Objective Analysis

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This technical paper is designed to document the numerical analysis methods used by the Weather Graphics Technologies software product Digital Atmosphere. It is intended to provide a basis for academic and operational understanding of the algorithms used for Digital Atmosphere contouring and objective analysis.

**Feedback.** Weather Graphics Technologies is committed to quality and improvement in all its products, and will gladly accept feedback and suggestions on these algorithms. This should be sent in writing, either to E-mail to support@weathergraphics.com or by fax to (405) 329-5275.

**Source Code.** For those users who want to examine specific parts of the objective analysis algorithms for academic or quality improvement purposes, some source code may be shared with end-users in special circumstances. We must have a nondisclosure agreement on file (see the end of this document) faxed to (405) 329-5275. For legal reasons, source code is not releasable outside the United States except to certain European countries, including Great Britain and Germany. The source code is written in Object Pascal V100.

**Expressions.** In this paper, \( f \) is used to represent the value of an observation. This observation may be located at grid coordinates \((x,y)\), which yield the expression \( f_{x,y} \). In other cases, \( f \) may represent an observation in a random list of reports at arbitrary position \( k \), which yields the value \( f_k \). Various coordinate transformation functions in Digital Atmosphere are responsible for assigning position \( k \) to an appropriate \((x,y)\) coordinate and will not be discussed here.

**Errors.** If you spot an error in this documentation or in these algorithms, be sure that you have the latest version of this technical document (see http://www.weathergraphics.com/da ). If the error exists in the latest technical document, this may be an issue that needs to be fixed in Digital Atmosphere. Help us improve the product! Details should be sent in writing, either to E-mail to support@weathergraphics.com or by fax to (405) 329-5275.

**GENERAL DESCRIPTION**

**Domain.** Currently, the analysis domain is a floating (fixed to the screen window) gridpoint model fixed at a size of 30 x 30 in the x and y direction (900 points). This scheme was chosen because the vast majority of objective analysis operations are performed with on-screen results in mind. Since the pixel size of a window rarely exceeds 1200 x 1200 pixels, this allows for 40 x 40 pixels within each grid box. This is close to the minimum level of meaningful on-screen data for most users. Therefore it has not been anticipated that it is necessary to boost the analysis domain beyond 30 x 30 gridpoints, and we have received few such requests. Each objective analysis is an operation that starts completely from scratch each time, therefore there are no complicating factors involved in moving the screen window to a different part of the world. The floating domain simply moves to whatever geographic area is displayed and is not used until an analysis is requested.

**Entry.** When a field is chosen for analysis or contouring, Digital Atmosphere enters the contouring module through the `GenerateContour` function. Here it is first determined whether a scalar or vector field must be calculated.

— If it is a scalar field, program flow goes directly to `ObjectiveAnalysis`.
— If it is a vector field, `ObjectiveAnalysis` is called for each component of the analysis (i.e. for wind calculations, a calculation is done on the U and then the V wind component).
Following this objective analysis, a contouring or grid plotting routine is called to display the data. The workings of this routine will not be discussed in this paper.

**PROCESSING FUNCTIONS**

- **ObjectiveAnalysis.** Upon entry of this function, BuildWeatherDataFile and Build2DGrid are called in succession (and if height calculations are involved and the user prefers Geostrophic Heights in Preferences > Analysis, the CalculateHeights function is called). The module aborts if there are 5 or less observations in the domain (i.e. not enough data).

Otherwise, the Preferences > Analysis panel is checked to see which objective analysis scheme is desired:
- For Nearest Neighbor method: Expand is called, followed by one HaltinerSmooth iteration, resulting in a crude but efficient objective analysis.
- For Weighted method: Weighted is called.
- For Barnes method: Barnes is called.
- For Cressman method: Cressman is called.

Following the objective analysis, regardless of type, Expand is called to make sure there are no null gridpoints. This is necessary because some gridpoint locations may reside at a distance from the nearest observation that far exceeds the maximum radius of weighting.

At this point, regardless of the analysis scheme, the Smoothing Passes value is obtained from the Preferences > Analysis panel, and the corresponding number of HaltinerSmooth iterations are performed. The primary purposes this serves is to smooth out remote gridpoints filled by the final Expand function pass.

- **BuildWeatherDataFile.** This function constructs a Domain Data File (filename OUTPUT.UX0). This is different from the Processed Data File (OUTPUT.*) in that every observation is applicable to the on-screen analysis window, matching the domain and the chosen date/time. Data outside the on-screen analysis window is discarded.

- **Build2DGrid.** This function uses the Domain Data File constructed in BuildWeatherDataFile to map the data to a two-dimensional grid. For each observation point, the latitude and longitude is evaluated in respect to the screen window (the domain available to the user in a screen window). The observation is assigned a real-number x coordinate \( (x=0..30) \) and y coordinate \( (y=0..30) \) as follows:

\[
\begin{align*}
  x_k &= x / x_m \times 30 \\
  y_k &= y / y_m \times 30
\end{align*}
\]

where
\[
  \begin{align*}
    x,y & \text{ is the coordinate of the observation on the screen map in pixels} \\
    x_m,y_m & \text{ is the size of the map in pixels} \\
    x_k,y_k & \text{ is the coordinate of the observation in grid units (0..30)}
  \end{align*}
\]

Then, the appropriate observation parameter is determined, using the value only if valid data for the parameter is present in the observation. The station pressure \( p \) was determined in the BuildWeatherDataFile unit.
- Temperature, dewpoint, sea-level pressure, altimeter setting, wind speed, height. The value
is used verbatim. A conversion to metric units may be accomplished.

— Wind components. Background maps are never displayed in Cartesian coordinates, therefore it is necessary that the declination for a given station be obtained. If a wind component is to be calculated (for any wind operation), the wind declination relative to the map is rectified through the \texttt{WindDeclinationCorrect} function. This angle, $\theta$, is the declination produced by plotting a point 300 miles north of the station through a forward coordinate transformation (allowing flexibility if another coordinate transformation is in use, and preventing the need to devise reverse coordinate transformations). From there, it is a simple matter to calculate wind component $(u,v)$, as follows:

$$
\begin{align*}
  u &= -1 \cdot \sin(\theta) \cdot V \\
  v &= -1 \cdot \cos(\theta) \cdot V
\end{align*}
$$

where $V$ is the wind velocity.

— Relative humidity. Calculated according to $f_k = \text{MixingRatio}(T_{v,p}) / \text{MixingRatio}(T,p)$.

— Wet bulb temperature. Calculated according to $\text{WetBulb}(T,T_{v,p})$.

— Heat index. Calculated according to $\text{HeatIndex}(T,T_{v,p})$.

— Humidex. Calculated according to $\text{Humidex}(T,T_{v})$.

— Equivalent potential temperature. Calculated according to $\text{EqPotTemp}(p,T,T_{v})$.

— Potential temperature. Calculated according to $\text{PotTempK}(p,T)$.

— Precipitation type. Freezing rain is triggered by $ww$ values of 56, 57, 66, or 67. Ice pellets are triggered by $ww$ values of 79, 87, 88, or 89. Snow is triggered by $ww$ values of 70-75 and 83-86. Rain is triggered by $ww$ values of 50-55, 60-65, 58, 59, 68, 69, or 80-84.

— IFR/MVFR. MVFR conditions are triggered by ceiling less than 3000 ft or visibility less than 8046 meters. IFR conditions are triggered by ceiling less than 1000 ft or visibility less than 4828 meters. LIFR conditions are triggered by ceiling less than 500 ft or visibility less than 1600 meters.

**OBJECTIVE ANALYSIS FUNCTIONS**

Nearly all of these algorithms use a smoothing coefficient, $s$, of the range (0..1) which is obtained directly from the Preferences > Analysis panel. This smoothing coefficient is used by the smoothing operators to remove unnecessary noise which would be otherwise evident in the data field.

The Barnes and Cressman algorithms also depend on the average station spacing, $a$. This may be computed \textit{automatically} by setting the Preferences > Analysis > Automatic Smoothing checkmark to \texttt{checked}. A \textit{manual} value may be specified by setting the above checkmark to \texttt{unchecked}, and the algorithms will use the values specified in Surface Radius or Upper Radius.

- **Nearest Neighbor analysis.** The Nearest Neighbor method is a crude algorithm designed for brute speed. Each observation is simply mapped to the nearest gridpoint, overwriting any previous values that exist for that gridpoint. Empty gridpoints are filled using an Expansion operator that nudges data from filled to void areas (see \texttt{Expand}). Then one pass of the HaltinerSmooth operator (q.v.) is performed to remove noise from the field, using whatever smoothing coefficient has been chosen by the user in the Preferences > Analysis panel.

- **Weighted analysis.** This is a single-pass objective analysis that simply uses distance-dependent values of observations. Then values at each observation point $f_k$ are used to produce a weighted average for $f_{x,y}$. \textit{NOTE: If the user has selected automated station spacing, then} $a = a \cdot 1.333$. The source of this analysis scheme is not known at this time.
The algorithm operates by iterating through all 900 gridpoints \((x,y)\). At each gridpoint, each observation \(f_k\) is examined. Only those observations whose distance is less than \(a\) from \((x,y)\) are considered. A distance-dependent weighting coefficient is calculated for each observation \(f_k\). The value \(d_k^2\) is the distance between gridpoint \(f_{x,y}\) and observation \(f_k\) in units of \(a\); therefore \(d_k^2/a = (0..1)\). It can be seen that the negative \(w\) term forces the expected inverse relationship of distance to weight.

\[
fx,y = \frac{\sum_{k=1..n} (f_k * w_k)}{\sum_{k=1..n} w_k} \quad \text{where} \quad w_k = \frac{(a^2 - d_k^2)}{(a^2 + d_k^2)}
\]

**Barnes analysis.** The Barnes analysis scheme (Barnes, 1964) is considered to be a refinement of the Cressman method. It uses a one-pass scheme, rather than successive iterations, to achieve convergence of the analysis field. **NOTE:** If automatic smoothing is enabled, the average station spacing value is set to \(a = a * 1.333\).

Only observations which fall within a rather large area of influence, \(a^3\), are considered. The value \(dk\) is the distance between gridpoint \(f_{x,y}\) and observation \(f_k\) in units of \(a\); therefore \(dk/a = (0..1)\). The distance-dependent weighting coefficient and the summation to produce a first guess of gridpoint data value \(fx,y\) are as follows:

\[
fx,y = \frac{\sum_{k=1..n} (f_k * \exp(-w_k))}{\sum_{k=1..n} w_k} \quad \text{where} \quad w_k = \frac{d_k^2}{a^2}
\]

At the completion of the above first-guess calculations, a difference pass is executed to compare the “error” of each actual data value \(f_k\) against its interpolated predicted value \(p_k\) within the objectively analyzed field. The value \(i_k\) and \(j_k\) will refer to the fractional coordinate (0..1) of the observation within its surrounding objective analysis grid box of \((x..x+1)\) and \((y..y+1)\). The calculations are done as follows:

\[
p_k = \frac{\left( ((f_{x+1,y} - f_{x,y}) * i_k) + f_{x,y} \right) + \left( ((f_{x+1,y+1} - f_{x,y+1}) * j_k) + f_{x,y+1} \right) + \left( ((f_{x,y+1} - f_{x,y}) * j_k) + f_{x,y} \right) + \left( ((f_{x+1,y+1} - f_{x+1,y}) * i_k) + f_{x+1,y} \right) }{4}
\]

The “error” of each data value \(f_k\) against its predicted value \(p_k\) is determined through simple subtraction.

\[
e_k = f_k - p_k
\]

Using this “error” information, a final pass is made which uses the above difference to correct the objective analysis field. Again, \(d_k\) is the distance between gridpoint \(f_{x,y}\) and observation point \(d_k\) in units of \(a\). Gamma, \(\gamma\), ((0..1), usually 0.3) is obtained from the Analysis settings panel. Using the weighting coefficient \(w\), an “error” value for each gridpoint, \(z_{x,y}\), can be calculated as follows.

\[
z_{x,y} = \frac{\sum_{k=1..n} (e_k * \exp(-w_j))}{\sum_{k=1..n} w_k} \quad \text{where} \quad w_k = \frac{d_k^2}{a^2} / \gamma
\]

Finally, the “error” field is added to the first-guess field to generate a corrected field, yielding a completed objective analysis.

\[
fx,y = fx,y + z_{x,y}
\]

**Cressman analysis.** The Cressman objective analysis scheme (Cressman, 1959) is known as the successive correction method. It achieves its result by forcing convergence of the data to observed, interpolated values using multiple iterations. **NOTE:** If automatic smoothing is enabled, the average station spacing value is set to \(a = a * 1.333\).
First, the number of convergence iterations, \( p \), is established. The value \( q \) originates from the Reduction value specified in the Preferences > Analysis panel. The value \( a \) is the average station spacing as determined above.

\[
p = \frac{a}{q}
\]

The predicted value \( f_{x,y} \) is calculated for a gridpoint using all observations \( k=1..n \). A distance-dependent weighting factor is determined for each observation before summing it into the equation. The value \( d_k \) is the distance between gridpoint \( f_{x,y} \) and observation \( f_k \) in units of \( a \); therefore \( \frac{d_k}{a} = (0..1) \).

\[
f_{x,y} = \sum(k=1..n) \left( f_k \times \exp(-w_k) \right) / \sum(k=1..n) w_k
\]

where \( w_k = \frac{d_k^2}{a^2} \)

At the completion of the above calculations, a difference pass is run to compare the “error” of the actual data value \( f_k \) against its interpolated, predicted value \( p_k \) within the objectively analyzed field. The value \( i_k \) and \( j_k \) refer to the fractional coordinate of the observation (0..1) within its surrounding objective analysis grid box of \((x..x+1)\) and \((y..y+1)\). The calculations are done as follows:

\[
p_k = \left[ \frac{((f_{x+1,y}-f_{x,y})i_k+f_{x,y}) + (((f_{x+1,y+1}-f_{x+1,y})i_k+f_{x+1,y})) + (((f_{x+1,y+1}-f_{x,y})j_k+f_{x,y}))}{4} \right]
\]

The difference between the observation value \( f_k \) and its predicted value \( p_k \) establishes an difference field (an error field) \( e_k \) in much the same way as the Barnes method.

\[
e_k = f_k - p_k
\]

Then a final pass is made using multiple observations for each gridpoint. A distance-dependent weighting coefficient, \( w \), is determined for each observation point throughout the iterations.

\[
z_{x,y} = \sum(k=1..n) \left( e_k \times w_k \right) / \sum(k=1..n) w_k
\]

where \( w_k = \frac{(a^2-d_k^2)}{(a^2+d_k^2)} \)

The difference field or “error” field is then added to the first-guess field to produce a refined analysis field.

\[
f_{x,y} = f_{x,y} + z_{x,y}
\]

Then the convergence counter value \( a \) is decremented by \( p \) as shown below. These values are not processed into the equations; they are only used to loop the Cressman iterations as necessary.

\[
a = a - p
\]

If \( a \leq 0 \), the objective analysis is complete and the resulting field \( f_{x,y} \) is valid. Otherwise further convergence is necessary, so that the difference values of \( d_k \) are reduced to lower and lower values, resulting in more accurate values of \( f_{x,y} \). Program flow cycles back to the difference field calculations to achieve this.

**NUMERICAL OPERATORS**

- **HaltinerSmooth.** This is a one-dimensional smoothing operator, which is a modified version of the Haltiner smoothing operator defined in Haltiner (1971). The **smoothing coefficient**, \( s \), is obtained from the user-defined value of (0..1) found in the Preferences > Analysis > Smoothing.

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Coefficient menu. The value of each gridpoint \( f_{x,y} \) is smoothed using iterations in all four x/y directions as described below in Steps 1-4. This is done to prevent “smearing” of the fields in a particular direction (something that has been observed in previous implementations). When this is completed, the result is a smoothed data field.

1. **Positive Y-direction iteration.** Iterating from \( f_{x,1} \) to \( f_{x,29} \), stepping through each value of x (0..30), \( f_{x,y} \) is altered as follows:
   \[
f_{x,y} = (1-s) \ast f_{x,y} + ((s \ast 0.5) \ast (f_{x,y-1} + f_{x,y+1}))
   \]

2. **Positive X-direction iteration.** Iterating from \( f_{1,y} \) to \( f_{29,y} \), stepping through each value of y (0..30), \( f_{x,y} \) is altered as follows:
   \[
f_{x,y} = (1-s) \ast f_{x,y} + ((s \ast 0.5) \ast (f_{x-1,y} + f_{x+1,y}))
   \]

3. **Negative Y-direction iteration.** Iterating from \( f_{x,29} \) to \( f_{x,1} \), stepping through each value of x (0..30), \( f_{x,y} \) is altered as follows:
   \[
f_{x,y} = (1-s) \ast f_{x,y} + ((s \ast 0.5) \ast (f_{x,y-1} + f_{x,y+1}))
   \]

4. **Negative X-direction iteration.** Iterating from \( f_{29,y} \) to \( f_{1,y} \), stepping through each value of y (0..30), \( f_{x,y} \) is altered as follows:
   \[
f_{x,y} = (1-s) \ast f_{x,y} + ((s \ast 0.5) \ast (f_{x-1,y} + f_{x+1,y}))
   \]

- **QuickFilter.** This fast, two-dimensional smoothing operator is called by certain objective analysis routines. It is essentially a two-dimensional averaging operator that uses 50% self-weight and 50% adjacent weight from neighboring observation values. The filter is iterated through each value of \( f_{x,y} \) in the +y direction for each increment of x as follows:
   \[
f_{x,y} = \frac{(f_{x,y} \ast 8) + f_{x,y-1} + f_{x,y+1} + f_{x+1,y} + f_{x-1,y} + f_{x+1,y+1} + f_{x,y+1} + f_{x+1,y+1}}{16}
   \]
   If null data or a border area contains an unusable value of \( f \), the value is not included in the summation total, and the divisor is reduced by one.

- **Expansion.** The Expansion operator is used by certain objective analysis functions to systematically fill null gridpoint values by causing any null gridpoint to assume the value of a neighboring gridpoint which has valid data. This assignment is done only if \( f_{x,y} \) is null and the source gridpoint is not null. The calculation, which is done in four directions to avoid “smearing” of the field in a particular direction, is done as follows:
   
   For \( x = 0..30 \) do [ for \( y = 0..29 \) do [ \( f_{x,y} = f_{x,y+1} \) ] ]
   For \( y = 0..30 \) do [ for \( x = 0..29 \) do [ \( f_{x,y} = f_{x+1,y} \) ] ]
   For \( x = 0..30 \) do [ for \( y = 30..1 \) do [ \( f_{x,y} = f_{x,y-1} \) ] ]
   For \( y = 0..30 \) do [ for \( x = 30..1 \) do [ \( f_{x,y} = f_{x-1,y} \) ] ]
   Repeat until there are no instances of \( f_{x,y} = \text{null} \)

- **AverageStationSpacing.** This is used to determine appropriate filtering values. In this function, Digital Atmosphere measures the great circle distance between all points in the domain and all other points in the domain. The result is the average of these values. Therefore if there are \( n \) number of observations, there will be \( (n-1)^2 \) number of distance measurements which will be averaged \( (n-1) \) since the distance from an originating station to itself cannot be included.

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REFERENCES


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Signature of User  x ___________________________________________ Date ____________________

Full name/address of User_______________________________________________________________

Types of Algorithms required ___________________________________________________________

Reason for request____________________________________________________________________