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On the Use of the Expanded Image in Quality Assessment of Pansharpened Images

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***Abstract*—This letter discusses whether the expanded multispectral image, i.e. the original multispectral image up-sampled to the panchromatic scale, can be used during the assessment of the quality of pansharpened multispectral images.**

By considering Wald's protocol, the authors demonstrate that the adoption of the expanded image as the reference is erroneous and brings a quality assessment of the fused images that is misleading. In addition, some recommendations about the valid role of the expanded image are provided.

The discussion is supported by a quantitative analysis and visual comparisons.

***Index Terms*—Expanded Multispectral Image, Hypersharpening, Image Fusion, Image Quality, Pansharpening, Wald's Protocol.**

I. Introduction

Many submitted manuscripts and several published papers use the original multispectral image up-sampled (expanded) to the panchromatic scale (full scale) to assess the quality of the fused images in a way that is erroneous.

For a clear choice of the authors, no quotation of these papers is reported. The authors, in fact, do not consider the adoption of the "shame and blame" style fruitful.

Even though some of the presented arguments are already expressed in previous works, this letter is original for its specific topic. As a matter of fact, it has the ambition to deeply reconsider the subject, providing a theoretical discussion and refuting the implicit assumptions behind this use.

Furthermore, it gives a contribution to diffuse a *best practice* for researchers in the development of their future methods.

The discussion is based on Wald's protocol [1] [2], i.e. the general and theoretical framework that defines the quality of the fused images. This protocol consists of three properties that define how the assessment should be carried out and which references have to be (or should be) used to correctly evaluate quality. The protocol does not introduce any specific quality index.

In the framework of Wald's protocol, the use of expanded image is fair and/or acceptable under certain conditions but it is completely inconsistent when a quantitative comparison with the fused image is carried out.

II. General Discussion

Wald's protocol defines three properties that each fused image should fulfill as closely as possible.

- *The first property* (*Consistency property*) requires that the fused image $\hat{M}_l$, once spatially degraded to its original scale, should be as identical as possible to the original image M_l.
- *The second property* (*Synthesis property*) states that any fused image $\hat{M}_l$ should be as identical as possible to the ideal image $\dot{M}_l$ that would be observed at the resolution of the panchromatic image by the corresponding hypothetical sensor.
- *The third property* (*Synthesis property*) considers the spectral properties of the whole set of fused images: the multispectral vector of fused images $\hat{\mathbf{M}}$ should be as identical as possible to the multispectral vector of ideal images $\dot{\mathbf{M}}$ that the corresponding sensor, if existent, would observe at the higher spatial resolution.

Clearly, only the first property can always be verified; the second and third can not usually be checked directly since the reference is not commonly available.

Regarding the verification of the first property, the expanded image could play a role, even though this approach can not be considered the best choice. In fact, expanding the original multispectral image to the panchromatic scale and comparing it with the fused low-pass filtered image could be an alternative way to assess the first property. Even though this approach usually provides correct numerical results, it has a significant weak point: it uses a not univocal reference image inasmuch it depends on the up-sampling filter. For this reason, evaluating the first property by expanding the original image is strongly discouraged.

Therefore, down-sampling the fused image to the scale of the original multispectral image and comparing them, as the first property clearly stated, is the correct approach because no processing is performed onto the original image.

Since only the first property of Wald's protocol can be directly verified, two approaches are possible in order to exploit the whole protocol.

The former was suggested by Wald himself and consists of downsampling all the dataset (panchromatic and multispectral image) and performing pansharpening at the reduced scale, so that the original multispectral is available as reference. This approach is based on the implicit assumption that the evaluations are also valid at the full scale as recently discussed deeply in [3]. Once this approach is accepted, the second and the third properties of the protocol can be verified by means of quantitative score indexes.

It should be mandatory to include in the comparison not only the fused images but also the multispectral image simply upsampled from the reduced resolution dataset. In this way, it would be possible to measure how much each fusion method improves the quality of the low resolution image and to score the fusion algorithms on the basis of this improvement. The

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improvement of performances could be also weighted with computational costs.

The latter approach exploits Wald's protocol by inferring the quality of the fused images by comparing them, somehow, with the original multispectral and panchromatic images, i.e. adopting the with *no reference* (NR) paradigm . Obviously, the advantage of disengaging from the availability of the ideal reference is balanced by the disadvantage that a full verification of the two last properties is not possible. Thus, the methods that implement this approach perform "approximated" realizations and their effectiveness depends on the validity of the corresponding assumptions.

With the intention of applying the NR paradigm, the spectral quality could be intuitively assessed by comparing the fused image with the expanded image, whereas the spatial or geometrical quality could be assessed by comparing each fused band with the panchromatic. Indeed, this approach, already criticized in [4] is based on the erroneous assumption that the fused images has to balance the spectral and the spatial quality.

With such an assumption, a good fusion method that improves the spectral quality, should be negatively judged since the fused image certainly presents some spectral difference when it is compared with the expanded image. Therefore, inferring the spectral quality by comparing the fused with the expanded image implicitly denies that fusion can improve the spectral quality of the multispectral image. On the contrary, the results reported in [5] (Table V, VI, VII, X and XI) show that many fusion methods improve the spectral quality of the expanded image. A good attempt to overcome the concept of the *tradeoff* between spectral and spatial quality is presented in [6].

Another pernicious implementation of the NR paradigm occurs when the expanded multispectral image replaces the hypothetical reference, realizing in this way an "approximated" evaluation of the quality of the fused image. This realization of the NR paradigm is not only questionable to assess the spectral quality but particularly to evaluate the spatial quality. However, it would be valid if it produced results consistent with those would have been obtained if the reference had been available. On the contrary, the analysis and the practical examples reported in the next section demonstrate that it is absolutely misleading.

From a qualitative point of view, however, a visual inspection of the expanded image helps to better understand the behavior of pansharpening methods. For instance, in the homogeneous areas, fused and expanded images should have exactly the same colors. Therefore it would be a good practice visualizing the expanded multispectral image.

When the application of the NR paradigm is required, one of the most fruitful realization is the QNR (Quality No Reference) index [7]. In its formulation, the expanded image is not present and no direct comparison between the fused image and the original multispectral and panchromatic images is performed. QNR, in fact, is based from one side on the analysis of the inter-relationships among the bands of the two multispectral data sets before and after fusion (spectral quality); on the other hand on the relationship between the original multispectral bands with the spatially degraded panchromatic, respectively, and between the fused multispectral with the panchromatic, respectively (spatial quality).

III. Analysis

In this section the theoretical considerations introduced in Sect. II are mathematically addressed in order to prove that the use of the expanded image as the reference for fusion assessment is an unsuccessful realization of the NR paradigm.

For the sake of simplicity, the experimentations carried out involve only a well established fusion method based on the Laplacian pyramid [8]. The conclusions obtained, however, have a general scope for pansharpening and can be extended also to hypersharpening [9].

In this discussion, the RMSE and ERGAS (Erreur Relative Globale Adimensionnelle de Synthse or Global Relative Error in Synthesis") [10] indexes have been adopted to assess the spatial quality. Since their use is an established practice in literature [5], they have been preferred to more innovative approaches such as the assessment of spatial quality of the fused image by the estimation of their MTF [11].

The Spectral Angle Mapper (SAM) index has been adopted for spectral quality assessment.

In addition, an improved version of QNR index has been developed to assess the overall quality. Considering the schema proposed in [12], the geometric component is implemented by the spatial term of QNR while the radiometric component by the spectral term. This new index is denoted as Context Based QNR (CB-QNR).

As an alternative interesting approach, image quality assessment could be based on an information extraction perspective [13].

Let now define all the symbols that are adopted in this letter:

- L is the number of multispectral bands; h and w are the number of rows and columns of each band at the panchromatic scale; l is the index of l-th band while m and n are the indexes of m-th row and n-th column, respectively.
- $\mathbf{M}(m,n) \triangleq \{M_l(m,n)\}$ is the pixel vector of the original MS image.
- $\mathbf{M}_{exp}(m,n) \triangleq \{M_{exp_l}(m,n)\}$ is the pixel vector of the MS image up-sampled to panchromatic scale.
- $\hat{\mathbf{M}}(m,n) \triangleq \{\hat{M}_l(m,n)\}$ is the fused pixel vector.
- $\dot{\mathbf{M}}(m,n) \triangleq \{\dot{M}_l(m,n)\}$ is the pixel vector of the reference MS image at the panchromatic scale. This vector is not available in real cases.
- $\mathbf{D}(m,n) \triangleq \{D_l(m,n)\}$ is the pixel vector of the injected detail extracted from the panchromatic image.
- $\mathbf{g}(m,n)$ is the diagonal matrix $L \times L$ where each element $g_{l,l}(m,n)$ is the gain at pixel (m,n) of the l-th band.

By defining

$$\boldsymbol{D}(m,n) = \mathbf{g}(m,n)\mathbf{D}(m,n) \tag{8}$$

pansharpening [8] can be formulated in the vectorial form (9) and for each band separately (10), respectively:

$$\hat{\mathbf{M}}(m,n) = \mathbf{M}_{exp}(m,n) + \boldsymbol{D}(m,n) \tag{9}$$

$$\text{RMSE}_{Ref_l} = \sqrt{E[(\dot{M}_l - \hat{M}_l)^2]} = \sqrt{\frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} \left[\dot{M}_l(m,n) - \hat{M}_l(m,n)\right]^2} \tag{1}$$

$$\text{RMSE}_{NoRef_l} = \sqrt{E[M_{exp_l} - \hat{M}_l)^2]} = \sqrt{\frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} \left[M_{exp_l}(m,n) - \hat{M}_l(m,n)\right]^2} \tag{2}$$

By substituting (10) in (2), it is obtained:

$$\text{RMSE}_{NoRef_l} = \sqrt{\frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} [M_{exp_l}(m,n) - M_{exp_l}(m,n) - g_l(m,n)D_l(m,n)]^2} = \sqrt{\frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} [g_l(m,n)D_l(m,n)]^2} \tag{3}$$

Supposing that the gain does not depend on the pixel (m, n) and that detail is zero-mean, the following simplified formula is obtained:

$$\text{RMSE}_{NoRef_l} = g_l \sqrt{\frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} [D_l(m,n)]^2} = g_l \sqrt{var\,(D_l)} \tag{4}$$

$$\overline{SAM}_{Ref} = \frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} SAM\left(\hat{\mathbf{M}}(m,n), \dot{\mathbf{M}}(m,n)\right) = \frac{1}{wh} \sum_{\substack{1 \le m \le h \\ 1 \le n \le w}} \arccos\left(\frac{\dot{\mathbf{M}}(m,n) \cdot \hat{\mathbf{M}}(m,n)}{\|\dot{\mathbf{M}}(m,n)\| \, \|\hat{\mathbf{M}}(m,n)\|}\right) \tag{5}$$

For simplicity, only one pixel is considered and the specific indexes (m, n) are omitted. Focusing on the $\arccos$ term, the term t_{Ref} is defined in the following way:

$$t_{Ref} = \frac{\dot{\mathbf{M}} \cdot \hat{\mathbf{M}}}{\|\dot{\mathbf{M}}\| \, \|\hat{\mathbf{M}}\|} = \frac{\dot{\mathbf{M}} \cdot (\mathbf{M_{exp}} + \boldsymbol{D})}{\|\dot{\mathbf{M}}\| \, \|\mathbf{M_{exp}} + \boldsymbol{D}\|} = \frac{\|\mathbf{M_{exp}}\|}{\|\mathbf{M_{exp}} + \boldsymbol{D}\|} \cos(\dot{\mathbf{M}}, \mathbf{M_{exp}}) + \frac{\|\boldsymbol{D}\|}{\|\mathbf{M_{exp}} + \boldsymbol{D}\|} \cos(\dot{\mathbf{M}}, \boldsymbol{D}) \tag{6}$$

analogously, when the expanded is used as the reference, the following relationship is obtained:

$$t_{NoRef} = \frac{\mathbf{M_{exp}} \cdot \hat{\mathbf{M}}}{\|\mathbf{M_{exp}}\| \, \|\hat{\mathbf{M}}\|} = \frac{\mathbf{M_{exp}} \cdot (\mathbf{M_{exp}} + \boldsymbol{D})}{\|\mathbf{M_{exp}}\| \, \|\mathbf{M_{exp}} + \boldsymbol{D}\|} = \frac{\|\mathbf{M_{exp}}\|}{\|\mathbf{M_{exp}} + \boldsymbol{D}\|} + \frac{\|\boldsymbol{D}\|}{\|\mathbf{M_{exp}} + \boldsymbol{D}\|} \cos(\mathbf{M_{exp}}, \boldsymbol{D}) \tag{7}$$

$$\hat{M}_l(m,n) = M_{exp_l}(m,n) + g_l(m,n)D_l(m,n) \tag{10}$$

The dataset used in the experiments is acquired over Rio de Janeiro (Brazil) in January 2010 by WorldView-2 satellite and was made available by Digital-Globe for the 2011 IEEE GRSS Data Fusion Contest [14]. The panchromatic image has a spatial sampling interval of 0.5 m while the eight multispectral bands of 2 m.

The scene covers a number of large buildings, skyscrapers, commercial and industrial structures, a mixture of community parks and private housings, highways and bridges in the downtown area of the city. Because of such heterogeneity, the dataset presents both homogeneous and very detailed areas and therefore is suitable to support our analysis.

The reference image is provided by downsampling the whole data set (panchromatic and multispectral) at lower scale and performing the analysis on the reduced resolution dataset.

A. Spatial Quality

Eq. (1) reports the expression of RMSE formula when the reference is available whereas (2) reports the formula when the expanded image is used as the reference. A direct comparison between (1) and (2) is not fruitful.

However, comparing (1) with (4), which is obtained from (2) through simple mathematical steps, it is evident that the expanded image can not replace the reference. In (4), in fact, there is not any information coming from the reference. As a matter of fact, (4) only measures the variance of the injected detail weighted by the gain.

Even though the inconsistency of the use of the expanded image as the reference is already evident, two specific case studies are considered to practically show how much this approach can be erroneous. Table I reports the numerical results for ERGAS and RMSE; for simplicity only the RMSE of the Red, Green, and Blue bands is shown.

In the first case study, the variance of the weighted detail

		Reference			Expanded		
		Fused	Fused by Reduced Gain	Expanded + Noise	Fused	Fused by Reduced Gain	Expanded + Noise
RMSE	Red	27.7	29.3	97.6	67.8	64.1	66.2
	Green	49.1	53.1	186.6	126.6	106.2	128.14
	Blue	33.6	35.1	112.2	76.9	56.5	76.9
ERGAS		3.35	3.47	10.11	6.90	5.76	6.89

Table I: *RMSE (for simplicity only the RMSEs of the Red, Green, and Blue bands are shown) and ERGAS values.*

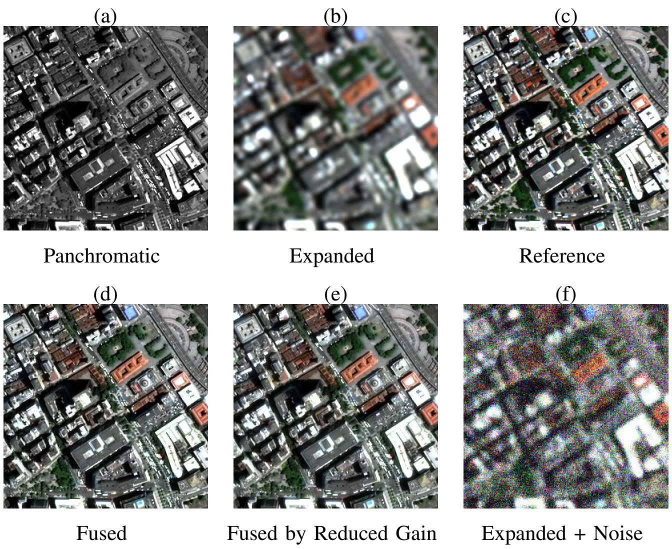

Figure 1: *Visual comparison of the images (256×256 pixels at 2.0 m scale).*

provided by the second terms of (9) is measured. Then a zero mean gaussian noise pattern is created with approximately the same variance of the weighed detail. This pattern is added to the expanded image and the result is considered as a new fused image. Obviously, the noisy expanded image (Fig. 1(f)) is very different from the fused image (Fig. 1(d)) and the reference (Fig. 1(c)). Comparing the fused image and the noisy expanded image with the original, respectively, the noisy image produces, as expected, an RMSE significantly greater. On the contrary, when the expanded image is used as the reference, the fused and the noisy images obtain the same RMSE value (Table I).

The second case study is less striking but shows a subtler error that can occur. Observing (4), it is clear that if the variance of the weighed detail decreases also the RMSE decreases. However, there is no evidence that this is valid also for (1). On the contrary the trend could be even opposite. To show this, the value of the gain is reduced by 20% (Fig. 1(e)). According to (4), the RMSE evaluated by using the expanded image decreases but the error with respect the reference increases (Table I). If the numerical comparison with the expanded image had been the guideline, the fusion performed with the reduced gain would have been erroneously judged as the best approach.

Regarding ERGAS [10], which is evaluated in these case studies on all eight bands, it shows the same misleading trend of RMSE (second part of Table I). This fact is not surprising because its value depends on the RMSEs of the bands.

Another interesting consideration regards the fact that numerical indexes are sensitive to differences that are very hardly noticeable by human observers. The images of Figs. 1(d), (e), in fact, appear extremely similar while the values of the corresponding numerical indexes are relevantly different. This reinforces the conviction that from one side the choice of the reference is crucial and from the other hand that the visual inspection only can be misleading.

B. Spectral Quality

This section is structured as the previous one. Therefore, (5) reports the formula of SAM when the reference is available. Starting from (5), through very simple mathematical steps, the term t_{Ref} (6) is defined. Analogously, when the expanded image is used as the reference, the term t_{NoRef} (7) is defined.

When SAM is computed by using the expanded image as reference, (7) should provide the same results of (6). Trivially, (6) and (7) are equal when $\mathbf{M_{exp}} = \dot{\mathbf{M}}$. Due to their formulations, they also give the same results when $\mathbf{M_{exp}}$ is parallel to $\dot{\mathbf{M}}$. When these two cases do not occur, however, the results can significantly diverge. The presence in (6) of the term $\cos(\dot{\mathbf{M}}, \mathbf{M_{exp}})$ can further emphasize this trend.

The term $\cos(\dot{\mathbf{M}}, \mathbf{M_{exp}})$ is, in fact, significantly lower than 1 when the reference multispectral image (usually not available) contains (or would contain) details completely absent from the low resolution multispectral whose spectral characteristics are (would be) completely different from the background where they appear. This case is not rare; many details, in fact, have these properties. For instance, in the adopted dataset, the cars have these characteristics.

A paradox is therefore evident: the two methods of measuring SAM provide results that differ more where fusion is more critical and the need of a valid estimation of the error is more necessary.

These considerations are evident observing Fig. 2 and Fig. 3. The former shows the SAM maps while the latter considers a case study area. The labels "SAM Reference" and "SAM Expanded" are used when the comparison is done with the reference image and the expanded one, respectively.

Therefore, Fig. 2(a) and Fig. 2(b) show how much inferring the characteristics of the first SAM map (processed when the reference is available) from the second one (when the expanded image is adopted as the reference) could be difficult and potentially erroneous.

In addition, comparing the fused image (Fig. 3(c)) with the original (Fig. 3(b)) and the expanded (Fig. 3(a)), it is evident that, on this detail, the colors of the fused image are more

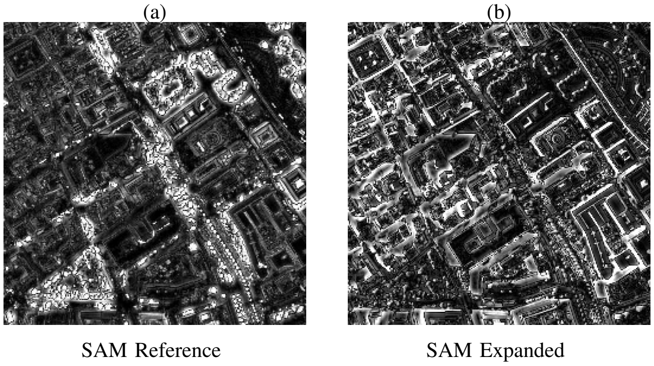

Figure 2: *SAM Maps*

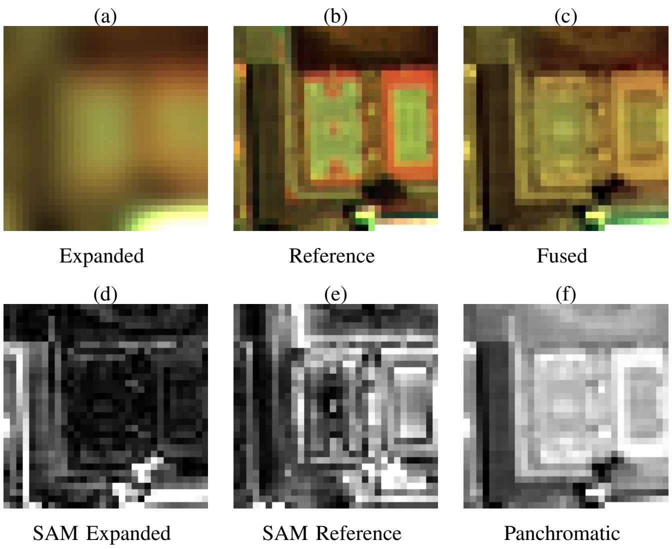

Figure 3: *Analysis of SAM maps: (a)(b)(c)(d)(e)(f) show a specific area of 32×32 pixels at 2.0 m scale.*

	Exp	Fused	Fused by Reduced Gain	Expanded + Noise
CB-QNR	0.7077	0.9346	0.9271	0.5970

Table II: *CB-QNR of the images.*

similar to the expanded than to the original. Accordingly, Fig. 3(d) is darker than Fig. 3(e). Thus, if only Fig. 3(d) was taken into consideration, the real error would be underestimated and the erroneous conclusion that the fusion gave excellent results could be arbitrarily formulated.

C. Overall Quality

The results obtained applying CB-QNR to the fused images are reported in Table II. CB-QNR shows, as expected, the same trend of ERGAS computed by adopting the original multispectral as the reference (first part of the last row of Table I).

Therefore the comparison between Table I and Table II confirms that QNR is a valid implementation of the NR paradigm and its theoretically assumptions are corrected.

IV. Conclusions

This letter demonstrates that evaluating the quality of the fused image by the direct comparison between the fused image and expanded multispectral leads to inconsistent results.

Moreover, it refutes the subtle statement that "direct comparison between fused and expanded images can be used to assess the spectral quality of the pansharpening algorithm".

It is also clarified that adoption of the expanded multispectral image as the reference is an implicit and erroneous adoption of the NR paradigm.

Actually, this letter provides some recommendations about the correct adoption of the expanded image in the assessment of the quality of pansharpened image, establishing a best practice to use it.

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