxes across satellite platforms both in time and space, the visible imager radiances are first intercalibrated with the Moderate Resolution Imaging Spectroradiometer (MODIS) 0.65 μm channel. A very unusual feature was noticed when intercalibrating MTSAT-1 with Terra-MODIS not observed with any other GEO satellites during the MODIS era.

The MTSAT-1R three-axis stabilized satellite hosts the unique Japanese Advanced Meteorological Imager (JAMI), which has one visible channel and four IR channels [3]. Borrowing from the MODIS design, it has an off-axis telescope utilizing dual focal plane architecture to mitigate stray light, particularly during local midnight. JAMI has a 336 visible and 84 IR element 1-D detector array and incorporates a slow, when compared with other three-axis stabilized geostationary imagers, west-to-east tapered elevation scan to eliminate coverage gaps. On the other hand, the GOES-8 three-axis stabilized imager scans in both directions with eight inline visible detectors using a scan mirror [4].

The intercalibration of coincident MTSAT-1R and MODIS ray-matched radiance pairs seem to indicate that the MTSAT-1R visible sensor has a nonlinear response, since over darker regions some of the MTSAT-1R radiances were brighter than from the corresponding MODIS radiances, whereas for brighter regions the radiance pairs were linearly aligned. The comparison of coincident MTSAT-1R and MTSAT-2 images revealed that bright clouds artificially increased the nearby clear-sky ocean visible count values in the MTSAT-1R imagery [5]. The impact of the bright clouds extended several hundred kilometers. However, large clear-sky ocean domains were not impacted.

The operational MTSAT-1R imager data was obtained from the Man–Computer Interactive Data Access System (McIDAS) [6]. The 5 days of coincident daytime MTSAT-2 commissioning images were received in High Rate Information Transmission (HRIT) format from the Japanese Meteorological Association (JMA) during December 17 to 21, 2010, and were subsequently converted to the McIDAS format. The MTSAT-1R and MTSAT-2 HRIT visible images are in 10-bit format. For this study, the 1-km spatial resolution full-disk HRIT data have been subsampled to 4 km in order to reduce the computation time. Both the MTSAT-1R and MTSAT-2 images followed the same imaging schedule with about a 2-min observation time difference. Thus, this series of nearly simultaneous observations has provided an excellent opportunity to analyze the differences in the raw digital count response between the two sensors.
This paper describes an algorithm that derives the point spread function (PSF) coefficients of the MTSAT-1R imager by using the coincident MTSAT-2 radiances as truth. The companion paper, Part 1 [5], assesses the CERES ray-matching procedure for any systematic biases critical in the conceptualization of the PSF correction, as well as the validation of the PSF correction and follows up with the calibration of the MTSAT using the Aqua-MODIS 0.65 μm band as a reference.

II. Spatial Alignment of MTSAT Imagery

In order to effectively analyze the MTSAT-1R and MTSAT-2 sensor-related differences, the comparison has to avoid any spectral or anisotropic differences in observations from the two satellites. MTSAT-1R has a slightly wider spectral response function in the visible channel compared with that of MTSAT-2 [3]. Since clear land regions may produce colored reflected spectra, they are excluded from this analysis using a land-water mask generated for each satellite’s projection at the pixel level. The mask also excludes water pixels within 100 km along the coastline, in order to mitigate any spectral dependence from the shallow waters of the West Pacific. All remaining ocean cloudy and clear-sky areas provide enough coverage for the PSF analysis.

The two MTSAT subsatellite positions differ by 5° of longitude (140° E for MTSAT-1R and 145° E for MTSAT-2), creating a slight viewing geometry difference, which may cause the top-of-atmosphere (TOA) radiances to differ due to bidirectional reflectance effects. However, the cloudy and clear-sky water radiances are nearly isotropic in the absence of sunglint, whereas aerosol effects are insignificant for view zenith angles less than 75°. For these reasons, the pixel level mask excludes pixels with the angle of reflection within 15° of the specular reflection point, as well as pixels with view zenith angles greater than 75° for either sensor. The difference in the solar zenith angle due to Earth’s rotation is even smaller. The 2-min delay in the sensor scan time translates into 0.5° difference of the solar zenith angle, which can be neglected for this study.

Analysis of the pixel level differences between the two MTSAT images requires precise collocation with an accuracy better than one pixel or 1 km. Geolocation errors of several kilometers have been observed with the McIDAS navigation routines using nominal georeferencing information contained in the HRIT data format, suggesting that an additional georeferencing correction is needed. Even if the georeferencing were perfect, cloud structures may not be aligned between the two images due to the parallax effect, dependent on the cloud height and view angle difference, and the advection displacement of clouds, which can be as great as 5 km due to the 2-min scan time difference. To resolve these alignment problems, collocation of the MTSAT HRIT images is implemented in two steps. First, instead of reprojecting each satellite’s image from the pixel and line space into a geographic projection, the MTSAT-2 image is remapped directly to the pixel and line space of the MTSAT-1R. This yields higher spatial accuracy and eliminates the MTSAT-1R resampling step, thus retaining the original digital counts. The algorithm uses the nominal latitude and longitude provided for each pixel of MTSAT-1R and then employs the gradient search method [7] to locate that latitude and longitude in the pixel and line space of MTSAT-2. The search produces a fractional position in terms of pixel and line, which is then used to interpolate the adjacent MTSAT-2 pixel values by means of a 6 × 6 point image resampling function. At the image boundaries, the missing contents of the 6 × 6 window is padded by replicating the edge pixel values. Here and further in our algorithm, image resampling operations are implemented as Lanczos filtering [8] extended to the 2-D case with the parameter α = 3. This interpolation method is based on the sinc filter, which is known to be an optimal reconstruction filter for band-limited signals, e.g., digital imagery.

The second step is to correct for any residual misalignment between the remapped MTSAT-2 and the original MTSAT-1R images, which originate from georeferencing errors, cloud advection, and parallax effect on elevated targets. All of these spatial differences can be corrected by means of the subpixel image matching technique described in [9]. In this paper, instead of preselected ground control points, the image matching uses a regular 2-D array of image subsets (or chips) each having dimensions of 32 × 32 pixels produced from both input images by simply subsetting at every tenth pixel and line. The chip size is three times larger than the chip spacing to improve the final reliability of the correlation calculations. For each pair of chips produced from the two input images, spatial correlation is repeatedly calculated for a range of their possible relative displacements. Highest correlation yields a fractional vector showing how much one image is displaced relative to another at that particular chip location. As a result, a 2-D vector field of displacements is obtained with a resolution ten times smaller than the input images. If, at any given location, the two image chips are too different, then the correlation matching may fail or worse generate an erroneous vector. For that reason, the obtained vector field is subsequently refined by excluding missing values and any values that differ significantly from their neighbors. The excluded values are replaced by the average of the adjacent neighbors. The refined vector field is then spatially interpolated with Lanczos filtering to the original input resolution in order to obtain the local displacement for each pixel of the input image. Finally, the remapping described in the first step is repeated with each pixel’s fractional position now corrected by the amount of the local displacement calculated in step two.

III. Comparison of MTSAT-1R and MTSAT-2 Imagery

A scatter plot of the spatially collocated pixel level MTSAT-2 and MTSAT-1R HRIT 10-bit visible counts pairs and the associated linear regression is shown in Fig. 1. The MTSAT-1R observed digital raw counts are proportional to radiance for this sensor, and all computations in this study are performed using the count values. If the nominal georeferencing is used, the linear regression for 1-km resolution yields $R^2$ value of 0.9094. With the image matching correction applied, the $R^2$ value increases to 0.9555, reducing the residual sum of squares (RSS) by more than half. This result demonstrates the advantage of the image matching technique for the purpose of our analysis.
If the pixel values are spatially averaged in $3 \times 3$ groups prior to the regression then the $R^2$ value becomes 0.9742 and 0.9863, without and with the image matching correction, respectively. Clearly, the application of the image spatial matching technique is advantageous in the reduction of the noise caused by the collocation errors. A regression slope of 1.0266 was computed for Fig. 1 and explains the relative calibration gain difference between sensors assuming a linear response. Some of the bright pixel noise about the regression line can be explained by cloud shadows or cloud fields with complex 3-D structures captured differently from the two lines of sight. However, the greatest deviations from the regression line are observed over dark clear-sky ocean pixels, where the MTSAT-1R reveals consistently brighter counts than MTSAT-2. This causes the regression line intercept to have a negative offset of $-13.1$, which ideally should be zero. The magnified lower left portion of the scatter plot reveals that the point dispersion from the linear regression does not converge but consists of several overlapping clusters of points. This suggests that the problem is not caused by the nonlinearity of the sensor response but is in the form of spatial crosstalk embedded in the image pixel level counts.

The MTSAT-1R visible pixel counts are shown in Fig. 2(a). A bright band of clouds transects the image diagonally with Australia on the left and the West Pacific to the right. Clusters of convective clouds lie to the south of the equator. The spatial distribution of the count difference between collocated MTSAT-1R and MTSAT-2 images is shown in Fig. 2(b). Bright halos (positive difference) over clear-sky ocean regions surrounding highly reflective cloud fields are easily identified in the count difference image. The clear-sky ocean regions near the equator away from bright clouds have near zero count differences. The highly reflective clouds have a negative count difference. The count differences over clear-sky land are due to the sensor spectral response function differences and are excluded by the pixel mask in Fig. 1. In order to highlight the positive visible count difference surrounding bright clouds, a cross section of the difference is taken across Fig. 2(b) represented by the diagonal line beginning at the northeast corner and ending in the southwest corner. The clear-sky ocean region along the 900 and 1100-km mark of the diagonal clearly shows that the MTSAT-2
The observed halo effect appears to be unrelated to sunlight and not dependent on the solar angle in general. It cannot be explained by multiple scattering from cloud edges, since its impact is on order of kilometers, whereas the spatial decay shown in Fig. 2(c) is on order of several hundred kilometers. The absence of such a spatial pattern in the infrared bands denotes that the instrument mirrors, beam-splitters and detectors in the optical path are properly aligned, since most of the visible and IR optical path is shared [3]. The fact that the MTSAT-1R visible anomaly is independent of the scan pattern and impacts the full disk suggests that the issue is not due to the detector layout differences between the two instruments. However, the optical path of MTSAT-1R instrument was extended compared with MTSAT-2 in order to reduce the stray light reaching the detectors. This was achieved by having two additional mirrors installed on the optical path. If the surface quality of either of these mirrors is hampered by flawed polishing or dust deposits then its reflective properties can create wavelength dependence. Dust particles smaller than 1 μm can cause the visible light to disperse slightly from its intended path, whereas the IR wavelengths will not be affected. Such dispersion will cause a slight blurring in the observed imagery and manifest itself as a weak halo around bright objects, thus explaining the difference in the vicinity of large bright cloud systems.

A similar wavelength-dependent effect was reported by the National Polar-Orbiting Operational Environmental Satellite System Preparatory Program (NPP) Visible Infrared Imager Radiometer Suite (VIIRS) status memo [10], which stated that tungsten dust has darkened the surface of the instrument mirror. The tungsten oxide dust was deposited on the mirrors during the mirror coating process. The darkening is irreversible and is expected to stabilize in a few years. The sensitivity may be reduced by half after 5 years of operation for wavelengths between 0.7 and 2.0 μm. The VIIRS IR and shorter visible wavelengths were not impacted [11]. Tahara et al. 2005 [12] stated that the JAMI visible channel sensitivity was reduced by half from the prelaunch value, which supports our hypothesis of the possible dust contamination of the mirrors.

### IV. Deconvolution With PSF

Assuming that the dispersion of light reflected by contaminated mirror is small and randomly distributed surrounding the direction of specular reflection, the scattering profile can be described by the normal distribution, i.e., the Gaussian function $G(x)$. Then, the PSF, which describes the response on the focal plane to a point source of light, will consist of the Dirac delta function corresponding to the specular reflection from clean areas on the mirror and the Gaussian function describing the scattering from the dust

$$\text{PSF}(x) = \delta(x) + AG(x).$$

Here, $A$ is an unknown scaling factor representing the relative amount of contamination and $x$ is the spatial coordinate. The blurring of the recorded MTSAT-1 image $f_1(x)$ can be represented as a convolution of the original signal $f_0(x)$ with the PSF(x) function

$$f_1(x) = \int f_0(x-u) \text{PSF}(u) \, du. \quad (\text{2})$$

According to the convolution theorem, the Fourier transform of a convolution is the product of Fourier transforms. Because the Fourier transform of the Dirac function is unity and the transform of a Gaussian function is another Gaussian function $G'(\omega)$, we obtain

$$F_1(\omega) = F_0(\omega) \cdot (1 + A \cdot G'(\omega)) \quad (\text{3})$$

where $\omega$ is the spatial frequency. Because $A$ is small, this can be rewritten as

$$F_1(\omega) \cdot (1 - A \cdot G'(\omega)) \approx F_0(\omega). \quad (\text{4})$$

Taking the inverse Fourier transforms, we finally obtain a deconvolution formula that recovers the original undistorted image $f_0(x)$ from the recorded image $f_1(x)$

$$f_0(x) = \int f_1(x-u) (\delta(u) - AG(u)) \, du. \quad (\text{5})$$

In the 2-D space, the Gaussian function can be written as

$$G(x, y) = \frac{1}{\pi\sigma_x\sigma_y} \exp \left(-\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right). \quad (\text{6})$$

Here, $\sigma_x$ and $\sigma_y$ are the characteristic half-widths of the function’s bulge along $x$- and $y$-coordinates of the image. Allowing them to be unequal, we can define the orientation of the bulge by introducing an unknown ellipticity $\varepsilon$ and rotation angle $\theta$

$$G(x, y) = \frac{1}{\pi\sigma^2\sqrt{1-\varepsilon^2}} \exp \left(-\frac{x^2 + y^2 - \varepsilon^2(x \sin \theta + y \cos \theta)^2}{\sigma^2(1-\varepsilon^2)}\right). \quad (\text{7})$$

Thus, the sought shape of the PSF function is defined by the four unknown parameters: $A$, $\sigma$, $\varepsilon$, and $\theta$.

These parameters can be solved by means of the maximum-likelihood estimator using the aligned MTSAT-2 image as truth. The algorithm minimizes the RSS based on the linear regression of the modeled MTSAT-1 image $f_0(x)$ and the colocated MTSAT-2 pixel count pairs. In discrete image coordinates, (5) can be written as

$$f_0(i, j) = \frac{\sum_n \sum_m G(m, n) f_1(i + m, j + n)}{1 - A \sum_n \sum_m G(m, n)} \quad (\text{8})$$

where $i$, $j$ are the current pixel and line coordinates and $m$, $n$ are pixel coordinates relative to the current pixel. Here, the infinite integration is replaced with finite sums and, for computational performance, the Gaussian function extent is limited to 579 × 579 pixels at 4 km/pixel resolution and hence $m, n = [-289, 289]$. Then the largest magnitude of $G(m, n)$ achieved at the boundary is only 0.25% of the central value (for a typical $\sigma$ of about 118, as shown below). The denominator in (8) represents the total integral of the PSF function, which
is needed to conserve the total signal power. It has to be re-calculated at the image boundaries where the range of $m, n$ is reduced due to clipping.

The optimal set of the four PSF parameters can be found by means of the Powell’s conjugate direction method [13], which iteratively converges to a local minimum of a function in multidimensional space without taking its derivatives. Due to the high dimension count of our problem, the Powell’s method may not converge efficiently if the sought parameters are not sufficiently independent. The introduced set of parameters $A, \sigma, \varepsilon, \text{and } \theta$ were chosen to ensure optimal decoupling of the variables during minimization: $A$ controls the strength of blurring with respect to the ideal reflection, $\sigma$ is the average half-width of the PSF not affecting its total integral [note $\sigma^2$ as the normalization factor in (7)], $\varepsilon$ and $\theta$ control the oblateness and rotation, respectively, of the PSF’s bulge not affecting its width and magnitude. To equalize the sensitivity of the minimization routine with respect to the nonlinear parameter $\varepsilon$, the term $\varepsilon$ is replaced with

$$\tau = \tan(\pi \varepsilon^2 - \pi/2).$$

Here, the parameter $\tau$ varies from minus infinity to infinity for $\varepsilon \in [0, 1]$ and allows for a more stable convergence of the minimization.

V. Results and Discussion

For the pair of coincident observations on December 21, 2010, 2:30 GMT shown in Fig. 2, the PSF parameter coefficients derived from the minimization routines are: $A = 0.14995 \pm 0.00073$, $\sigma = 119.27 \pm 1.30$, $\varepsilon^2 = 0.2546 \pm 0.0185$, and $\theta = 20.8 \pm 7.1^\circ$. The errors shown here correspond to minimization residuals obtained when the requested tolerance of achieving the minimum RSS is set to $10^{-4}$. Thus, the portion of the light dispersed by the mirror contaminant is $A/(1 + A)$ or about 13% for this case. The width of the PSF is $2 \sigma \times (4 \text{ km/pix})$ or 954.16 km. Ellipticity with $\varepsilon^2 = 0.2546$ denotes that the horizontal width is only about 14% shorter than the vertical, and indicates that the PSF profile is very close to the circular symmetric form. With such a low ellipticity, the angle of rotation of the PSF bulge is a poorly defined, nearly unmeasurable parameter with an associated large uncertainty. The nonzero ellipticity suggests that the scattering of light in the optical path is not exactly uniform, since the optical axis of the MTSAT instrument is not normal to the mirror’s surface.

Fig. 3 shows the regression scatter plot of the spatially collocated MTSAT-2 and PSF-corrected MTSAT-1R pixel level counts. Note the scatter about the regression line has been significantly reduced when compared with Fig. 1, particularly over dark clear-sky ocean regions effectively removing the weak halo effect surrounding bright clouds. The RSS is reduced by $\sim$52% and the $R^2$ has increased to 0.99304. The slope of regression is 0.92737 and represents the true relative calibration gain difference between MTSAT-1R and MTSAT-2 assuming a linear detector response. The regression intercept is 3.47 and much closer to the expected offset of zero. Some outliers at the lower count range are attributed to cloud shadows, which may introduce a noticeable discrepancy under low sun conditions due to slight difference in view zenith angles of the two satellites. Overall, these regression statistics clearly quantify the improvement due to the application of the PSF parameter coefficients.

It would be desirable to find a set of PSF parameter coefficients that are valid over the entire MTSAT-1R imager record. However, only 5 days of coincident MTSAT-1R and MTSAT-2 images during December 17, 2010, 02:30 GMT to December 22, 2010, 01:30 GMT are available over the record. If the PSF coefficients are found to be consistent over the 5-day time period, it will justify the use of a single set of coefficients over the MTSAT-1R record. One possible indicator of the long-term stability of the PSF coefficients is to regress the MTSAT-1R PSF corrected and the Aqua-MODIS coincident collocated co-angled radiances over the MTSAT-1R record and monitor the regression coefficients over time. This analysis has been carried out in [5] and is also summarized here in the Conclusions.

The PSF parameter coefficients retrieved from the 5 days of hourly daytime coincident data have been examined for consistency. The PSF coefficients were calculated for 59 coincident observations, which include only images with the number of pixels over 15% of the total image, screened by the mask described in Section II. The results of the PSF parameter calculation are summarized in Fig. 4. The top panel displays the percentage of imager pixels screened or valid for PSF analysis. The second panel shows the slope of the linear regression between MTSAT-2 and MTSAT-1R PSF corrected collocated pixel level digital counts. For this analysis, the linear regression offset was forced through the origin as recommended by [5] and a $4 \times 4$ pixel averaging routine was applied prior to computing the linear regression to smooth over the small scale pixel noise caused by cloud shadows and complex 3-D cloud effects. The minimization errors are found to be small.
Fig. 4. Summary of the PSF parameters calculation for all coincident observations between MTSAT-1R and MTSAT-2. The top panel shows the percentage of pixels screened for PSF analysis and included in the minimization process.

and not to correlate with the screened pixel percentage. For the scale factor $A$, the average observed relative fitting error is $0.61\%$, for the half-width $\sigma$, the error is $1.89\%$, for $\varepsilon^2$ it is $9.8\%$, and for $\theta$ it is $13.8\%$. Because the fitting errors are very small, the error bars in Fig. 4 include the inverse dependence on the percentage of valid pixels. The weighted average of
the regression slope computed from the 59 images is 0.945 ± 0.018. A diurnal pattern is clearly noticeable, where for the first four early morning images the slopes tend to decrease toward the time of sunrise (i.e., the MTSAT-1R counts are higher than MTSAT-2), whereas for the last three late evening images the slopes tend to increase toward the time of sunset, and the midday slopes tend to be consistent. The sunrise and sunset images are comprised of dark and lit portions, where the solar zenith angles in the illuminated portion are large. The large solar zenith angles increase the bidirectional reflectance effects due to the collocated pixel sensor view angle differences and may explain the 3–4% difference in the slope. The middle panel in Fig. 4 displays the derived PSF scaling factor \( A \) and seems to be diurnally anti-correlated with the slope, which means that \( A \) is larger when the MTSAT-1R observed counts is high due to the bright clouds. Apparently, the minimization routine responds to the higher counts accordingly and converges to the larger scale factor correcting for the stronger halo around bright clouds. It is therefore concluded that the observed hourly variations are caused by external factors and are not related to the instrument intrinsic parameters. Fig. 4 displays the PSF half-width \( \sigma \) in the fourth panel and the PSF ellipticity \( \epsilon \) is displayed in the bottom panel and these parameters do not show any correlation with image time.

The fact that the midday images provide consistent PSF parameters values, where most of the image is illuminated and available to characterize the PSF, verifies that the instrument PSF characteristics are constant in time. For the early morning and late afternoon images the PSF parameter values may deviate from the midday values, because the illuminated portion is decreasing geographically and the solar zenith angles are rising, increasing the bidirectional effects of the collocated pixel level counts and reducing the number of available pixels for PSF analysis. These circumstances increase the uncertainty of the PSF parameters making them less valuable to evaluate the PSF characteristics. The computed weighted averages, based on their corresponding image uncertainties, of the PSF parameters are given in Table I. The overall parameter averages are within most of the individual image error bar ranges.

VI. Optimization of Performance

On average, the minimization routine converges within 190 ± 40 iterations using a tolerance factor of 0.0005, which is the smallest achievable relative reduction of the RSS. The most computationally intensive phase of the minimization routine is the pixel level calculation of the (8) for the portion of the image screened by the mask. The full-disk dimension of the MTSAT-1R HRIT format is 2200 × 2200 pixels at a 4-km nominal pixel resolution. The number of pixels screened in the routine ranges from 18 to 64% depending on the image time. For a single image there can be as many as \( 3.1 \cdot 10^6 \) pixels to process, which requires over \( 10^{12} \) inner loops of (8) to be computed for each iteration. Each inner loop performs one multiplication and two additions, which require on average about 10–12 cycles of a modern x86 compatible CPU. With a typical CPU clock rate of 3 GHz this translates into 3.7 ns per loop, or about 1 h per iteration, or about 200 h for a complete convergence. The convergence of the iteration process does not necessarily guarantee the optimal solution of the PSF-parameters due to the mathematical complexity of the problem. Therefore, a single image was selected to perform several trials of the convergence routine in order to find the best initial set of the sought parameters, which can then be utilized for all remaining images, since the PSF function should be identical for each image.

One way to reduce the processing time is to degrade the pixel resolution by 2, which reduces the number of pixels in the image by four times. Then, the dimensions of the PSF matrix can be reduced accordingly, which gives a total reduction factor of 16 in the computation time. Another solution, which is used in our algorithm, is to improve its computational performance by software optimization [14]. This was achieved by programming the part of the algorithm calculating the convolution in assembly language using SSE3 instruction set [15]. This not only reduces the number of CPU cycles needed for the inner loop to 7–8 but also, more importantly, allows 4 operations (multiplication or additions) to be performed in parallel. With this optimization, the time required by one iteration is reduced to ~12 minutes for images with the greatest number of screened pixels. Furthermore, because the convolution operation is applied to each pixel independently, the processing can be split in several threads of execution, which can be processed in parallel by several CPUs or CPU cores. This is realized by dividing the full-disk image into several horizontal partitions and precalculating their heights to maintain equal area splitting. However, the total number of pixels screened by the mask will be different within each partition. In addition, the time required to calculate (9) is reduced at the image boundaries due to clipping of the PSF matrix. For these reasons, the actual time spent by each execution thread averaged over the four most recent iterations is used as a feedback to automatically recalculate the segment heights on the fly during parallel processing. It was found that splitting the calculation into more than 12 parallel threads does not yield any significant processing improvement due to difficulties with thread synchronization. Overall, the parallel processing optimization increases the computational performance by at least a factor of 10 and reduces the total run time required to derive the PSF parameters to 3–4 h.

The computational performance can be improved even further if the exact mathematical accuracy is not critical. The summation term in the numerator of (8) presents a convolution of the image \( f_1(x) \) with an extremely wide kernel \( G(x, y) \). The result of this convolution is a smooth function with a very small spatial gradient, which may not need to be calculated at every
pixel. Instead, this function can be calculated over a coarse grid and subsequently interpolated to obtain the individual pixel values. Even interpolation with the 2-D Lanczos filtering is still more efficient than the calculation of the sum at every pixel and line. A similar approximation can be implemented to compute the denominator of (8). If only one line and pixel are interpolated by this method then the result matches the exact calculation with an \( R^2 = 0.999994 \), which is extremely close to an \( R^2 \) of unity, whereas the run time is reduced by almost four times. If two pixels and two lines are interpolated, then the execution time is reduced by a factor of 9 and the \( R^2 \) has only degraded to 0.999986, which is still two orders of magnitude better than the best \( R^2 \) achieved by the optimal PSF correction.

VII. CONCLUSION

This paper describes a mathematical methodology to improve the quality of the slightly blurred MTSAT-1R visible channel imagery. The weak blurring is observed only in the visible channel, which infers wavelength-dependent light dispersion apparently caused by imperfect mirror polishing or a mirror dust contaminant. Since the dispersed light contribution is small compared with the specular point reflection, it was possible to implement image restoration as a deconvolution with an inverted PSF function. The MTSAT-1R PSF was characterized by four parameters and was solved by means of a maximum-likelihood estimator using coincident MTSAT-2 images as truth. The MTSAT-2 imager pixels were collocated into the MTSAT-1R satellite projection using a subpixel image matching algorithm that corrected for misalignment caused by navigation errors, parallax effects, and cloud advection due to the 2-min scan time difference. Only five days of hourly daytime coincident MTSAT-1R and MTSAT-2 images were available for this study. The PSF parameters were derived for all available images and examined for consistency, in order to determine if a single set of parameters can be used for the entire MTSAT-1R record.

It was shown that for most near fully illuminated images, the PSF parameters were consistent and did not vary over time over the five-day period. The PSF parameters values derived for each image were averaged using all available coincident observations weighted by their respected uncertainties. For the early morning and late afternoon, the imagery is only partially illuminated, and the PSF parameters were less consistent but their associated uncertainties encompassed the averaged parameter values. These images are observed at large solar zenith angles over limited geographical domains, where cloud shadow, bidirectional reflectance, and 3-D cloud geometry effects are more noticeable among the sensor matched pixels and are less than ideal to quantify the PSF parameters.

It is impossible to determine the long-term drift of the PSF parameters with only five days of coincident images. The PSF parameters were applied to the entire MTSAT-1R data record and calibrated against Aqua-MODIS coincident collocated radiances [5]. The application of the PSF parameters reduced the monthly calibration gain noise by one third, where the monthly gains were most erratic during 2005 and 2006. The regression slope intercepts based on Aqua-MODIS are approaching zero over time. These results may indicate a slight change of the coefficients over the MTSAT-1R record, however the consistent improvement in image quality over the record warrants the application of the PSF correction method for all images.

Readers can easily apply the PSF correction coefficients in Table I to the MTSAT-1R HRIT 4-km visible record using (7) and (8). If the reader would like to apply the PSF correction to another pixel resolution, e.g., \( N \) km/pixel, then the half-width \( \sigma \) must be scaled by the factor of \( N^2/4 \) and the scaling factor \( A \) must be multiplied by \( N^2/16 \) in order to conserve the total signal power. It must be noted, that the MTSAT-1R High Resolution Image Data format has a nominal pixel resolution of 1.25 km/pixel, whereas the HRIT format has a 1 km/pixel resolution.

The deconvolution method described in this paper assumes that the dispersed portion of the reflected light is small in order to approximate the nondistorted image in (5). The methodology also assumes that the light dispersion is mainly in the direction of the instrument mirror specular reflection, which allows the PSF shape to be described in a simple analytical form. In spite of these minor deficiencies, the described algorithm presents a reliable and straightforward method that can be applied to any past MTSAT-1R observations to recover the original nondistorted visible imagery of this advanced instrument.

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