Adaptive Unsharp Masking in Image Enhancement

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April 16, 2019

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Abstract

This thesis will start with exlaining the process of Unsharp masking and the theory behind concepts like *connectivity* and *hyperconnectivity*, *connected filters*, *max-tree filtering*. After this underlying theorym I will explain the methods I

used to use these concepts for the purpose of improving Unsharp Masking. Finally I will show my results, comparing my produced results with the unfiltered results. Concluding will be the section which explains in which ways the results were useful and what future work can be done to further improve on them.

1 Introduction

In this document I will present the findings I made while working on my Bachelor's Thesis. When take a look at images produced in certain fields like astronomy, we would like these images to be sharp and have clear detail, however in reality this is often far from the case and images are blurry and unclear. Unsharp Masking is an existing technique used to increase the sharpness of an image, in other words, it will accentuate the details of an image. This technique however is far from perfect and has a couple of big drawbacks, There are a multitude of ways to adapt and improve this technique and in this thesis I will focus on one specific technique, namely using connected filters in combination with max-trees and k-flat zones. Connected filters are morphological operators acting on connected components, think of openings and closings using structuring elements. A max-tree is a way to construct a hierarchical region-based representation of an image, which can then be easily filtered and then the image reconstructed. A k-flat zone is defined as a connected region of maximal extent, in which the total greylevel variation is no more than k[3]

In essence, the question this Bachelor's Thesis should answer is: "Can connected filters be used to improve on Unsharp Masking?"

To achieve this goal I adapted some existing code provided my Dhr. M.H.F. Wilkinson and developed some of my own algorithms, mainly for the gaussian blurring and the process of Unsharp Masking itself. All was done in C, which means runtimes are swift but we have to manage memory and make sure there are no leaks.

2 Unsharp Masking

Unsharp Masking is the process wherein a blurred version or mask of the original image is combined with the original image. It improves the visual quality of the image using high-pass filtering and dynamic range compression. In more detail, if we consider the original image f, we can produce a low-pass filter of f by averaging each pixel with its neighbour pixels, using a kernel that is based on a Gaussian curve, also known as Gaussian blurring. Then we can subtract this low-pass filter from the original image, the result is called a high-pass filter. This result can then be multiplied by a factor β and then be added to the original image. The β represents the factor of sharpening. A higher β results in a sharper image, however this will also increase potential noise. This can be

more formally presented as

$$f' = \alpha * f + \beta * (f - L_p(f)) \tag{1}$$

where f' is the new image after unsharp masking.

There are two main drawbacks of Unsharp Masking. Firstly, it will amplify all the details, including any noise. Secondly, it will leaving ringing artifacts around objects with high contrast in the image. In this document I will primarily be focusing on images from astronomy. These images have in common that there usually are one or more bright components combined with a darker background containing potential noise.

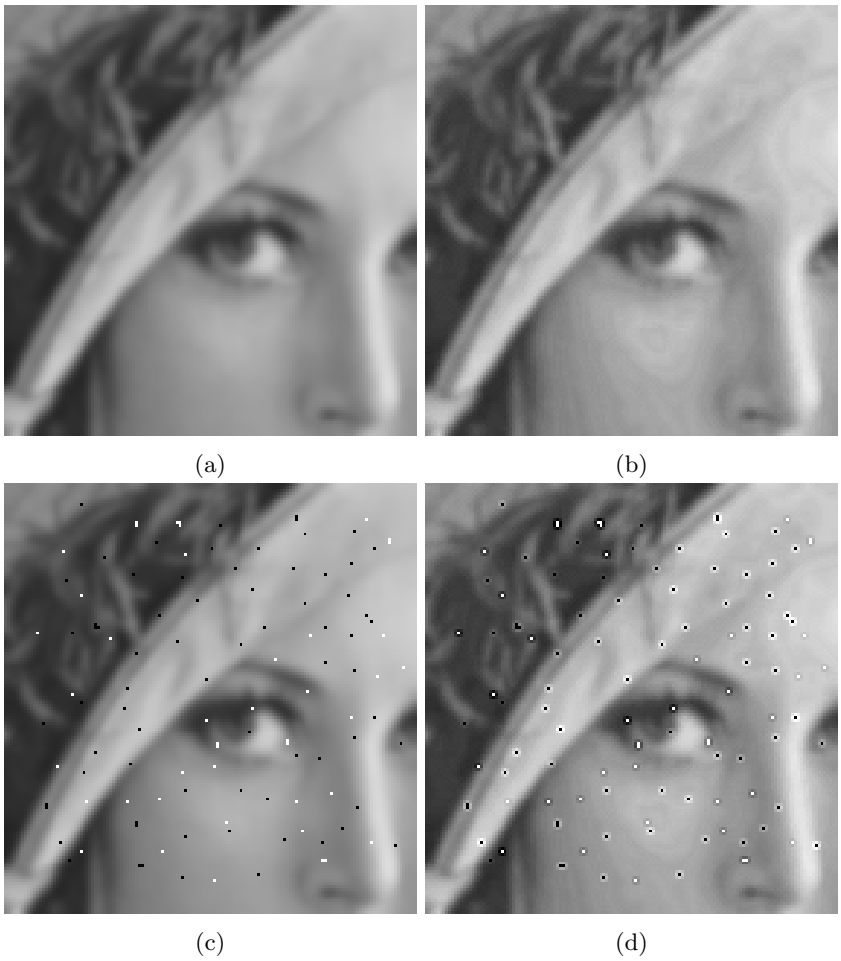


Figure 1: Effects of unsharp masking on a blurred image (a) Cropped part of the classic Lena image (b) After unsharp masking (c) Added noise (d) Effects of unsharp masking on noise.

3 Related Concepts

3.1 Connectivity

In the context of discrete image analysis, the set-theoretic concept of connectivity describes the way pixels are grouped to form so-called connected component or flat-zones. Connected components in a gray-scale image are regions of constant intensity (equal greyscale value) in which pixels are characterized by path-wise connected relation. In a 2-dimensional discrete space $\mathbb{Z}_2$, pixels are typically either 4 or 8-connected.[4] 4-connected means a pixel is connected horizontally and vertically, in terms of pixel coordinates this means every pixel

that has the coordinates $(x \pm 1, y)$ or $(x, y \pm 1)$ is connected to the pixel at (x, y), whereas 8-connected pixels are also connected diagonally, meaning every pixel that has the coordinates $(x \pm 1, y \pm 1)$ or is connected to the pixel at (x, y).

3.1.1 Connectivity classes

We can use this idea of connectivity in the context of discrete image analysis to group pixels into meaningful structures. A common way to address this is in the context of set-theory and mathematical morphology is through *connections* or *connectivity classes* as described in [4][3].
Definition 1: Let E be an arbitrary non-empty set. A connectivity class or connection $\mathcal{C}$ on E is any family $\mathcal{P}(E)$ that satisfies:

1) $\emptyset \in \mathcal{C}$ and for all $x \in E$, $\{x\} \in \mathcal{C}$
2) for any $C_i \subseteq \mathcal{C}$, $\bigcap_i \neq \emptyset \Rightarrow \bigcup_i C_i \in \mathcal{C}$

This definition shows that both the empty set and the singleton sets are connected and any union of sets which have a non-empty intersection is also connected. A member of $\mathcal{C}$ is called a *connected set*. Connected components or grains are accessed by means of a *connectivity opening* Γ_x, which is an operator which when given a point $x \in E$ extracts the union of all connected sets within an image X that have x in their intersection[4]

$$\Gamma_x(X) = \bigcup \{C_i \in \mathcal{C} | x \in C_i, C_i \subseteq X\} \tag{2}$$

for every $X \subseteq E$, yielding the largest connected subset of X which contains x.

3.2 Connected operators

Connected morphological operators are a set of powerful and computationally efficient tools used in image filtering. Classic examples are extensive and anti-extensive reconstructions using a structuring element, also known as openings and closings. Typically, a connected operator acting on an image is a transformation that enlarges the partition of the space created by the flat zones of the image. [8]

3.2.1 Attribute Filters

A morphological operator is called a filter if it is idempotent, i.e. $\Psi(\Psi(X)) = \Psi(X)$. Attribute filters come in in two varieties, increasing and non-increasing. An filter is increasing if for any two sets $X, Y \subseteq E$, $X \subseteq Y$ implies $\Psi(X) \subseteq \Psi(Y)$.[3] Whereas with a non-increasing filter this is not necessarily the case. In attribute filters, connected components are either preserved unmodified if they meet an attribute criterion Λ or removed if they do not. This means no new components can be added. Attribute critera for connected components $C_x \subseteq X$ are usually given in the form of

$$\Lambda(C_x) = (Attr(C_x \geq \lambda) \tag{3}$$

Where *Attr* is some real-value attribute of C_x and λ an attribute threshold, implemented by means of a trivial opening $\Gamma^\Lambda : \mathcal{C} \rightarrow \mathcal{C}$. For a connected component C_x, Γ_Λ returns C_x if $\Lambda(C_x)$ is true and $\emptyset$ otherwise.[4][3]
Definition 2: The binary attribute opening Γ^Λ of a set X with inceasing criterion Λ is given by

$$\Gamma^\Lambda(X) = \bigcup_{x \in X} \Gamma_\Lambda(\Gamma_x(X)) \tag{4}$$

If Λ is non-increasing, we refer to it as an *attribute thinning* rather than an attribute opening. [9]

3.2.2 Extensions to Greyscale

Connected filters extend to greyscale by treshold superposition [2]. Given a grey-scale image $f : E \rightarrow \mathbb{R}$, thresholding f in an increasing order from h_{min} to h_{max} produces a stack of nested binary sets where each binary image at level h is given by

$$T_h(f) = \{x \in E | f(x) \geq h\} \tag{5}$$

and for any two levels $h_1 < h_2 \implies T_{h_1}(f) \subseteq T_{h_1}(f)$. Now the response of the greyscale counterpart of a binary increasing filter $\Psi^\Lambda(x)$ on each point x is given by

$$\Psi^\Lambda(f)(x) = sup\{h | x \in \Psi^\Lambda(t_h(f))\} \tag{6}$$

This operator Ψ^Λ will assign to each x the highest threshold at which it still belongs to a connected component which satisfies a certain attribute criterion Λ.
Now we can define three types of components that are ussed for defining connected filter in greyscale. Given a greyscale image f, a *peak component* P_h at level h is a connected component of the thresholded image $T_h(f)$, meaning that for some x

$$P_h^x(f) = \Gamma_x(T_h(f)) \tag{7}$$

and a *regional maximum* M_h at level h is a component or flat-zone which has no neighbours a larger intensity that h. A flat-zone F_h is a connected component of the set of pixels with level equal to h, i.e. [3][9]

$$F_h^x(f) = \Gamma(\{x \in E | f(x) = h\}) \tag{8}$$

Greyscale attribute openings act on peak components while connected filters generally act on flat-zones. [8]

3.3 Max-tree Algorithm

One way of efficiently implementing an anti-extensive attribute filter is to use tree-based algorithms for greyscale image representation, originally introduced by Salembier et al.[7] The Max-Tree algorithm is a process in which the construction of the tree and computation of node attributes is independent from the filtering process. This tree structure encodes the set-theoretical notion of

connectivity and its greyscale extension. Given a greyscale image f. the tree structure represents the nesting order of its peak components P_h^i. The nodes C_h^i, at level h with index i, correspond to sets of pixels for which there exists a unqiue mapping to peak components.[3]

$$C_h^i = \{x \in P_h^i | f(x) = h\} \tag{9}$$

Every Max-Tree node except for the root will point to its parent at level $h' < h$. The root node points at level h_{min} to itself. Max-tree nodes contain four important fields: *Level* storing the original level h, *NewLevel* storing the new value after filtering. *Attribute* containing the value used for filtering, and *Parent* which points to the address of its parent.[3] The tree is recursively constructed by means of a flooding function using hierarchical FIFO queues as described in [4], [3], [9]. It is initiated by first accessing the root pixel from the queue at level h_{min} and then proceeds with flooding nodes along the different root paths that emerge during this process. This function, upon receiving a pixel from the queue, updates the *Attribute* value of the node currently being flooded, it then inspects its neighbouring pixels and places them in the appropriate queue. If a neighbouring pixel is at a higher level $h' > h$, flooding proceeds recursively at h'. When a node is fully flooded, it will be finalized by determining its *Parent* and *Attribute* fields. The process terminates when all pixels have been processed.

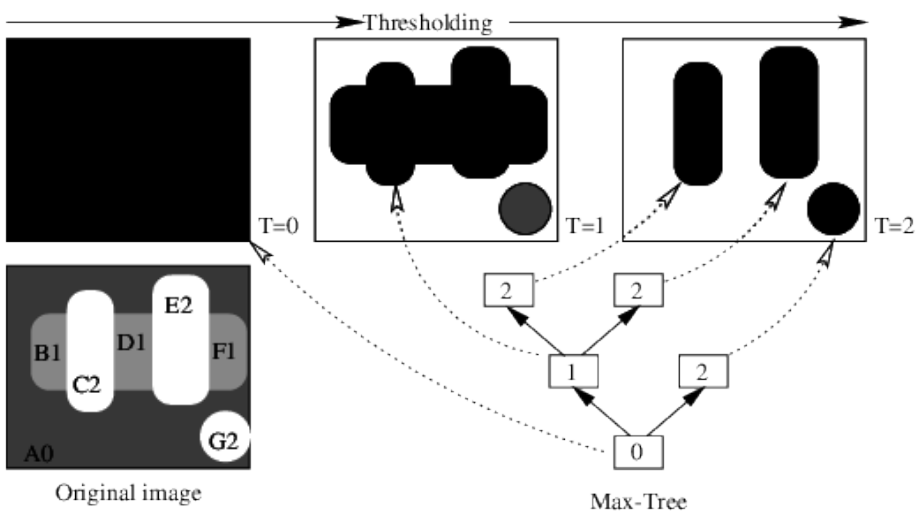


Figure 2: Max-tree representation of a greyscale image, original image from [10]

After the flooding is completed, we can start the filtering process using a filter function which visits each node, starting from the root. At every node, the *Attribute* field is used to evaluate Λ against a given thresholdλ. Nodes failing this criterion are removed by lowering the greyscale value of its member pixels. By what degree these values are lowered depends on the filtering rule chosen.

3.4 Hyperconnectivity

Before we explain k-flat zones, we have to introduce the theory behind it, i.e. hyperconnectivity[11, 1]. Hyperconnectivity extends the notion of connectivity by relaxing the second condition of Def. 1 where instead of needing a strict non-empty intersection of sets for their union to be connected, *hyperconnectivity classes* involve a degree of overlap, specified by an *overlap criterion*.

Definition 3: An overlap criterion in $\mathcal{P}(E)$ is a mapping $\perp$: $\mathcal{P}(\mathcal{P}(E)) \rightarrow \{0,1\}$ such that $\perp$ is decreasing, i.e. for any $\mathcal{A}, \mathcal{B} \subseteq \mathcal{P}(E)$

$$\mathcal{A} \subseteq \mathcal{B} \implies \perp(\mathcal{B}) \leq \perp(\mathcal{A}) \tag{10}$$

Any $\mathcal{A} \subseteq \mathcal{P}(E)$ for which $\perp(\mathcal{A})$ is said to be overlapping, otherwise $\mathcal{A}$ is non-overlapping. We can interpret (13) as ensuring that a non-overlapping family cannot become overlapping by adding more sets. Next, we define the hyperconnectivity class.

Definition 4: A hyperconnectivity class $\mathcal{H} \subseteq \mathcal{P}(E)$ with an overlap criterion $\perp$ is a family of sets with the following properties:

1) $\emptyset \in \mathcal{H}$ and for all $x \in E$, $\{x\} \in \mathcal{H}$

2) for any $\{A_j\} \subseteq \mathcal{H}$ for which $\perp(\{A_j\}) = 1 \implies \bigcup A_j \in \mathcal{H}$

Members of hyperconnectivity class are called hyperconnected. Now we can use this underlying theory of an overlap criterion and use it to define a more practical example, namely k-flat zones. This is the most relevant definition since the filters used in this project are designed around the concept of k-flat zones.

Definition 5: A k-flat zone $F_{h,k}$ at level h and depth k is the set of all path-wise connected pixels, marked from $x \in E$, with intensities from h down to $h-k$.

$$F_{h,k}(x) = \Gamma_x(\{p \in E | h-k \leq f(p) \leq h\}) \tag{11}$$

A 1-D example is shown in Fig. 2, using a k of 2. See [3] to see how a hyperconnectivity class can be derived from k-flat zones.

3.5 Atrribute Filters Based on k-flat Zones

If we replace regular peak components with k-peak components, we have to consider what the k-flat-zone equivalent of a regional maximum constitutes. A regional maximum at level M_h at level$h$ is a 0-flat zones with neighbours of strictly lower greylevel. A k-regional maximum $M_{h,k}$ is a k-flat zone at level h which has neighbours of greylevel strictly smaller than $h-k$.

When we consider the threshold decomposition of a greyscale image f. A component $P_{h,k}$ is preserved if $Attr(P_{h-k}) \geq \lambda$ and this decision will propogate to all regular peak components from P_{h-k} up to P_h, independent of whether each one of them seperately satistfies Λ or not. It is obvious that k-peak components are only defined from k levels above the background. Regular peak components P_h which are not members of some k-peak component, i.e. $P_h + k = \emptyset$ are then

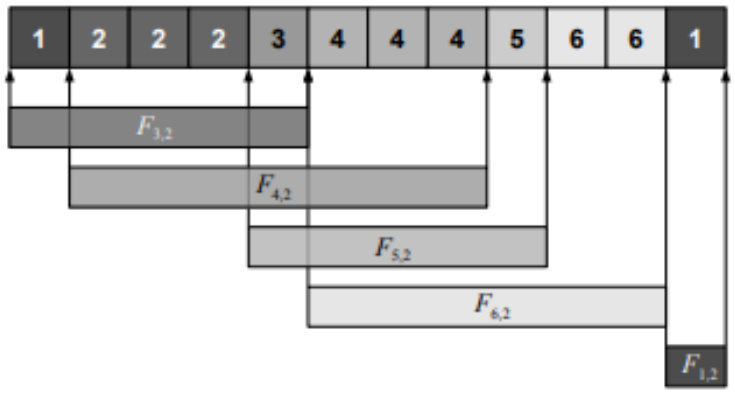


Figure 3: A signal and its k-flat zones for k = 2, each shaded box and associated arrows indicate a 2-flat zone

rejected because of low contrast. A modified criterion Λ_k can be derived from any criterion Λ used for regular Max-Tree filtering as

$$\Lambda_k(P_h) = \begin{cases} \Lambda(P_h) & \text{if } \exists x \in P_h L : f(x) \geq h + k \\ 0 & \text{otherwise} \end{cases} \tag{12}$$

This first checks if the contrast within a peak component is sufficient, and only then computes $\Lambda(P_h)$. However, just modifying this criterion is not sufficient because it violates idempotence. For example, let P_h be preserved because it meets Λ_k but its descendants do not. If these descendants are not restored up to a level k above the current P_h, another application of the filter would remove P_h because it automatically fails Λ_k. The classical subtractive Max-Tree filtering rule is therefore modified, in a way that propagates preserve decisions based on Λ_k upwards within a range k above the preserved ancestors. This is known as k-subtractive filtering which is extensively explained in [3], the pseudocode for this k-subtractive filtering rule is shown below.

Algorithm 1 The k-Subtractive filtering rule.

```
procedure kSubtractive (var t : MaxTree , λ : AttributeType, k : GreyLevel)
   /* input: Max-Tree t of an image f, attribute threshold λ and k-flat value */

   var root, node, parnode ; /* type MaxNode, pointers to root, current node and its parent */
   var l, difflevel ;        /* type GreyLevel, level and level difference */

   /* process root */
   root = t.root
   l = root.Level    /* sets l = h_min */
   if root.Attribute > λ then
      root.kprime = k /* preserve and set maximal k-restoration level */
      root.NewLevel = root.Level
   else
      root.kprime = 0
      root.NewLevel = 0
   endif
   for all levels l starting at h_min + 1 to h_max do
      for all nodes node at each level l do
         parnode = node.parent
         difflevel = node.Level − parnode → Level
         if node.PeakLevel − parnode.Level > k AND node.Attribute > λ then
            /* preserve and set maximal k-restoration level */
            node.NewLevel = parnode.NewLevel + difflevel
            node.kprime = k
         else
            if difflevel > parnode.kprime then
               node.NewLevel = parnode.NewLevel + parnode.kprime
               node.kprime = 0
               /* k-restoration completed */
            else
               node.NewLevel = parnode.NewLevel + difflevel
               node.kprime = parnode.kprime − difflevel
               /* remainder to be k-restored */
            endif
         endif
      endfor
   endfor
   for all pixels p restitute the filtered image
```

Figure 4: Pseudocode of k-subtractive filtering rule

4 Methods

For the purpose of this Bachelor Project we would ideally be able to remove all noise and unwanted artefacts without influencing the important parts of the image we want enhanced after the unsharp masking process is done, however removing all unwanted noise and artefacts is likely impossible so instead we will aim to reduce it as much as possible.

Before we start using any attribute filtering we have to understand what the formula shown in (1) means. If we take a look at the right part of (1), $f - L_p(f)$, means we subtract the low-pass or blurred version of the original image from the original image, this process is called high-pass filtering. At pixels with high contrast to its neightbors, this is going to leave these neigboring pixels with either high positive or negative values, when this part is then added to the original image, is where ringing artefacts may appear. A bright star on a darker but not completely black background for example.

Noise in the background means that in the high-pass filter of f pixels are going to have low positive or negative values, once these get multiplied by a significant β and added to the original is where the noise amplification comes from. So we realise that we have to use our max-tree algorithm with attribute filtering on high-pass filter of $f(1)$. To do that have to start with the blurring.

For the purpose of reading and writing images we use a library called `freeimage.h` and two functions called `readTIFF(..)` and `writeTIFF(..)`. These two functions provided by the code received from Prof. Wilkinson. `readTIFF(..)` has the ability to read in an image with multiple channels or planes, i.e. an RGB image. The way it does this is by using a 2D array for the image, where the rows of the array represent the number op planes. The image itself is then read in as a 1D array, per plane. For the purpose of this project, only greyscale images are used, which only have 1 channel. Having a 1D array representation of an image can be tricky, so one could change `readTIFF(..)` to read in the image as a 2D array, but I decided not to do this, because this would remove a dynamic element.

4.1 Gaussian blurring

There are already many tools developed to produce a Gaussian blur of an image, like OpenCV in python or when using *GIMP* or Photoshop, however I decided to develop my own version of gaussian blurring in C, mainly because OpenCV does not work well with 16-bit images, which is what I will mostly be using. Also it makes for quicker usage and easier debugging than when using a tool like GIMP or Photoshop. The idea of the gaussian blur is fairly simple, first we can build a gaussian kernel x wide by using this formula:

$$G(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{x^2}{2\sigma^2}}$$

for 1 dimension where x must be uneven and this formula:

$$G(x, y) = \frac{1}{2\pi\sigma} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

in 2 dimensions where x and y must be uneven. However the first part of both formulas is not necessary in practice, since we normalize the kernel so that the sum of its parts is 1. This is what happens in the `double *generateKernel(double`

`stdDev)` part of the program `gaussianBlur.c` in the appendix.

Now we can use this kernel to produce a blurred image, for every pixel (x, y) we multiply $(x - i, y - j)$ by the value of the kernel with the same offset, starting in the middle, with i and j in range $(-a/2, a/2)$ Where $a$is the length of the kernel in x and y the direction. Using this kernel we can generate a Gaussian blur, however we first have to realise what to do with edge cases.

There are several methods we can use to deal with the edge cases, the method I chose was to extending the image at the edges and corners by $ksize/2$ where k is the kernel size. We lets the extended edges and corners have the pixel values of the old edges and corners, this is done in the function `extendImage()`, now we can convolve the image with the kernel without any problems by only looping over the pixel values of the original image and applying the Gaussian blur as explained above.

4.2 High-pass Filter

Looking at the right part of (1), $f - L_p(f)$ is going to leave us with positive or negative values, however, an image can not contain any negative values, so we save our our positive and negative values to images representing the positive part and an image representing the negative, by multiplying the negative values by -1. Then we can use these images in our Max-tree filtering algorithm. These values will usually be quite small, so the resulting image might be mostly black. For debugging purposes, it can be useful to multiply all values by a certain β, however if we do that, we have to make sure to not overflow, as shown in the function `void highPass()`.

4.3 Max-tree Filtering

Now that we have our positive and negative parts, we can start our filtering process using the max-tree filtering algorithm. As explained before, the flooding algorithm, `int flood(..)`, builds our max-tree. The original filtering algorithm `void MaxTreeFilter(..)` uses area attribute filtering, however, area is not the attribute we care about, so we choose a different attribute. For the purpose of this project I have tried two different approaches which I will explain below.

4.3.1 Sum of Squared Greylevels

If we make the assumption that for an object or group of pixels to be seen as something other than noise, there has to be a certain amount of contrast within it. While in regular k-flat filtering, if a peak component is not part of a k-peak component, this means there is not enough contrast and the node is removed, however, in many cases, we also want to remove a node when the contrast is too high. Another way to measure contrast is to, per node, track the of sum of squared greylevels. So whenever a new pixel is processed we increase the

`SumGreyLevel` variable by `h*h` with `h` being the current greylevel. This process ensures that pixels with higher greylevels will have exponentially higher attribute values.

We adapt our filtering algorithm to properly deal with this new attribute. In `void MaxTreeProcessNode(..)` we first calculate the propagation range `k` by checking if the sum of squared greylevels is high enough for a certain node, if this is not the case k becomes 0, if it is high enough `k` becomes equal to the `k` given as an argument. Now we can use this `k` to check if, for a certain node, the difference between its `PeakLevel`, and its parent's `NewLevel` is larger than `k`. When this is the case, we change the node's `NewLevel` to that of its parent. This ensure that things like ringing artefacts, which will usually have a high enough sum of squared greylevels will also get removed.
One thing to realise is that this operation is not actually idempotent, so technically it is a connected operator and not a filter. However we can reach a sort of idempotency by repeating the process until no more change is found.

4.3.2 PeakLevels

A more basic approach to the problem is to use a greyscale attribute opening which checks, for a branch in the tree, if the `PeakLevel` is higher than a given λ, if this is not the case, the entire branch is flattened to the greylevel of its parent. This approach is more useful in images which already have a low amount of noise, which we will see in the results below. Note that in this approach there is not any kind of k-flat filtering.

4.4 Unsharp Masking Completion

After our max-tree filtering, all that is left is to complete our Unsharp Masking so it becomes visible what kind of effects our adapted Max-tree filtering algorithm has delivered on the final result. This part is pretty trivial since we know our images representing our positive and negative values are completely disjoint, meaning $Pos \cap Neg = \emptyset$. So all we have to do is add the positive and negative parts multiplied by a given β to our original image which can be confined into one line. $ORI(x, y) = ORI(x, y) + \beta * (Pos(x, y) - Neg(x, y))$. Where the limits for a pixel value are $(0, N)$. So if any underflow or overflow occurs, we flatten to 0 and N respectively. N in a 16-bit greyscale image is $2^{16} - 1$.

5 Results

Firstly, we look at the effects of our algorithm on a normal greyscale image, specifically the classic Lenna picture. This image is an 8-bit greyscale image, using a *beta* of 2, the image already has some large changes in contrast. When we apply our filtering using sum of squared greylevels, using a Λ of 5000, we can see that it does reduce the noise in the form of outliers and it the image appears a little smoother. The PeakLevels approach seems a little less effective, since noise with high contrast to the background does not get supressed.

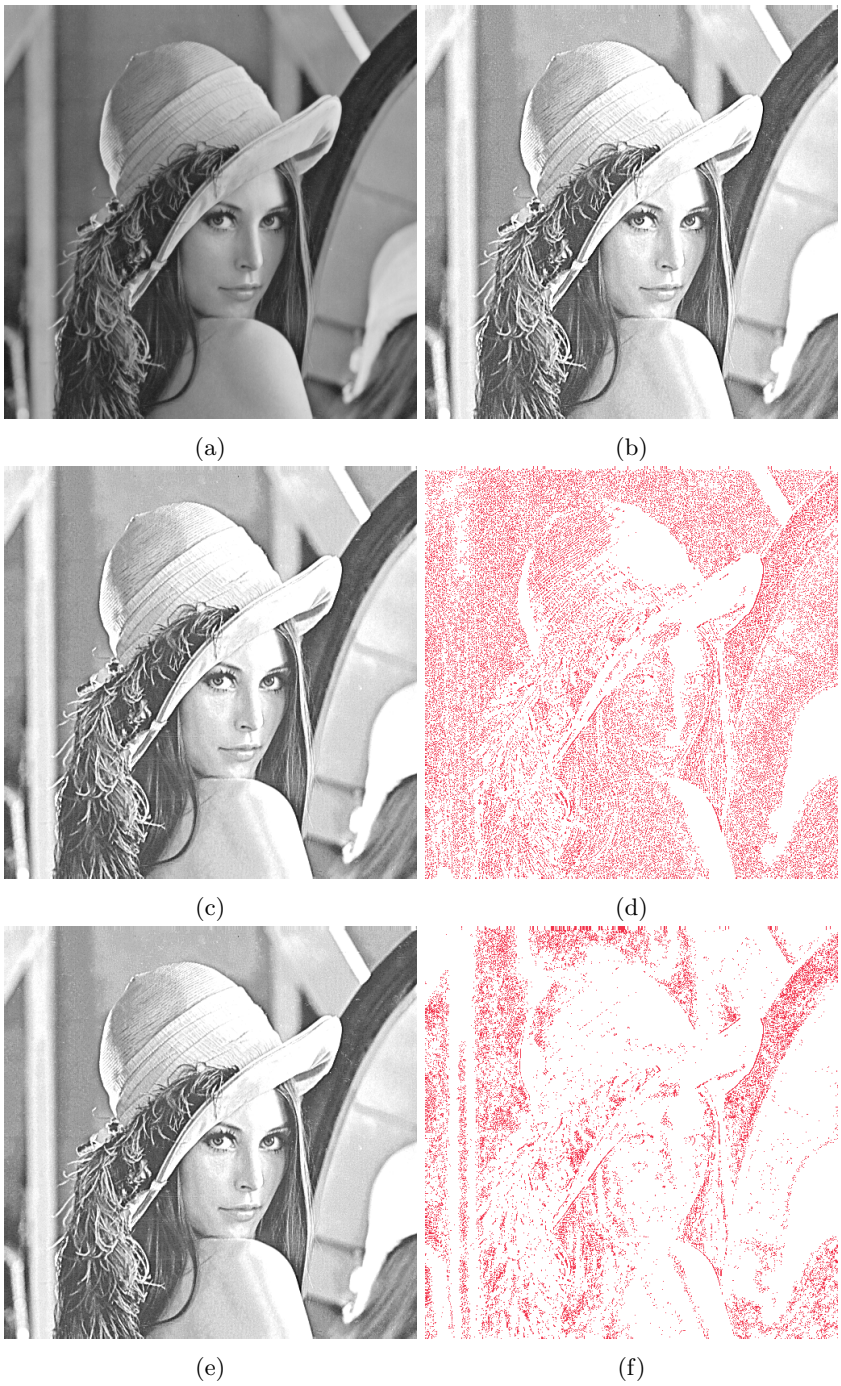
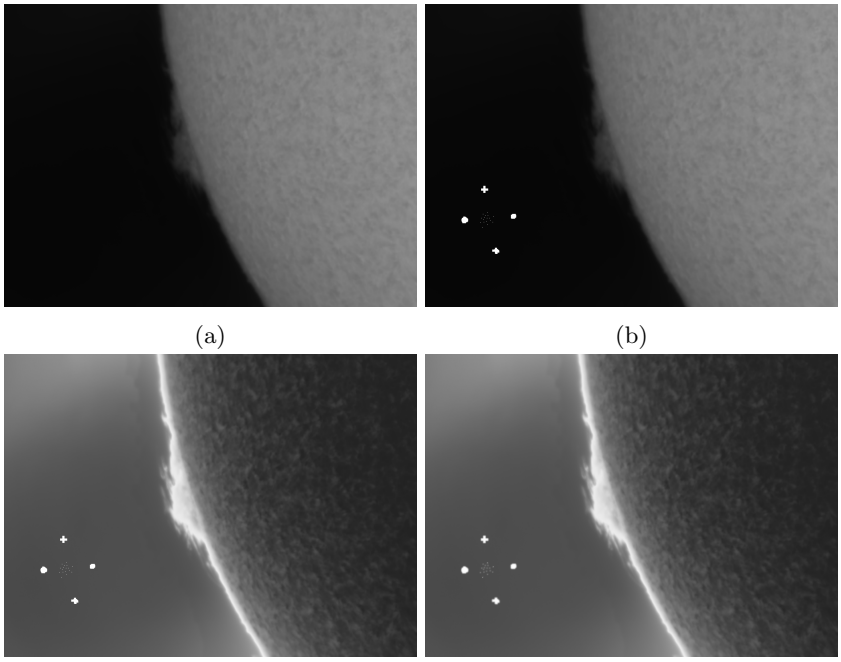


Figure 5: (a) Lenna Image in 8-bit greyscale (b) Unsharp masking using a β of 2 (c) Filtered using Sum of Greylevels (d) difference between b and c, (e) Filtered using PeakLevels, (f) Difference between b and e

While the filtering can have a visually pleasing effect on images like the Lenna picture in Fig. 5, these images are not very useful for the purpose of research, so for the following experiments I will use an image showcasing a blurry view of surface of the sun against an otherwise black background. Also some adaptations of this image, adding stars or switching up the greyvalues to accentuate the noise, as seen in Figure 6.



(a) (b)

(c) (d)

Figure 6: (a) Image of surface of the sun, (b) Image of surface of the sun with added stars, (c) Swapped colours, (d) Swapped colours and blurred stars.

5.1 Low Noise

Firstly, lets take a look at our unaltered image and see what happens when we execute the unsharp masking process without any filtering. Looking at figure 2a we can see that using a β of 25, the sun already shows more detail and the noise in the background is hardly noticable, however there is definitely some noise present. If we pump up the β to 100, the sun obviously starts to look weird, however we can see the noise present in the sharpened image.
When we apply our max-tree filtering we can see that when the sum of squared greylevels approach is used, the end result looks barely any different from the unfiltered image. This however does not mean nothing has happenened, taking

a look at figure 2d, we can see that the noise has been smoothened out in a way, reducing the greylevels of outliers. However it does retain the larger areas of noise. Using our other filtering method using peaklevels we can get a better result for an image like this with fairly low amounts of noise. As you can see in figure 2e, there is a significant decrease in the amount of visible noise.

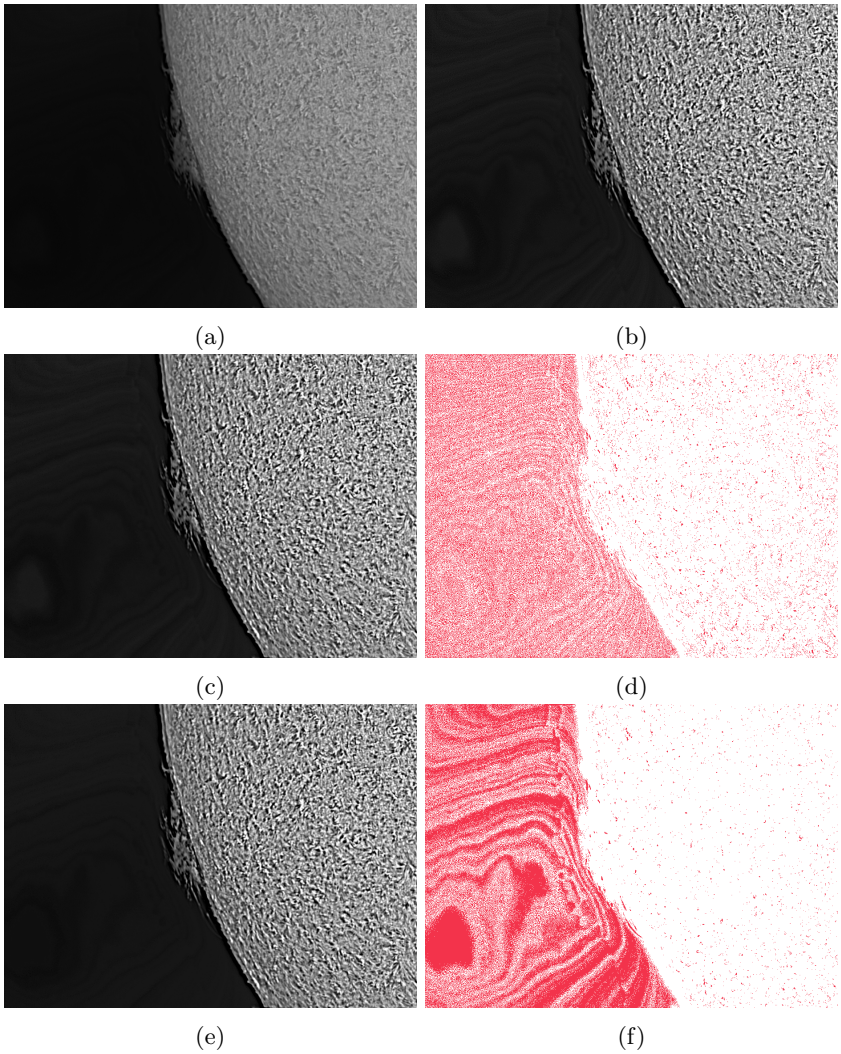
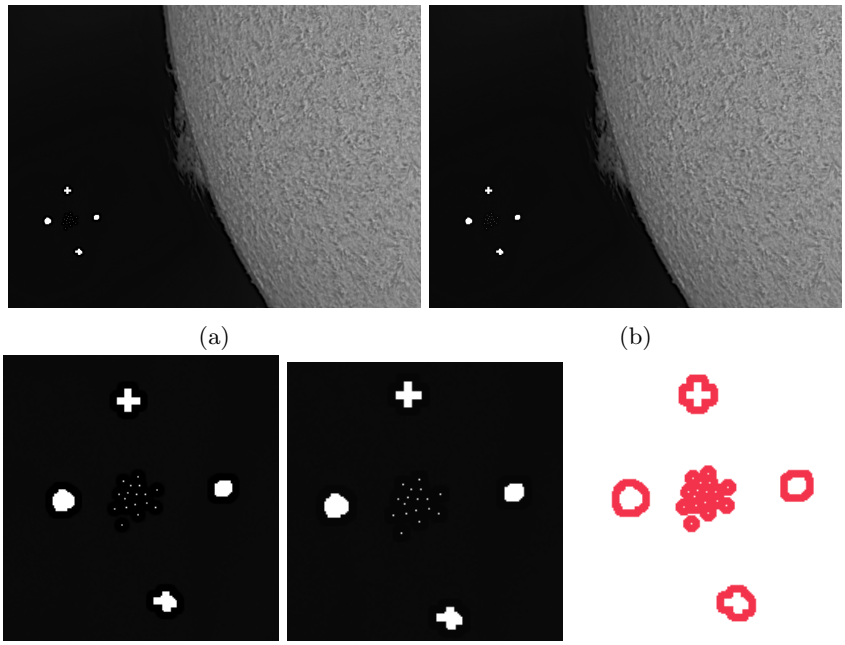


Figure 7: (a) Unsharp masking using a β of 25, (b) Unsharp masking using a β of 100 (c) Filtered using Sum of Greylevels (d) difference between b and c (e) filtered using PeakLevels, (f) difference between b and e

5.2 Ringing Artefacts

Obviously the examples shown in fig 2 are using an absurdly high β making the image itself look weird and inaccurate, so now we look at a more realistic proposition using our image with the added stars in the background. When we look closer at the stars in figure 3b we can see they are encircled in dark rings, these are the ringing artefacts that occur when we execute our unsharp masking process without any filtering. Larger artefacts means a larger kernel size was used in the Gaussian blurring of the image. In this case a kernel size of 11 is used. In this case it is a bright object on an otherwise dark but not completely black background, meaning that the negative part of the high-pass filter around the stars is significant. When we apply our attribute filtering process using sun of greylevels to the negative part, these ringing artefacts will be completely removed if we use the appropriate k , as seen in figure 3d which represents the difference between the original negative part and the filtered one. The artefacts are still visible in the end result, this is due to the greylevels of the noise around it still being increased by the unsharp masking. Technically there also exists a ringing artefact around the edge of the sun, however the contrast between the edge of the sun and the background is not high enough to filter out this artefact without negatively influencing the final result.



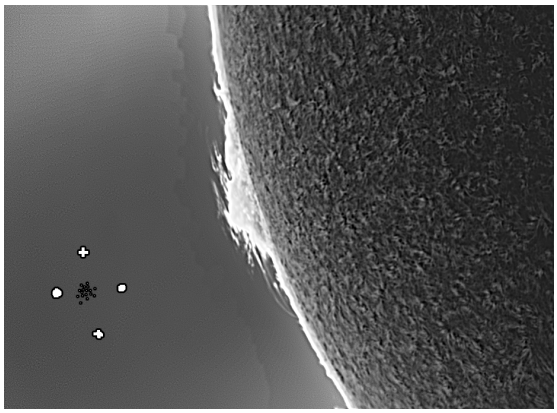
(a) (b) (c) (d) (e)

Figure 8: (a) Unsharp masking using a β of 15, (b) Filtered, (c) zoomed in part of a, (d) Zoomed in part of b, (e) Difference between the negative parts of the high-pass filter of figure 1b.

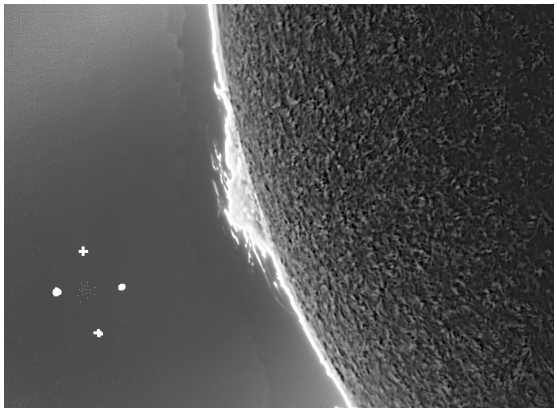
5.3 Different Colour Curves

Now let's look at the same image, however using GIMP I have adjusted the color courves, as you can see in figure 1d. The reason for this is that, not only that any present noise will be more visible than with a mostly dark background, but ringing artefacts will also become much more apparent after unsharp masking. Taking a look at figure 4a, the unfiltered image which went through the process of unsharp masking using a β of only 25, we can already clearly see the noise present in the image, as well as the artefacts around the artificial stars. However, when we filter the positive part using a λ of 40000 and a k of 3000 and our negative part using a λ of 20000 and a k of 1350, it has a significant effect on the noise. As we can see in figure 4b and 4c, the noise has been reduced significantly, except for some parts, specifically the top right corner. Taking a look at the artefacts, it was even possible to eliminate the larger ringing artefact around the sun in this case, since the contrast between the edge of the sun and the background was significantly high enough. The filtering did affect some low contrast parts of the sun aswell, but this maybe a tradeoff one should be willing to make.

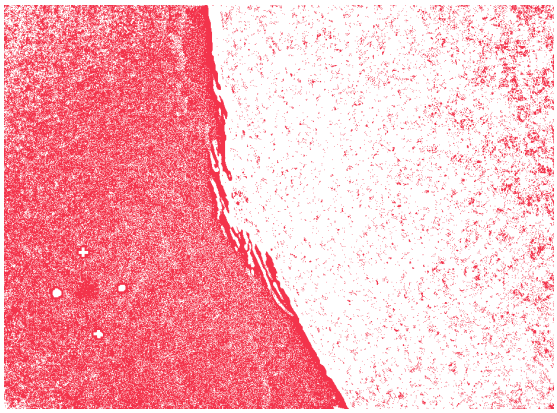
One thing to note is that the artificial stars added to the image are completely clear and sharp and do not have the same kind of blurring as the sun has. So we have to wonder if we can still filter out artefacts when we apply some kind of blurring to these celestial bodies. Taking a look at figure 5a and b, it is clear that it can indeed still work with the level of blurring used. However we have to use a fairly high k, 10000 in this case, when filtering the positive parts, because these artificial stars still have really high contrast compared to the background, meaning they can be mistaken for other artefacts.



(a)



(b)



(c)

Figure 9: (a) Unsharp masking using a β of 25, (b) Filtered, (c) Difference.

6 Thesis Conclusions

Connected filters or attribute filters have already shown great promise in the world of image enhancement and the field of astronomy, and I do believe that a case can be made for its use in Unsharp Masking. Looking at the results we can definitely see some promosing things in the case of ringing artefacts. Especially when we consider the effects it can have on artefacts around small bright objects, which in the case of images of outer space can be quite prevalent. What is noticable is that even though ringing artefacts of bright objects are removed in the filtering of the negative part of our high-pass filtering, the surrouding noise is still increased, so the artefact is still apparent. Therefore, in the case of general noise removal, the results can be improved, however I do believe that with the right implementation or adaptation of the filtering algorithm, it can be quite a useful tool.

Using C together with the `freeimage.h` library provides a quick and fairly approachable way to work with 16-bit greyscale images. The implementation of my high-pass filter and unsharp masking produced in provide an easy way to debug and produce your desired images. Some speed-ups are likely achievable since computation time was not my main concern for this project.

To answer the question posed in the Introduction: "Can connected filters be used to improve on Unsharp Masking?" The answer would be yes, connected filters are an incredibly useful and robust tool and with the right implementation I think it can also have a considerable impact in the context of Unsharp Masking.

7 Future Work

As mentioned above, the process of differentiating the noise from actual structures is key to producing results and I do think the way it is done in this Bachelor Project can be improved upon, especially when looking at the type of k-flat filtering used which is probably too rudimentary. A type of variable k-filtering as described in [3] where $k(h) = k_p h^p$ might be a useful tool in detecting the type of photon-noise found in images of astronomy.

7.1 Dynamic Lookup Table

When researching proper ways to detect noise using Max-Tree filtering, it can be taken one step further. The way the max-tree filtering algorithm works now is that nodes either get removed by changed the greylevel of a child to that of its surviving ancestor, or by leaving it unaltered. After this process is done the image gets restituted from the filtered max-tree. A possible improvement on this is, when in the filtering process, something is detected that can be removed, to not only remove it, but also reduce the value in the lookup table of the actual image. This way noise can be reduced to an even further extent.

7.2 Combination with other Unsharp Masking Techniques

Obivously, using connected operators and max-tree filtering is not the only way to improve on Unsharp Masking, as there are many adaptive techniques already out there. It may be entirely possible that combining the implementations described in this Thesis with other ones like Nonlinear Unsharp Masking[6] or Cubic Unsharp Masking[5] can improve the final result.

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A Code Attachments

A.1 kabsMaxTreeFilter.c

```
/*
    ********************************************************
    */
/*

    */
/* Area/shape preserving extensive and anti-extensive
        */
/* operators using Max-Trees
                                    */
/*

    */
/* by Georgios K Ouzounis - Jan. 2004
                            */
/* original Max-Tree code by Erik Urbach June 2000.
          */
/*

    */
/*
    ********************************************************
    */

#include <assert.h>
#include <stddef.h>
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <sys/times.h>
#include <unistd.h>
#include <math.h>

```

```
#include <FreeImage.h>


typedef short bool;
#define false 0
#define true  1

typedef unsigned char ubyte;

typedef unsigned short greyval;

#define NUMLEVELS     65536
#define CONNECTIVITY  4

double kbase, background = 0, alpha=0;

typedef struct FIFOQueue
{
   long *Pixels;
   long Head;
   long Tail; /* First free place in queue, or -1 when
        the queue is full */
} FIFOQueue;



/*** Max-Tree definition ***/

typedef struct MaxNode MaxNode;
typedef struct MaxNode *MaxTree;

/* MaxNode Status */
#define MTS_Ok       0
#define MTS_Deleted  1

struct MaxNode
{
  long Parent;
  long Status;
  long SumGreyLevel;
  int PeakLevel;
  int kPrime;
  int Level;
  int NewLevel;
};

```

```
MaxTree Tree;



/*** Globals used by Max-Tree ***/

long numbernodes[NUMLEVELS]; /* Number of nodes C^k_h at level h */
greyval **P_ORI;  /* Denotes the original gray level value of pixel p in processed image*/
greyval **ORI;    /* Denotes the original ... in the unproceesed input image */

/* STATUS stores the information of the pixel status: the pixel can be
 * NotAnalyzed, InTheQueue or assigned to node k at level h. In this
 * last case STATUS(p)=k. */
#define ST_NotAnalyzed  -1
#define ST_InTheQueue   -2
long *STATUS;

bool NodeAtLevel[NUMLEVELS];

/*** HQueue globals ***/
long  MaxPixelsPerLevel[NUMLEVELS];   /* Original image  */
long PMaxPixelsPerLevel[NUMLEVELS];   /* Processed image */
FIFOQueue HQueue[NUMLEVELS];

/*** Other globals ***/
long ImageWidth;
long ImageHeight;
long ImageSize;
long NumPlanes;

long NumPixelsBelowLevel[NUMLEVELS];
long PNumPixelsBelowLevel[NUMLEVELS];

#define ReadPixel(t,i,h)  (t[NumPixelsBelowLevel[h]+i].NewLevel)

/*** Queue functions ***/
#define HQueueFirst(h)     (HQueue[h].Pixels[HQueue[h].Head++])
```

```
#define HQueueAdd(h,p)      HQueue[h].Pixels[HQueue[h].Tail++] = p
#define HQueueNotEmpty(h)  (HQueue[h].Head != HQueue[h].Tail)
void HQueueCreate(void);
void HQueueDelete(void);

/*********************************************/
/* HQueue is an array segmented based on the   */
/* processed image histogram.                  */
/*********************************************/

void HQueueCreate(void)
{
   int i;

   HQueue->Pixels = calloc((size_t)2*ImageSize, sizeof(long));
   assert(HQueue->Pixels != NULL);
   HQueue->Head = HQueue->Tail = 0;
   for (i=1; i<NUMLEVELS; i++)
   {
      HQueue[i].Pixels = HQueue[i-1].Pixels + PMaxPixelsPerLevel[i-1] + MaxPixelsPerLevel[i-1];
      HQueue[i].Head = HQueue[i].Tail = 0;
   }

} /* HQueueCreate */


/*********************************************/
/* Image I/O functions                         */
/*********************************************/



/** Generic image loader
@param lpszPathName Pointer to the full file name
@param flag Optional load flag constant
@return Returns the loaded dib if successful, returns NULL otherwise
*/
FIBITMAP* GenericLoader(const char* lpszPathName, int flag) {
  FREE_IMAGE_FORMAT fif = FIF_UNKNOWN;
```

```
/*  check the file signature and deduce its format */
/* (the second argument is currently not used by FreeImage) */
  fif = FreeImage_GetFileType(lpszPathName, 0);
  if(fif == FIF_UNKNOWN) {
    /* no signature ? */
    /* try to guess the file format from the file extension */
    fif = FreeImage_GetFIFFromFilename(lpszPathName);
  }
  /* check that the plugin has reading capabilities ... */
  if((fif != FIF_UNKNOWN) && FreeImage_FIFSupportsReading(fif)) {
    /* ok, let's load the file */
    FIBITMAP *dib = FreeImage_Load(fif, lpszPathName, flag);
    /* unless a bad file format, we are done ! */
    return dib;
  }
  return NULL;
}

greyval **ReadTIFF(char *fnm, long *width, long *height, long *numplanes){
   FIBITMAP *dib = GenericLoader(fnm,0);
   unsigned long  bitsperpixel;
   greyval **im;
   unsigned int x,y,i,j,imsize;
   if (dib == NULL) return NULL;

   bitsperpixel =  FreeImage_GetBPP(dib);
   *numplanes=1;
   if ((bitsperpixel==24) ||(bitsperpixel==48))
     *numplanes=3;
   *height = FreeImage_GetHeight(dib),
   *width = FreeImage_GetWidth(dib);

   imsize = (*width)*(*height);
   im = calloc((size_t)*numplanes, sizeof(greyval *));
   assert(im!=NULL);
   for (i=0;i<*numplanes;i++){
     im[i] = calloc((size_t)imsize, sizeof(greyval));
     assert(im[i]!=NULL);
   }
   switch(bitsperpixel) {
```

```
  case 8 :
    i=0;
    for(y = 0; y <*height; y++) {
      BYTE *bits = (BYTE *)FreeImage_GetScanLine(dib, *height - y -1);
      /*printf("y=%d\n",y);*/
      for(x = 0; x < *width; x++,i++) {
    im[0][i] = bits[x];
      }
    }

    FreeImage_Unload(dib);
    return im;
  case 16 :
    i=0;
    for(y = 0; y < *height; y++) {
      unsigned short *bits = (unsigned short *) FreeImage_GetScanLine(dib,*height - y -1);
      for(x = 0; x < *width; x++,i++) {
    im[0][i] = bits[x];
      }
    }
    FreeImage_Unload(dib);
    return im;
  case 24 :
    i=0;
    for(y = 0; y <*height; y++) {
      BYTE *bits = (BYTE *)FreeImage_GetScanLine(dib, *height - y -1);
      /*printf("y=%d\n",y);*/
      for(x = 0; x < *width; x++,i++) {
        for (j=0;j<*numplanes;j++)
      im[j][i] = bits[3*x+j];
      }
    }

    FreeImage_Unload(dib);
    return im;
  case 48 :
    i=0;
    for(y = 0; y <*height; y++) {
      unsigned short *bits = (unsigned short *) FreeImage_GetScanLine(dib, *height - y -1);
      /*printf("y=%d\n",y); */
      for(x = 0; x < *width; x++,i++) {
        for (j=0;j<*numplanes;j++)
```

```
        im[j][i] = bits[3*x+j];
        }
      }

      FreeImage_Unload(dib);
      return im;

    default :
      FreeImage_Unload(dib);
      fprintf(stderr, "unsupported format\n"); exit(-1);
      return NULL;
    }

}


void WriteTIFF(char *fname, long width, long height, int bitspp, long numplanes){
  FIBITMAP *outmap;
  long i,j,y,x,plane;
  FREE_IMAGE_FORMAT fif = FreeImage_GetFIFFromFilename(fname);

  if (bitspp == 8){
    ubyte *imagebuf;
    RGBQUAD *pal;
    outmap = FreeImage_AllocateT(FIT_BITMAP,width,height,numplanes*bitspp,0xFF,0xFF,0xFF);
    if (numplanes==1){
      pal = FreeImage_GetPalette(outmap);
      for (i = 0; i < 256; i++) {
    pal[i].rgbRed = i;
    pal[i].rgbGreen = i;
    pal[i].rgbBlue = i;
      }
    }
    i = 0;
    for (j=height-1; j>=0; j--){
      imagebuf = FreeImage_GetScanLine(outmap,j);
      for (x=0;x<width;x++,i++)
        for (plane=0;plane<numplanes;plane++)
     imagebuf[numplanes*x+plane]=ORI[plane][i];
    }

  } else {
```

```
    greyval *imagebuf;
    if (numplanes==1)
      outmap = FreeImage_AllocateT(FIT_UINT16,width,height,16,0xFFFF,0xFFFF,0xFFFF);
    else
      outmap = FreeImage_AllocateT(FIT_RGB16,width,height,48,0xFFFF,0xFFFF,0xFFFF);

    i = 0;
    for (j=height-1; j>=0; j--){
      imagebuf = (greyval *)FreeImage_GetScanLine(outmap,j);
      for (x=0;x<width;x++,i++)
        for (plane=0;plane<numplanes;plane++)
     imagebuf[numplanes*x+plane]=ORI[plane][i];

    }
  }

  FreeImage_Save(fif,outmap,fname,0);
  FreeImage_Unload(outmap);

}


void ReadPGM(char *fname,short buffer)
{
   long width, height;
   int c;


   if(buffer==1)
     {
       ORI = ReadTIFF( fname, &width, &height, &NumPlanes);
       ImageWidth = width;
       ImageHeight = height;
       ImageSize = width*height;

     }
   else
     {
       P_ORI = ReadTIFF(fname, &width, &height, &NumPlanes);
       ImageWidth = width;
       ImageHeight = height;
```

```
        ImageSize = width*height;
      }

} /* ReadPGM */


greyval FindMax(greyval *buf, long width, long height) {
  greyval max = buf[0];
  long i,size = width*height;
  for (i = 1; i<size;i++){
    max = (buf[i]>max) ? buf[i] : max;
  }
  return max;
}


void WritePGM(char *fname, long width, long height, long numplanes)
{


  if (FindMax(ORI[0],width,height)>255)
    WriteTIFF(fname, width, height, 16, numplanes);
  else
    WriteTIFF(fname, width, height, 8, numplanes);


} /* WritePGM */

/*********************************************/
/* Setting up the Max-Tree structure         */
/* MaxPixelsPerLevel already initialized     */
/*********************************************/

MaxTree MaxTreeCreate(long size)
{
   MaxTree t;
   int i;

   t = calloc((size_t)2*size, sizeof(MaxNode));
   if (t)
   {
      *NumPixelsBelowLevel = 0;
      for (i=1; i<NUMLEVELS; i++)
      {
```

```
         NumPixelsBelowLevel[i] = NumPixelsBelowLevel[
            i-1] + MaxPixelsPerLevel[i-1] +
            PMaxPixelsPerLevel[i-1];
      }
   }
   return(t);
} /* MaxTreeCreate */

/*****************************************************/
/* Finds a pixel of minimum intensity in the image */
/* MaxPixelsPerLevel : Histogram of original image */
/* PMaxPixelsPerLevel: Histogram of processed image*/
/*****************************************************/

long FindHMinPixel(greyval *ORI,greyval *P_ORI)
/*  */
{
   long i, p=0;

   /* initialise level entries */
   for (i=0; i<NUMLEVELS; i++)
     {
       MaxPixelsPerLevel[i] = 0;
       PMaxPixelsPerLevel[i] = 0;
     }
   /* compute histogram */
   for (i=0; i<ImageSize; i++)
   {
      MaxPixelsPerLevel[ORI[i]]++;
      PMaxPixelsPerLevel[P_ORI[i]]++;
      if (P_ORI[i]<P_ORI[p])  p = i;
   }
   return(p);
} /* FindHMinPixel */

/*********************************************/
/* Retrieves the neighbors of pixel p        */
/*********************************************/

int GetNeighbors(long p, long *neighbors)
{
   long x;
   int n=0;

   x = p % ImageWidth;
   if (x<(ImageWidth-1))  neighbors[n++] = p+1;
```

```
   if (p>=ImageWidth)     neighbors[n++] = p-ImageWidth;
   if (x>0)               neighbors[n++] = p-1;
   p += ImageWidth;
   if (p<ImageSize)       neighbors[n++] = p;
   return(n);
} /* GetNeighbors */


/*********************************************/
/* Max-Tree Creation: Here it is the modified  */
/* image that is being processed               */
/*********************************************/

int flood(greyval *ORI, greyval *P_ORI, int h
, int *thispeaklevel, long *thisSumGreyLevel)
{
   long neighbors[CONNECTIVITY];
   long p, q,idx;
   int numneighbors, i, m, level, peaklevel = h, childpeaklevel;
   long sumGreyLevel = *thisSumGreyLevel, childSumGreylevel;
   MaxNode *node;

   while(HQueueNotEmpty(h)){
     p = HQueueFirst(h);
     STATUS[p] = numbernodes[ORI[p]]; /* in all cases */

     if(ORI[p]!=h){/* unstable regions */
       level = ORI[p];
       NodeAtLevel[level]=true;

       /* Detect the node */
       node = Tree + (NumPixelsBelowLevel[level] + numbernodes[level]);
       peaklevel = (peaklevel<level)? level : peaklevel;
       if(level>h){ /* Anti-extensive case */

     /* set the singleton node at ORI[p]*/
     node->Parent = NumPixelsBelowLevel[h] + numbernodes[h];
     node->Status = MTS_Ok;
     node->Level  = level;
```

```
      node->PeakLevel  = level;
      numbernodes[level] += 1;    /* increase this for next time */
      NodeAtLevel[level] = false; /* finalise this node */;
      sumGreyLevel += h*h;           /* Need to update the parent area also  */\

        }
      }else /* Stable or background regions */
        sumGreyLevel += h*h;
      /* process the neighbors */
      numneighbors = GetNeighbors(p, neighbors);
      for (i=0; i<numneighbors; i++){
        q = neighbors[i];
        if (STATUS[q]==ST_NotAnalyzed){
      HQueueAdd(P_ORI[q],q);
      STATUS[q] = ST_InTheQueue;
      NodeAtLevel[P_ORI[q]] = true;
      /* The neighbor is greater than p */
      if (P_ORI[q] > P_ORI[p])
        {
          m = P_ORI[q];
          childpeaklevel = m;
              childSumGreylevel = 0;
          do
            {
          m = flood(ORI, P_ORI, m, &childpeaklevel, &childSumGreylevel);
            } while (m!=h);
              sumGreyLevel += childSumGreylevel;
          peaklevel = (peaklevel<childpeaklevel)? childpeaklevel : peaklevel;
        }
        }
      }
    }/* end of while loop*/

    /* Retrieve the parent and finalise the node*/
    numbernodes[h] = numbernodes[h]+1;
    m = h-1;
    while ((m>=0) && (NodeAtLevel[m]==false))  m--;
    if (m>=0)
      {
        node = Tree + (NumPixelsBelowLevel[h] + numbernodes[h]-1);
```

```
      node->Parent = NumPixelsBelowLevel[m] + numbernodes[m];
    }
  else
    {
      idx = NumPixelsBelowLevel[h];
      node = Tree + idx;
      node->Parent = idx;
    }
  node->Status = MTS_Ok;
  node->Level = h;
  node->PeakLevel = h;
  node->SumGreyLevel += sumGreyLevel;
  NodeAtLevel[h] = false;
  *thispeaklevel = node->PeakLevel;
  *thisSumGreyLevel = node->SumGreyLevel;
  return(m);
} /* flood */


/*********************************************/
/* Filtering Functions                       */
/*********************************************/

typedef long (*kFunc)(long, long, long);

long kflatConstant(long greylevel, long sog, long lambda2){
  return (long) kbase;
}

long kflatLinear(long greylevel, long sog, long lambda2){

  return (long) (kbase*(double)greylevel/100.0);
}

long kflatConditional(long greylevel, long sog, long lambda) {
  return (sog > lambda ? kbase :  0);
}



void MaxTreeProcessNode(MaxTree t, long lambda, long idx, kFunc kf, long maxarea)
```

```
/* Deletes node idx and possible one or more of its parents. */
{
  long k,parent, diflevel,newlevel;

   parent = t[idx].Parent;

   diflevel = t[idx].Level - t[parent].Level;
   newlevel = t[parent].NewLevel + diflevel;
   k = (*kf)(diflevel, t[idx].SumGreyLevel, lambda);
   if (t[idx].PeakLevel - t[parent].Level> k){
       /* initiate absorption */
       t[idx].NewLevel = t[parent].NewLevel;
       t[idx].kPrime = -k;
   } else {
     if (t[parent].kPrime<0){
       t[idx].NewLevel = t[parent].NewLevel;
       t[idx].kPrime = 0;
     } else {
       if (diflevel>t[parent].kPrime){
     t[idx].NewLevel = t[parent].NewLevel + t[parent].kPrime;
     t[idx].kPrime = 0;
       } else {
     t[idx].NewLevel = t[parent].NewLevel + diflevel;
     t[idx].kPrime = t[parent].kPrime - diflevel;
       }
     }
   }

} /* MaxTreeProcessNode */

void SetPeakLevels(MaxTree t)
{
  long i, idx,parent;
   int h;

   for ( h= NUMLEVELS-1; h>=0;h-- )
   {
      for (i=0; i<numbernodes[h]; i++)
      {
     idx = NumPixelsBelowLevel[h] + i;
         parent = t[idx].Parent;
         if (t[parent].PeakLevel < t[idx].PeakLevel)
       t[parent].PeakLevel = t[idx].PeakLevel;
      }
```

```

   }

} /* SetPeakLevels */


void MaxTreeFilter(greyval *ORI, MaxTree t, long lambda, kFunc k, long maxarea)
{
   long i, idx;
   int h=0;

   SetPeakLevels(t);
   while (numbernodes[h]==0)
     h++;                    /* find root*/


   /*process root*/


   idx = NumPixelsBelowLevel[h];

   t[idx].kPrime = (*k)(t[idx].Level, t[idx].SumGreyLevel, lambda);
   t[idx].NewLevel = t[idx].Level;

   h++;

   while ( h< NUMLEVELS )
   {
      for (i=0; i<numbernodes[h]; i++)
      {
     idx = NumPixelsBelowLevel[h] + i;
         MaxTreeProcessNode(t, lambda, idx, k,maxarea);
      }
      h++;
   }
   /* Modify the output image */
   for (i=0; i<ImageSize; i++)
     ORI[i] = ReadPixel(t, STATUS[i], ORI[i]);

} /* MaxTreeFilter */

/*
    ------------------------------------------------------------------------
```

```
     */
/* Notes :  If the attribute threshold lambda is set to a large    */
/*          value, the extensive log reports the parent node index */
/*          as a number out of the node index range for that level.*/
/*          That is because although the node level reduces, the   */
/*          parents of each child nodes above that are different.  */
/*          ------------------
```

```
    fprintf(fp,"Filenames: '%s' - '%s'\n",fname1,fname2);
    fprintf(fp,"Image Size %ld\n",ImageSize);
    fprintf(fp,"h_min:%d\n",hmin);

    for (l=NUMLEVELS-1; l>=0; l--)
    {
      for (i=0; i<numbernodes[l]; i++)
      {
          idx = NumPixelsBelowLevel[l] + i;
          level  = t[idx].Level;
          parent = t[idx].Parent;
          /* parent level*/
          parent_level = t[parent].Level;
          parent_node =  parent - NumPixelsBelowLevel[parent_level];
          status = t[idx].Status;
          /*if(status==0)*/
            fprintf(fp,"level: %d, node: %d, area: %ld, parent_level: %ld, parent_node: %ld, status: %ld\n",l,i,area,parent_level,parent_node,status);
      }
    }
    fprintf(fp,"--- End of Session ---\n");
    fclose(fp);
}

int main(int argc, char *argv[])
{
  long i, p,plane;
   long area=0,k=0, maxarea;
   int peaklevel;
   long sumGreyLevel;
   long lambda;;
   int hmin;
   short buffer;
  struct tms timestruct;
  clock_t start;
  long ticksize=sysconf(_SC_CLK_TCK);
  float museconds;

   if (argc<5)
   {
      printf("Usage: %s <original inputimage> <processed input image> <outputfile> <lambda>
```

```
        [k] \n", argv[0]);
      exit(0);
  }
  lambda = atol(argv[4]);
  FreeImage_Initialise(0);

  ReadPGM(argv[1],buffer=1); /* ORI image buffer */
  ReadPGM(argv[2],buffer=2); /* P_ORI  image buffer */
  /*printf("\n   Read Buffers Ready\n");*/
  if (argc>5) k=atoi(argv[5]);
  /* STATUS keeps track of each pixel's labelling */
  /*printf("\n   Levels initialised\n");   */

  kbase = k;

  /*printf("%f\n",kbase);*/
 times(&timestruct);
 start=timestruct.tms_utime;

  for (plane=0; plane<NumPlanes; plane++){

    STATUS = calloc((size_t)ImageSize, sizeof(long));
    assert(STATUS!=NULL);
    for (i=0; i<ImageSize; i++)  STATUS[i] = ST_NotAnalyzed;
    InitLevels();
    p = FindHMinPixel(ORI[plane],P_ORI[plane]);
    hmin = P_ORI[plane][p];
    peaklevel = hmin;
    sumGreyLevel = 0;
    NodeAtLevel[hmin] = true;
    HQueueCreate();
    /*   printf("\n   Hierarchical Queues Ready\n"); */

    HQueueAdd(hmin, p);
    STATUS[p] = ST_InTheQueue;
    Tree = MaxTreeCreate(ImageSize);
    assert(Tree!=NULL);
    /*printf("\n   Max-Tree structure Ready\n");*/

    flood(ORI[plane],P_ORI[plane],hmin, &peaklevel, &sumGreyLevel);
    /*printf("\n   MaxTree Structure Completed!\n"); */
```

```

      MaxTreeFilter(ORI[plane],Tree, lambda,
         kflatConditional, maxarea);
      /*   printf("\n   Area Opening Completed!\n");*/

      /* Generate a log file */
      /* CreateLog(Tree,hmin,argv[1],argv[2]); */

      free(Tree);
      free(HQueue->Pixels);
      free(STATUS);
    }
  times(&timestruct);
  museconds=1E6*(timestruct.tms_utime-start)/(float) (
     ticksize);
  printf ("%8ld %10.4f\n", lambda, museconds/1000000);
  WritePGM(argv[3], ImageWidth, ImageHeight, NumPlanes
     );



    for(plane=0; plane<NumPlanes; plane++){
      free(ORI[plane]);
      free(P_ORI[plane]);
    }
    free(ORI);
    free(P_ORI);
    FreeImage_DeInitialise();
    return(0);

} /* main */
```

A.2 highPass.c

```
#include <assert.h>
#include <stddef.h>
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <sys/times.h>
#include <unistd.h>
#include <FreeImage.h>
#include <math.h>

long ImageWidth;
```

```
long ImageHeight;
long eWidth;
long eHeight;
long ImageSize;
long NumPlanes;
int ksize;

typedef unsigned short greyval;
typedef unsigned char ubyte;
greyval N;

#define NUMLEVELS     65536

greyval **ORI;    /* Denotes the original ... in the unproceesed input image */
greyval **new;    /* Denotes the output image */
greyval **eImage; /* Denotes the extended image */


/* Find maximum of array*/

greyval findMax(greyval *buf, long width, long height) {
  greyval max = buf[0];
  long i,size = width*height;
  for (i = 1; i<size;i++){
    max = (buf[i]>max) ? buf[i] : max;
  }
  return max;
}

/* Getting standard deviation */

double getStdDev () {;
  return 0.3*((ksize-1)*0.5 - 1) + 0.8;
}

/* Sum of array */

double sumArray(double *arr, int size) {
  int i;
  double sum = 0;
  for (i = 0; i < size; i++){
    sum+= arr[i];
  }
  return sum;
```

```
}

/** Generating kernel used for gaussian blurring
 * @param sigma, the standard deviation
 * @returns the kernel
 */


double *generateKernel(double sigma) {
  int k = ksize;
  int kh = ksize/2;
  double *kernel = malloc(k*k*sizeof(double));
  printf("half k:%d\n", kh);


  int i = 0, j = 0;

  for(i = 0; i < k; i++) {
    for (j = 0; j < k; j++) {
      double alpha = (double) -(((i-kh)*(i-kh)) + ((j-
          kh)*(j-kh)));
      kernel[i*k+j] = exp(alpha/(2*sigma*sigma));
    }
  }

    double sum = sumArray(kernel, k*k);

  for(i = 0; i < k*k; i ++) {
    kernel[i] /= sum;
  }
 /* for(i = 0; i < k; i++) {
    for(j = 0; j < k; j++) {
      printf("%lf ", kernel[i*k + j]);
    }
    printf("\n");
  } */

  return kernel;
}

/* Extending image corners and edges for easier
    gaussian blurring */


void extendImage() {
```

```
  eImage = calloc((size_t)NumPlanes, sizeof(greyval *));
  assert(eImage != NULL);
  long imsize = (eWidth) * (eHeight);
  int i,j, plane;
  for (i=0;i<NumPlanes;i++){
    eImage[i] = calloc((size_t)imsize, sizeof(greyval));
    assert(eImage[i] != NULL);
  }

  for (plane = 0; plane < NumPlanes; plane++) {

    //Top left

    for(i = 0; i < ksize/2; i++) {
      for(j = 0; j < ksize/2; j++) {
        eImage[plane][i*(eWidth) + j] = ORI[plane][0];

      }
    }

    //Top right

    for(i = 0; i < ksize/2; i++) {
      for(j = eWidth - ksize/2; j < eWidth; j++) {
        eImage[plane][i*(eWidth) + j] = ORI[plane][ImageWidth-1];

      }
    }

    //Bottom left

    for(i = eHeight - ksize/2; i < eHeight; i++) {
      for(j = 0; j < ksize/2; j++) {
        eImage[plane][i*(eWidth) + j] = ORI[plane][(ImageHeight-1)*ImageWidth];

      }
    }

    //Bottom right

    for(i = eHeight - ksize/2; i < eHeight; i++) {
      for(j = eWidth - ksize/2; j < eWidth; j++) {
```

```
        eImage[plane][i*(eWidth) + j] = ORI[plane][ImageHeight*ImageWidth-1];
      }
    }

    //Horizontal Edges

    for(i = ksize/2; i < eWidth - ksize/2; i++) {
      for(j = 0 ; j < ksize/2;j++) {
        eImage[plane][i + j*eWidth] = ORI[plane][i-ksize/2];
      }
    }

    for(i = ksize/2; i < eWidth - ksize/2; i++) {
      for(j = 0 ; j < ksize/2;j++) {
        eImage[plane][i + (j+eHeight-ksize/2)*eWidth] = ORI[plane][i+(ImageHeight-1)*ImageWidth-ksize/2];
      }
    }


    //Vertical edges

    for(i = ksize/2; i < eHeight - ksize/2; i++) {
      for(j = 0 ; j < ksize/2;j++) {
        eImage[plane][i*eWidth + j] = ORI[plane][ImageWidth*(i-ksize/2)];
      }
    }

    for(i = ksize/2; i < eHeight - ksize/2; i++) {
      for(j = eWidth -ksize/2 ; j < eWidth;j++) {
        eImage[plane][i*eWidth + j] = ORI[plane][ImageWidth*(i-ksize/2) +ImageWidth -1];
      }
    }

    //Rest of image;

    for(i = ksize/2; i < eHeight- ksize/2; i++) {
      for(j = ksize/2; j < eWidth - ksize/2; j++) {
        eImage[plane][i * eWidth + j] = ORI[plane][(i-ksize/2)*ImageWidth + j-ksize/2];
      }
```

```
    }
  }

}

/* Gaussian blurring of image */

void gaussianBlur() {
  int i,j,k, l, plane;
  extendImage();
  long imsize = ImageWidth*ImageHeight;
  new = calloc((size_t)NumPlanes, sizeof(greyval *));
  assert(new!=NULL);
  for (i=0;i<NumPlanes;i++){
    new[i] = calloc((size_t)imsize, sizeof(greyval));
    assert(new[i]!=NULL);
  }
  double *kernel = generateKernel(getStdDev());

  /* Blurring is happeninng here */
  for (plane = 0; plane < NumPlanes; plane++) {

    for(i = 0; i < ImageHeight; i++) {
      for(j= 0; j < ImageWidth; j++) {
        for(k = 0; k < ksize; k++) {
          for(l = 0; l < ksize; l++) {
            new[plane][i*ImageWidth+j] += kernel[k*
                ksize + l] * eImage[plane][i*eWidth + j
                 +  l + k*eWidth];
          }
        }
      }
    }
    free(kernel);
  }
}

/* Original image minus low pass filter */


void highPass(int beta) {
  greyval **pos, **neg;
  long i, plane;
  long imsize = ImageWidth*ImageHeight;

  //Positive values
```

```

  pos = calloc((size_t)NumPlanes, sizeof(greyval *));
  assert(pos!=NULL);
  for (i=0;i<NumPlanes;i++){
    pos[i] = calloc((size_t)imsize, sizeof(greyval));
    assert(pos[i]!=NULL);
  }

  //Negative values

  neg = calloc((size_t)NumPlanes, sizeof(greyval *));
  assert(neg!=NULL);
  for (i=0;i<NumPlanes;i++){
    neg[i] = calloc((size_t)imsize, sizeof(greyval));
    assert(neg[i]!=NULL);
  }

  //High-pass
  for (plane = 0; plane < NumPlanes; plane++) {
    for(i = 0; i <ImageWidth*ImageHeight; i++) {
      int pixel = (int) (ORI[plane][i] - new[plane][i
          ]);
      if(pixel < 0) {
        neg[plane][i] = (pixel*beta*-1 > N) ? N :(
            greyval) pixel*-1*beta;
      } else {
        pos[plane][i] = (pixel*beta > N) ? N : (
            greyval) pixel*beta;
      }
    }
  }

  //Writing images

  if ( N> 255) {
    WriteTIFF("pos.tif", ImageWidth, ImageHeight, 16,
        NumPlanes, pos);
    WriteTIFF("neg.tif", ImageWidth, ImageHeight, 16,
        NumPlanes, neg);
  } else {
    WriteTIFF("pos.tif", ImageWidth, ImageHeight, 8,
        NumPlanes, pos);
    WriteTIFF("neg.tif", ImageWidth, ImageHeight, 8,
        NumPlanes, neg);

  }
```

```


  for(plane=0; plane<NumPlanes; plane++){
    free(pos[plane]);
    free(neg[plane]);
  }

  free(pos);
  free(neg);

}

int main(int argc, char *argv[]) {

  FreeImage_Initialise(0);
  int i,plane, beta =1;

  if (argc < 3)  {
    printf("Usage: %s inputfile ksize [beta][\n", argv[0]);
    exit(0);
  }
  ksize = atoi(argv[2]);
  if(ksize % 2 == 0) {
    printf("ksize must be odd\n");
    exit(0);
  }

  if (argc  == 4) {
    beta = atoi(argv[3]);
  }

  long width, height;
  ORI = ReadTIFF(argv[1], &width, &height, &NumPlanes);
  N = (findMax(ORI[0], width, height) > 255 ? NUMLEVELS-1 : 255);
  ImageWidth = width;
  ImageHeight = height;
  eWidth = width + ksize -1;
  eHeight = height + ksize -1;
  gaussianBlur();
  highPass(beta);

 // printf("ImageHeight: %ld, ImageWidth: %ld\n", ImageHeight, ImageWidth);
```

```

  for(plane=0; plane<NumPlanes; plane++){
     free(ORI[plane]);
     free(eImage[plane]);
     free(new[plane]);
   }

  free(ORI);
  free(eImage);
  free(new);

  FreeImage_DeInitialise();
}
```

A.3 unsharpMasking.c

```


#include <assert.h>
#include <stddef.h>
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <sys/times.h>
#include <unistd.h>
#include <FreeImage.h>
#include <math.h>

long ImageWidth;
long ImageHeight;

long ImageSize;
long NumPlanes;

typedef unsigned short greyval;
typedef unsigned char ubyte;

#define NUMLEVELS     65536

greyval N;

greyval **ORI;    /* Denotes the original ... in the
    unproceesed input image */
greyval **neg;    /* Denotes the processed input image
     */
```

```
greyval **pos;


/* Unsharp Masking*/

void usm (int beta) {
  int i, plane;
  for (plane = 0; plane < NumPlanes; plane++) {
    for(i = 0; i < ImageSize; i++) {
      int pixel = (int) ((int)(ORI[0][i] + pos[0][i]*beta - neg[0][i]*beta));
      if(pixel > N) {
        ORI[plane][i] = N;
      } else if(pixel < 0) {
        ORI[plane][i] = 0;
      } else {
        ORI[plane][i] = (greyval) pixel;
      }
    }
  }
}


int main(int argc, char *argv[]) {

  FreeImage_Initialise(0);
  int beta = 1;
  if (argc < 5) {
    printf ("Usage: %s original positive negative beta \n", argv[0]);
  }

  ORI =ReadTIFF(argv[1], &ImageWidth, &ImageHeight, &NumPlanes);
  pos = ReadTIFF(argv[2], &ImageWidth, &ImageHeight, &NumPlanes);
  neg = ReadTIFF(argv[3], &ImageWidth, &ImageHeight, &NumPlanes);
  N = (findMax(ORI[0], ImageWidth, ImageHeight) > 255 ? NUMLEVELS-1 : 255);


  ImageSize = ImageWidth * ImageHeight;

  if(argc == 5) {
    beta = atoi(argv[4]);
```

```
  }

  usm(beta);

  FreeImage_DeInitialise();
  if (N > 255) {
    WriteTIFF("usm.tif", ImageWidth, ImageHeight, 16,
        NumPlanes, ORI);
  } else {
    WriteTIFF("usm.tif", ImageWidth, ImageHeight, 8,
        NumPlanes, ORI);
  }


}
```