INVESTIGATION OF TARGET TRACKING TECHNIQUES IN THE MSG MPEF ENVIRONMENT

G. Dew

EUMETSAT, Am Kavalleriesand 31, 64295 Darmstadt, Germany

ABSTRACT

Cross-Correlation and Euclidean Distance are two of the most common statistical techniques used for target matching. Calculation of the Cross-Correlation can be carried out in both the Spatial and Fourier domain. Significant performance benefits have been achieved by computing the Fourier domain Cross-Correlation using the Mixed Radix Fast Fourier Transform (FFT). This technique is currently implemented operationally in the MSG (Meteosat-8) MPEF environment. This paper provides the first results of the comparison of these techniques in the MSG operational environment. The results show that the two Cross-Correlation techniques are well matched, however there are noticeable differences for water vapour moisture features in cloud-free areas, as well as the IR 10.8 µm channel winds for which a form of image enhancement has been applied prior to tracking. The paper also provides a comparison of the Cross-Correlation and Euclidean Distance matching techniques and concentrates on assessing potential benefits of the latter for tracking water vapour features. The results indicate that Euclidean Distance is a better tracking technique in cloud-free areas.

1. INTRODUCTION

In August 2002 the first Meteosat Second Generation (MSG) satellite was launched, and in January 2004 routine operations as Meteosat-8 were started. The Meteorological Product Extraction Facility (MPEF) is part of the MSG Ground Segment and the Atmospheric Motion Vector (AMV) product is the main output of the MPEF. For the winds generated in the AMV product, there are three target matching techniques available; Cross-Correlation in the Spatial domain, Cross-Correlation in the Fourier domain, and Euclidean Distance (SSD). Currently, four channels are used to generate AMVs for Meteosat-8 – visible 0.8 µm cloud targets over land and sea, infra-red 10.8 µm cloud targets, water vapour 6.2 and 7.3 µm cloud and clearsky targets. Cross-Correlation in the Fourier domain is currently implemented operationally for all these channels.

While the Cross-Correlation method has been demonstrated to be a valid tracking method, it is computationally intensive, and uses up a significant proportion of processing time. Dew and Holmlund (1998) introduced the Mixed Radix Fast Fourier Transform (FFT) technique to be used for carrying out Cross-Correlation in the Fourier domain. This technique was shown to have significant performance benefits (in terms of CPU usage) over the Spatial domain method, however, previously in the MSG environment, only simulated image data has been used to compare the output of the two techniques, (Dew and Holmlund (2000)). Section 2 provides the first results of direct comparison of the two techniques in the MSG environment using the Meteosat-8 Level 1.5 image data.

Euclidean Distance is another statistical technique which is widely used in the winds community for target matching. It can be preferred to the Cross-Correlation technique on the perceived basis of being computationally less intensive. Dew and Holmlund (2000) provided some theoretical analysis of the comparison of these two techniques and produced some preliminary results using simulated data to show that the relative wind fields diverge in low contrast areas. Section 3 further compares the two techniques using Meteosat-8 data and concentrates on analysing the tracking of water vapour features.

Section 4 assesses the conclusions to be drawn from this study, and Section 5 provides recommendations for operational implementation and further investigations.

2. CROSS-CORRELATION

2.1. Overview

Given a target area denoted by T and a search area by S, for a square target size, with side length N_T, if the pixels within the target area are identified by (m,n) and the target location within the search area by (i,j), such that the target is always fully contained within the search area, then T_{mn} and $S_{i+m,j+n}$ uniquely identify pixel count values within the target and search areas. The standard expression for the Cross-Correlation coefficient in the Spatial domain is defined by:

$$r_{ij} = \frac{\sum_{m=1}^{N_T}\sum_{n=1}^{N_T}\left(T_{mn}-\mu_T\right)\left(S_{i+m,j+n}-\mu_{Sij}\right)}{\left[\sum_{m=1}^{N_T}\sum_{n=1}^{N_T}\left(T_{mn}-\mu_T\right)^2\right]^{1/2}\left[\sum_{m=1}^{N_T}\sum_{n=1}^{N_T}\left(S_{i+m,j+n}-\mu_{Sij}\right)^2\right]^{1/2}} \qquad (1)$$

where $\mu_T = \frac{1}{N_T}^{2}\sum_{m=1}^{N_T}\sum_{n=1}^{N_T} T_{mn}$ and $\mu_{Sij} = \frac{1}{N_T}^{2}\sum_{m=1}^{N_T}\sum_{n=1}^{N_T} S_{i+m,j+n}$

The basic Cross-Correlation term ($\Sigma\Sigma$ TS) can also be implemented in the Fourier domain by 3 Fourier transforms.

$$R_{ij} = \left[F^{-1}\left\{F(S)F^{*}(T)\right\}\right]_{ij} \qquad (2)$$

This implementation has the advantage of being computationally more efficient, depending on the data set size (Dew and Holmlund (1998)). The traditional implementations of the Cross-Correlation in the Fourier domain generally use Fast-Fourier Transform (FFT) algorithms, in particular the Radix-2 FFT method which uses a data set-size the nearest power of 2 above the search area size, and calculates and combines transforms of size 2. However, there are necessarily a large number of redundant calculations of padded data outside the search area size. Dew and Holmlund (1998) introduced the more efficient Mixed-Radix FFT implementation, which uses a smaller data set exactly equal to the search area size. The data set is decomposed into prime factors and the method calculates and combines transforms of the size of the prime factors. As long as the prime factors are small enough, this method offers significant performance benefits.

In the current operational implementation of MSG MPEF a cloud target is assigned a target area of 24 x 24 pixels, and search area of 80 x 80 pixels. A clearsky target is assigned a target area of 32 x 32 and search area of 96 x 96. The highest prime factors for these 2 search area sizes are 5 and 3 respectively. Dew and Holmlund (1998) showed that for the Fourier domain Cross-Correlation of a 24 x 24 target over an 80 x 80 search area, the computation time for the Mixed-Radix FFT method is about 50% that of the Radix-2 method and about 40% that of the Spatial domain method. For the 32 x 32, 96 x 96 combination the figures are about 60 and 20% respectively. So clearly the Fourier domain implementation is more computationally efficient. However, it is important that the relative quality of the wind fields produced by the Spatial and Fourier domain implementations is assessed.

2.2. Criteria for analysis

Results are presented for the visible 0.8 µm, water vapour 6.2 µm and infra-red 10.8 µm channels. The differences between the wind vectors produced by the two techniques can be demonstrated by:

- Histogram representations separating the direction differences and speed differences into classes.

- Speed bias, mean vector difference, RMS vector difference, normalised RMS vector difference.
- Mean quality index of the winds.

The first two criteria are shown for an Intermediate Product (timestamp 121500Z May 26th 2004) which contains wind vectors correlated from the 120000Z to 121500Z images. The statistics are presented for three quality indices – all vectors, and vectors with quality indices above 0.3 and 0.6 respectively. For the third criteria, the mean quality index is shown for the Final Product wind vectors (timestamp 124500Z May 26th 2004). The Final Product combines vectors from the three contributing Intermediate Products for that hour. These results provide an accurate reflection of the general trends observed.

2.3. Results and discussion

2.3.1. General

Figures 1 and 2 provide examples of wind fields using Cross-Correlation (Fourier domain), to illustrate that this tracking technique is providing a good representation of the wind flows observed from the satellite data.

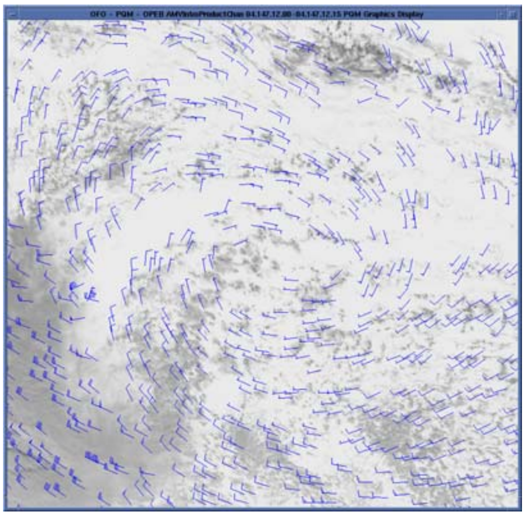


Figure 1: VIS 0.8 µm Cloud Targets.

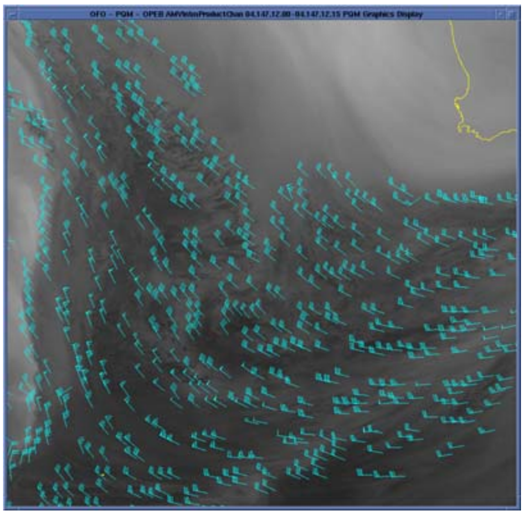


Figure 2: WV 6.2 µm Cloud Targets.

In analysing the histograms of speed (m/s) and direction (degrees) differences, for the VIS 0.8 µm channel, Figure 3 shows there is very little difference between the two techniques. For the WV 6.2 µm channel cloud targets, Figure 4 shows similar results. For WV 6.2 µm clearsky targets, however, Figure 5 shows some important divergences. Figure 6 shows that for the IR 10.8 µm channel the two techniques appear to be well correlated, however the wind field example in Figure 7 illustrates that there are areas where the two techniques diverge, with the Fourier domain representation producing some poorer quality winds.

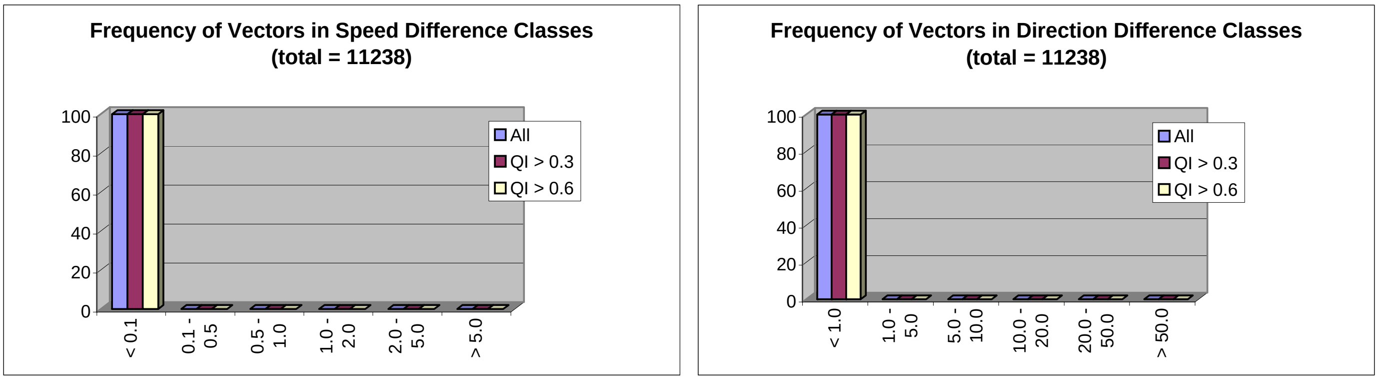
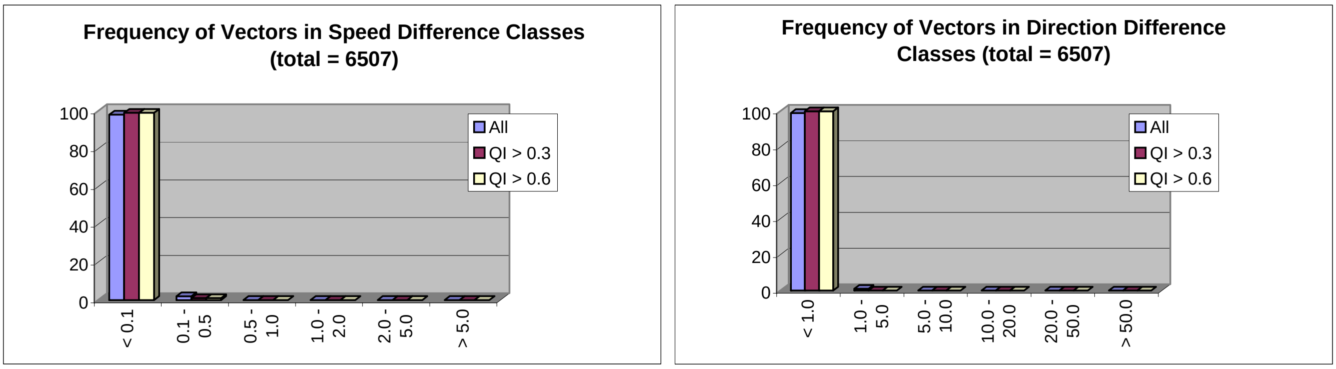


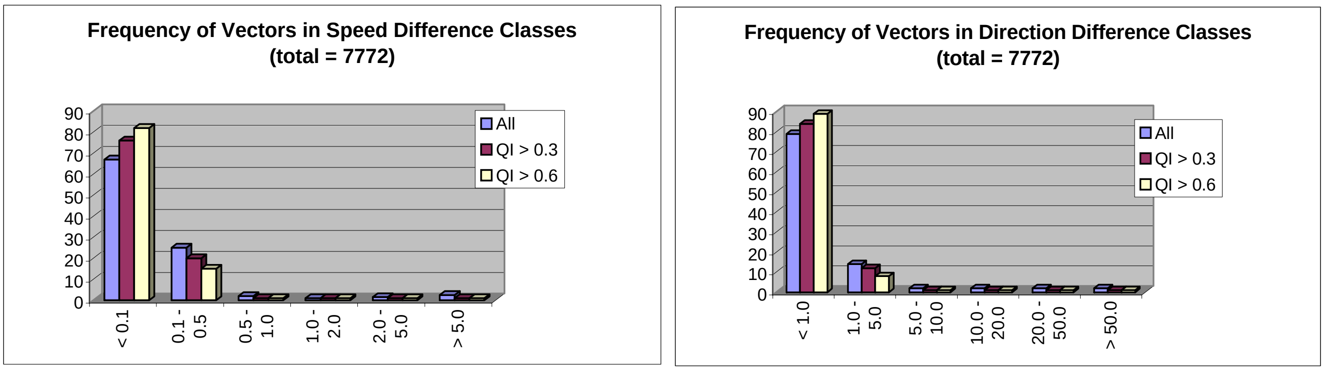
Figure 3: VIS 0.8 µm Channel Speed (m/s) and Direction (deg) Difference Statistics.



Frequency of Vectors in Speed Difference Classes (total = 6507)

Frequency of Vectors in Direction Difference Classes (total = 6507)

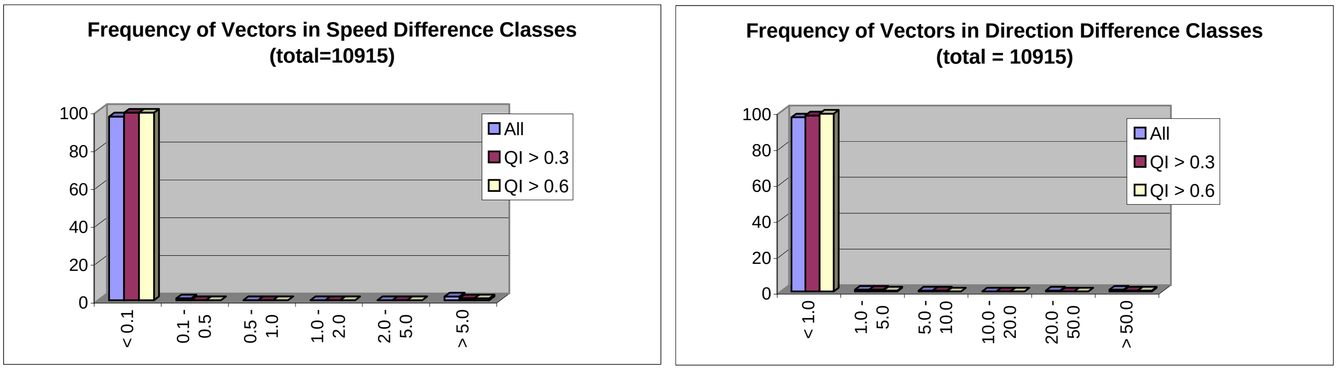
Figure 4: WV 6.2 µm Channel (Cloud Targets) Speed (m/s) and Direction (deg) Difference Statistics.



Frequency of Vectors in Speed Difference Classes (total = 7772)

Frequency of Vectors in Direction Difference Classes (total = 7772)

Figure 5: WV 6.2 µm Channel (Clearsky Targets) Speed (m/s) and Direction (deg) Difference Statistics.



Frequency of Vectors in Speed Difference Classes (total=10915)

Frequency of Vectors in Direction Difference Classes (total = 10915)

Figure 6: IR 10.8 µm Channel Speed (m/s) and Direction (deg) Difference Statistics.

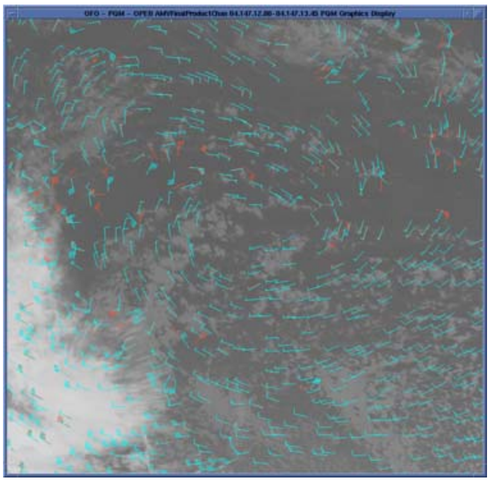


Figure 7: IR10.8µm Final Product Winds (Blue Spatial Domain; Red Fourier Domain – Blue Overlays. Red).

These results are further corroborated by analysing the vector difference statistics summary, as shown in Table 1. For the VIS 0.8 and WV6.2 µm cloud targets, the speed biases and RMS vector differences are negligible. However for the WV 6.2 µm clearsky targets the RMS vector differences are not insignificant, and for the IR 10.8 µm channel, speed biases and RMS vector differences are large. Table 2 shows that the mean quality of the two techniques is well-matched, but also reflects the channel differences shown in Table 1. VIS 0.8 and WV6.2 µm cloud targets have a mean quality above 0.7. The quality for the IR10.8 µm targets is a little lower at 0.65. The quality for the WV 6.2 µm clearsky targets is significantly lower at 0.47.

Channel	Quality	No. of Vectors	Speed Bias	Mean VecDiff	RMS VecDiff	Mean Speed	NRMS
VIS 0.8	All	11238	1.2 E-05	2.5 E-04	2.7 E-03	9.6	2.8 E-04
	QI > 0.3	8942	1.5 E-05	2.3 E-04	2.7 E-03	9.4	2.9 E-04
	QI > 0.6	6967	2.6 E-06	1.8 E-04	1.7 E-03	9.8	1.7 E-04
IR 10.8	All	10915	0.03	1.9	15.3	16.0	0.95
	QI > 0.3	7949	0.6	0.9	10.7	14.3	0.75
	QI > 0.6	5969	0.5	0.7	9.0	15.4	0.58
WV 6.2 cloud	All	6507	0.001	0.03	0.4	21.8	0.02
	QI > 0.3	5211	-0.002	0.01	0.2	21.7	0.01
	QI > 0.6	4309	0.000	0.01	0.1	23.1	0.005
WV 6.2 clearsky	All	7772	0.03	1.2	9.8	24.5	0.40
	QI > 0.3	4566	0.09	0.5	4.1	15.7	0.26
	QI > 0.6	2704	0.05	0.3	2.9	15.9	0.18

Table 1: RMS Vector Difference Statistics (m/s).

	Spatial			Fourier		
Channel	Mean QI	No. of vectors QI > 0.3	No. of vectors QI > 0.6	Mean QI	No. of vectors QI > 0.3	No. of vectors QI > 0.6
VIS 0.8	0.71	10091	7903	0.71	10091	7903
IR 10.8	0.65	8841	6679	0.65	8820	6680
WV 6.2 cloud	0.74	5538	4669	0.74	5537	4673
WV 6.2 clearsky	0.47	3557	2021	0.47	3569	2039

Table 2: Final Product Mean Quality.

2.3.2. IR 10.8 µm channel - image enhancement

The reasons there are discrepancies in the two Cross-Correlation techniques for the IR 10.8 µm channel can be ascribed to the effect of applying image enhancement to the Level 1.5 image count data, prior to the correlation calculations. The aim of the image enhancement is to enhance the contrast between the highest scene layer, suitable for tracking, and other lower level scenes. This is described in the MSG Ground Segment : MPEF Algorithm Specification Document (Heinemann et al (2004)). The technique is currently used in the Meteosat Transition Programme (MTP) series of satellites (eg Meteosat-7), and applied only to the IR 10.8 µm channel in MSG. However, the tuning of this technique for use in the MSG environment still needs to be completed. Switching off image enhancement (No Enhance) significantly reduces differences between the two Cross-Correlation techniques and improves the mean quality of the winds by about 10 %, as indicated by the results in Tables 3 and 4.

The reason that the use of image enhancement has introduced differences in the two techniques needs to be investigated, but the problem might at least be partly attributed to the use of random count data, in extreme cold or warm localised areas within a target, as a form of masking to avoid correlation peaks. The Fourier domain representation of the Spatial domain data set has an inherent bandwidth dependent on the spatial resolution of the count data. The higher the spatial resolution, the higher the frequency bandwidth. It may be that the use of random (noisy) count data has introduced high frequency components which alias into the frequency bandwidth. This would have a negative impact on the Cross-Correlation in the Fourier domain.

Channel	Quality	No. of Vectors	Speed Bias	Mean VecDiff	RMS VecDiff	Mean Speed	NRMS
IR10.8 Image Enhance	All	10915	0.03	1.9	15.3	16.0	0.95
	QI > 0.3	7949	0.6	0.9	10.7	14.3	0.75
	QI > 0.6	5969	0.5	0.7	9.0	15.4	0.58
IR10.8 No Enhance	All	10915	3.5E-04	5.8E-03	0.2	13.4	0.01
	QI > 0.3	8606	-2.0E-04	3.3E-03	0.02	13.5	0.001
	QI > 0.6	6690	-1.0E-04	2.9E-03	0.01	14.5	8.5E-04

Table 3: Effect of Image Enhancement (Vector Difference Statistics (m/s)).

	Spatial			Fourier		
Channel	Mean QI	No. of vectors QI > 0.3	No. of vectors QI > 0.6	Mean QI	No. of vectors QI > 0.3	No. of vectors QI > 0.6
IR10.8 Image Enhance	0.65	8841	6679	0.65	8820	6680
IR10.8 No Enhance	0.72	9774	7735	0.72	9774	7739

Table 4: Effect of Image Enhancement (Product Quality).

The lower overall wind vector quality for both Cross-Correlation techniques when image enhancement is used indicates that the set-up parameters need improved tuning for this method. They also point to a need to assess the scenes analysis processing within the AMV algorithm, which separates the target data into scene layers prior to the image enhancement.

2.3.3. Clearsky targets

The differences in results for the two Cross-Correlation techniques for the WV6.2 water vapour clearsky features indicates that Cross-Correlation may not be the most effective tracking technique for these low contrast features. The next section investigates the potential benefits of the Euclidean Distance tracking technique and compares this with Cross-Correlation for water vapour features.

3. EUCLIDEAN DISTANCE

3.1. Overview

The alternative template matching technique, Euclidean Distance or Sum of Squared Distances (SSD), can be expressed using the same terms and expressions as for Cross-Correlation to give an SSD coefficient:

$$ssd_{ij} = \frac{1}{N_T}^2 \sum_{m=1}^{N_T} \sum_{n=1}^{N_T} \left(S_{i+m,j+n} - T_{mn} \right)^2 \qquad (3)$$

The minimum of the SSD surface provides the best target location. Dew and Holmlund (2000) provided results to suggest this technique is more beneficial in low contrast areas. So this study concentrates on assessing the differences between the Cross-Correlation and SSD techniques in the WV6.2 µm channel.

3.2. Criteria for analysis

Results are presented for water vapour 6.2 µm cloud and clearsky targets. As for the two Cross-Correlation techniques in Section 2, comparisons have been undertaken on the differences between the wind vectors produced by the SSD and Cross-Correlation (Fourier domain) techniques, for the same input data set, ie

- Histogram representations separating the direction differences and speed differences into classes.
- Speed bias, mean vector difference, RMS vector difference, normalised RMS vector difference.
- Mean quality index of the winds.

3.3. Results and discussion

In analysing the histograms of speed (m/s) and direction (degrees) differences, for all targets, Figure 8 shows a clear discrepancy between the two techniques.

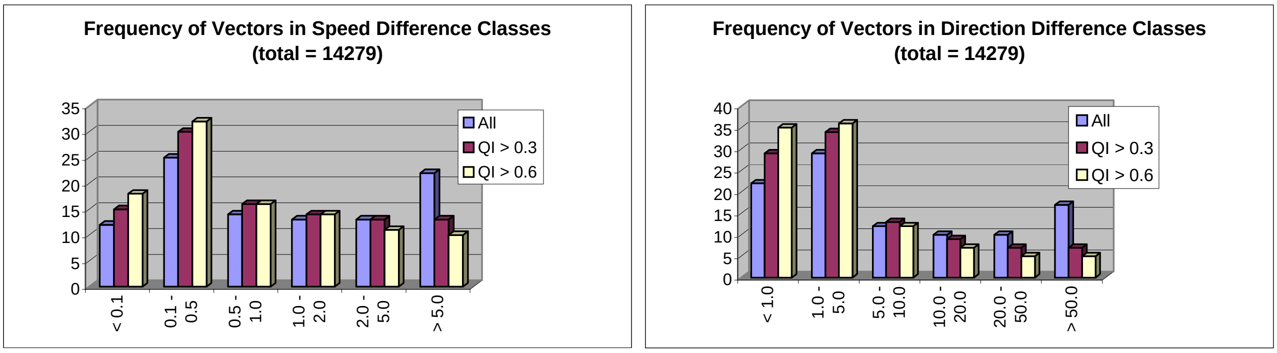


Figure 8: WV 6.2 µm Channel Speed (m/s) and Direction (deg) Difference Statistics.

Figures 9 and 10 provide illustrations to indicate where the differences lie. Figure 9 shows the wind fields provided by the 2 techniques for cloud targets (Blue Euclidean Distance; Red Cross-Correlation – Blue Overlays Red). There are some differences but generally both wind fields are fairly smooth. Figure 10, however, shows that for clearsky targets the Euclidean Distance wind field is significantly smoother than the Cross-Correlation.

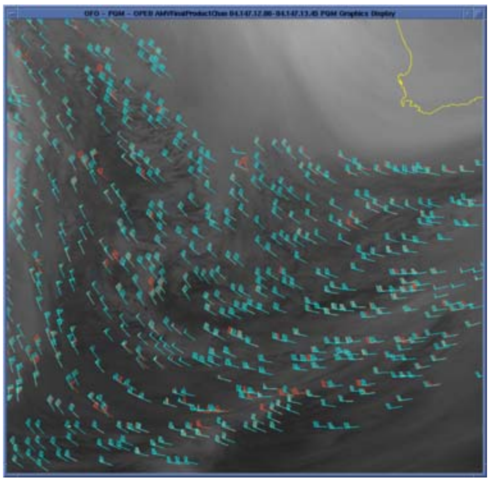


Fig. 9: WV 6.2 µm Final Product Cloud Targets.

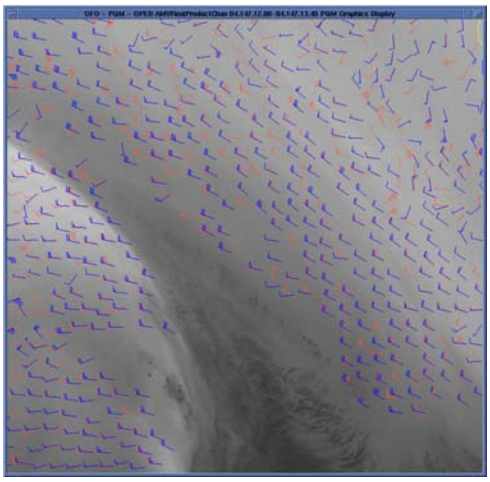


Fig. 10: WV 6.2 µm Final Product Clearsky Targets.

Table 5 shows the vector difference statistics and Table 6 shows the product quality, both of which are separated into cloud and clearsky targets. For cloud targets, there is a slow speed bias between the two techniques and the normalised RMS vector difference is not negligible. However, the overall product quality is similar. For clearsky targets, however, the speed bias is much greater, the vector difference statistics are significant, and the mean quality of the wind field is improved by 5% when using the Euclidean Distance tracking technique.

So it is clear that the Euclidean Distance (SSD) technique has performed better than Cross-Correlation for clearsky targets, but for cloudy targets, while there are differences between the two techniques, no clear benefit of using the Euclidean Distance technique has been demonstrated.

Channel	Quality	No. of Vectors	Speed Bias	Mean VecDiff	RMS VecDiff	Mean Speed	NRMS
WV 6.2 cloud	All	6507	-2.0	5.8	21.1	21.8	0.97
	QI > 0.3	5217	-0.6	3.0	11.0	21.7	0.51
	QI > 0.6	4310	-0.6	2.7	9.9	23.1	0.43
WV 6.2 clearsky	All	7772	-11.9	18.8	43.2	24.5	1.76
	QI > 0.3	4594	-2.7	6.9	21.4	15.7	1.37
	QI > 0.6	2719	-1.6	4.9	16.1	16.1	1.00

Table 5: RMS Vector Difference Statistics (m/s).

	Fourier			SSD		
Channel	Mean QI	No. of vectors QI > 0.3	No. of vectors QI > 0.6	Mean QI	No. of vectors QI > 0.3	No. of vectors QI > 0.6
WV 6.2 cloud	0.74	5537	4673	0.74	5661	4692
WV 6.2 clearsky	0.47	3569	2039	0.52	4647	2528

Table 6: Mean Final Product Quality.

4. CONCLUSIONS

The Cross-Correlation tracking technique has for many years been demonstrated in the winds community as a viable technique for tracking targets. This study and previous others have emphasised that it remains a standard technique to adopt and produces very smooth and high quality wind fields. However, in seeking ways to optimise the implementation of this method, originally driven by the requirements to minimise CPU time, there are essentially three factors to consider when comparing the Cross-Correlation in the Spatial domain to that of the Fourier domain:

- The CPU time is less for the Fourier domain method, thereby affording more time for additional parallel MPEF processing to be carried out,
- There are less numerical operations carried out for the Fourier domain method, therefore less mathematical rounding errors,
- The Fourier domain implementation has a frequency spectrum whose width is restricted by the Spatial domain resolution. This may be susceptible to noisy data aliasing into the frequency bandwidth and has yet to be fully investigated.

The Mixed Radix Fourier domain Cross-Correlation technique has been validated in the MSG environment. For the visible 0.8 µm and water vapour 6.2 µm channel cloud targets the results are closely correlated with the Spatial domain Cross-Correlation technique and the technique produces high quality smooth wind fields. For the IR 10.8 µm channel the wind field quality is lower and there are discrepancies between the two Cross-Correlation techniques which are due to the affects of the applied image enhancement (image enhancement is applied to this channel only). Removing the image enhancement increases the quality of the wind fields for both techniques to the levels of the visible and water vapour cloud wind fields, and discrepancies between the two techniques become negligible.

For water vapour 6.2 µm clearsky targets there are significant discrepancies between the two techniques and the quality of the wind fields is low. In analysing the performance of the Euclidean Distance tracking technique, this provides a significantly higher quality wind field for the water vapour clearsky targets compared to the Cross-Correlation. So Euclidean Distance has been demonstrated to be a better tracking technique than Cross-Correlation for the water vapour clearsky targets. This confirms previous studies which suggest this technique is more beneficial in low contrast areas. No benefits of this technique have been observed for water vapour cloud targets.

5. RECOMMENDATIONS

The results presented in this study have demonstrated that Mixed Radix Fourier domain Cross-Correlation is a valid operational tracking technique, which should continue to be used in the MSG environment. It is recommended, however, that for water vapour clearsky targets, the Euclidean Distance tracking method be adopted.

The image enhancement implementation and fine-tuning that is applied to the IR 10.8 µm channel count data clearly needs to be investigated, as to why this is having a negative impact on the wind fields. Investigations should concentrate on assessing the scene analysis scheme used to separate the target into scene layers, tuning of set-up parameters to more accurately reflect the MSG environment, and analysing if introducing pixel masking instead of random count data in extreme cold or warm localised areas benefits the Fourier domain Cross-Correlation. More investigations need to be carried out to assess if frequency aliasing occurs in the Frequency domain representation and if this has a negative impact.

At present MSG has the capability to generate winds in visible 0.6, infra-red 8.7, 9.7 and high resolution visible 0.75 µm channels. The high resolution visible channel is likely to become operational in the near future and it is recommended for this channel and for any others that are likely to become operational, that the target tracking techniques are assessed prior to operational implementation.

6. REFERENCES

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