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Innovative Data Processing for Push-Frames Technology for iSIM sensors

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Abstract

iSIM (integrated Standard Imager for Microsatellites) is an innovative technology for Earth Observation developed by SATLANTIS. The iSIM camera is designed to be diffraction-limited, hence its spatial resolution is limited by the size of the optics, rather than the detector pixel size. This design allows for Ultra High Resolution techniques to improve the native resolution of the imager by a factor of 2. Thanks to a well characterized optical system and a 2D field of view of CMOS sensors, the Ultra High Resolution extracts all the information available in overlapping images acquired in a single satellite pass through its processing pipeline. The algorithm removes any sensor, telescope, and payload effects that degrade the raw image quality. Then, the algorithm aligns, fuses, and up-samples several raw frames to produce a stack of ultra-high resolved image strips. Finally, strips are mosaicked, deconvolved, radiometrically calibrated, and spatially re-sampled. The Ultra High Resolution algorithm enables us to increase the resolution, signal-to-noise ratio, and contrast, without producing artifacts or the need to train a model. Depending on the application, the process can be adjusted to prioritize one of these three features. The iSIM technology, and especially the image processing and Ultra High Resolution feature, was demonstrated in orbit in two missions during 2020 and 2022, aboard the International Space Station (ISS), and the recently launched satellite called ARMSAT1.

Keywords: CubeSats, Image Processing, High Resolution, Optical Imager, Earth Observation

Acronyms/Abbreviations

Central Processing Unit (CPU)
Commercial Off-The-Shelf (COTS)
Configurable and Autonomous Sensor Processing Research system (CASPR)
Department of Defense (DoD)
Earth Observations (EO)
Edge Spread Function (ESF)
Frames Per Second (FPS)
Ground Sampling Distance (GSD)
Ground Resolved Distance (GRD)
Integrated Standard Imager for Microsatellites (iSIM)
International Standards Organization (ISO)
International Space Stations (ISS)
In-Orbit Demonstrator (IOD)
Line Spread Function (LSF)
Modulation Transfer Function (MTF)
Point Spread Function (PSF)
Signal-to-Noise Ratio (SNR)
Solar Elevation Angle (SEA)
Space, High-Performance and Resilient Computation (SHREC)
Technology Readiness Level (TRL)
Thermal Control Subsystem (TCS)
Ultra High Resolution (UHR)
Visual and Near Infra-Red (VNIR)
World Geodetic System 1984 (WGS84)

1. Introduction

The "integrated Standard Imager for Microsatellites" (iSIM) is a high resolution, multispectral imager designed and manufactured by SATLANTIS. The imager is intended for new-generation microsatellite constellations devoted to Earth Observations (EO). iSIM cameras have a binocular configuration with a diffraction-limited optical system over the entire field-of-view (0.8-1.8ºdiameter, depending on the model) and the whole wavelength range (400-1700nm). iSIM uses three optical elements with all spherical surfaces (modified Maksutov-Cassegrain design). Mirrors are mounted on a quasi-athermal structure of a robust and light alloy and point the light rays towards two COTS 2D CMOS sensors modified to resist vibrations, thermal, and radiation hazards. The cameras are provisioned with a central processing unit (CPU) and a thermal control subsystem (TCS). The former mainly manages the images and communicates with platform. The latter controls and monitors payload's temperature. SATLANTIS has built and tested two version of the camera called iSIM90 and iSIM170 with different specifications (see Section 1.1), which are suitable for 12-16U CubeSats and 50-100kg Microsatellites, respectively. A third version, called iSIM300, is currently being developed by SATLANTIS for Minisatellite platforms (1000-300kg).

1.1 Model specifications

The iSIM90 and iSIM170 (Fig. 1) acquire multispectral images in the spectral range of 450-900 nm. Multispectral information is retrieved by placing filters in front of the detectors. By default, both cameras combine 5 spectral bands in the blue (459-525nm), green (541-577nm), red (650-680nm), near-infrared (780-886nm) and panchromatic (450-750nm) spectral regions. However, the band configuration is flexible depending on the mission requirements. An iSIM170 compared to iSIM90 has a larger aperture diameter (150 vs. 77.5 mm) and focal length (1500 vs. 775 mm). These differences translate into a smaller ground sampling distance (GSD) for the iSIM170 (<1m) than for the iSIM90 (2-2.5 m) when orbiting at an altitude of 500km and their swaths are 7.5 and 13 km respectively.

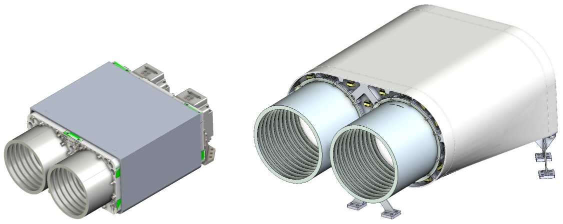

Fig.1. Isometric views of the iSIM90 (left) and the iSIM170 (right) camera models (not at scale)

1.2. Acquisition strategy

The acquisition strategy of iSIM cameras brings three major technological benefits. First, the rate of acquisition allows the application of super-resolution techniques to improve the quality of raw frames. The two channels of an iSIM capture 26 frames per second (FPS) of nearly the same area on the ground (Fig. 2). Ultra High Resolution (UHR) is the super-resolution algorithm integrated with iSIM. Second, the design enables acquiring images as the satellite moves along or across track (agility mode). Agility is convenient to scan non-linear features on Earth's surface, such as pipelines, country borders, or coastlines. Third, the spatial resolution constant regardless the number of bands since filters are placed in different rows in front of the detector and distributed over the channels. The filters are oriented perpendicular to the travelling direction of the satellite (Fig. 2). Thus, all filters scan the same areas as the satellite travels along its orbit.

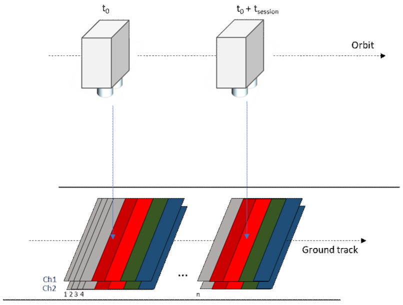

Fig. 2. Observation strategy of iSIM cameras.

The iSIM concept aims at providing cost-effective and customized solutions for remote-sensing applications. The goal entails implementing technically challenging designs to compete in resolution against more expensive alternatives that purely rely on optical considerations. For this, SATLANTIS has developed a simple and robust product (e.g., no moving parts), with a balanced trade-off between swath and pixel sampling using COTS detectors. UHR, as an integral component of the imager, allows reaching a competitive spatial resolution of 1-2m, depending on telescope model. The innovations and features of iSIM are being tested in several missions on the International Space Station (ISS) and satellite missions. The aim of this paper is to demonstrate the role of UHR in the telescope-algorithm tandem and its capabilities with real EO, when available. Section 2 describes the UHR algorithm, missions, and methods to test the features of the iSIM imager. Section 3 shows the main results and Section 4 discusses the limitations and ways forward for UHR and mission activities. Finally, Section 5 summarizes the main conclusions.

2. Material and methods

UHR corrects, aligns, and fuses raw sequences captured with iSIM imagers to deliver high-quality super-resolved multispectral mosaics (Section 2.1). The current version of UHR is the result of incremental changes after testing and experimenting in several missions (Section 2.2). Through those experiences, the pipeline has moved from processing panchromatic super-resolved mosaics into high-resolution multispectral bundles. Demonstrations of the UHR capabilities are consolidated in the form of image samples, quality metrics, and visual inspection of noise, resolution, and contrast (Section 2.3).

2.1. UHR algorithm

UHR is an algorithm that corrects, fuses, mosaics, and deconvolves mono-band frames and co-registers information from different filters to generate a multiband bundle (Fig. 3). In the first step, dark and flat corrections restore the artifacts triggered by the sensor due to temperature, read-out patterns and pixel-to-pixel differential gains. Corrections require dark and flat masters acquired in orbit during calibration campaigns. Moreover, the pipeline removes the optical distortion by warping the image according to deflection profile. The optical distortion pattern is obtained in orbit, during the commissioning phase. Comparing subsequent frames with structures and features like urban landscapes reveal the optical distortion pattern.

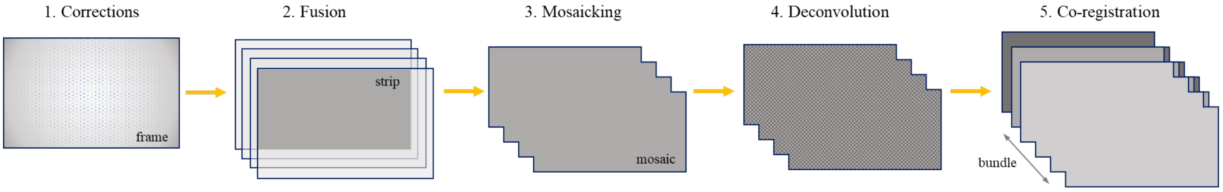

Fig. 3. Processing steps of the Ultra High Resolution algorithm

In the second step, UHR aligns and fuses the overlapping frames. Information from the platform, such as speed and attitude, are used to estimate the shifts between frames and speeds up the alignment process. Once aligned, the fusion combines several observations of a given location. The result is a narrow image in the along-track direction with a higher resolution than raw frames called strip. In the third step, the algorithm infers the relative position of strips using the shifts from the earlier alignment and forms a multi-strip mosaic. Next, the processing chain combines the strips, cutting and smoothing the edges to remove border effects and ensure a seamless integration.

During the fourth step, the algorithm performs the deconvolution. The deconvolution attempts to recover a scene before blurring. Blurring is caused by light diffraction and defocus. In iSIM, motion blur is effectively zero thanks to short exposure times. The blurring is defined by the point spread function (PSF) of the imager. The PSF is obtained from laboratory measurements and in-orbit calibration campaigns. The final step is the alignment of the spectral bands through co-registration. For convenience, the result is a super-resolved multiband bundle of nearly the same swath across and along track. See [1] for further details about the processing algorithm.

UHR has been designed and tuned with accurate simulations of satellite images, both before and during missions. Furthermore, it has been tested and validated (qualitatively) with real imagery from 3 missions: IOD, CASPR and ARMSAT1. Further quantitative validation is being carried out with commissioning data from real observations from ongoing missions.

2.2. Missions

iSIM accumulates the experience of three missions in orbit: the In-Orbit Demonstrator (IOD) [2], the Configurable and Autonomous Sensor Processing Research system (CASPR) [3], and ARMSAT1. The IOD mission begun on May 20th, 2020, with the launch of panchromatic iSIM170 to the ISS. The camera was installed on the external platform of the Japanese KIBO module. The camera performed 1400 orbits and delivered 141 GB of data. The camera was decommissioned on September 10th, 2020, and the payload received the TRL-8 qualification with the successful evaluation of uplink and downlink communications. One of the mains goals of the mission was the demonstration of the capabilities of UHR.

CASPR is an ongoing mission that started on December 21st, 2021, with the launch of a multispectral iSIM90 camera abord the CRS-24 SpaceX mission. The mission is managed by a consortium of public and private entities led by the University of Pittsburgh. The consortium is the Space, High-Performance and Resilient Computation (SHREC) from the National Science Foundation. CASPR is part of the Space Test Program - Houston 7 (STP-H7) of the Department of Defence (DoD), managed by NASA. The goals of the mission are acquiring high-resolution multispectral imagery and proving agility, the ability to take images while moving along and across track.

ARMSAT1 is an ongoing mission, staring on May 25th, 2022, with the launch from Cape Canaveral of a 16-U CubeSat with an iSIM90 multispectral camera on board. The satellite operates in a low inclination sun-synchronous orbit at 530 km nominal altitude with an expected lifetime of 4 years. The mission belongs to the Armenian government and will be used for agricultural and environmental applications among others. The main objective of this mission is the release of the UHR version and demonstrate its applications for EO.

2.3. Quality metrics

The above-mentioned experiences have resulted in high-resolution multispectral images, proving the capability of UHR to process frames from iSIM telescopes successfully. The goal of UHR is to enhance the quality of raw scenes in terms of noise, spatial resolution, and contrast. Here, we run a preliminary assessment of each of these aspects using real observations, whenever available. Otherwise, we refer to laboratory measurements as proof of the UHR capabilities. Note that the quantitative assessment of image quality is still an ongoing activity.

The signal-to-noise ratio (SNR) is a frequently used image quality metric that quantifies the precision of an instrument. SNR is the ratio between the average signal of the image and its noise. Noise is usually measured as the standard deviation of the pixel values. For the SNR analysis, we selected small, uniform, and flat regions to avoid confounding spatial variability with random noise. These regions were at least 10x10 pixels in the raw frames to ensure representative statistical estimates. For comparison purposes, the same region in the super-resolved images was evaluated. The higher resolution in the UHR output implies a larger sample size. However, this should not have an impact on the comparison since both statistics are representative.

Resolution is associated to the ground sampling distance (GSD). The GSD refers to the distance between consecutive pixels on the ground on a row-to-row or column-to-column basis. Here, we estimate the GSD by comparing the real size of objects and structures with their extension in the image. We favoured large objects to compensate for errors when delimiting distances. In every scene, we chose objects across the scene to sample the entire swath. Note that the GSD is a measure that only considers the geometry of the detector elements. Hence, it does not provide the full perspective on spatial resolution.

The Modulation Transfer Function (MTF) is a geospatial quality metric to assess the contrast of an image. SATLANTIS has developed tools to assess the MTF according to the slanted-edge approach ISO12233:2017 [4]. This method uses a checkboard target image tilted 10-30 degrees to obtain the MTF. Through the MTF, one can define the ground resolved distance (GRD). The GRD is the minimum distance between objects to be distinguished. One way to define the GRD is the distance at which the MTF crosses the Rayleigh criterion. The Rayleigh criterion states that two object can be differentiated when the contrast falls 10% between them. The GRD is usually linked to spatial resolution. Real images of spatial calibration targets are not available to date. Hence, we evaluate contrast qualitatively through visual inspection. We explore image features before and after UHR to evaluate the sharpness and the smallest visible objects.

2.4. Scenes

Table 1 contains a list of 8 sequences from both iSIM90 and iSIM170 used in the quality analysis of UHR. Images from the iSIM170 correspond to the IOD mission, windows 84 and 249. These sequences were captured near Saint Tropez (France) and San Diego (USA), respectively. The camera orbited the Earth on the ISS at an altitude of roughly 421 km at the time of observation. The camera pointed close to nadir, but the exact orientation was unknown and changed over time. In both sequences, the solar elevation angle is similar.

Table 1. List of sequences used in the image quality assessment of UHR.

Camera	Mission	Window	Location	Altitude[1]	Attitude[2]	SEA
iSIM170	IOD	84	Saint Tropez, France	421	-	68.31
		249	San Diego, USA	421	-	66.26
iSIM90	ARMSAT1	60	Canary Islands, Spain	524	0.24/0.05/-0.63	57.74
		69	Sahara, Mauritania	532	0.00/0.01/-0.01	45.30
		104	Adelaide, Australia	533	9.60/0.01/0.00	71.32
		111	McMurdo, Antarctica	541	0.95/-2.21/24.98	14.61
		118	Muscat, Oman	530	0.00/0.00/0.00	38.83

[1] Camera orbital altitude, in kilometres
[2] Camera attitude with respect to the orbital reference frame as roll/pitch/yaw, in degrees
[3] Solar elevation angles in the local plane at time of acquisition, in degrees

The iSIM90 imagery belongs to the ARMSAT1 mission. At the time of this assessment, windows 60, 69, 104, 111, and 118 were particularly suitable for the analysis. Among the sequences available, these images contain large objects and different land-uses. The windows cover 4 continents (Africa, Oceania, Antarctica, and Asia), which were observed at altitudes between 524-541 km above the WGS84 ellipsoid. The camera attitudes were mostly nadir, with the only exception of Adelaide and Antarctica which were observed with slight roll and pitch angles, respectively. In contrast to the IOD, these observations were made with 14.61º-71.32º solar elevation angle (SEA), covering a wide range of illumination conditions.

3. Results

3.1. Visual inspection

Figure 4 shows sections of a panchromatic super-resolved mosaic from the windows 84 and 249 of the IOD mission. The traveling direction of the ISS is 7.4º and 7.9º to the left from the sensor vertical axis, reducing the swath of the mosaic. However, UHR proved the ability to align and mosaic super-resolved strips in such conditions. In CASPR, UHR was modified to ingest multispectral frames. The pipeline incorporated the band-to-band co-registration to generate multispectral bundles. UHR provided VNIR imagery successfully with sequences from central Spain, Oakland, Florida, and Chile. In ARMSAT1, UHR has a greater number of overlapping frames. The algorithm was refined with an improved deconvolution method to better balance contrast and noise. CASPR and ARMSAT1 imagery are not shown due to restrictions in the publishing permits.

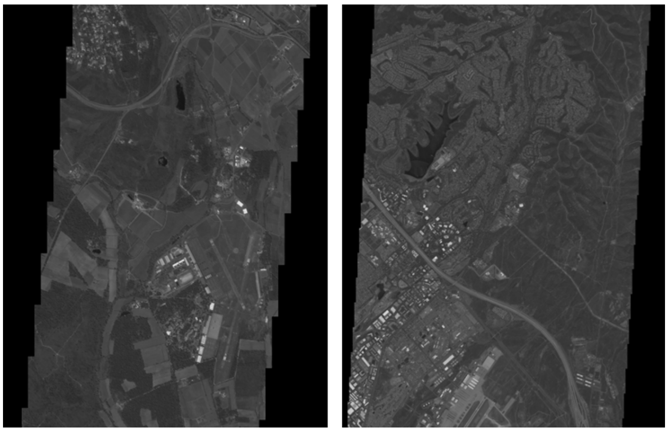

Fig. 4. UHR outputs from panchromatic images captured over Saint Tropez, France during (left) and San Diego, USA (right) on windows 84 and 249, respectively, during the IOD mission.

3.2. Signal-to-noise ratio

The results of the SNR analysis of the panchromatic iSIM170 camera are in Table 2. The table exhibits the values of other influencing factors like the solar elevation angle (SEA), albedo, and spectral band. The table lists the SNR values before (SNR raw) and after UHR (SNR UHR), and the gain factor achieved the through processing algorithm

(Factor). The table also shows that the SNR is roughly equal or greater after applying UHR, with the only exception of very low albedos. The average gaining factors are 1.32±0.59, 1.02±0.25, and 1.37±0.25 for low, mid, and high albedos respectively. Two main factors limited the performance of UHR during this mission: (1) a fewer number of overlapping images than nominal, (2) a deconvolution process with a pre-fixed number of iterations.

Table 2. SNR assessment of an iSIM170 dual panchromatic telescope during the IOD mission

Albedo[1]	Window	Surface	SEA	Band	No.[3]	SNR raw	SNR UHR	Factor
Very low (<0.1)	84	Water	68.31	PAN	8	25	10	0.38
Low (0.1-0.2)	84	Grass	68.31	PAN	8	29	28	0.97
	249	Asphalt	66.26	PAN	8	28	51	1.81
Mid (0.5)	84	Gravel	68.31	PAN	8	38	33	0.86
	249	Concrete	66.26	PAN	8	35	42	1.21
High (0.8-0.9)	84	Roof	68.31	PAN	8	35	42	1.21
	249	Roof	66.26	PAN	8	51	79	1.56

[1] Approximate classification of albedo based on usual spectral signatures and image intensity

[2] PAN stands for panchromatic

[3] Number of overlapping images fused

The iSIM90 currently in orbit shows a better performance in SNR (Table 3). Here, the average gain is 1.25 based on the results from Table 3. The likely reasons for the improvement are: (1) the higher number of images fused (8 vs 12-26) and (2) the incorporation of an improved deconvolution technique in UHR. The SNR gain is higher even though the average solar elevation angle is higher in the iSIM170 dataset. There is a high variability in the results related to different performances in each spectral band and various albedos. The wide range of albedos (Fig. 5) is the primary source of variation in SNR, with improvement factors of 0.48±0.22, 1.13±0.24, 1.83±0.54, 1.87±0.66 and 1.61±0.28 for very-low, low, mid, high, and very-high albedos. The relevance of the albedo is followed by the solar elevation angle. The SNRs are the highest for the mid albedo and higher solar elevation angles (32-76). The variability in SNR is high, probably indicating that there is a non-random component in the noise estimates.

Fig. 5. Regions to study the SNR of iSIM90 and UHR with increasing levels of albedo. Images, from left to right, correspond to Google Earth imagery for windows 60, 118, 104, 69 and 111. The green contour shows the location of the SNR assessment.

Table 3. SNR assessment of an iSIM90 VNIR telescope during the ARMSAT1 mission.

Albedo[1]	Window	Surface	SEA	Band[2]	No.[3]	SNR Raw	SNR-UHR	Factor
Very low (<0.1)	60	Sea water	57	NIR	12	8	3	0.44
				R	26	9	4	0.40
				G	26	27	10	0.37
				B	12	25	21	0.84
Low (0.1-0.2)	118	Asphalt	38	NIR	12	12	16	1.26
				R	26	13	19	1.43
				G	26	25	25	0.99
				B	12	27	25	0.93
Mid (0.2-0.3)	104	Vegetation	71	NIR	12	32	76	2.36
				R	26	18	32	1.78
				G	26	24	55	2.26
				B	12	36	42	1.17
High (0.3-0.5)	69	Desert	45	NIR	12	23	61	2.63
				R	26	23	51	2.28

				G	26	28	51	1.82
				B	12	30	33	1.11
Very High (>0.5)	111	Ice	17	NIR	12	18	25	1.41
				R	26	17	34	2.02
				G	26	29	48	1.65
				B	12	32	46	1.44

[1] Approximate classification of albedo based on usual spectral signatures and image intensity

[2] NIR, R, G, B stand for near-infrared, red, green, and blue bands

[3] Number of overlapping images fused

3.3. Ground sampling distance

GSD is a simplistic measure of resolution. However, assessing the GSD is important in UHR to confirm that the upsampling is properly balanced with the GRD (the minimum distance between objects to distinguish one from another). To measure the GSD, we searched clearly delimited objects distributed across the image, with a high contrast over the background, having standard measurements (e.g., runways or swimming pools), and preferably large. Larger objects provide more accurate results, as the relative error delimiting the object decreases. The real size of objects obtained from georeferenced map are compared against the number of pixels in the image gives an estimate of the GSD.

The GSD of the iSIM170 dual panchromatic camera was analysed on acquisitions made in San Tropez, France (windows 84) and San Diego, USA (window 249), with a similar orbital altitude. Table 4 displays the results for several objects in the two scenes. The table includes the GSD for the same objects in raw frames and the corresponding super-resolved images. The average GSD in raw frames is 1.60±0.05m, which is close to the theoretical GSD pointing at nadir (1.54 m). The discrepancy between the two suggest a slight pitch or roll angles or a slight error in the camera-terrain distance. After UHR, the output has an average GSD 0.83±0.03m, which implies an average factor of resolution improvement of 1.92±0.07. The result is close to 2, indicating that the GSDs in Table 4 are consistent with an input parameter of UHR. The upsampling factor is an arbitrary number set in advance in UHR, that should be coupled with gains in GRD. The final balance between GSD and GRD determines the definitive resolution and contrast in the output image.

Table 4. GSD assessment of an iSIM170 dual panchromatic telescope during the IOD mission

Window	**Object**	**Raw GSD[1]**	**Length[2]**	**Size[1]**	**GSD[1]**
84	Runway	1.63	31.98	28.00	0.88
84	Road	1.58	10.28	9.00	0.88
84	Field	1.53	195.64	155.00	0.79
84	Roundabout	1.54	37.22	30.00	0.81
249	Runway	1.60	33.84	28.00	0.83
249	Road	1.65	17.52	14.00	0.80
249	Bridge	1.64	16.20	13.00	0.80
249	Pool	1.61	60.47	50.00	0.83

[1] size in meters

[2] length in number of pixels

We repeated the assessment with the iSIM90 from ARMSAT1. The results are available in Table 5. Raw images show on average a GSD of 3.83±0.07m. Note that (1) ARMSAT1 carries a VNIR iSIM90 and orbits at a higher altitude than the IOD (see Table 1) and (2) the orbital altitude is higher that the assumptions made Section 1.1. After UHR, the GSD is 1.92±0.02m, so the upsampling factor is 2.00±0.04. Again, there is a consistency between the UHR input parameter and the results in Table 5, which is an additional proof of robustness. The definitive factor will depend on accurate measurements of contrast with MTFs, considering the desired level of contrast and spatial resolution.

Table 5. GSD assessment of an iSIM90 VNIR telescope during the ARMSAT1 mission

Window	**Object**	**Raw GSD[1]**	**Length[2]**	**Size[1]**	**GSD[1]**
118	Runway	3.79	30.38	58	1.91
118	Harbour	3.95	90.89	175	1.93

118	Road	3.72	100.85	195	1.93
118	Roundabout	3.80	20.22	38	1.88
104	Field	3.80	161.36	310	1.92
104	Crossroads	3.89	837.81	1630	1.95
104	Field	3.85	592.73	1140	1.92
104	Facility	3.88	70.47	135	1.92

[1] size in meters

[2] length in number of pixels

3.4. Ground resolved distance

The ground resolved distance (GRD) is a key metric of image quality. It represents the ability of the camera system to resolve contiguous objects. No calibration target was visited during the IOD mission, and we found no structures fulfilling some of the requirements for an appropriate MTF analysis (sharp edges, 10-30 degrees tilted with respect to the image main axis, high contrast, and constant illumination on both sides of the edge). For the iSIM90, suitable imagery from calibration targets is still pending. Therefore, the following describes results from laboratory measurements and a qualitative analysis of the IOD imagery.

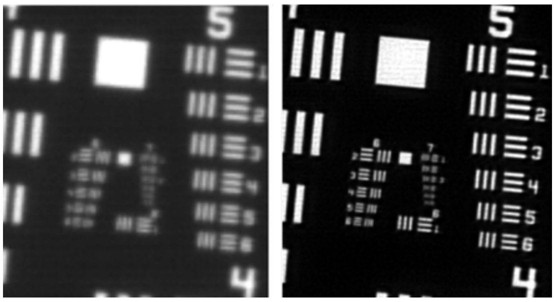

Fig. 6. Improved resolved distances with UHR with laboratory measurements of a 1951 USAF test target using a panchromatic iSIM170.

Tests demonstrate that UHR improves the contrast of raw imagery from iSIM. Figure 6 shows the laboratory measurements of a test target before (left panel) and after (right panel) using UHR. A panchromatic iSIM170 took images of a 1951 USAF target in a clean room with a collimator. The camera was set to reproduce the nominal operations in orbit. Figure 6 demonstrates how UHR improves contrast over the entire range of spatial scales. The sharpness of larger lines (e.g., 5th line set) increases on the super-resolved image (right) compared to raw one (left). Smaller lines (e.g., 6th line set) that are indistinguishable from each other in the raw image, become discrete after applying UHR. This suggests that the processing algorithm recovers information at lower spatial scales that is not present in raw frames. The retrieval of information at small spatial scales can be attributed to a fusion effect., whereas the deconvolution is responsible for the overall contrast improvement.

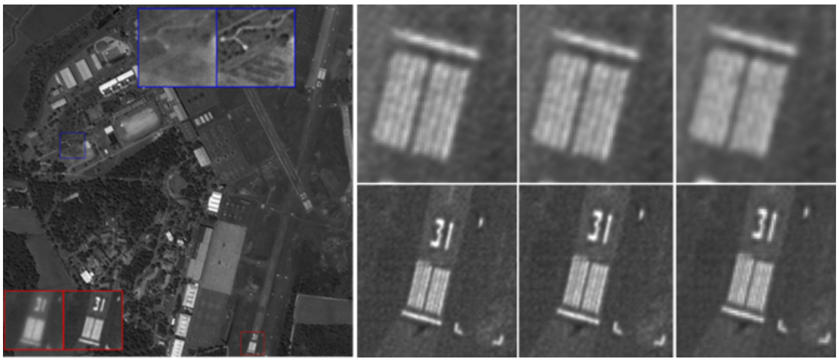

Fig. 7. Left: super-resolved image of an airport near Saint Tropez, France, from the IOD mission. Blue and red contours illustrate the difference before and after UHR. Right: Assessment of the minimum resolved distance over the runway signs by downsampling from 0.8 to 1 and 1.5 meters.

Results from the IOD mission are in line with the laboratory measurements. On the left, Figure 7 presents the super-resolved image of an airport in the vicinity of Saint Tropez (window 84). The blue contour presents a nearby trail before and after UHR. The comparison illustrates the overall enhancement of contrast with UHR. The red contour shows a closer view of the signs in the runway, with UHR revealing finer details of runway lines. On the right, there is a sequence of degraded images of the runway threshold markings from 0.8m to 1 and 1.5m. These signs with tilted parallel stripes, separated 1m from one another, and high contrast, are suitable for the qualitative analysis of the GRD. Spatial information is significantly reduced when transitioning from 1 to 1.5 meters, which suggests that the minimum resolved distance is below 1 meter. This number is close to the GSD estimated in the previous section (0.83±0.03m). Since the GSD and GRD are in balance, UHR achieves a meaningful improvement in resolution.

Similar assessments are being made with the iSIM90 in orbit. Visual inspection of smaller features, such as houses, roads, and runway signs confirm similar gains. Similar behaviour was expected since laboratory measurements prove that the iSIM90 optical performance resembles the iSIM170. These evidence cannot be published due to the lack of the corresponding permits.

4. Discussion

Overall, results so far confirm that the that the iSIM strategy can capture high-resolution multispectral imagery. This study shows that UHR is an essential component of the iSIM concept to reduce noise and increase the spatial resolution and contrast. These features make iSIM a cost-effective and a competitive imager for EO. The quality assessment uses real in-orbit data whenever available. However, the results do not represent definitive image quality measures. Further efforts should be made to achieve more accurate results using more rigorous methods and more data.

For instance, SNR requires a systematic assessment with balanced combinations of albedos, solar and viewing angles to characterize the data quality and the major drivers limiting SNR gains. New observations will contribute to such a structured dataset. Additionally, the SNR evaluation method is a preliminary approach. We are currently developing and testing more rigorous statistical test, making repeated measurements over pseudo homogeneous regions (e.g., radiometric calibration sites). Some results of SNR might be ascribing spatial variability to random noise. This can explain the large variability in SNR, not fully dominated by photon and readout noise. If so, noise reductions are being underestimated in the current analysis. Our tests suggest that UHR generally improves the SNR of raw images, with the only exception of low albedos. The reason might be that in dark conditions, images are not Poisson-limited. Yet, more accurate assessments are needed before reaching to robust conclusions.

This paper shows that UHR improves GSD and GRD in a balanced manner. Our assessment shows that the GSD after UHR is twice the GSD in raw images. This means ~0.8 m for the iSIM170 and below 2m for the iSIM90. In the case of the iSIM170, the GSD is close to the 1m GRD qualitatively assessed. However, these statements should be supported with further evidence. SATLANTIS is working on the analysis of the MTFs of the iSIM90 in orbit. The Modulation Transfer Function (MTF) is a geospatial quality metric to assess the sharpness of the image. Algorithms that apply the slanted-edge approach ISO12233:2017 have been developed. The telescope is scheduled to acquire imagery from geometric calibration targets. To be valid, the observation should be conducted with clear skies, with enough edge points, and at an appropriate viewing angle that ensures the 10-30º tilt from the vertical image axis of the imager.

Other aspects related to image quality should be included in future assessments, such as the band-to-band registration errors or the radiometric calibration and evaluation tests. The quality assessment of iSIM is work in progress. SATLANTIS is doing efforts to increase meaningful and systematic datasets while conforming automated quality checks to international standards [5].

5. Conclusions

The integrated Standard Imager for Microsatellites (iSIM) in combination with the Ultra High Resolution algorithm (UHR) aim at providing detailed multispectral Earth observations in an innovative way. The telescope design and observation strategy are tailored for the integration of UHR as an additional component of the imager. UHR counteracts sensor and telescope effects thanks to well characterized electro-optical system and the high frame rate makes possible for UHR to fuse overlapping images. Through missions in orbit, we are gathering experience on the application of UHR and its capabilities. Evidence so far demonstrates that UHR can generate multispectral images and deal with cross-track satellite movements. Early estimates of SNR show that UHR improves the noise of raw imagery. More rigorous noise assessments will determine the actual level of improvement in the future. The study shows that UHR improves the contrast, increasing the sharpness of larger objects and restoring information at smaller scales. The latter implies an improvement in spatial resolution. Current efforts in SATLANTIS are devoted to implement robust an accurate quality checks of UHR imagery.

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