INVESTIGATIONS OF CROSS-CORRELATION AND EUCLIDEAN DISTANCE TARGET MATCHING TECHNIQUES IN THE MPEF ENVIRONMENT

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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 are achieved by computing the Fourier domain Cross-Correlation using the Mixed Radix Fast Fourier Transform (FFT). This paper provides further results of a comparison of these techniques undertaken in the Meteorological Product Extraction Facility (MPEF) environment, by comparing the displacement vectors derived from pseudo-real imagery data, including analysis of behaviour in different contrast regions. The results show that the two techniques are well matched.

In assessing the relative benefits of alternative matching techniques, this paper additionally provides results for the Euclidean Distance method. It includes comparison with Cross-Correlation of the displacement vectors in different contrast regions and analyses where maximum discrepancy is observed between the two methods. The results indicate that differences between the two techniques are more apparent in lower contrast regions.

1. Introduction

The Meteorological Product Extraction Facility (MPEF) is being developed as part of the Meteosat Second Generation (MSG) Ground Segment. The Atmospheric Motion Vector (AMV) product, generated as part of the MSG MPEF, poses the highest CPU load. For calculating AMV there are three target matching techniques available; Cross-Correlation in the spatial domain, Cross-Correlation in the Fourier domain, and Euclidean Distance. 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 over the spatial domain method, and a preliminary comparison was undertaken of the wind vectors produced with the two techniques in the MPEF environment. This paper provides further comparisons, using simulated MSG MPEF data for 3 channels: WV6.2, VIS0.6 and IR10.8. It also carries out a similar comparison of the spatial domain Cross-Correlation and Euclidean Distance methods, with the view to isolating conditions under which the behaviour of the two techniques diverge.

Section 2 provides a theoretical overview of the target matching techniques, highlighting the performance benefits of the Mixed Radix FFT, and predicting potential differences in behaviour between the Euclidean Distance and Cross-Correlation methods. Section 3 analyses the two Cross-Correlation techniques, and compares the spatial domain and Mixed Radix FFT methods for a series of wind vectors generated from simulated MSG channel data, investigating potential areas of discrepancy across different contrast regions. Section 4 concentrates on comparing the spatial domain cross-correlation and Euclidean distance methods, using similar analysis criteria as for Section 3. Section 5 assesses the conclusions of the work carried out so far and provides recommendations for further investigations.

2. Overview of MSG MPEF target tracking techniques

2.1 Cross-Correlation

Cross-correlation is one of the standard statistical techniques used for target matching. Given a target area denoted by T and a search area by S, for a square target size, with side length N_T, the total number of pixels used to compute one correlation value is $N = N_T^2$. 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 cross-correlation between T and S can be normalised to prevent false correlation peaks arising from changes in the search area local means, and any local additive bias differences can also be removed. The expression for the cross-correlation is expanded to produce the cross-correlation coefficient defined by:

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

where

$$m_T = \frac{1}{N_T}^2 \sum_{m=1}^{N_T}\sum_{n=1}^{N_T} T_{mn} \quad \text{and} \quad m_{Sij} = \frac{1}{N_T}^2 \sum_{m=1}^{N_T}\sum_{n=1}^{N_T} S_{i+m,j+n}$$

The cross-correlation can also be implemented in the Fourier Domain by three Fourier transforms. Before normalisation and biases are removed, equation (1) can be expressed by :

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

Dew and Holmlund (1998) showed that a Mixed Radix FFT implementation is considerably more efficient than the traditional Radix-2 FFT, and the performance benefits compared to the spatial domain Cross-Correlation method are also significant (CPU load is approximately 60% for a 16/72 target/search area combination, and 20% for a 32/96 target/search area). In assessing the relative quality of the wind vectors produced for the two Cross-Correlation methods, results using real water wapour imagery (Dew and Holmlund, 1998) indicated a strong correlation between the Mixed Radix and the spatial domain correlation. Further results are provided in this paper in Section 3.

2.2 Euclidean Distance

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

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

While the the maximum of the correlation surface described in (1) provides the best match, it is the minimum of the SSD surface in (3) which gives the best target location. Equation (3) can be expanded, so that minimising the *ssd* surface is equivalent to maximising the expression:

$$pseudo\_ssd_{ij} = 2\sum_{m=1}^{N_T}\sum_{n=1}^{N_T} S_{i+m,j+n}T_{mn} - \sum_{n=1}^{N_T} S_{i+m,j+n}{}^2 \qquad (4)$$

By introducing the bias and normalisation terms to T and S, which are used to expand the Cross-Correlation term into (1), the $\sum S^2$ term in (4) becomes invariant and the *pseudo-ssd* surface simply equates to the correlation surface of (1). Hence, the relative performance of the Euclidean Distance and Cross-Correlation matching techniques can be addressed by considering the affect of the normalisation and bias terms. The use of normalisation terms and removal of image biases have been shown to significantly improve the Cross-Correlation performance. The use of normalisation would be expected to be especially beneficial in high contrast search areas in which the search area local means are variable. In low contrast search areas, however, where the correlation surface has shallow slopes and a broad maxima, this may not be so important. In these cases, normalisation may degrade the accuracy of the surface peak location (in the limiting case of no contrast, the Cross-Correlation expression becomes undefined). It is possible that the Euclidean Distance technique will yield better quality results in these regions. This is investigated in this paper in Section 4.

3. Comparison of cross-correlation techniques

3.1 Criteria for Analysis

Dew and Holmlund (1998) provided preliminary results of investigations into validating the Mixed Radix FFT method against the spatial domain technique in the MPEF environment. Further results are presented for a series of wind vectors generated over the Earth's globe from simulated MSG MPEF WV6.2, IR10.8 and VIS0.6 channels. A statistical analysis has been undertaken for each channel which lists the number of vectors, speed bias, mean vector difference, RMS vector difference, mean speed , normalised RMS (RMS difference/mean speed) and mean search area contrast. The search area contrast associated with each target is defined in units of counts as the difference between the maximum and minimum local mean within the search area centred on the target. The statistics are also presented for three quality indices - all vectors, vectors with a quality index above 0.3, and vectors with a quality index above 0.6. A statistical analysis of the differences is carried out for the WV6.2 channel, highlighted in two histogram representations which respectively concentrate on separating the direction differences (degrees) and the speed differences (m/s) of the 24999 generated wind vectors into classes.

A further statistical analysis is undertaken to investigate the relative behaviour of the two techniques in different contrast regions, which concentrates on the WV6.2 channel. This is summarised into a histogram representation which separates into contrast regions the normalised RMS for the three quality indices. In addition, differences between the speed bias, mean vector difference, RMS difference and mean speed in a low and high contrast region are provided, and relative numbers of high quality winds for the two techniques in each region are also assessed.

3.2 Results and Discussion

3.2.1 General

Figure 1 provides an example to illustrate the observation that there is very good correspondence between the spatial domain and the Mixed Radix FFT technique. The FFT vectors are plotted in red and the spatial domain vectors are overlaid in yellow. Hence, where there is very good correspondence, the FFT vectors are obscured by those produced by the spatial domain technique. Each wind vector starts at the same point for the two techniques (i.e. target selection is independent of matching technique).

Figures 2 and 3 and Table 1 detail the statistics, which show that in over 80% of cases there is less than 0.1 m/s speed difference and in over 90% of cases there is less than 1.0 degree direction difference. As the quality index rises, the two methods further converge. Table 1 shows that the normalised RMS is reduced for the higher quality threshold. The table also shows that the normalised RMS is highest for the channel (WV6.2) in which the contrast is lowest. This has led to further analysis of the WV6.2 channel derived vectors in different contrast regions.

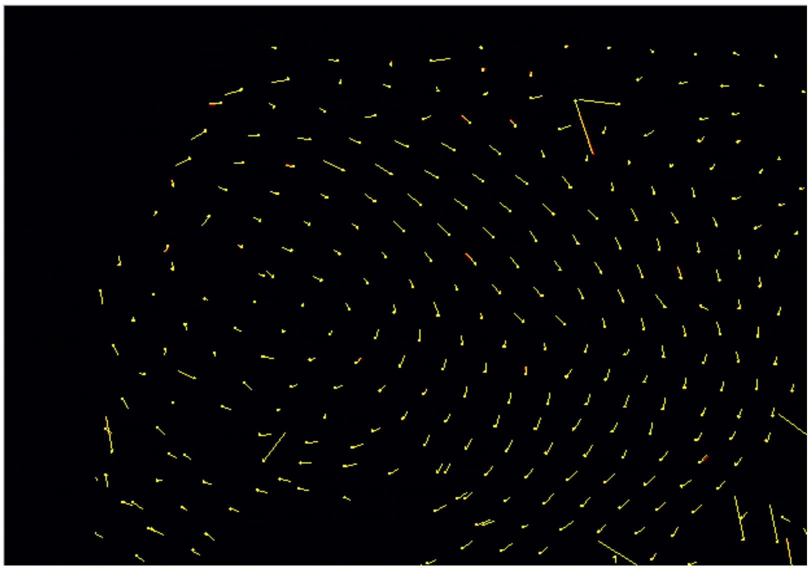

Figure 1. High Level View of a Wind Field (WV6.2) (Yellow: Spatial Domain Red: Mixed Radix FFT).

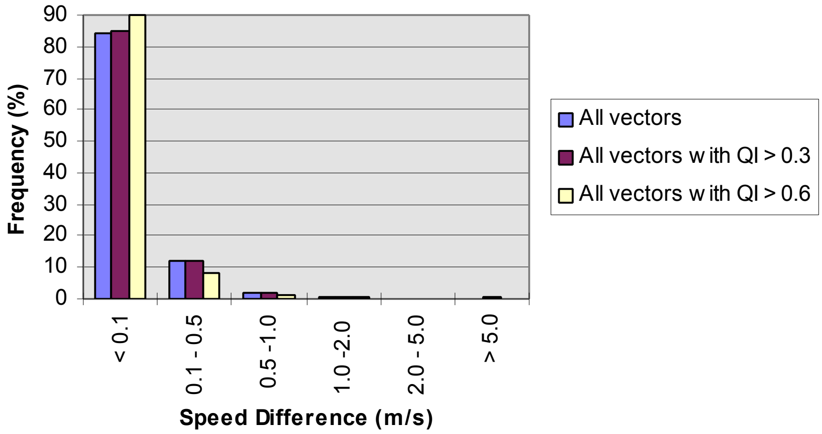

Figure 2. Frequency of Vectors in Speed Difference Classes (WV6.2) (Cross-Correlation Spatial Domain vs Mixed Radix Fourier Domain).

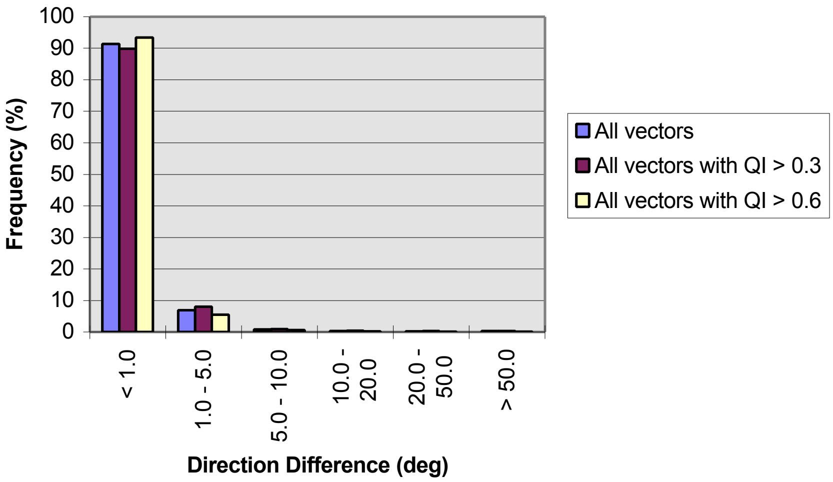

Figure 3. Frequency of Vectors in Direction Difference Classes (WV6.2) (Cross-Correlation Spatial Domain vs Mixed Radix Fourier Domain).

Table 1. Vector Difference Statistics (Cross-Correlation Spatial Domain vs Mixed-Radix Fourier Domain)

Channel	Quality	No of vectors	Speed bias	Mean vecdiff	RMS vecdiff	Mean speed	NRMS	Mean contrast
WV6.2	All	24999	0.00	0.22	2.22	23.95	0.093	76.62
	QI > 0.3	17609	0.02	0.21	1.87	18.62	0.101	79.03
	QI > 0.6	7225	0.01	0.12	1.19	16.79	0.071	88.21
IR10.8	All	17827	-0.00	0.04	0.39	14.04	0.028	260.01
	QI > 0.3	14105	-0.00	0.04	0.37	11.01	0.034	252.69
	QI > 0.6	8486	0.00	0.03	0.09	9.65	0.010	220.93
VIS0.6	All	19230	0.00	0.02	0.07	11.45	0.006	380.19
	QI > 0.3	15866	-0.00	0.02	0.04	9.06	0.005	381.79
	QI > 0.6	10247	0.00	0.01	0.03	7.76	0.004	370.67

3.2.2 Search Area Contrast

For all of the contrast regions, there is virtually no difference in the number of vectors above quality thresholds of 0.3 and 0.6 produced by the two techniques. Figure 4 shows how the normalised RMS varies across contrast regions. It indicates that for all vectors the normalised RMS decreases as the contrast increases, but this trend is reversed in the 150 -300 contrast region. The lowest contrast region (0- 25) produces the highest normalised RMS and the contrast region 100 -150 produces the lowest. Table 2 shows the vector difference statistics for these two regions.

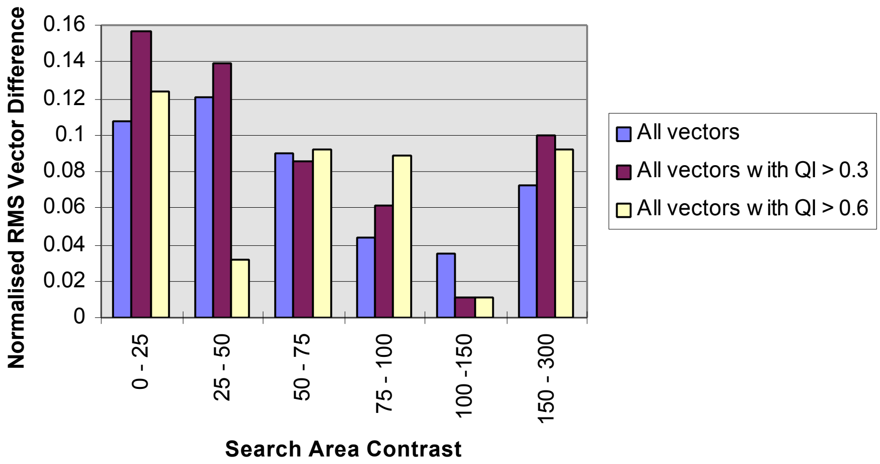

Figure 4. Normalised RMS Vector Difference in Search Area Contrast Classes (WV6.2)
(Cross-Correlation Spatial Domain vs Mixed-Radix Fourier Domain)

Table 2. Search Area Contrast Vector Difference Statistics (Cross-Correlation Spatial Domain vs Mixed-Radix Fourier Domain) (WV6.2)

Contrast	Quality	No of vectors	Speed bias	Mean vecdiff	RMS vecdiff	Mean speed	NRMS
0-25	All	1346	0.05	0.39	2.91	27.15	0.107
	QI > 0.3	865	0.05	0.44	3.21	20.50	0.156
	QI > 0.6	153	-0.04	0.31	2.01	16.22	0.124
100-150	All	4607	-0.00	0.08	0.71	19.90	0.036
	QI > 0.3	3517	0.00	0.06	0.19	16.64	0.011
	QI > 0.6	1932	0.00	0.05	0.17	15.73	0.011

4. Comparison of cross-correlation with Euclidian Distance technique

4.1 Criteria for Analysis

The criteria used for analysing differences between the Cross-Correlation (spatial domain) and Euclidean Distance techniques are identical to those used to compare the Mixed Radix FFT technique, hence are described in Section 3.1.

4.2 Results and Discussion

4.2.1 General

Figures 5 and 6 and Table 3 detail the statistics, which emphasise differences between the Cross-Correlation and Euclidean Distance techniques. In over 90% of cases there is greater than 0.1 m/s speed difference, and in over 35% of cases there is greater than 5 m/s speed difference. In over 80% of cases there is greater than 1.0 degree direction difference, and in over 25% of cases there is greater than 50 degree direction difference. The discrepancy reduces as the quality threshold increases. For a 0.6 quality threshold the distribution of speed and direction differences is more even, but 50% of vectors have a speed difference above 1.0 m/s and a direction difference above 5.0 degrees.

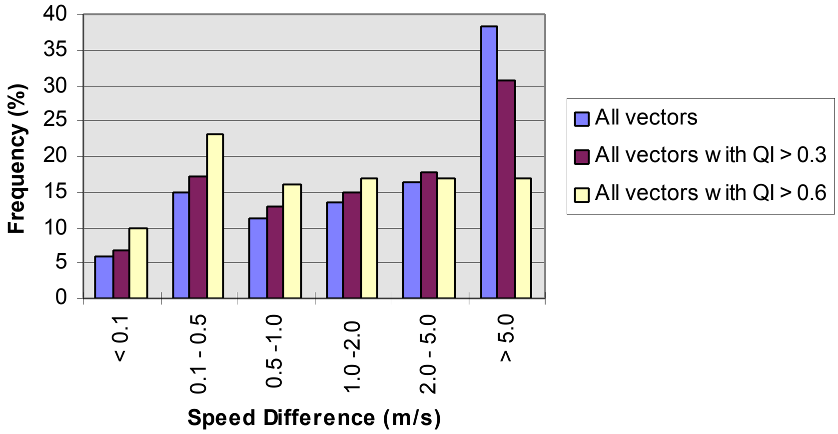

Figure 5. Frequency of Vectors in Speed Difference Classes (WV6.2) (Cross-Correlation vs Euclidean Distance).

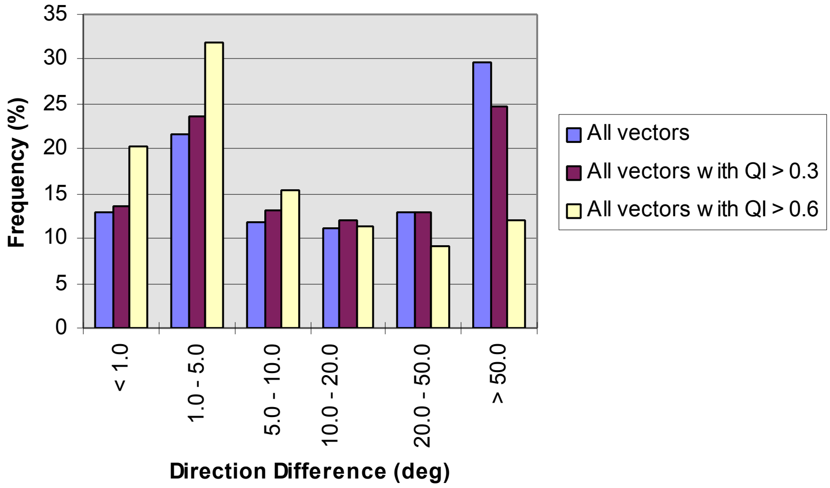

Figure 6. Frequency of Vectors in Direction Difference Classes (WV6.2) (Cross-Correlation vs Euclidean Distance).

Table 3. Vector Difference Statistics (Cross-Correlation Spatial Domain vs Euclidean Distance)

Channel	Quality	No of vectors	Speed bias	Mean vecdiff	RMS vecdiff	Mean speed	NRMS	Mean contrast
WV6.2	All	24999	-4.72	18.13	31.46	23.95	1.314	76.62
	QI > 0.3	17609	-1.29	12.78	24.26	18.62	1.303	79.03
	QI > 0.6	7225	-0.05	6.89	16.55	16.79	0.985	88.21
IR10.8	All	17827	0.14	8.23	21.08	14.04	1.501	260.01
	QI > 0.3	14105	1.37	5.80	16.49	11.01	1.497	252.69
	QI > 0.6	8486	1.43	3.19	10.94	9.65	1.134	220.93
VIS0.6	All	19230	1.86	9.30	24.63	11.45	2.151	380.19
	QI > 0.3	15866	2.70	6.64	20.01	9.06	2.208	381.79
	QI > 0.6	10247	2.26	3.69	14.89	7.76	1.919	370.67

For low quality vectors the results would not be expected to be significantly divergent for the Cross-Correlation spatial domain and Mixed Radix techniques because the respective correlation surfaces would be virtually identical. However, by definition, the Cross-Correlation and Euclidean Distance surfaces are different and, in cases where they are both ill-defined, are likely to produce significantly different maxima/minima locations. Hence, it would be expected that for low quality vectors the results would be significantly divergent, and hence affect the overall statistics.

The results are more convergent for higher quality vectors, but by focusing on a small region, Figure 7 illustrates the discrepancies between the two techniques, even in well defined wind fields. The Euclidean Distance vectors are plotted in red and the Cross-Correlation vectors are overlaid in yellow. Where there is very good correspondence, the Euclidean Distance vectors are obscured by the Cross-Correlation vectors. Figure 7 highlights the small direction and speed differences, where the speed bias is -0.22 and the Normalised RMS Vector Difference is 1.420. (Filtering out vectors below a quality of 0.6 leads to a speed bias of -0.59 and a Normalised RMS Vector Difference of 0.169). Hence, these results illustrate the differences between the two techniques even for well defined wind fields and high quality vectors.

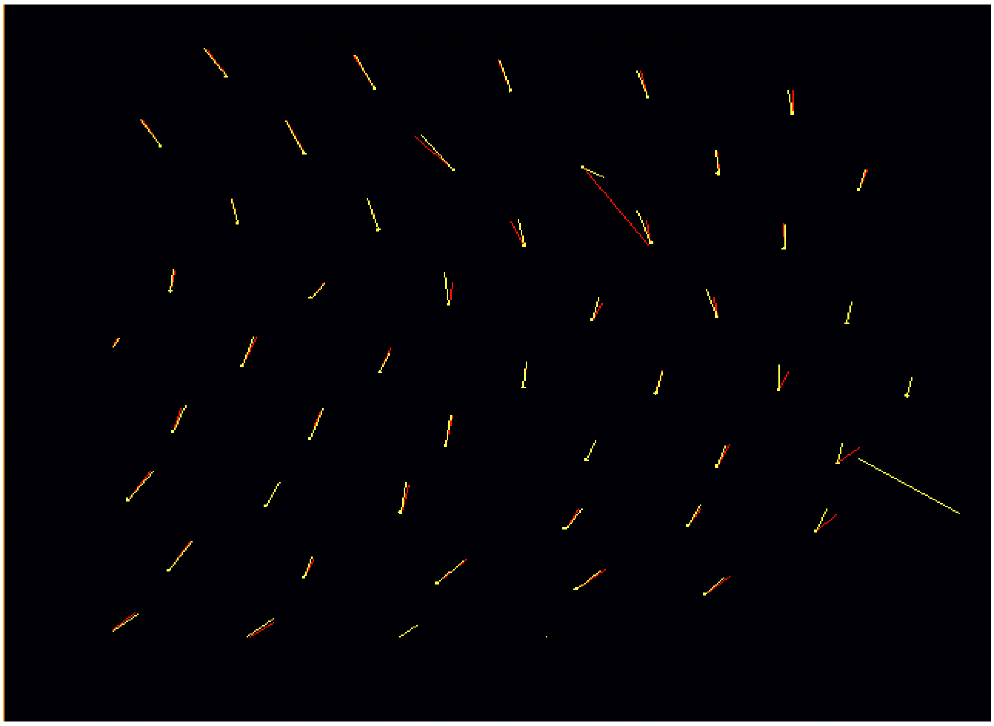

Figure 7. Low Level View of a Wind Field (WV6.2) (Yellow: Cross Correlation Red: Euclidean Distance) (All wind vectors).

4.2.2 Search Area Contrast

Figures 8 and 9 summarise the relative behaviour of the two techniques in different search area contrast regions. The Euclidean Distance technique generally produces more vectors with a quality index above 0.3 and 0.6 than the Cross Correlation technique (as opposed to the Mixed Radix FFT technique in which the numbers are virtually identical). This is illustrated in Figure 8 which shows the percentage difference in number of Euclidean Distance vectors, compared with Cross-Correlation, above the quality index thresholds of 0.3 and 0.6. It should be noted that when the quality index threshold is zero, the vector numbers will be identical. Figure 8 also shows that as the search area contrast decreases, the percentage difference increases, i.e. the relative quality of the Euclidean Distance vectors compared to Cross Correlation is greater for the lower contrast regions. Figure 9 further supports this view by showing that the Normalised RMS Vector Difference increases as the search area contrast decreases. Table 4 shows the vector difference statistics for the highest and lowest contrast regions to illustrate this point.

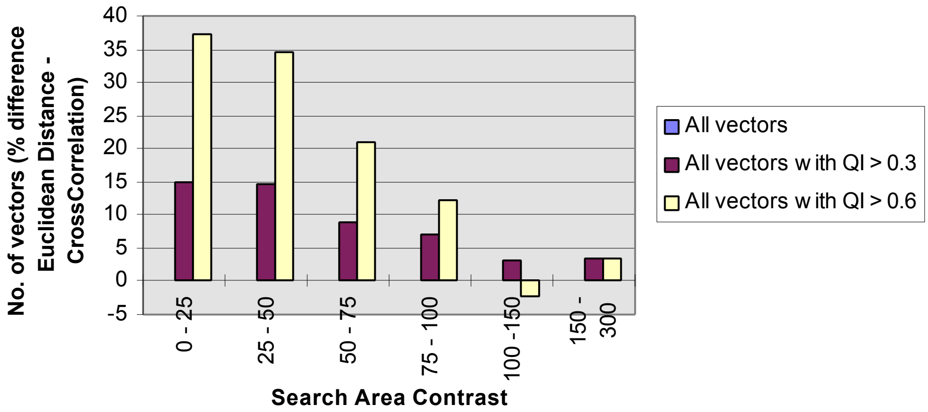

Figure 8. Percentage Difference in No. of Euclidean Distance to Cross Correlation Vectors.

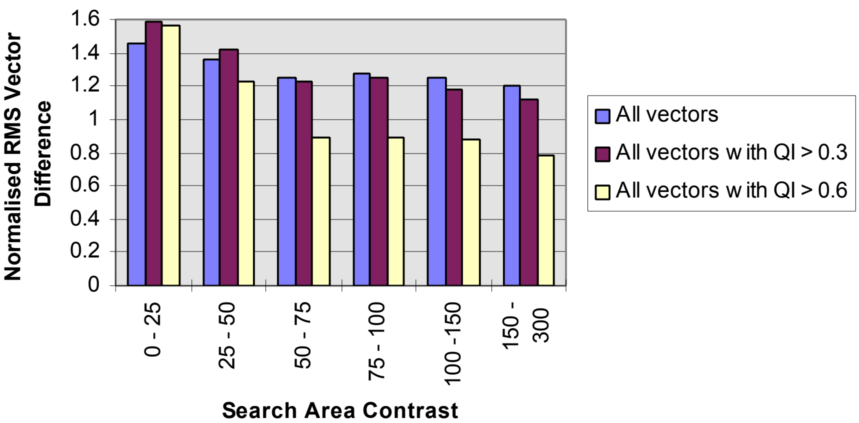

Figure 9. Normalised RMS Vector Difference in Search Area Contrast classes (WV6.2) (Cross-Correlation Spatial Domain vs Euclidean Distance).

Table 4. Search Area Contrast Vector Difference Statistics (Cross-Correlation Spatial Domain vs Euclidean Distance) (WV6.2)

Contrast	Quality	No of vectors	Speed bias	Mean vecdiff	RMS vecdiff	Mean speed	NRMS
0-25	All	1346	-5.60	29.06	39.53	27.15	1.456
	QI > 0.3	865	-0.10	22.39	32.49	20.50	1.585
	QI > 0.6	153	2.62	14.91	25.42	16.22	1.568
150-300	All	1860	-2.16	9.72	21.23	19.90	1.198
	QI > 0.3	1411	-0.57	7.23	16.46	14.68	1.121
	QI > 0.6	664	-0.05	3.95	10.26	13.05	0.787

5. Conclusions and recommendations

This paper has provided a comparison of three template matching techniques which are to be available for operational use in the MSG MPEF environment. The paper is essentially split into two areas. Firstly, validation of the Cross-Correlation Fourier domain Mixed Radix FFT technique has been carried out against the spatial domain method. Secondly, investigations have been undertaken into the performance of the Euclidean Distance technique compared to the Cross- Correlation spatial domain method.

The Mixed Radix FFT technique was introduced and validation commenced by Dew and Holmlund (1998). Further validation has since been undertaken for a large wind vector set using simulated MSG MPEF data, concentrating in particular on the WV6.2 channel. The results confirm a much stronger correlation between the Mixed Radix FFT and spatial domain methods. Preliminary investigations have been carried out into how the relative behaviour of the two techniques varies over different contrast regions. These suggest some small differences between the two techniques in lower contrast regions. However more investigations need to be undertaken before any constructive prognosis can be made.

Comparison of the Euclidean Distance technique to Cross-Correlation has been undertaken using the same simulated MSG MPEF data set, and also concentrating on WV6.2. The results show differences between the two techniques. This is best illustrated when analysing regions which produce good quality wind fields for both techniques, yet show minor discrepancies in wind speed and direction for a significant proportion of vectors. A strong correlation exists between search area contrast and the relative behaviour of the two techniques. As the contrast reduces, the Euclidean Distance technique produces a relatively larger number of high quality wind vectors compared to Cross Correlation. The divergence of wind speed and direction between the two techniques also increases as the contrast reduces.

It is important to emphasise that these investigations need to be taken forward by analysing real imagery data. Discrepancies between the two Cross-Correlation techniques may be exaggerated in the presence of noisy data, and this may provide a more decisive insight into possible variation with contrast. Similarly, in comparing the Euclidean Distance and Cross-Correlation techniques, the use of real imagery data would be a necessary validation procedure. It would also be prudent to investigate methods of statistically analysing future results with the aim of focusing on regions of interest and specific discrepancies in techniques.

This paper has assessed areas of discrepancy between the three matching techniques and the eventual aim is to achieve an understanding of which techniques are more beneficial in certain environments, hence enabling more intelligent selection in operational use.

REFERENCES

Dew, G. and Holmlund K., 1998: Improved Computing Efficiency in the Fourier Domain. Proc. Of the Fourth International Winds Workshop 20 - 23 October 1998, Saanenmoser, Switzerland. EUMETSAT EUM P 24, 289 - 298. [Available from EUMETSAT]