A quality index for radar data

OPERA deliverable OPERA_2010_03

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5th November 2010

Introduction

The compositing of radar data is one of the most important uses for quality indices: the indices can be used to compare the quality of radar data in areas where there is coverage from more than one radar and decide which data to use. However there are many other potential users of an estimate of quality: Radar data is increasingly being assimilated into numerical weather prediction (NWP) models (Gaussiat et al (2009), Macpherson (2001)) and hydrological models (Zappa et al (2007)). The associated quality information is important for the successful and efficient use of radar data in these models. Quality indices can also be used as a visual tool to aid interpretation of the radar data as done in France (Harrison and Boscacci (2007)) and increasingly, quality information is being requested by hydrologists using radar data for water management and flood risk.

Quality indices can also be used to filter weather radar data for different applications (Peura et al (2006)). They can be used to remove or ignore echoes which may not be precipitation, depending on the user's requirements. For example, the assimilation of radar rainfall data into NWP models requires a high probability of detection, but for issuing automated heavy rainfall or flood alerts, a low false alarm rate is a priority.

Quality indices for European radar can either be generated at each national meteorological service (NMS) and exchanged, or the relevant quality information can be exchanged, and the indices generated at the same location as the European composite. The operational data centre (ODC), currently being developed by the Met Office and MeteoFrance, aims to receive volume data from European radars and process the data to produce a European composite. If European radar data are eventually to be processed using common algorithms by the ODC, then it will be most efficient to generate the quality index to accompany this data on the ODC as well. The data processing on the ODC will become more sophisticated as agreement is reached on a set of algorithms to use for filtering and correcting radar data. Hence, it is proposed that the QI could be generated on the ODC, incorporating additional quality information as it becomes available.

The primary philosophy for the quality index proposed in this report is to make use of information already available in the data processing: Quality information such as visibility maps in Switzerland (Harrison and Boscacci (2007)) and monthly rainfall accumulations are used by many NMSs to correct for beam shielding. Both of these are continuous variables and in most cases a threshold is applied to this data to decide where and where not to make a correction. In many cases the quality can be defined as a function of the variables used in the quality control. Examples of similar methods can be found in Szturc et al (2008) and Friedrich et al (2006).

Section 1 outlines the three proposed quality indices and in Section 2, the use of the quality framework to generate the three indices is described. Sections 3 and 4 contain a more detailed description of the indices and suggest how they evolve alongside the algorithms used to process radar data in the ODC. The quality indices were used to generate a composite of UK radar data, the results of one case study are presented in Section 5.

1. Three quality indices

In this report, the quality of radar data has been broken down in to three components, which correspond to the different types of quality information users may wish to receive:

(1) Information related to the likelihood of an echo being from a hydrometeor.

> Although radar data processing removes the majority of non-meteorological echoes, some will always remain in the data. This causes problems for advection-based nowcasting systems which will advect erroneous data as well as precipitation data. A quality index related to the probability of an echo being a particular type of target (Peura et al (2006)), in this case a hydrometeor, will enable further filtering of the data to meet this data quality requirement.

(2) The quality of the radar measurement of reflectivity.

> Errors in radar data can result from the inability to accurately measure reflectivity in certain locations due to beam shielding or attenuation. These errors propagate through to the surface rainfall rate estimate, so this quality index is most useful for deriving the final quality index for compositing. However it may also be useful for the assimilation of radar reflectivity into mesoscale models.

(3) The quality of the conversion of reflectivity at a height above the earth's surface to an estimate of the rainfall rate at the surface.

> This quality index relates to the meteorology and the estimation of precipitation rates at the surface. These can be affected by the vertical profile of reflectivity (VPR), orographic effects, wind drift etc.

(4) Final combined quality index

> It is envisaged that the two volume quality indices ((1) and (2)) and the surface quality index (3) will be combined into a final quality index (4) so that it is only necessary to exchange one quality index field for each radar. The final quality index will represent the overall quality of the radar derived surface precipitation rate estimate, on a two-dimensional Cartesian grid akin to the precipitation rate data.
>
> The surface precipitation rate estimate can either use data from one elevation scan for each bin of data, or a weighted combination of all elevation scans. The two volume quality indices which correspond to the scan elevation used or a weighted combination of the index at all elevations is combined with the surface rainfall estimate quality index to produce the final quality index.

This quality index scheme is a combination of quantitative estimates of individual gross errors in the radar data. It is not a good representation of the error or uncertainty in the estimate, but a complementary measure of the quality of the radar data at any given time. The uncertainty in the final precipitation rate estimate is a separate and complex issue. One method of deriving an estimate of uncertainty in the radar precipitation rate is by generating ensembles of radar data, by building models of radar errors based on ground truth estimates (Germann et al (2009), Llort (2006), Ciach et al (2007)) or modelling individual sources of error (Jordan et al (2003)).

2. Quality Framework

Holleman et al (2006) presented a framework for producing a quality index, which aims to facilitate the exchange of quality information tailored to the end users needs by generating various *quality indices* for different users within the same framework. The framework is shown schematically in
Figure **1**. *Quality indicators* are an intermediate stage, which can be combined in different ways to create the quality indices, tailored to user's requirements.

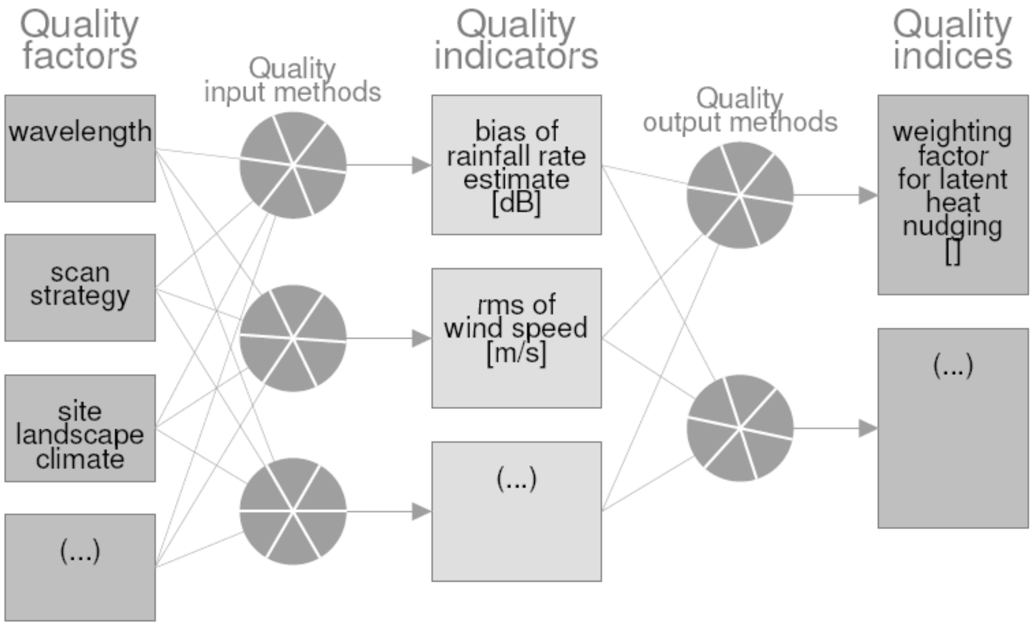

Figure 1: Schematic diagram of quality framework for generating a quality index (taken from Holleman et al (2006)).

2.1. Quality Factors.

Quality factors refer to a wide range of information relating to the estimate of surface precipitation rate. A list of quality factors is given in the previous document by Scovell et al (2009); an updated version of this is given in Table 1, which details the availability of each quality factor on the ODC. There are other quality factors that can be derived from those in the list in Table 1, such as frequency of detection and attenuation (derived from reflectivity data).

2.2. Quality indicators.

Quality input methods translate the quality factors into quality indicators. As suggested by Holleman et al (2006), the quality indicators could be harmonised by scaling the values linearly (or logarithmically as appropriate) between 0 and 1. For each quality factor, h, values of minimum and maximum quality, h_{min} and h_{max}, must be defined. Values in between can be assigned values of quality indicator (Q) between 0 and 1 as in Equation 1. In this report, a quality indicator is generated for each variable associated with a radar error. For example a quality indicator derived from the height of the radar beam could be used to show the quality of the surface precipitation rate estimate.

$$Q_h = \frac{h - h_{\min}}{h_{\max} - h_{\min}}$$

Equation 1

Many NMSs use quality information to generate data flags, to indicate where and what data quality issues are manifest in the radar data. Here h_{min} is set to the same value as the threshold used in the processing of radar data at the Met Office to generate these data flags. For example, where an attenuation correction is capped (because the correction factor is unacceptably large) data are given a quality indicator value of 0. 0 is reserved for errors in radar data where the data cannot be used, which must be reflected in the choice of value for h_{min}. h_{max} is chosen to represent no error in the data, or the maximum quality. For example, an attenuation correction factor of 1 (no correction) shows the data is very unlikely to be suffering from attenuation, and therefore is an obvious choice for h_{max}. The choice may not be so simple for other quality indicators.

Quality Factor	Availability on ODC	Source
Azimuth Angle Step	All sites	File descriptors
Range gate length	All sites	File descriptors
Vertical 3dB beam width	Some sites	OPERA radar database
Horizontal 3dB beam width	Some sites	OPERA radar database
Height of radar antenna	All sites	File descriptors
Wavelength of transmitted signal	Some sites	OPERA radar database
Z-R relation ‘a’ coefficient	All sites	ODC algorithm
Z-R relation ‘b’ coefficient	All sites	ODC algorithm
Receiver calibration factor	None	
Noise	None	
Pulse-to-pulse signal variability	UK and France	Additional exchange
Gauge adjustment factor	Some sites	Additional exchange
Height of the radar beam	All sites	Inferred from Antenna height and elevation angle and range
Height of the freezing level	All sites	NWP
Height of the cloud top	All sites	NWP / Satellite
Ground height (topography)	All sites	Topography map
Complex refractive index of the atmosphere	None	
Temperature	All sites	NWP / Observations
VPR correction factor	All sites	ODC algorithm
Antenna elevation angle	All sites	File descriptors
Radar reflectivity factor	All sites	Exchanged

Table 1: List of relevant quality factors, their availability and source on the ODC

2.3. Quality indices.

The final quality indices can be a multiplicative or additive combination of the relevant quality indicators. Additive combination may result in the misrepresentation of very bad quality data. Unusable radar data are represented by zeros in the quality indicators and these should propagate through to the final quality indices. Therefore, multiplicative combination via the geometric mean seems more appropriate.

In this proposal we have split the quality information into 3 different indices (quality of reflectivity measurement, likelihood of an echo from a hydrometeor and quality of surface rainfall rate estimate) and we have combined these multiplicatively into a final quality index which can be used for compositing. In the future, specific users of data could receive weighted combinations of specific quality indicators, suited to their specific requirements.

3. Volume quality indices

In this section, the quality indices associated with volume reflectivity measurements will be presented. (The index associated with Surface precipitation rate estimates is given in the next section). There are two quality indices proposed to accompany volume data: The quality of the reflectivity measurement and the likelihood of an echo being from a hydrometeor. These will be split into three levels of complexity: the first (level 1) being the simplest, relies only on reflectivity data and some global quality factors. The second (level 2) incorporates "climatological" data such as frequency of detection maps or topography and the third (level 3), most complex level, uses additional dynamic information such as the height of the freezing level.

3.1. Quality of reflectivity measurement.

The quality of the reflectivity measurement is dependent on several factors including how attenuated the signal is, whether the beam has been shielded and whether the signal can be measured above the noise level. Firstly, the reflectivity can be used to estimate how attenuated the signal is, and therefore the quality of the radar measurement at long range or beyond heavy precipitation. Measurements at long ranges from the radar are also of poorer quality, because the minimum detectable reflectivity increases as a function of range. Areas close to the radar are able to detect lower reflectivities than areas at long range. However this is dependent on the algorithm used to flag the noise in the volume data as noted in the discussion at the end of this report.

Beam shielding occurs where the beam interacts with the ground or buildings, causing only a fraction of the transmitted power to interact with the atmosphere further along the ray. This causes a reduction in the power returned from hydrometeors or other targets further along the ray, compared to the power that would be received if there was no shielding.

Attenuation quality indicator

An attenuation factor can be derived from reflectivity data using the relationship given by Gunn and East (1954) in Equation 2. This equation applies for C-band in rain, though other wavelengths and precipitation types are also given in the paper. *A* is an estimate of the two way attenuation of the signal in dB/km. F_n can be used to correct radar reflectivity data (in Z units) as in Equation 3. In order to create a quality indicator from this factor, we propose, that F_{max}=1 (no attenuation, maximum quality) and F_{min}=2 (100% estimated error in Z due to attenuation)

$$A_i = 0.0044 R_i^{1.17} dB/km$$

Equation 2

$$F_n = \prod_{i=0}^{n} 10^{\left(\frac{A_i r_b}{10}\right)}$$

Equation 3

Radar sensitivity quality indicator

In bins where the signal is above the noise, Q is set to 1, but in areas where the signal is below the noise, the sensitivity quality indicator is calculated. The minimum detectable reflectivity (MDZ) increases with range. At close range the MDZ will be lower and correspond to a high quality ($MDZ_{max.}$) This has been chosen to be -50 dBZ, corresponding to the MDZ of the most sensitive meteorological radars. The minimum quality ($MDZ_{min.}$) was chosen to be MDZ = 20 dBZ. 20 dBZ was chosen arbitrarily as a figure which caused decay in quality to about 0.6 at maximum range. This value may need tuning in the future.

Beam shielding quality indicator

A simple quality indicator can be derived using the percentage of the beam that is shielded (S), where S_{min}= 100 % and S_{max}= 0 %. Here, the calculation is done simply in terms of the illuminated area, though ideally this should be calculated in terms of Power assuming a Gaussian distribution (Friedrich et al (2006). A field of radar horizon values for each azimuth which contain the angle of the horizon from the radar site have been used in this calculation. More complex methods for calculating beam shielding use a digital terrain model (Delrieu et al (1995)).

Examples of the quality indicators outlined above, corresponding to the reflectivity field in Figure 2 are given in Figure 3 (attenuation) and Figure 4 (sensitivity). Figure 5 shows the beam shielding quality indicator combined multiplicatively with the sensitivity and attenuation quality indicators to create a quality index representing the quality of the reflectivity measurement.

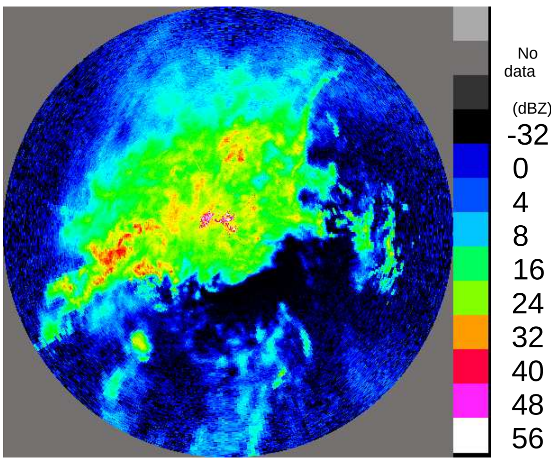

Figure 2: Un-corrected lowest elevation reflectivity data from Preddanack radar (South West England).

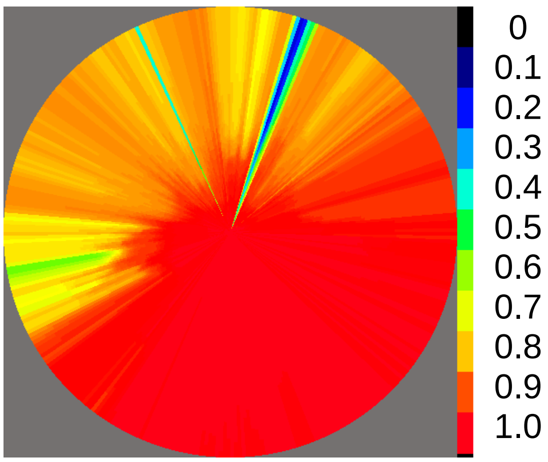

Figure 3: Quality indicator relating to the estimated attenuation along each ray.

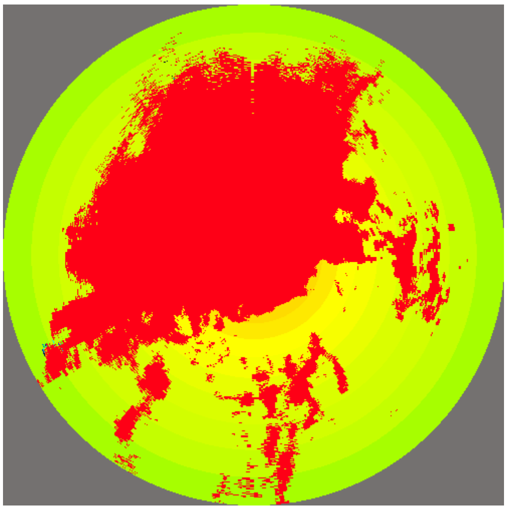

Figure 4: Quality indicator relating to radar sensitivity.

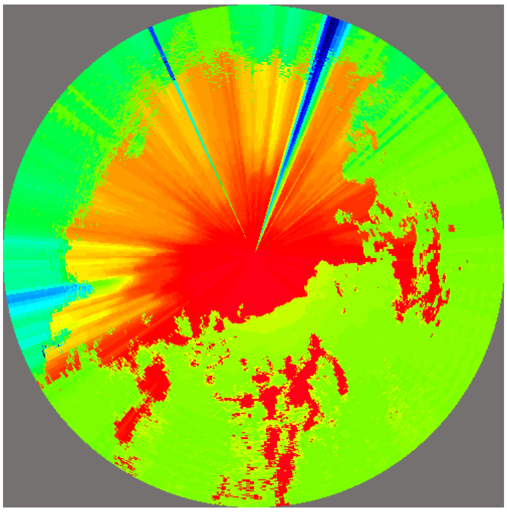

Figure 5: Quality index representing the quality of the reflectivity measurement.

Initially, for the level 1 quality index, the attenuation and sensitivity indicators could be combined to generate the index representing the quality of the reflectivity measurement. The beam shielding quality indicator could be included when topographical data sets / radar horizon / radar visibility data are available on the ODC. (level 2)

3.2. Likelihood of measuring a hydrometeor

The second aspect of the quality of volume data for precipitation rate estimation is whether or not the right type of target is being measured. This can vary between scan elevations and neighbouring bins. Echo identification is a relatively complex problem and solutions vary greatly from one NMS to another. Some of the quality factors used by the Met Office to identify non-hydrometeors are detailed below with corresponding quality indicators. This quality index only applies where the signal is greater than the noise, so the remainder of the data has a quality of one.

Frequency of detection quality indicator

Many algorithms for echo identification make use of relatively static or climatological data, such as frequency of detection maps. An example of a quality indicator based on the frequency of detection generated for Predannack radar in the UK is given in Figure 6. This type of quality information could eventually be generated on the ODC; therefore no additional data exchange would be required.

Satellite probability of precipitation quality indicator

Satellite data can be used for identifying areas likely to have no precipitation, where any echoes are likely to be a result of anomalous propagation. Figure 7 shows a quality indicator derived from satellite data alpha values (See Pamment and Conway (1998) for details) which are used to remove anaprop from UK radar data. Alpha values are the satellite-derived probability of

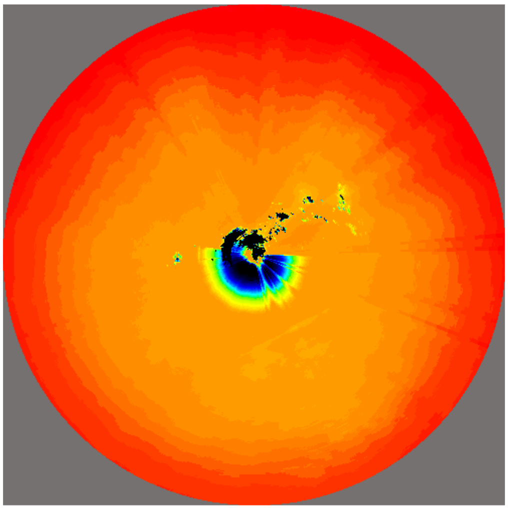

Figure 6: Quality indicator derived from frequency of detection data (F) over 3 months (F_{min}= 20% F_{max}= 0 %).

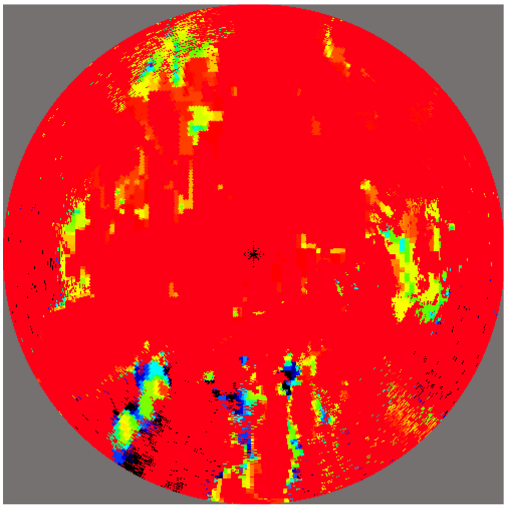

Figure 7: Quality indicator derived from satellite data **α**. (**α** $_{min}$= 1 **α** $_{max}$= 100)

precipitation divided by the probability of no precipitation. A logarithmic scale was found to be most suitable for the scaling of alpha values to a quality indicator because alpha values are ratios.

Clutter indicator quality indicator

Other variables from radar sites such as Clutter Indicator (CI) (Sugier et al (2002), as used by UK and France, may be used to generate quality indicators, an example of which is given in Figure 8. CI is used to remove ground clutter from weather radar data in the UK.

Figure 9 shows the quality index relating to the likelihood of an echo being from a hydrometeor, it uses quality indicators derived from frequency of detection, satellite data and CI (Figure 6, Figure 7 and Figure 8).

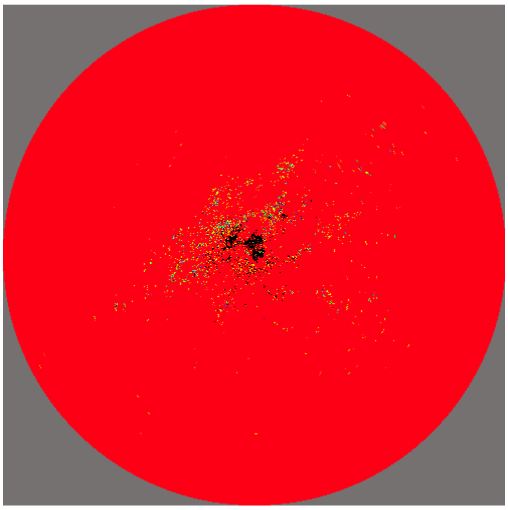

Figure 8: Quality indicator derived from CI data. (CI_{min}=2.0, CI_{max}= 4.5)

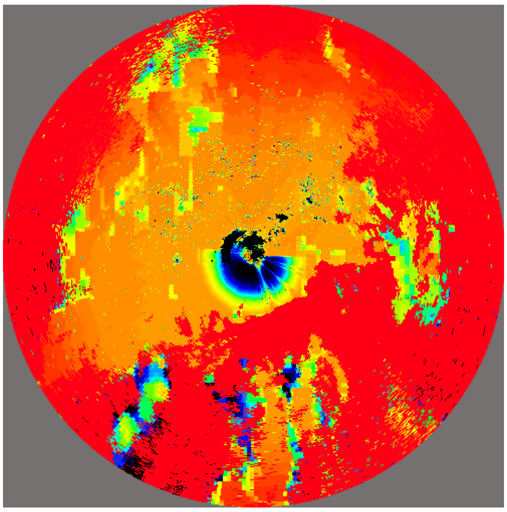

Figure 9: Quality index (probability of target being a hydrometeor).

As no arrangement to remove non-meteorological echoes in volume data received by the ODC yet, no specific algorithm can be described. However, there are ways of producing a quality indicator for the likelihood of measuring a hydrometeor using reflectivity data only. For example, using diagnostics from algorithms that use image processing techniques (Peura (2002)); however these are relatively complex and therefore inappropriate as an initial indicator. Initially there will be no quality index relating to the likelihood of a target being a hydrometeor, as this aspect of quality is particularly difficult to harmonise if it were to be generated at each NMS. Or, if it were generated by the ODC, relevant information and algorithms would need to be available.

4. Surface quality indices.

The conversion of a reflectivity measurement to a precipitation rate estimate at the surface is prone to many errors, such as an incorrect VPR, orographic enhancement or wind drift. The quality of the final precipitation rate estimate depends on the correction you make to the data. The types of VPR corrections made to radar data vary widely throughout Europe, so harmonising a quality index at each NMS and exchanging it, would be very difficult. When a correction algorithm is chosen for the ODC, all European data will be processed using the same algorithm, so a quality index relevant to the correction algorithm can be derived.

In the meantime, a simple quality indicator based on the height of the beam could be used. Such a quality indicator will capture the quality of data that is not corrected for VPR. Deriving a quality indicator for the height of the radar beam, H, will require no extra exchange of data to take place. Figure 10 gives an example of the quality indicator where the heights of the highest and lowest quality are 0 and 10000 m above sea level respectively. An example of the final quality index when combined with the lowest elevation volume scan quality indices is shown in Figure 11. This quality indicator could be improved fairly easily by using the height relative to the height of the ground instead of 0 m.

Information from NWP models and satellite data can also be used to improve the quality indicators shown previously: for example the quality associated with the height of the radar beam should be set to zero at the cloud top instead of 10 km as used previously. Diagnostics from processing algorithms could also be used as quality information; for example the size of the correction made for VPR could be used as a quality factor. The measured VPR, or a profile used for the purposes of correction could also be used as quality factors.

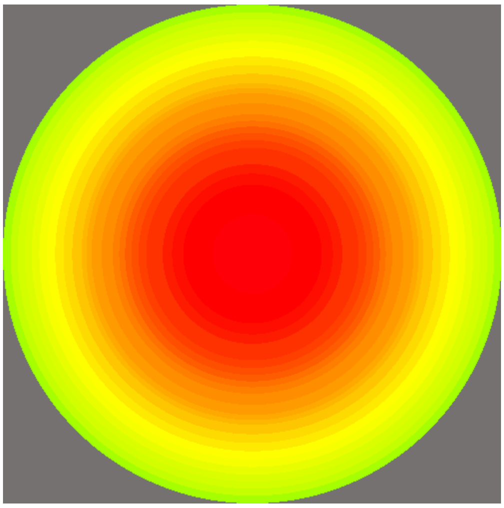

Figure 10: Quality indicator related to the height of the beam used to derive surface precipitation estimates and the sample volume.

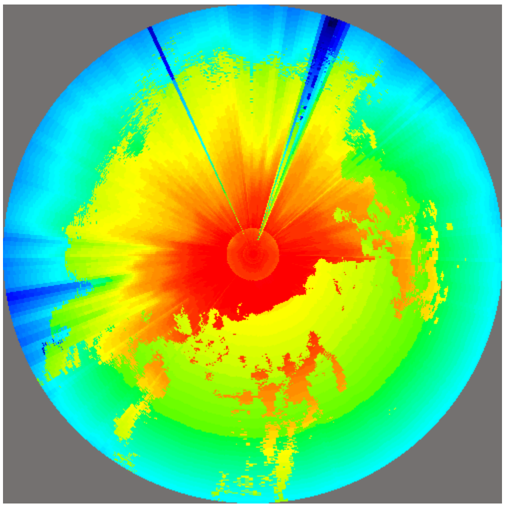

Figure 11: Final quality index.

For the initial level 1 surface rainfall rate quality index, H_{min} and H_{max} could be set to 10000 m and 0 m respectively. As more data is available to the ODC, such as topography, satellite or NWP model data, H_{min} and H_{max} can vary both spatially and temporally as described above. One deviation from the framework here, for uniformity, is the use of h_{fl} when there is freezing level information. h_{fl} is used so samples at the height of the freezing level consistently have the same quality, the quality indicators are then scaled between 1.0 and h_{fl} between the surface and the freezing level, and h_{fl} and 0.0 between the freezing level and the cloud top. In these examples, h_{fl} is set to 0.5. Unfortunately, in precipitation where there is strong convection, this quality index may be unrepresentative.

5. Compositing using the quality indices.

The quality indices described in the previous sections were used to composite UK radar data both vertically and horizontally. The scan elevation used to produce the surface precipitation rate was chosen based on a weighted comparison of the combined volume quality indices at each scan elevation. The weights used are shown in Figure 12. The surface rainfall quality index was then generated using the reflectivity data in the bins chosen previously. Four composites were produced, one using the quality index from each level of complexity, and another using the algorithm for producing the UK composite. Each was based on the highest final quality index. The current UK composite is generated using data from the sample volume closest to the surface, the scan elevation used in each bin is chosen based on flags for clutter, anaprop, speckle, noise etc. The level 1 final quality index used the attenuation, sensitivity and beam height quality indicators. The level 2 composite used the frequency of detection and beam shielding indicators in addition to those in level 1. The level 3 index used the indicators used by levels 1 and 2, as well as satellite cloud top heights, NWP freezing level heights and CI indicators.

Precipitation rate, radar site usage and composite quality index for each of the schemes can be found in the Appendix.

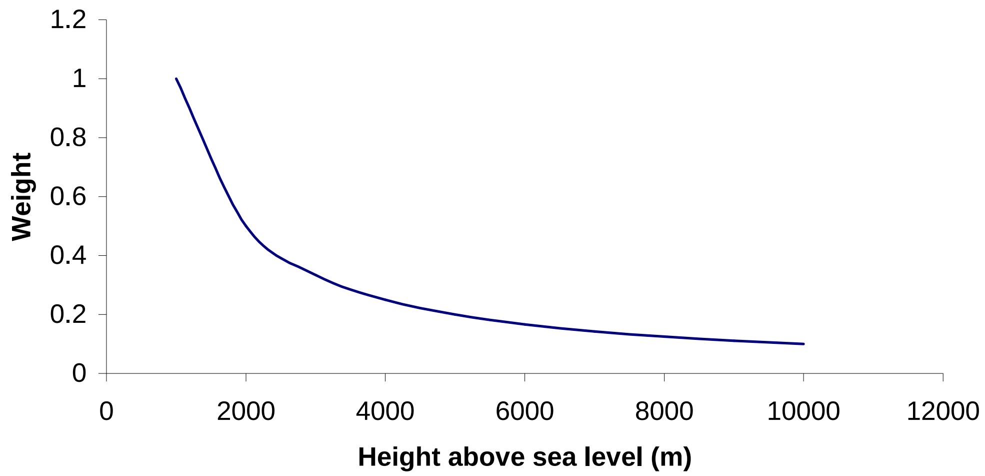

Figure 12: Weights used for choosing scan elevation to use in each pixel (reciprocal of the beam height in kilometres).

5.1. Level 1

The principal improvement seen by using the level 1 quality index compared to the one used by Met Office currently, is the elimination of the discontinuities associated with the lines of equal beam height between radars. This is shown in Figure 13. However, the obvious difference is the presence of clutter, as the level 1 quality index does not use the likelihood of an echo from a hydrometeor quality index.

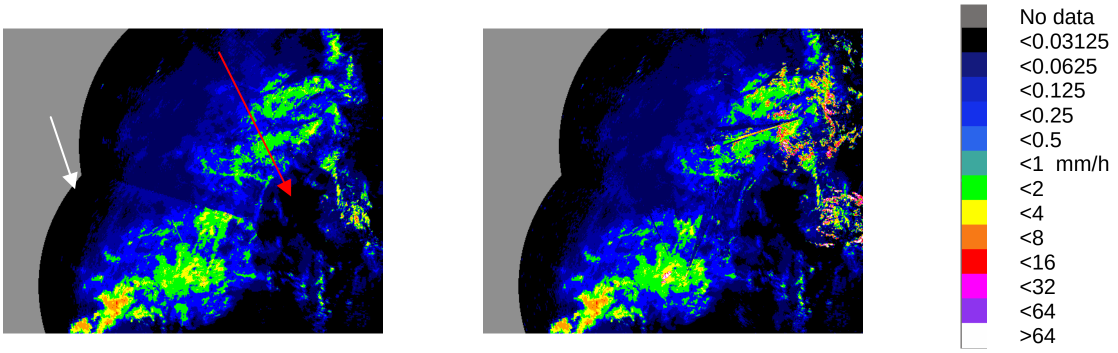

Figure 13: (Left) UK composite. (Right) Level 1 composite.

5.2. Levels 2 and 3

These composites use some information on target identification. Unfortunately, this manifests itself in large areas around the radar site being of very low quality, resulting in other radars (sometimes at far range) being used instead in these areas. This is the case in Figure 14, where other radars detect no rain at long range, which leads to gaps in the composite in areas where there is a low density of radar coverage. This may be a problem that can be solved by tuning the weights or h_{min} or h_{max},

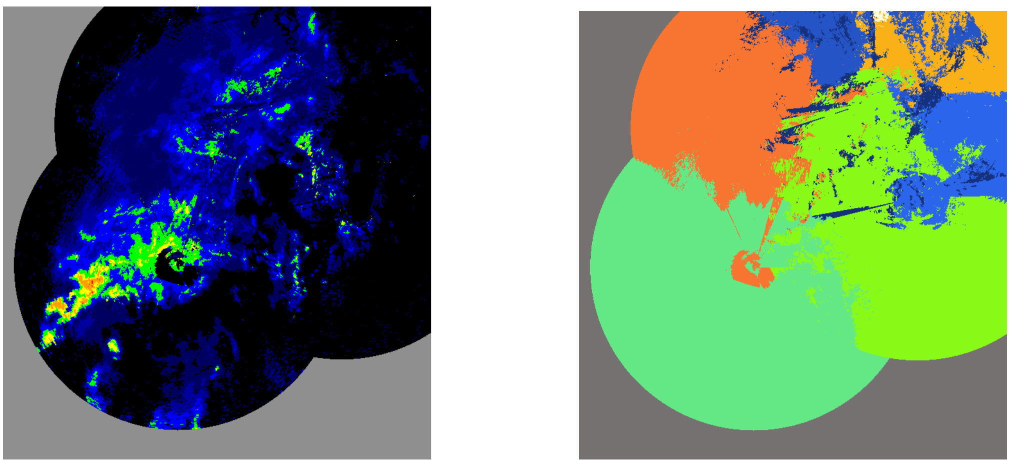

Figure 14: Level 2 composites for South-West UK (Left: precipitation rate, Right: Radar site used at each pixel)

6. Discussion

Qualitatively, the example of the level 1 quality indicator (which excludes any target identification information) given in Figure 11 looks to be a good representation of radar data quality. However, due to the sensitivity quality indicator, data containing a signal above the noise is given a greater quality than data with no signal above the noise, which means that all echoes will appear in the composite. This could have a negative impact if spurious echoes or evaporating precipitation are present. Other quality indices or flags will have to be relied upon to remove these echoes.

The example composites generated showed that the attenuation quality indicator made the most improvement to the composite, due to the elimination of the discontinuities where data from two different radars meet. However, the target identification quality indicators were detrimental to the composite, causing large areas close to the radar to be in-filled with data from another radar instead of higher elevation scans. This is mainly due to the values of h_{min}, h_{max} and the weights used for choosing the scan elevation, which need better tuning.

As the quality index is developed and new quality indicators are added, testing of the individual quality indicators will be needed to decide whether h_{min} and h_{max} are defined correctly and whether they show overall skill. Different scores could be used for the 3 quality indices: The quality of the reflectivity measurement and quality of the surface rainfall rate estimates could be tested by calculating the RMSF and bias compared to rain gauge accumulations or disdrometer data. Whereas the likelihood of measuring a hydrometeor quality index could be tested using the false alarm rate.

One difficulty associated with the sensitivity quality indicator arises from the methods of flagging noise at different NMSs: Some NMSs flag all reflectivity data that is below a given threshold, in dBZ. This does not account for the increasing reflectivity of the noise with range, and does not exploit the higher sensitivity of the radar at short range. Hence the MDZ remains constant with range, whereas other methods set this threshold at a constant power. Due to the range correction, the threshold in dBZ then varies with range. This allows lower reflectivities to be flagged as valid data close to the radar.

In order for the sensitivity quality indicator to be effective we need to know which method (if any) has been applied to the data used by the ODC as well as an estimate of the minimum detectable reflectivity at 1km.

7. Recommendation

It is recommended that at first, only an estimate of the minimum detectable reflectivity at 1km is exchanged. This will allow a quality index containing information on the sensitivity of the radar to be generated. The exchange could take place on a volume, scan or ray basis. A summary of the data to be exchanged and quality indicators to be generated for the level 1 index is given in Table 2.

Quality Indicator	Quality Factors required	Proposed additional exchange?
Attenuation	Reflectivity	No
	Wavelength	No
Sensitivity	MDZ at 1km	Yes
Height of beam	Elevation angle	No
	Height of sensor	No

Table 2: Quality factors to be exchanged for initial (level 1) quality index.

The attenuation and height of the beam quality indicators can be generated without any additional exchange on the ODC, or at individual NMSs.

8. Conclusions

Three quality indices have been proposed that represent three aspects of radar data quality: the quality of the reflectivity measurement, the likelihood that an echo is from a hydrometeor and the quality of the surface precipitation rate estimate. These three indices allow quality information to be used in different ways, by different users.

Information on how attenuated the radar signal is has improved the quality of the composite more than other quality indicators. Other quality indicators could be improved by tuning.

Three levels of complexity were suggested to give an indication of how the quality index product could evolve within this framework. The first level uses reflectivity data, the wavelength of the radar and the minimum detectable reflectivity. Level 2 uses relatively static information such as topography and frequency of detection maps. Level 3 indices make use of dynamic information, such as clutter indicator, NWP freezing level heights or satellite data. As the ODC processing becomes more sophisticated, the additional dynamic, local quality information in levels 2 and 3 may become available and can be included in the generation of the appropriate quality index

Initially, only two indices will the generated, due to the data requirements of the probability of hydrometeor quailty index. Only a measurement or estimate of minimum detectable reflectivity at 1 km is required (in addition to information already available and reflectivity) to generate the two indices, which incorporate the height of the radar beam, attenuation and the sensitivity of the radar.

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Appendix

Here, the composites generated by the four different algorithms are presented. Composites generated using the Met Office algorithm are on this page and levels 1, 2 and 3 are on the following pages in that order. The image on the upper left shows which radar is being used in which pixel. Each radar is represented by a different colour. The upper-right image is the composited final quality index. The image underneath shows the precipitation rate.

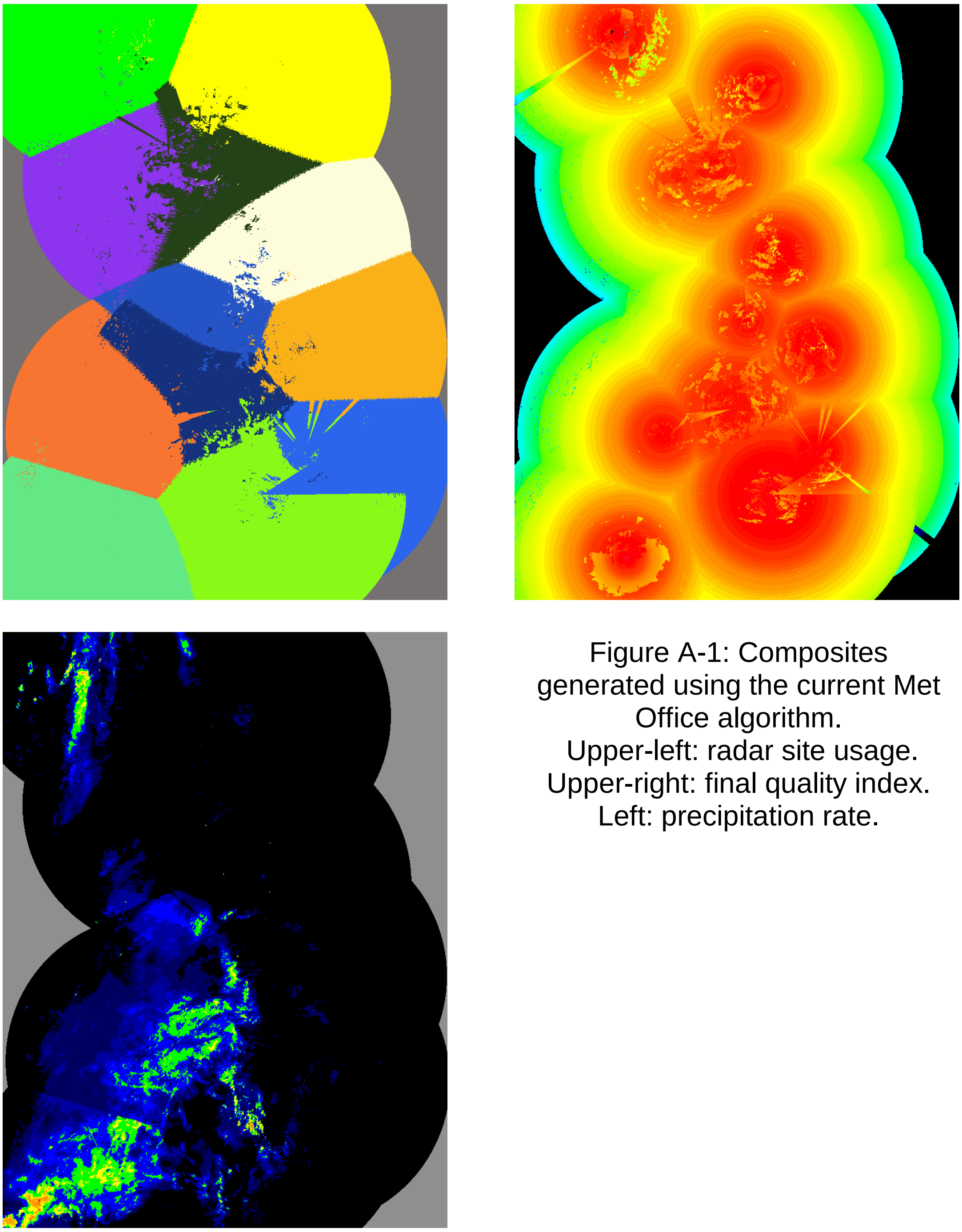
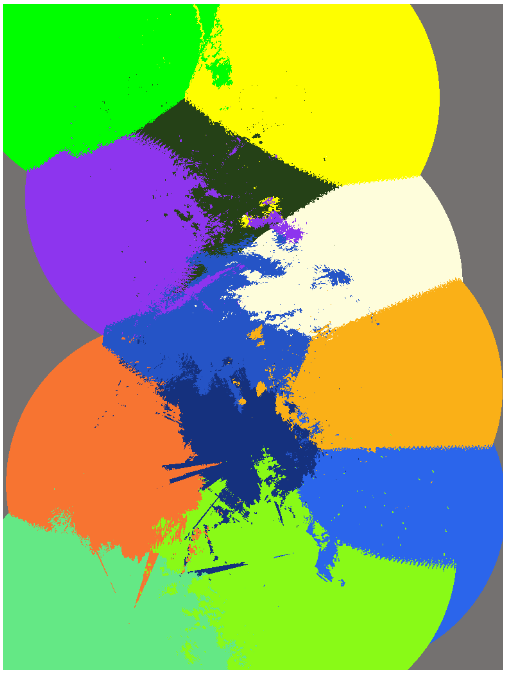
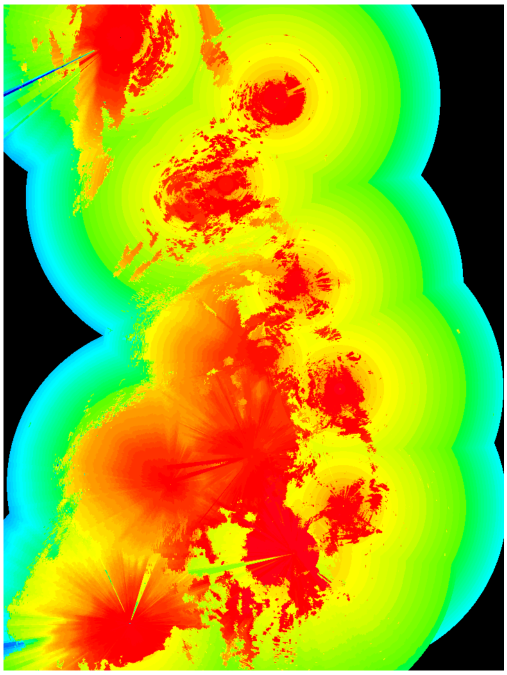


Figure A-1: Composites generated using the current Met Office algorithm.
Upper-left: radar site usage.
Upper-right: final quality index.
Left: precipitation rate.





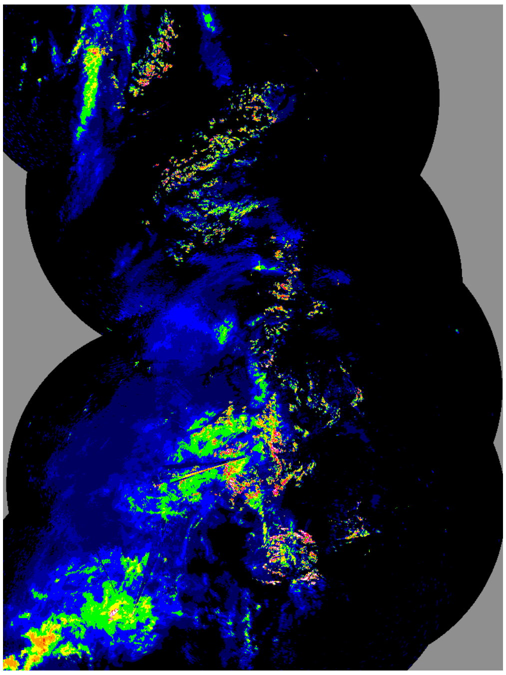


Figure A-2: Composites generated using the level 1 algorithm.
Upper-left: radar site usage.
Upper-right: final quality index.
Left: precipitation rate.

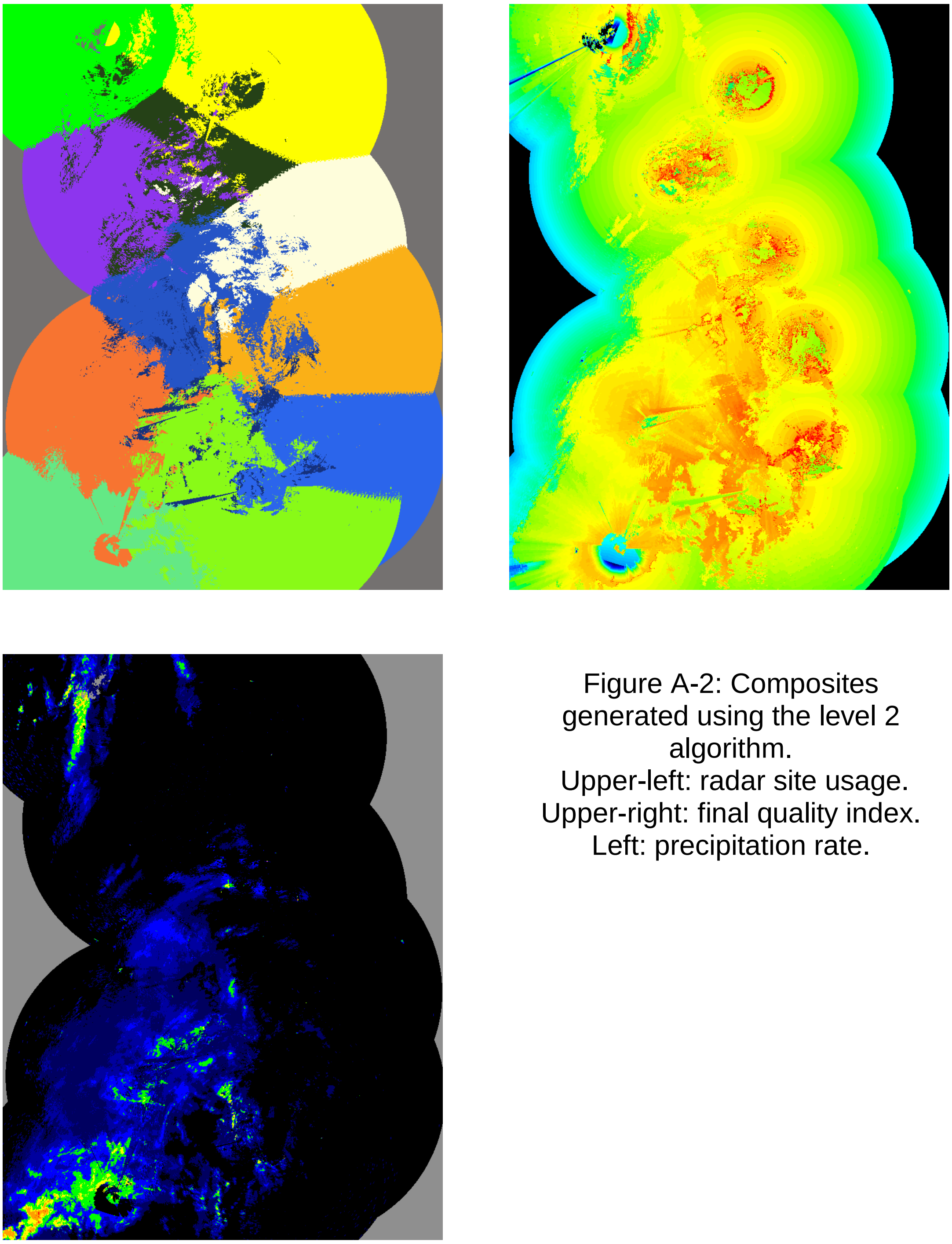


Figure A-2: Composites generated using the level 2 algorithm.
Upper-left: radar site usage.
Upper-right: final quality index.
Left: precipitation rate.

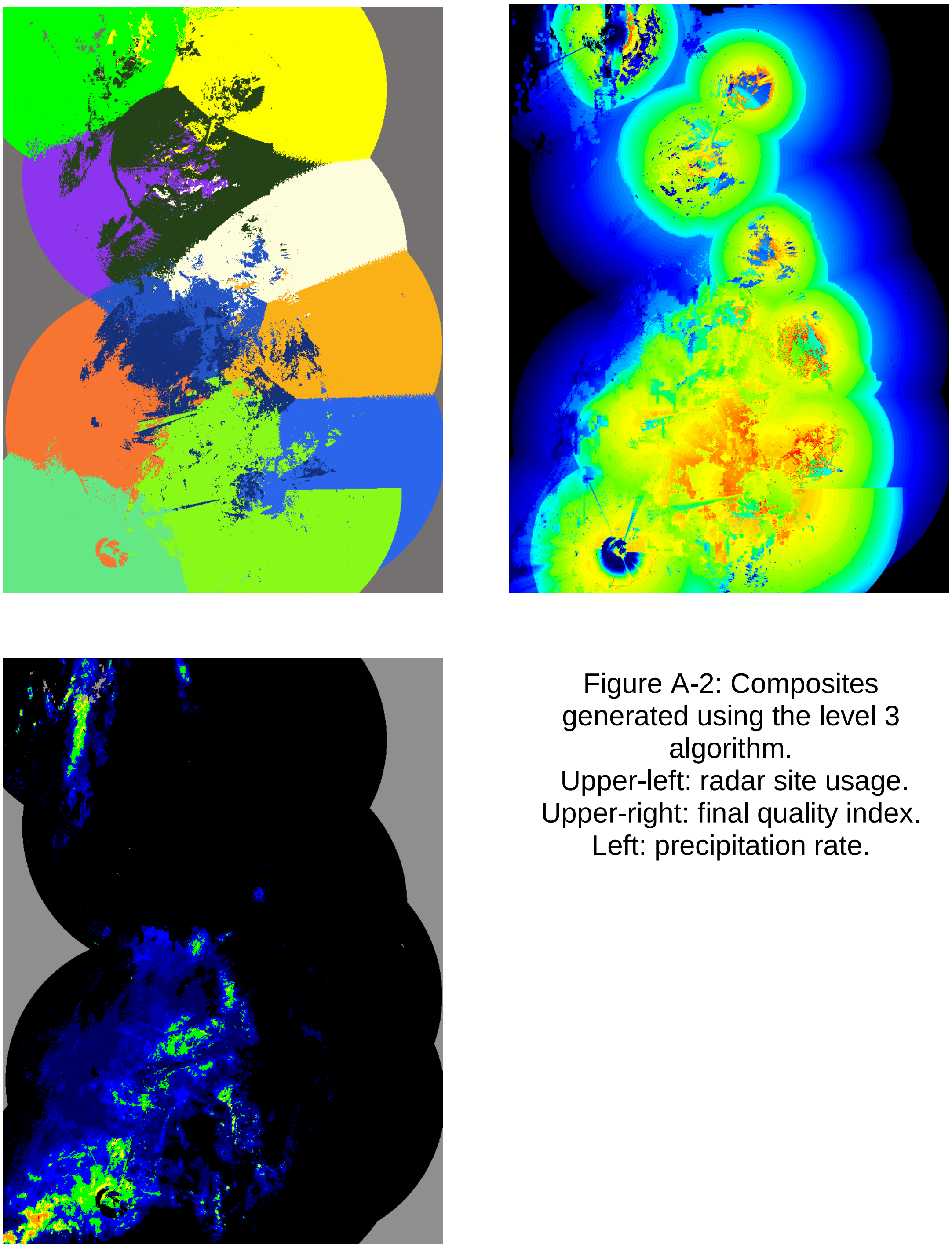


Figure A-2: Composites generated using the level 3 algorithm.
Upper-left: radar site usage.
Upper-right: final quality index.
Left: precipitation rate.