An Open-Source Application and a Benchmarking Framework for Sentinel-2 Image Sharpening

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Abstract

Earth Observing (EO) satellites are an invaluable tool in remote sensing and have various applications. Spatial resolution is often crucial to those applications. The current work focuses on sharpening Sentinel-2 images. Moreover, a new application/program has been developed towards this goal. The application sharpens Sentinel-2 lower resolution bands (20m, 60m) and creates a 12-band image in 10m resolution. To run the program, one needs to load a Sentinel-2 L2A product, select one or more pansharpening methods and click the fuse button. This process will fuse the whole scene, but it is possible to crop areas of interest and process them instead. To validate the process, 14 pansharpening methods were employed and tested against well-known image quality metrics. On all areas of interest, the quality indices agree with each other. However, the indices tend to penalize methods who fail spectrally, which is correct, but they also tend to favor images with poor performance in the spatial domain. MS-SSIM seems to rank better the algorithm images and is closer to the visual comparison assessment. HPF is one of the best performing methods for sharpening a L2A product of Sentinel-2. ATWT, AWLP, HCS and LMM are good alternatives according to our results. The application, S-2 Sharpy (A Sentinel-2 Image Sharpening GUI) is made available on Github. Furthermore, its generic counterpart, PanFusion (Image pansharpening GUI for various sensors) is also made available on the mentioned platform, since it was the application that set the foundation for the current application and study.

1. Introduction

Sentinel-2 satellite imagery provides valuable multispectral data for diverse Earth Observation applications. However, its inherent spatial resolution differences across bands pose challenges for tasks requiring high spatial detail combined with spectral fidelity. To address this, image sharpening through data fusion techniques has become a critical preprocessing step.

This paper presents an integrated software solution developed for Sentinel-2 image sharpening, implementing a collection of state-of-the-art fusion methodologies. The software is designed to streamline the fusion process, providing an intuitive interface and automated workflow for end-users, with an emphasis on open-source availability to support community uptake. A comparative analysis highlights its advantages over existing tools, focusing on usability and effectiveness. For example, if 10m resolution is needed in an application which classifies vegetation using the 20m narrow VNIR bands, then this software can be proven useful.

Beyond describing the fusion approaches, this work introduces a benchmarking approach for objective comparison of method performance on representative datasets using relevant metrics. In this work, we aim to offer the Earth Observation community a comprehensive resource for image sharpening through fusion, promoting reproducibility, transparency, and accessibility in preprocessing Sentinel-2 data.

2. Review of Fusion Methodologies

Most EO optical satellites acquire two primary types of imagery: a panchromatic image with high spatial resolution and a multispectral image characterized by higher spectral but lacking in spatial resolution. The process of merging these datasets, commonly referred to as pansharpening, integrates the spatial detail of the panchromatic image with the spectral richness of the multispectral image, resulting in a product with both enhanced spatial and spectral fidelity. Recent studies (Vaiopoulos & Karatzalos, 2016), (Park et al., 2017) have demonstrated that a similar sharpening approach can be applied to Sentinel-2 imagery, despite the absence of a dedicated panchromatic band. In this case, the 10 m bands that are spectrally closest to a given lower-resolution band are employed as high-resolution references for sharpening the corresponding 20 m or 60 m bands.

3. Benchmarking Framework

A curated dataset comprising of several Sentinel-2 images was selected for the benchmark evaluation. Dataset includes diverse scenarios to test sharpening performance in coastal waters, sea, urban areas and vegetation.

The evaluation of the fusion techniques was carried out using the protocol proposed by (Wald et. al., 1997). Image quality indices were calculated, such as UIQI, ERGAS, SSIM, in order to estimate a level of success in the spatial enhancement and spectral fidelity fields.

Our preliminary benchmark results indicated that some methods yield satisfactory results with HPF, SFIM, ATWT, AWLP proving to result in superior performance in most cases. HPF achieves a "golden ratio" between computation speed and overall performance. Faster algorithms like IHS and Brovey tend to give poor results in the spectral aspect.

In order to quantify the performance of the fusion algorithms, the AOIs 1,2,3 were downsampled by a factor of 2, and the sharpening pipeline of the Sentinel-2 took place following the steps mentioned in section 4.

Afterwards, the validation of the compared sharpening methods was carried out by computing the image quality indices presented in the Tables 1 through 5.

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Figure 1. Areas Of Interest for the current study. From South to North: area1, area2, area3. The full Sentinel-2 scene, is the fourth area of interest (area4).

For the full scene (Figure 1, area4), the sharpening pipeline was run on full resolution to test whether or not it is feasible for a modern computer to sharpen the complete un-cropped Sentinel-2 scene. For this reason, the indices available for area4, are QNR (quality no-reference), D_λ (spectral distortion) and D_s (spatial distortion).

Method	ERGAS	MS-SSIM	PSNR
ATWT	6.271	0.995	45.452
AWLP	6.302	0.995	45.373
BDSD	4.532	0.997	48.617
BROVEY	6.124	0.995	45.860
GSA	6.946	0.994	45.320
GS	6.125	0.995	45.856
HCS	6.719	0.994	44.939
HPFC	7.815	0.994	43.421
HPF	5.560	0.997	46.877
IHS	6.103	0.995	45.926
LMM	5.888	0.996	46.465
LMVM	43.919	0.913	27.537
MTF_GLP	43.754	0.973	27.568
SFIM	5.598	0.997	46.831

Table 1: Image quality metrics for validation of the fusion algorithms of the proposed sharpening methodology of Sentinel-2 images for area 1 (part 1).

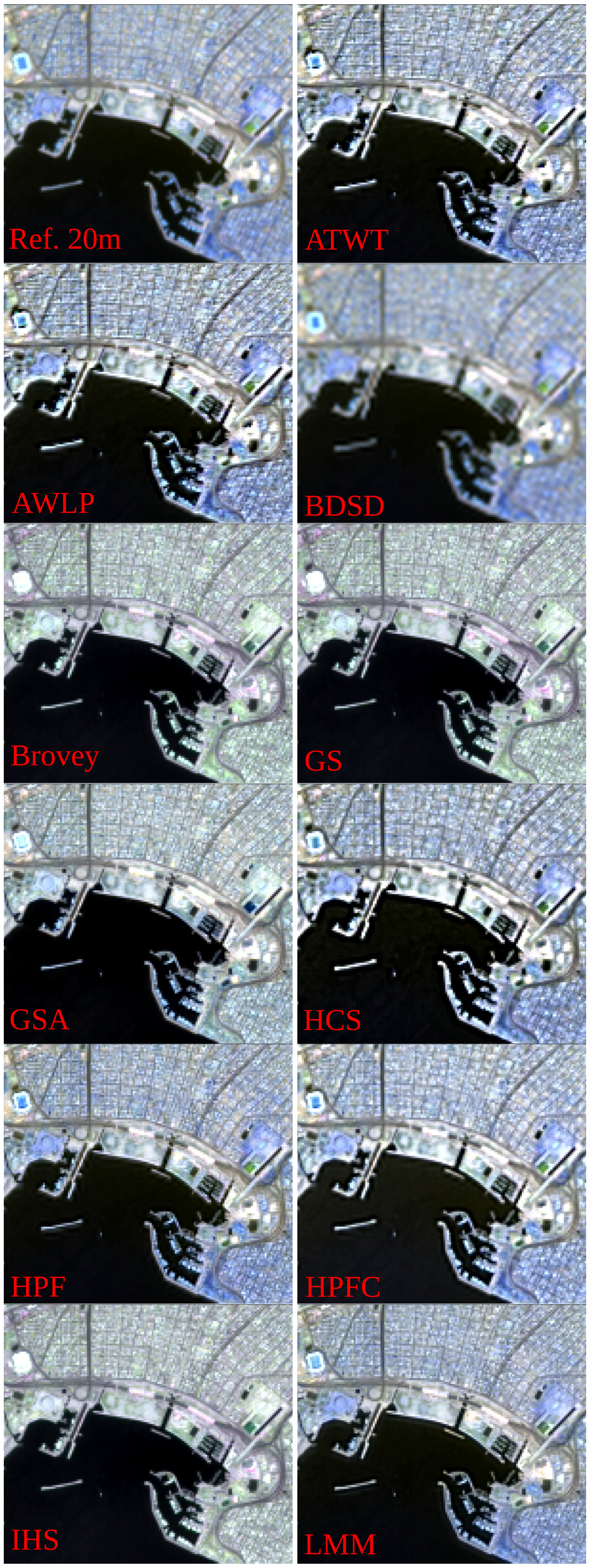

Figure 2. Pansharpening method results for area1. Displayed images are color composites of B12/B11/B07 as R/G/B.

Method	SAM	UIQI	QNR_avg
ATWT	0.113	0.993	0.617
AWLP	0.113	0.993	0.620
BDSD	0.077	0.997	0.900
BROVEY	0.109	0.992	0.535
GSA	0.115	0.989	0.508
GS	0.109	0.992	0.535
HCS	0.119	0.992	0.542
HPFC	0.105	0.984	0.785
HPF	0.097	0.995	0.571
IHS	0.108	0.992	0.533
LMM	0.103	0.995	0.522
LMVM		0.331	0.058
MTF_GLP	0.083	0.755	0.679
SFIM	0.098	0.995	0.574

Table 2: Image quality metrics for validation of the fusion algorithms of the proposed sharpening methodology of Sentinel-2 images for area 1 (part 2).

Method	ERGAS	MS-SSIM	PSNR
ATWT	5.437	0.996	47.381
AWLP	5.440	0.996	47.290
BDSD	3.838	0.998	51.077
BROVEY	5.940	0.996	46.266
GSA	6.740	0.995	46.362
GS	5.923	0.996	46.365
HCS	5.986	0.995	46.409
HPFC	7.305	0.995	44.028
HPF	4.781	0.998	49.080
IHS	5.908	0.996	46.448
LMM	5.056	0.997	48.524
LMVM	43.066	0.915	27.669
MTF_GLP	42.934	0.975	27.693
SFIM	4.814	0.997	49.061

Table 3: Image quality metrics for validation of the fusion algorithms of the proposed sharpening methodology of Sentinel-2 images for the average of all AOIs (part 1).

Method	SAM	UIQI	QNR_avg
ATWT	0.098	0.995	0.630
AWLP	0.099	0.995	0.635
BDSD	0.065	0.998	0.917
BROVEY	0.102	0.992	0.530
GSA	0.107	0.990	0.519
GS	0.102	0.992	0.528
HCS	0.106	0.994	0.547
HPFC	0.087	0.985	0.795
HPF	0.084	0.996	0.578
IHS	0.102	0.992	0.528
LMM	0.089	0.996	0.531
LMVM		0.332	0.061
MTF_GLP	0.076	0.756	0.674
SFIM	0.084	0.996	0.581

Table 4: Image quality metrics for validation of the fusion algorithms of the proposed sharpening methodology of Sentinel-2 images for the average of all AOIs (part 2).

Method	QNR_avg	D_lamda_avg	D_s_avg
ATWT	0.466	0.096	0.473
AWLP	0.471	0.089	0.472
BDSD	0.970	0.002	0.028
BROVEY	0.300	0.083	0.662
GSA	0.340	0.087	0.611
GS	0.306	0.073	0.659
HCS	0.373	0.108	0.565
HPFC	0.687	0.114	0.240
HPF	0.411	0.080	0.540
IHS	0.299	0.087	0.662
LMM	0.338	0.122	0.603
LMVM	0.103	0.840	0.283
MTF_GLP	0.533	0.104	0.390
SFIM	0.411	0.081	0.539

Table 5: Image quality metrics for validation of the fusion algorithms of the proposed sharpening methodology of Sentinel-2 images for the full scene experiment (area4).

4. Software Overview & Competitive advantages

The developed software is a Python-based graphical user interface (GUI) built with the Tkinter library. It employs the Geospatial Data Abstraction Library (GDAL) for Sentinel-2 L2A imagery IO. Through an intuitive interface, the user can select desired fusion algorithms and perform the sharpening of all non-10 m bands with a single operation.

#	Short Name	Full method Name
1	ATWT	Additive A Trous Wavelet Transform (Vivone et al., 2014)
2	ATWT-M2	A Trous Wavelet Transform (Model 2) (Ranchin & Wald, 2000)
3	ATWT-M3	A Trous Wavelet Transform (Model 3) (Ranchin & Wald, 2000)

4	AWLP	Additive Wavelet Luminance Proportional (Otazu et al. 2005), (Núñez et al. 1999)
5	BDSD	Band-Dependent Spatial-Detail (Garzelli et al., 2008)
6	Brovey	Brovey transform (Gillespie et al., 1987)
7	GS	Gram Schmidt (Laben & Brower, 2000)
8	GSA	Gram Schmidt Adaptive (Aiazzi et al., 2007)
9	HCS	Hyperspherical Color Space (Padwick et al., 2010)
10	HPF	High-Pass Filtering (Chavez & Sides, 1990)
11	HPFC	High-Pass Filtering (Implementation 1)
12	IHS	Fast Intensity-Hue-Saturation (GIHS) image fusion (Tu et al., 2001)
13	LMM	Local Mean Matching (Stanislas et al., 1998)
14	LMVM	Local Mean and Variance Matching (Stanislas et al., 1998)
15	MTF-GLP	Generalized Laplacian Pyramid (GLP with MTF-matched filter and unitary injection model (Aiazzi et al., 2002), (Aiazzi et al., 2006)
16	MTF-GLP-CBD	GLP with MTF-matched filter (Aiazzi et al., 2006), and regression based injection model (Alparone et al. 2007)
17	MTF-GLP-HPM	GLP with MTF-matched filter and multiplicative injection model (Aiazzi et al., 2006), (Aiazzi et al., 2003)
18	SFIM	Smoothing Filter-based Intensity Modulation (Liu, 2000)

Table 6. Fusion / sharpening methods available in the software.

The processing workflow of the application consists of eight main steps. First, the software automatically identifies the Sentinel-2 image folders, distinguishing the 10/20/60 m subdirectories. The second step performs the sharpening of the narrow near-infrared (NIR) 20 m bands (B05, B06, B07), where the 10 m bands B04 and B08 are averaged to form a high-resolution reference image. By default, the interpolation uses the Lanczos4 method,Once interpolation is complete, the chosen fusion algorithm is applied. In the third step, band B8A (narrow NIR) is sharpened using B08, followed by the sharpening of the shortwave infrared (SWIR) bands in step four, again using B08 as the reference. Step five sharpens the 60 m ultra-blue band (B01) using the blue band (B02), while step six enhances the 60 m water vapor band (B09) from B08. The seventh step writes the fully sharpened Sentinel-2 image (all bands at 10m). Finally, an optional eighth step removes artifacts and outlier values, typically occurring over marine areas when certain fusion methods, such as HPF, are employed.
Beyond sharpening, the software offers additional functionalities, including the creation and visualization of custom color composites, simultaneous display of multiple georeferenced images for synchronized panning, and cropping.

5. Results

In our tests, as shown in figure 2, most pansharpening techniques managed to succeed in spatial enhancement of the Sentinel-2 imagery. There are a few notable exceptions however. LMVM and MTF_GLP methods failed completely in providing a usable image in all areas of interest. ATWT-M2/M3, MTF_GLP_HPM and MTF_GLP_CBD were excluded from testing, due to the inferior perfomance compared to their simpler counterparts.
The BDSD algorithm produced an image with high spectral integrity, but with no visual improvements on the spatial domain.
The Brovey, GS, GSA and IHS methods, although they tend to output a spatially sharp result, they fail to preserve the spectral information correctly (mostly green hues instead of blue).
The other methods, ATWT, AWLP, HCS, HPF, HPFC and LMM succeed on both spatial and spectral domains in general. ATWT, AWLP, HCS and HPFC yield somewhat sharper images than the reference image. HPFC result is also brighter than the rest of the discussed images. SFIM result is almost identical to that of HPF.
After index analysis, we observe:
1. Indices between different aois do not vary significantly. On the contrary, the ranking of the algoritms is relatively consistent.
2. BDSD is favored by all indices due to its high spectral similarity with the reference image, while at the same time, it is characterized by the absence of spatial detail which is present in the most of the rest methods.
3. In general, indices rank more or less the algorithms in the same way.
4. The failure of MTF_GLP and LMVM algorithms to produce a satisfactory image is captured by the indices, as almost all of them penalize them significantly.
5. The visually high-performing methods, HPF, ATWT, AWLP, HCS and LMM are ranked better than the low-performing methods (GS, GSA, Brovey, IHS). This fact, apparrently, is explained due to the high sensitivity of the indices in the spectral domain.
6. MS-SSIM seems to rank better the fusion techniques and is the only index to rank HPF as best method, along with BDSD.
7. The spatial distortion in QNR index computation (Ds) still favors algorithms who fail in spatial enhancement, such as BDSD.
8. The index evaluation framework followed in this study seem to validate correctly the spectral integrity of the sharpened images. However, it appears that spatial enhancement is not validated correctly, by most employed indices.

6. Conclusions & Discussion

In summary, the proposed application contributes to three main aspects:
(1) the sharpening of Sentinel-2 imagery through the implementation of 18 distinct image fusion methods;
(2) the visualization and optical comparison of the resulting sharpened products; and
(3) the cropping of multiple georeferenced images using an interactive rectangular selection tool.

Overall, the presented software provides an intuitive graphical environment for the sharpening of Sentinel-2 images. It is particularly beneficial for users analyzing the 20 m or 60 m spectral bands, as it delivers a uniformly sharpened product containing all 12 Sentinel-2 bands at 10 m spatial resolution.
The results presented in Figures 2 and 3 demonstrate that the sharpening of the lower-resolution Sentinel-2 bands has been successfully achieved. Beyond the evident spatial enhancement, the employed fusion method (HPF) has effectively preserved spectral integrity, indicating its suitability for multi-band image fusion tasks.

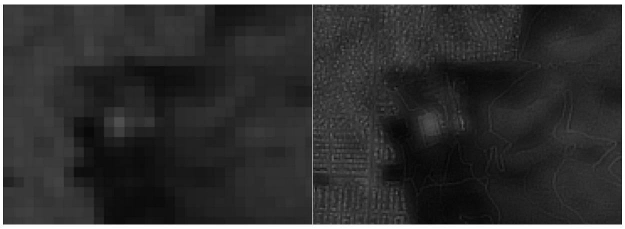

Figure 3. Band 1 (Coastal aerosol) before and after sharpening.

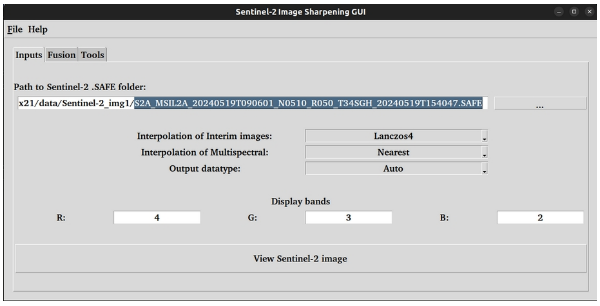

Figure 4. S-2 Sharpy: Sentinel-2 Image Sharpening GUI. Here the initial “Inputs” tab is displayed.

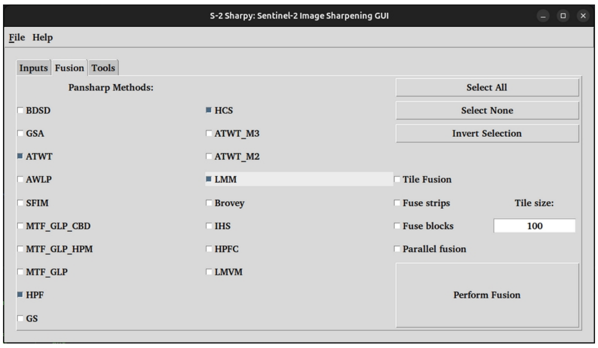

Figure 5. S-2 Sharpy: Sentinel-2 Image Sharpening GUI. Fusion tab is displayed.

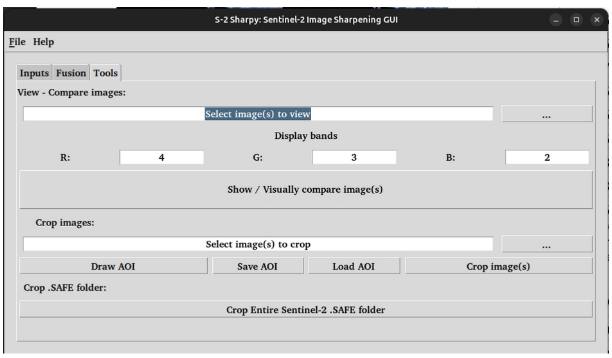

Figure 6. S-2 Sharpy: Sentinel-2 Image Sharpening GUI. Tools tab is displayed.

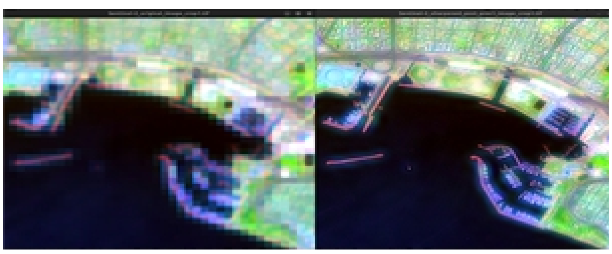

Figure 7. Comparison of the original Sentinel-2 image (left) with the HPF sharpened image (right). The images are staying on the same extent after pan and zoom operations.

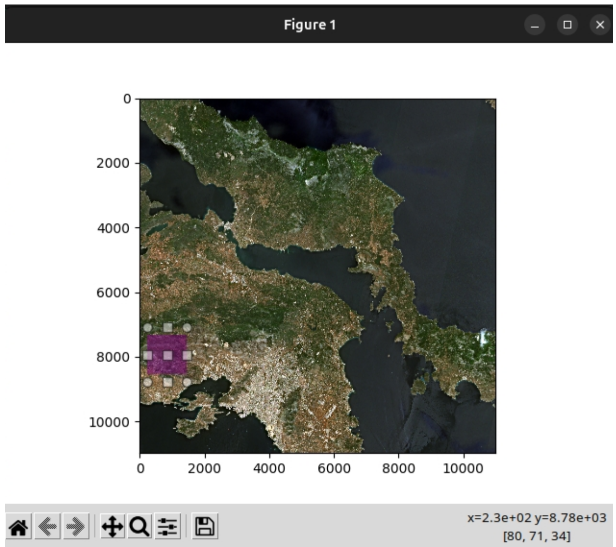

Figure 8. User can draw an Area Of Interest (purple area) instead of processing the full Sentinel-2 scene.

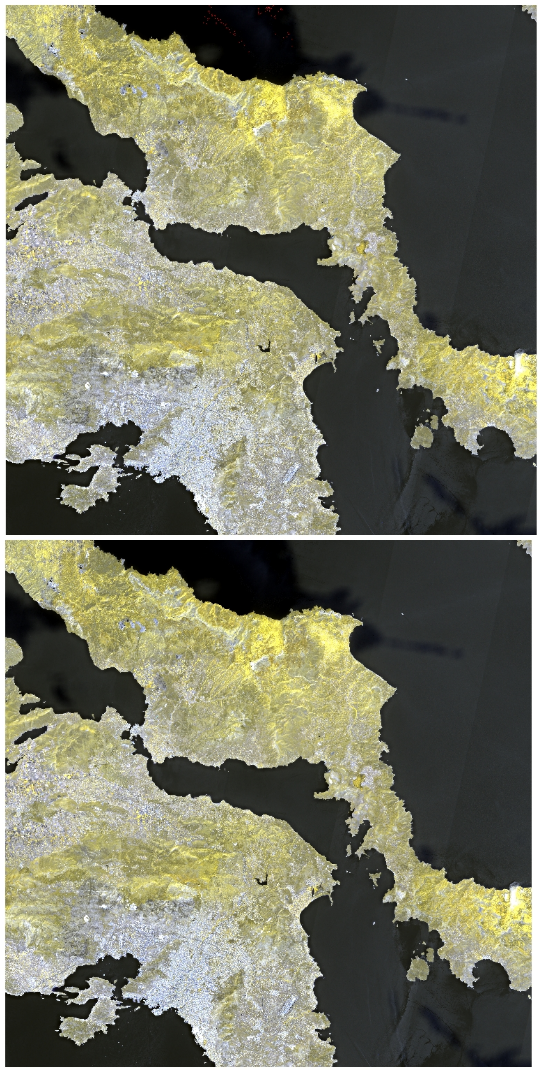

Figure 9. Sharpening the full Sentinel-2 scene with the HPF method. Processed image (Up), post-processed image (Down). We can observe that without post-processing, certain artifacts may appear in usually marine areas. In this case, the red artifacts are located in the central North sea area of the image. The color composite of the images is B7/B6/B5 as R/G/B.

7. Application Interface

In Figure 4, the initial “Inputs” tab of the software is presented. From this interface, one can select the full path to the desired Sentinel-2 .SAFE directory. The interpolation settings of the interim products, which are calculated for the image sharpening, can be adjusted. A quick preview of a custom RGB color composite of the Sentinel-2 image can be prepared as well in this tab.
In Figure 5, the “Fusion” tab of the application is displayed. Here the user can select and perform various fusion methods.
In Figure 6, the “Tools” tab of the S-2 Sharpy application is depicted. Multiple images can be viewed as custom RGB color composites in the first section of the tab. Useful for comparing the original Sentinel-2 multispectral image with several fused images. The resulting images are staying on the same extent after pan and zoom operations, as shown in Figure 7. In the second section of the tab, the user can draw an AOI (Figure 8) and use it to crop the entire Sentinel-2 .SAFE folder. In this manner, one can effectively process a small area of interest instead of the full Sentinel-2 scene.
In Figure 9, we observe the benefits of the post-processing algorithm, as it tends to remove several artifacts that are usually present in marine areas.

8. Source Code

The full source code of the presented application has been made available to the Github code sharing platform:
https://github.com/advaiop/S-2_Sharpy

The source code of the PanFusion, which is the generic counterpart of this software, allows to fuse images from various sensors and is available here:
https://github.com/advaiop/PanFusion

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