Automated image analysis for marine icing events

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SUMMARY

Describes an automated approach for detecting ice thickness on vessels. Uses Marine Icing Monitoring System and Python to calculate the total ice accumulation and rate of increase during icing events on the Atlantic Kingfisher

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AUTOMATED IMAGE ANALYSIS FOR MARINE ICING EVENTS

SR-2008-04

Wayne Bruce

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Table of Contents

Table of Figures

Appendices

Automated Image Analysis for Marine Icing Events

1.0 Introduction

This report will focus on the analysis of ice accumulation using the Marine Icing Monitoring System (MIMS). Ice build-up continues to be a concern for offshore structures and vessels during the winter months. Python, a programming language, along with images from the MIMS technology uses an automated approach to calculate the rate and thickness of ice during icing events. Currently, the program investigates icing events occurring in the 2006/2007 winter on the Atlantic Kingfisher, an offshore supply vessel providing support for Petro-Canada's Terra Nova project. MIMS, developed by the Institute for Ocean Technology, continues to try and improve this technology and increase safety conditions during icing events.

2.0 Ice Accumulation

Ice accumulation on vessels can be a dangerous and cause both operation and safety problems if the issue is not monitored. The accumulation is caused by precipitation and marine icing spray under cold weather conditions. With significant amounts of ice build-up, the vessel's weight can increase dramatically. This problem can result in stability issues as the centre of gravity of the vessel may be altered. Figure 1 shows large amounts of ice on the Atlantic Kingfisher during the winter of 2006/2007. This type of accumulation can become a major hazard to the standard operations of the vessel. With the potential to capsize vessels, icing is a danger that must be monitored during the winter.

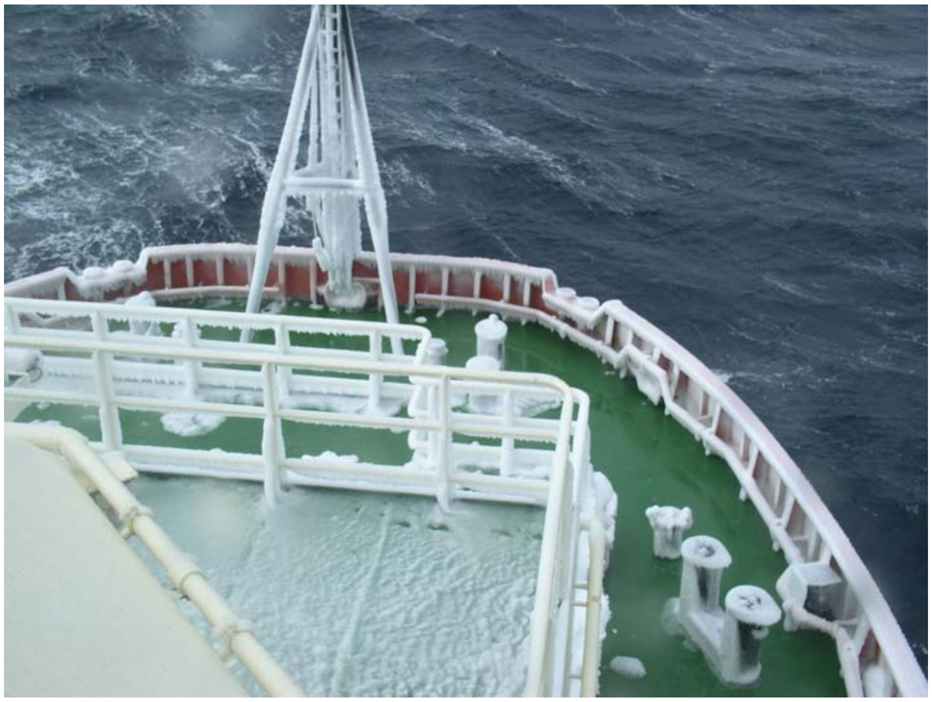


Figure 1: Icing event on the Kingfisher

2.1 Marine Icing Spray

Marine icing spray refers to large sprays of water onto the deck of the ship. It is caused by waves crashing into the hull of the ship under certain weather conditions. Marine icing spray, as shown in Figure 2, can produce large amounts of water on the vessel’s deck, as the excess water will cause icing on susceptible areas of the vessel. High wind speed of approximately 9 m/s is needed to create sufficient waves (1m or higher) for the icing spray and a temperature of –10 °C is sufficient for icing to occur on the vessel. Under these conditions, marine icing spray is prone to create ice build-up and safety issues.

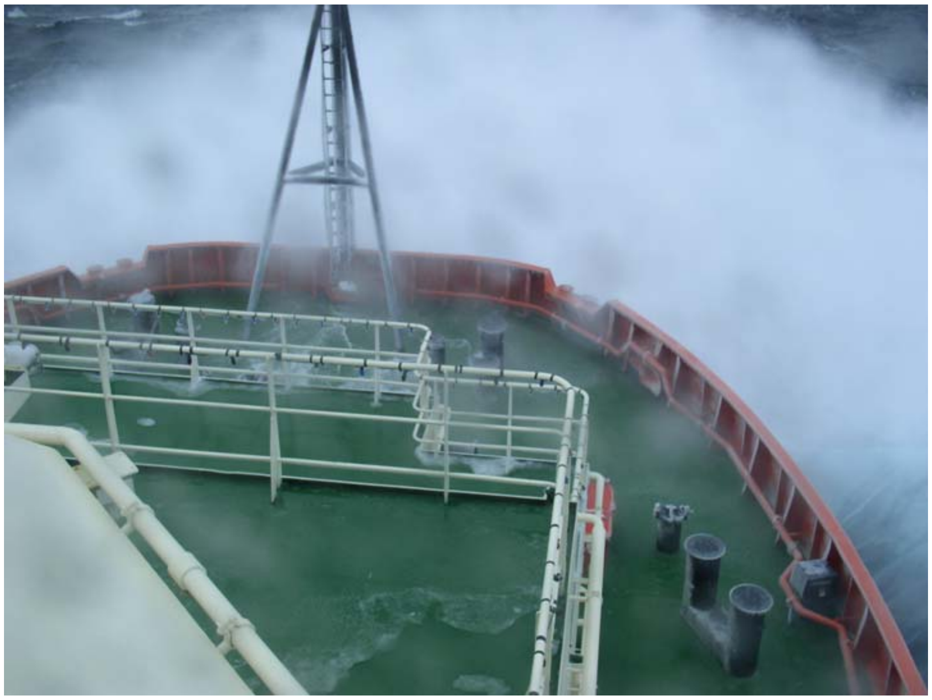


Figure 2: Splash occurred against the Kingfisher

3.0 Marine Icing Monitoring System

To monitor the icing events that occur on vessels, the Institute for Ocean Technology (IOT) developed the Marine Icing Monitoring System (MIMS). With the use of this technology, ice accumulation can be continuously observed to avoid problems that can occur during these circumstances.

MIMS technology is comprised of two cameras connected to a CPU (see Figure 3). The stationary cameras are located at the starboard and port sides of the vessel facing the front of the vessel. Each camera is programmed to take a picture in intervals of 12 minutes. The timing of both cameras is offset from each other creating one picture every 6 minutes. As well, the system includes a metal casing around the camera and a well-insulated area for all electronic components during marine conditions.

For monitoring purposes, a satellite phone was established to control the technology from IOT. The capabilities of the phone include zooming the camera in and out and downloading images captured by the technology. Thumbnail images are often downloaded for monitoring since large full-scale images take great deal of time to produce. Instead, these images are retrieved from the vessel after the winter season.

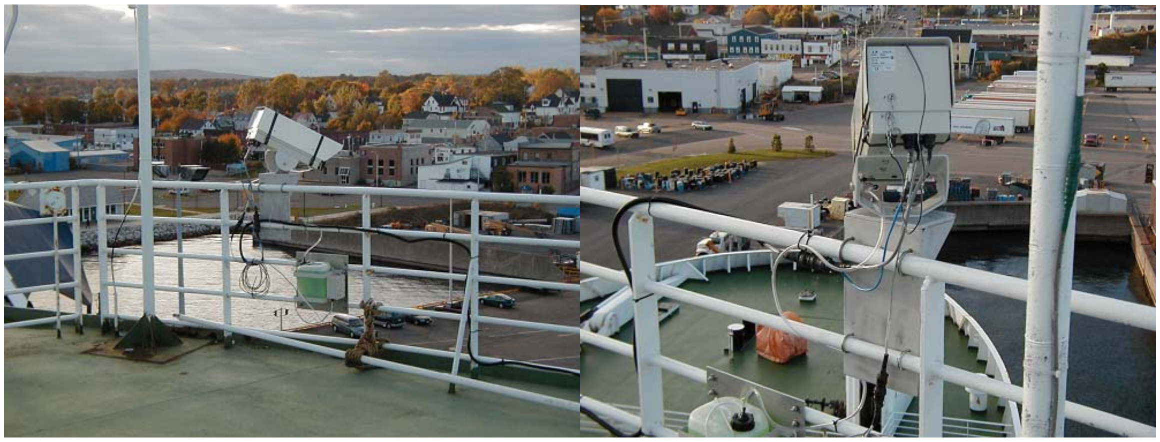


Figure 3: MIMS cameras on the Caribou

The first Marine Icing Monitoring System was installed on Marine Atlantic's ferry, the MV Caribou. This system was used to gain information on the system's ability to tolerate the environmental conditions. From observations of the first cameras, additional heaters needed to be installed as the camera window continued to freeze during icing events. Adjustments were made to improve the second MIMS installed on the Atlantic Kingfisher. Visibility has increased from the first MIMS but some ice can still form on the camera window (shown in Figure 4). The images from the second MIMS are used for the automated analysis during the 2006/2007 winter. Currently, as of October 2007, these cameras have been moved to a similar oil supply vessel called the Atlantic Eagle. Seals, antenna, and power supply all needed to be replaced before installation.

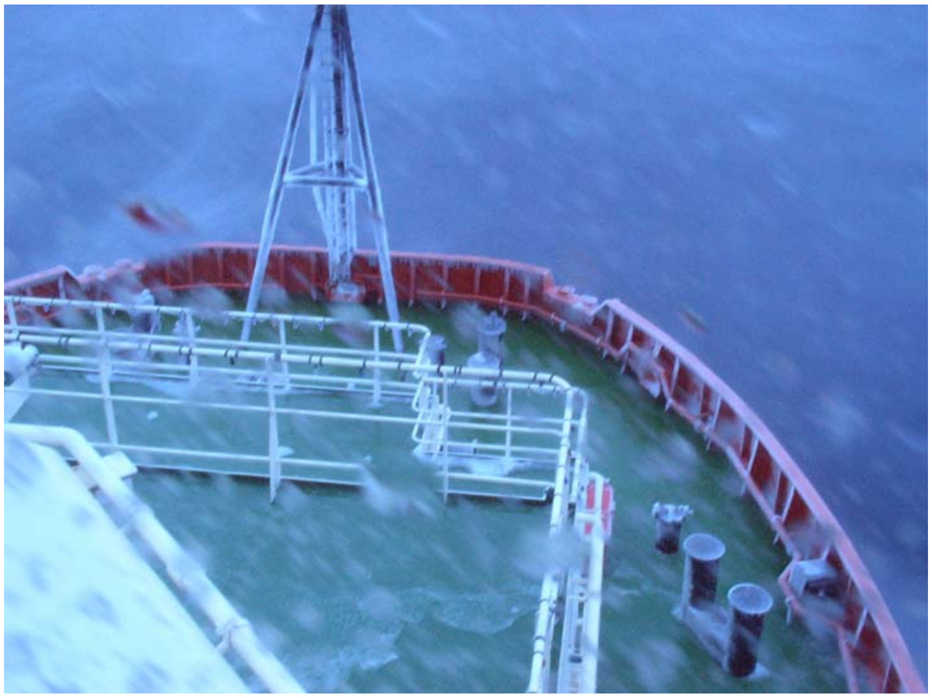


Figure 4: Icing and precipitation on MIMS camera

4.0 Image Analysis

The images collected using the MIMS technology can be analyzed further to incorporate the amount and rate of ice accumulation during icing events. Python, an object-oriented programming language, is used for analysis in an automated approach. The program uses edge detection techniques to find the width of particular structures for each image during the icing event. By comparing these measurements to the actual width found with no ice, the computer can output the ice thickness. Currently, the analysis has been conducted for icing events occurring on the Atlantic Kingfisher in December 2006 – February 2007. The program incorporates positions from the fixed images of the Kingfisher, however, the method could be modified for other vessels in the future.

4.1 Positions

The positions for analysis have been chosen to correspond with the techniques used in the program. There are many factors that make one position more suitable than another to analyze. For example, linear structures result in more accurate edge detection calculations than rounded or elliptical structures. This result is caused by the edge detection method chosen for analysis. The method focuses on pixels of the image in a linear approach causing rounded structures to be less accurate.

As well, positions with vertical members have ice accumulation that is more uniform than horizontal structures. During icing events, horizontal structures, such as the white railing shown in Figure 11, will create icicles. The analysis can become flawed at these positions as it becomes difficult to find ice thickness.

There have been 17 positions chosen for analysis during the icing events. As you can see from the figure below, the majority of which are located on the black pole structure. This structure appeared to give the most accurate results when computing the ice thickness on the vessel. With so many positions on this structure, relationships with respect to height and distance can be observed from analysis. As well, significant ice build-up has been observed on the black circular structures and the railing of the vessel in which three positions each have been analyzed.

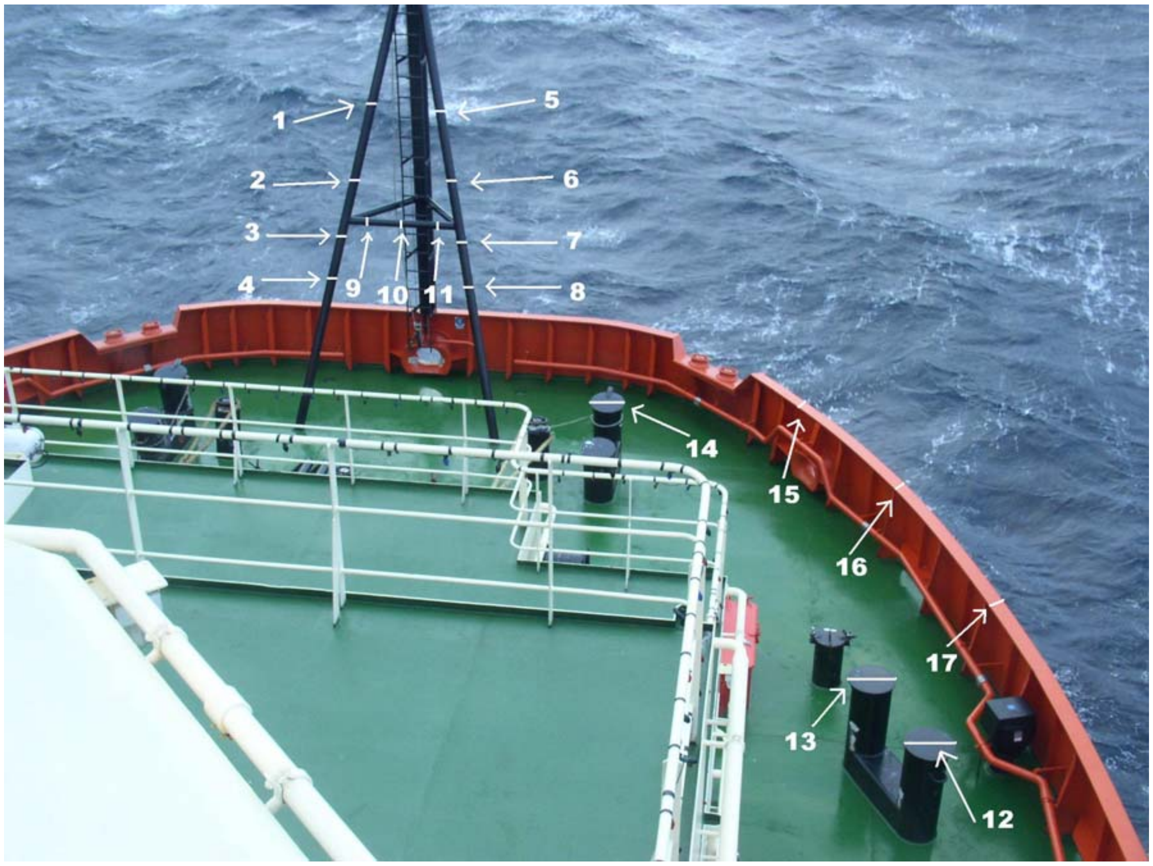
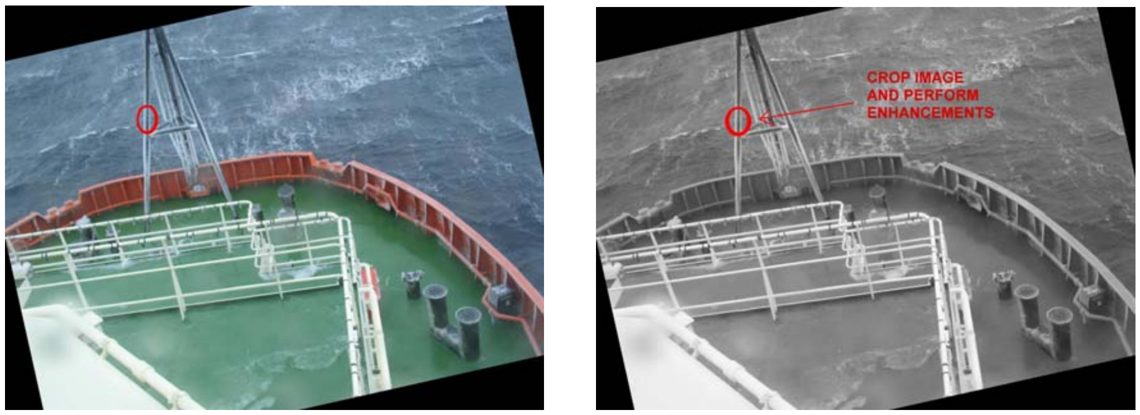


Figure 5: Positions used during automated analysis

4.2 Image Processing

Each image in the icing event must undergo the same filters and enhancements to ensure the best possible results. When conducting image processing in Python, a new module called Python Imaging Library (PIL) must be imported into the script. PIL adds image-processing capabilities to your interpreter and contains all basic commands needed to manipulate your image. The commands are created to simplify programs and reduce the time it can take to run large self-written modules for images.

When the image is uploaded, it is rotated by a particular amount calculated for each position. This occurs so that the structure analyzed is in a vertical position required for edge detection. Next the image is changed completely to greyscale (see Figure 6). A greyscale image is easier to process as all pixels in the image can be related using the same numerical scale (black = 0 and white = 255). After these processes, the program uses the crop command to focus on the position that is being calculated. The cropped image is modified to a size that will exclude as much noise and possible edges that can interfere. However, ice growth on the structure must be accounted for when determining a convenient size for the newly cropped image. This order of commands is created through testing of different configurations. The image has a greater clarity if the rotation and greyscale command precedes the cropping of the image.



(a) (b)

Figure 6: (a) Icing image rotated (b) rotated and converted to greyscale

Following these modifications, the image undergoes enhancements to continue to make the image clear for processing. Auto contrast is one command that is used with a particular cut off level. Any greyscale pixel that is above or below the percentage used for cut off will be changed to black or white, respectively. Another important command is a Median Filter, used for reducing noise in the image. The program uses a 3x3 filter, which analyzes the pixels in that window size. The value of each pixel is examined and all pixels are changed to the median value of the area. This will help avoid speckle noise that can occur in the image. Other commands that can be used for noise reduction include smoothing or blurring the image as well as an EDGE_ENHANCE command to expose the edges better. However, from further tests, these commands were not included in the script. These seemed ineffective or did not improve the calculated widths of the structure. The final image modification is a command known as FIND_EDGES. With this command, the image is converted to black and white as the greyscale pixels are changed to whichever extremity is closer. This results in a black image with edges surfacing as white pixels.

The image processing has changed slightly depending on the particular position during the calculation. For example, color can be a factor for the railing because it has a distinctive red color compared to the positions on the black structure. This creates a lighter image when the greyscale is incorporated. Therefore, changes have been made to create the most accurate results. Image processing for edge detection can be created with only a small amount of code with the use of Python Imaging Library. This module has made very technical processes into conveniently small commands for the script.

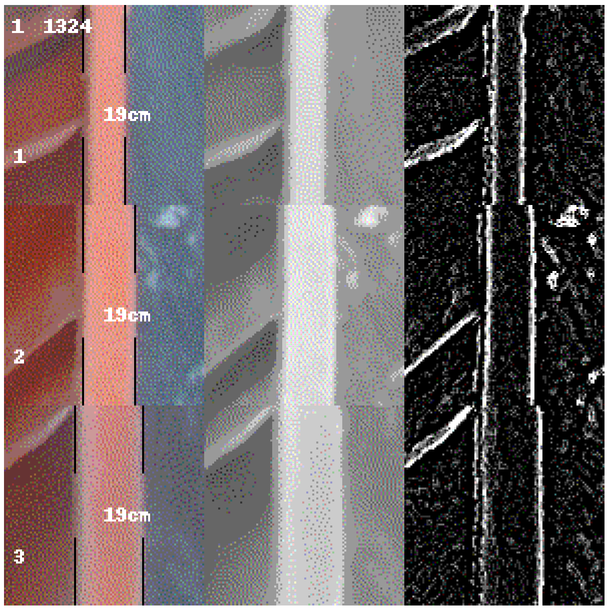


Figure 7: Generated image of the railing with image enhancements

4.3 Edge Detection

When the image has gone through the image processing steps, the program is ready to detect its edges. Images are comprised of pixels, single points in the graphic image that occupy a definable area. Each pixel is represented in a numerical scale which can be anywhere between black at 0 or white at 255. The values of each column of pixels in the image are averaged and compiled in a table in an Excel spreadsheet for easy access. The program begins a loop process at the left side of the image and continues through each column until it has found the maximum value for half of the columns. The loop will end at this maximum and this pixel value is determined as the left edge of the structure. The same method is used for the right edge as the program checks from right to left of the image for the maximum. The subtraction of the right and left edges calculates the width of the structure in pixels.

4.4 Calibration

The width at each position analyzed has no significant meaning without any calibrations. The positions used have been manually measured on the Kingfisher vessel to use for this calibration process. The program is run through images with no ice accumulation to calculate the initial pixel width. The calibration factor of each position is equal to the actual width of structure (in centimetres) divided by the pixel width of the positions with no ice. This value will increase as positions are farther away from the camera. With a list of calibration factors multiplied by each position, respectively, the calculated widths can be displayed in centimetres. The ice accumulation can now be related in actual measurements that are suitable for the analysis.

4.5 Sub-Pixels

A problem that occurred after observing the analysis included frequent time intervals with the exact same width as the icing event progressed. This occurrence was not due to the lack of ice accumulation during these images. The problem is a result of the edge detection process whereby the calculated width can only be from one pixel to another (Ex. From the black structure each measurement is at least 0.68cm apart). The result is data that becomes fixed at the same value for a period of time instead of steadily increasing data. To resolve this problem, the measured widths must be calculated in a sub-pixel level. The edge detection process discussed earlier needed small adjustments to achieve this goal. Instead of averaging pixel values of each column, you could use the same method numerous times with a selected amount of rows (used sections of 5 rows). By using the edge detection technique several times and averaging these values found, the data set becomes more accurate for the ice thickness analysis. The data shows an improved uniform increase as expected for actual conditions. As well, necessary error factors have been implemented to this list of edge values to ensure that flawed values do not affect the analysis.

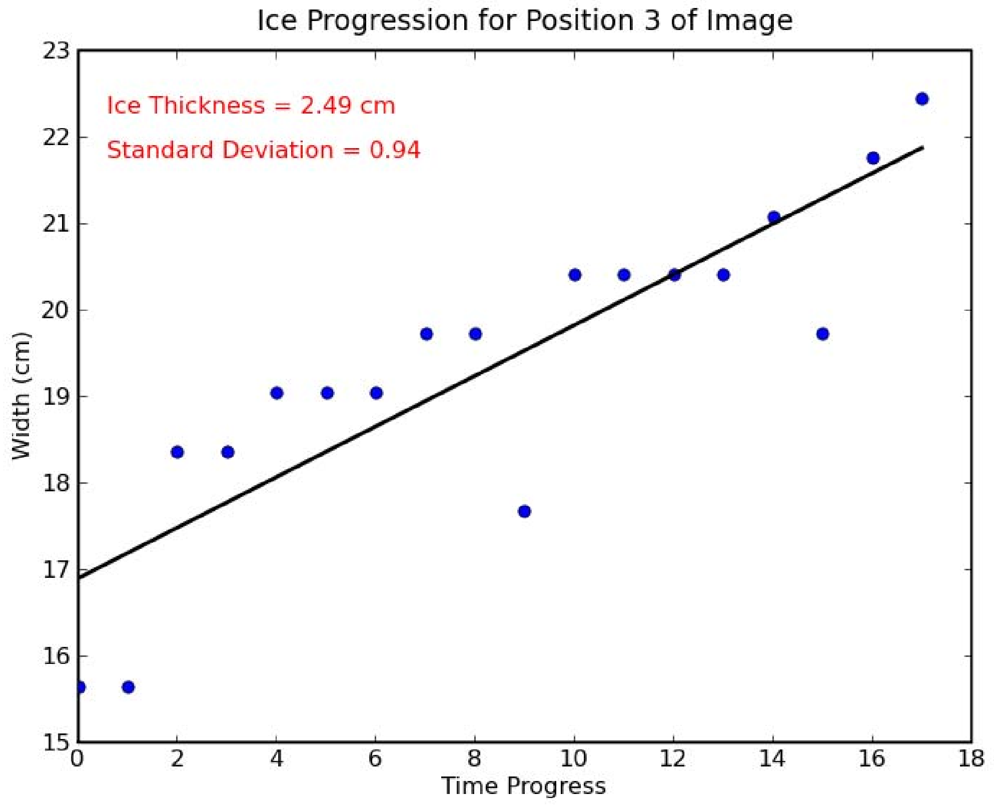


Figure 8: Before sub-pixel method was incorporated into edge detection

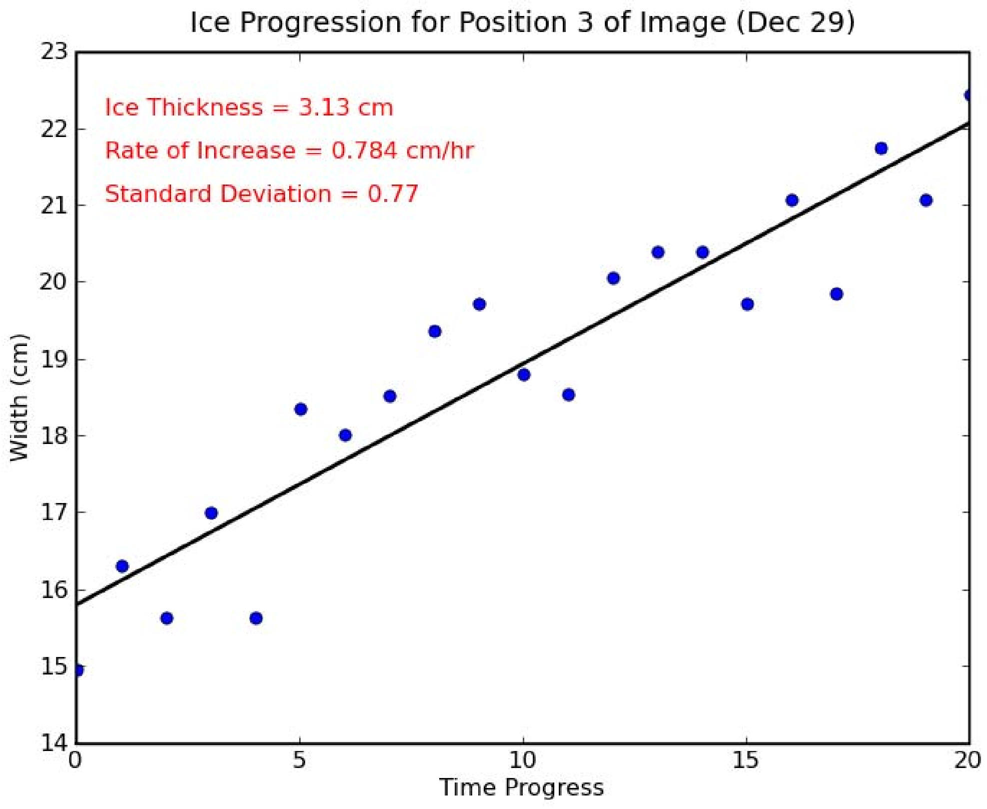


Figure 9: After sub-pixel method incorporated

4.6 Generated Images

To assist with the analysis of the icing event, the program generates a progressive image to incorporate three stages of the image analysis. All three sections of the image are the cropped image at the particular position that is analyzed. The first section includes the image cropped and rotated while the second contains the image changed to greyscale with the other enhancements implemented by the program. Finally, the last section includes all edge commands and the final appearance that the edge detection will use for calculations. As well, the script produces lines as markers for the left and right edge of the structure. These appear on the first section as vertical lines for the linear structures and horizontal lines for the elliptical. These lines give an indication on whether the program is running properly and detecting the edges well. It also gives the ability to show the ice accumulation increase with each new image. The images include reference number, time of day, and position number. Another property that has been included in the images is whether or not the detection process could not find an edge. If this is the case, the program will output ‘Could not find edges’ directly on the photo. This width value for the particular position is removed from the data. The indication creates further inspection and helps the detection process. Often you can reference back to the original image to check if any precipitation on the camera is the problem or if the process is not responding well.

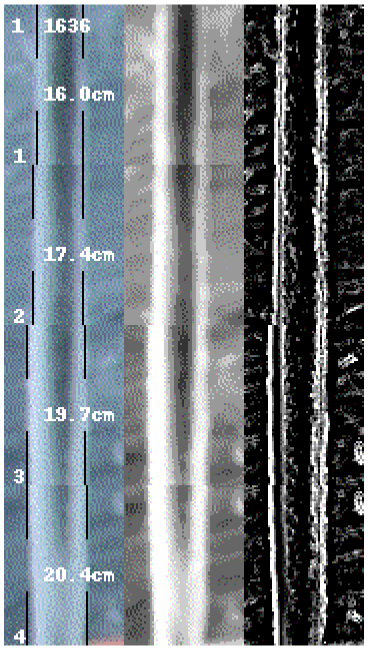


Figure 10: Generated image of linear structure (black pole structure)

4.7 Elliptical Structures

The Edge detection method that has been used is ideally suited for linear structures such as black pole structure in the image. However, from inspection, there is significant ice accumulation on the circular black covers as shown in Figure 11. This accumulation warrants analysis at these positions. Three positions have been chosen to analyze with the program. Unfortunately, the techniques previously used for the linear structures do not accurately determine the edges of the elliptical shape. To resolve this problem, the program has been adjusted with small changes to the edge detection. Instead of evaluating all rows of pixels, the program will average the pixel values of several rows in the middle of image. This will determine the rounded edge more effectively from the elliptical shape. This method works significantly better than the original, but the linear structures continue to show a more accurate result.

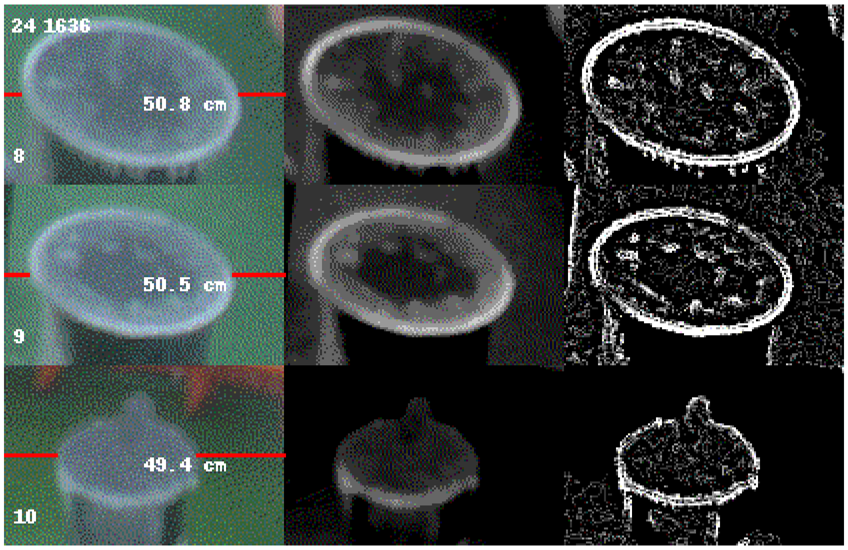


Figure 11: Generated image of the elliptical structure

5.0 Ice Progression Graph

With the addition of the matplotlib extension to Python, the program is given graphing capabilities to help display the ice analysis (see Appendix C). As shown in Figure 12, the script will output and save a graph displaying all the necessary calculations of the icing event in an organized manner (see Appendix B for additional graphs of each position during the December 29, 2006 icing event).

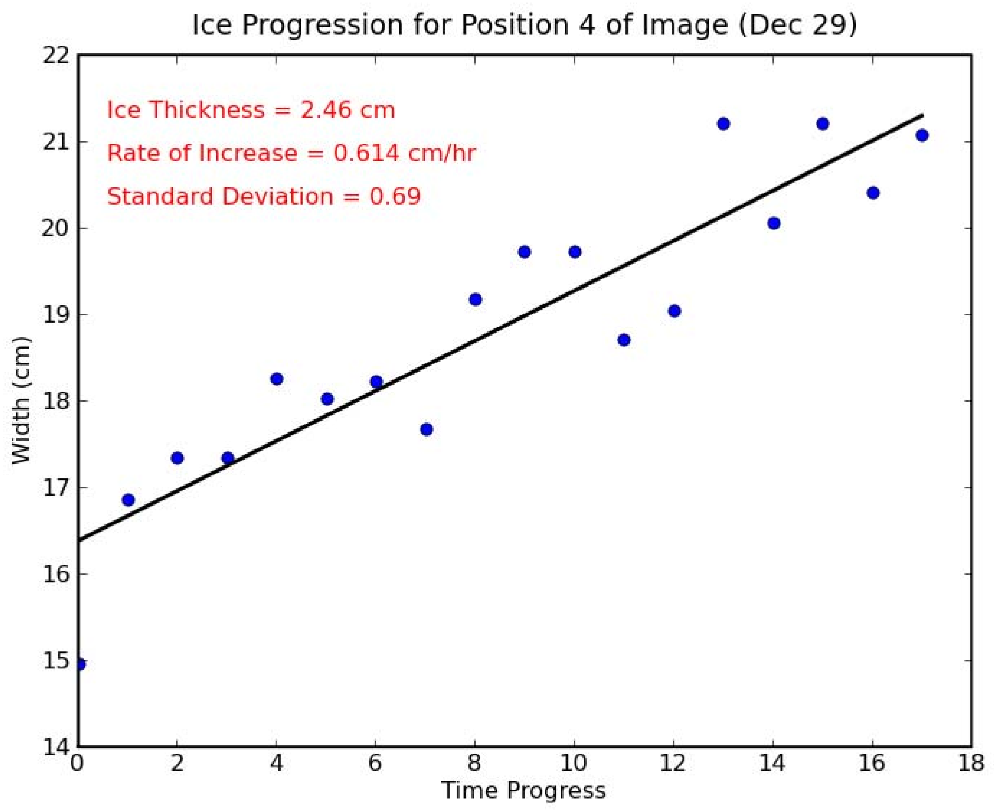


Figure 12: Graph generated from Dec. 29 icing event

5.1 Features

The graph includes a scattered plot of the width of each structure as the icing event progresses. A line of best fit is incorporated with respect to the data using standard commands in Python. The accuracy of this line is given in the top left corner of the graph as standard deviation. The residual standard deviation represents the average distance that each point is away from the best-fit line. As well, the ice thickness is calculated from the data by comparing the width of the standard structure with no ice and the icing width after the accumulation. The third calculation given at the top of the graph is the rate at which the ice is growing. This refers to the thickness of ice divided by the length of time for the icing event (five images are captured during one hour).

To increase the accuracy of the results, an error calculation is incorporated to avoid flawed data points (shown in Python Code, Appendix A). Edges that are not detected correctly can lead to a best-fit line that does not represent the entire data set well. By using the error formula, these points are removed from the data by comparing all points to the median value.

5.2 Relationships

From inspection of the graphs generated by the program, the most accurate data is retrieved from the black pole structure (see Appendix C for all positions). These positions have a smaller residual standard deviation than other position as the values are more closely related to the line of best fit. However, the horizontal pole of the black structure (positions 9, 10, and 11) does not calculate with the same accuracy. This is caused by the fact that some icicles have formed on the bottom of the pole creating ice build-up that is not uniform and difficult to calculate.

In addition to the black structure, the data from the railing positions were accurate with small deviation. However, more flawed values were removed and resulted in a smaller data set. These positions create better results than the elliptical data, as the computer often cannot detect the round edge effectively.

Another trend that can be observed from the data collected is with respect to the height and distance from the exterior of the vessel. As the height of the position decreases (seen in positions 1-4 and 5-8 of Figure 5), the ice accumulation increases. This occurrence is based on the marine icing spray as the lower positions of the structure tend to be sprayed in greater amounts. As well, the railing shows a relationship with the bow of the vessel. There is significantly greater ice accumulation the closer to the bow since this is the part of the vessel, which the icing spray initially originates (positions 15, 16, and 17 of railing). Distance also plays a role with the white poles displayed in the image since they seem to be too far from the hull of the vessel to get sufficient icing spray to create accumulation.

6.0 Conclusion

The MIMS technology continues to be employed on the Atlantic Eagle as it captures a large amount of images during each winter. The images give the ability to monitor and research icing on offshore vessels and have the potential to avoid dangerous situations.

With the use of Python, ice accumulation and the rate of growth has been calculated in an automated approach. The accuracy of the automated analysis continues to improve and demonstrate the positions susceptible to icing. As MIMS and the detection methods develop, it can be a significant safety feature for vessels. Monitoring these icing events is necessary for all vessels travelling in waters that are prone to marine icing.

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Appendix A

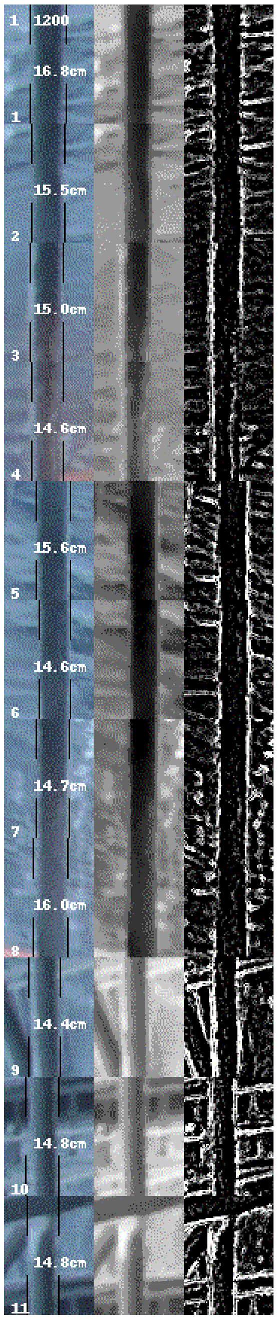
Python Code for Automated Image Analysis

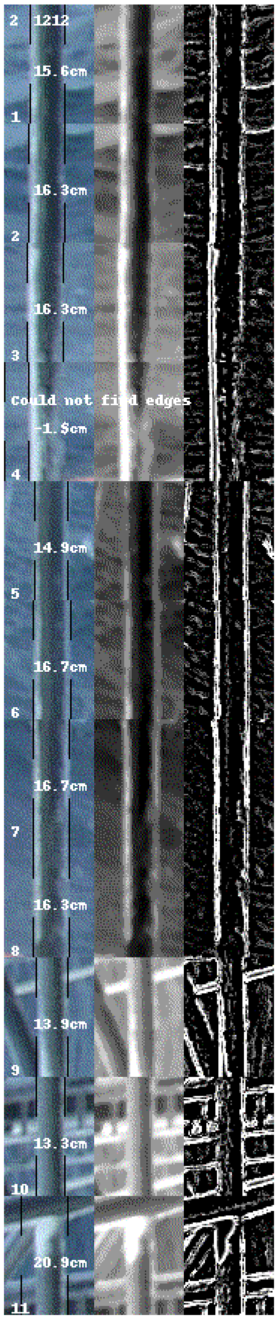
```
                import Image  # PIL Python Image Library
import ImageOps
import ImageFilter
import ImageDraw
import ImageFont
import glob, os
import csv
from pylab import *


frame = 100000

calib = (0.68, 0.68, 0.68, 0.68, 0.68, 0.68, 0.68, 0.68, 0.68, 0.68,
0.68)
boxS = (60,80)    # size of image segment
boxR = [12.6, 12.6, 12.6, 12.5, -9.5, -9.6, -9.6, -9.6, 94, 94, 94] #
rotation of image segment
boxO = [(575,350), (575,400), (575,575), (575,630),
        (950,225), (950,275), (950,425), (950,500),
        (725,1230), (725,1170), (725,1113)
        ] # location of corner of image segment after rotation

cmlist = [[] for i in range(len(boxR))]


boxesSize = [(a[0], a[1], a[0]+boxS[0], a[1]+boxS[1]) for a in boxO]
holdSize =  [ 0, 0 , boxS[0]*3, boxS[1]*len(boxO)] # output image gif

cnt = 1

fo = csv.writer(open("E:\Icing Event\icing.csv", 'wb'))
fof = csv.writer(open("E:\Icing Event\icingNum.csv", 'wb'))

col = [(' ')]*(3) # output data

for infile in glob.glob("E:\\Icing Event\\Icing Pics\\J*.jpg"):
    filepath, filename = os.path.split(infile)
    filename, ext = os.path.splitext(filename)

    results = [filename] # list of file names
    results.append(cnt) # append counter to list of file names

    im = Image.open(infile) # open image

    hold = im.crop(holdSize) # create image to hold visual results

    for i, box in enumerate(boxesSize):  # for each area to analyze
        region = im.rotate(boxR[i], resample=2) # rotate image
        hold.paste(region.crop(box), (0, boxS[1]*i)) # save cropped
original


        #region = region.crop(box)
        region = ImageOps.grayscale(region)
        #region = region.filter(ImageFilter.SMOOTH)
        #region = region.convert('L')
        #region = region.filter(ImageFilter.BLUR)
        region = ImageOps.autocontrast(region, cutoff=10)
        region = region.filter(ImageFilter.MedianFilter(3))
        region = region.filter(ImageFilter.SMOOTH)
        region = ImageOps.autocontrast(region, cutoff=3)
        #region.show()
        #edge = region.filter(ImageFilter.EDGE_ENHANCE)
        edge = region.filter(ImageFilter.MedianFilter(3))
        edge = edge.filter(ImageFilter.FIND_EDGES)
        edge = ImageOps.autocontrast(edge, cutoff=2)
        #edge.show()
        edge = edge.crop(box)


        hold.paste(region.crop(box),(boxS[0], boxS[1]*i)) # save
processed segment

        hold.paste(edge,(boxS[0]*2, boxS[1]*i)) # save edge segment


        width,height = edge.size # get the size of the image

        temp = [0]*width # temp list to hold average values
        string = ''
        data = list(edge.getdata()) # convert image to list of values

        first1 = []
        last1 = []

        for n in range(height/5):
            rge_htx = (0 + 5*n)
            rge_hty = (5 + 5*n)
            for j in range(width): # average values for each column
                for k in range(rge_htx,rge_hty):
                    temp[j] += float(data[k*width+j])
                temp[j] = temp[j]/(height/5)

                if i == 0:  # for first segment output column averages
                    col[1] = j
                    col[2] = '%5.1f' % (temp[j])
                    col[0] = cnt
                    fo.writerow(col)


            peak = int(max(temp[5:-5])*0.7) # define peak value as 70%
of max


            for k in range(5, width/2): # find left edge
                if peak < temp[k]:
                    first1.append(k-1)
                    break

            for k in range(width-5, width/2, -1):  # find right edge
                if peak < temp[k]:
                    last1.append(k+1)
                    break

##        print first1, last1

        if len(first1) != 0 and len(last1) != 0:
            error = (first1 - mean(first1))**2
            ermedian = median(error) * 1.5
            g = 0
            for f in range(0,len(first1)):
                if error[f] > ermedian:
                    first1 = delete(first1, [g])
                    g = g-1
                elif error[f] < ermedian/2.5:
                    first1 = delete(first1, [g])
                    g = g-1
                g += 1

            error = (last1 - mean(last1))**2
            ermedian = median(error) * 1.5
            g = 0
            for f in range(0,len(last1)):
                if error[f] > ermedian:
                    last1 = delete(last1, [g])
                    g = g-1
                elif error[f] < ermedian/2.5:
                    last1 = delete(last1, [g])
                    g = g-1
                g += 1


        first = mean(first1)
        last = mean(last1)
##        print first1,last1
##        print first,last



        pixelwidth = (last-first)
        draw = ImageDraw.Draw(hold)
        cmwidth = calib[i] * pixelwidth

        if len(first1) == 0 or len(last1) == 0:
            draw.text((5, boxS[1]*i+20), 'Could not find edges')
        else:
            cmlist[i].append(cmwidth)


        results.append(pixelwidth) # append width of edges to results

        text = ' %s ,%3d, %3d, %3d' % (filename, pixelwidth, int(first),
int(last))


        string = '%2.1f' % (cmwidth) + 'cm'
        pos = (int(boxS[0]/3), int(boxS[1]*i+boxS[1]/2)-1)
        draw.text( pos, string) # write edge width on image

        topline = int(boxS[1]/3+boxS[1]*i)
        botline1 = int(boxS[1]*2/3+boxS[1]*i)
        botline2 = int(boxS[1]+boxS[1]*i)

        draw.line(((first,boxS[1]*i), (first,topline)),fill=256,width=1)
        draw.line(((first,botline1), (first,
botline2)),fill=256,width=1)
        draw.line(((last,boxS[1]*i),(last,topline)),fill=256,width=1)
        draw.line(((last,botline1),(last,botline2)),fill=256,width=1)


# displays text for position counter, image counter, and time of each
image
        for h in range(0,len(boxR)):
            string1 = (('%d' % (h+1)), ('%d' % (cnt)), (infile[-9:-5]))
            pos = ((5, boxS[1]*h+70), (4,5), (20,5))
            for g in range(0,len(string1)):
                draw = ImageDraw.Draw(hold)
                draw.text(pos[g], string1[g])
            g += 1
        h += 1
    print text, cnt # output to screen

    fof.writerow(results)   # write results to second file


    picture = 'E:\Icing Event\\Analysis Pics\\'
    frame += 1
    string = '%s' % (frame)
    pic = '%s%s.gif' % (picture, string[-4:] )
    hold.save(pic[0:len(picture)] + 'jan15pole' + pic[-8:], "GIF")


    cnt +=1

    if cnt >= 40:    # exit after first file
        break


for j in range(len(cmlist)):

    x_list = arange(0,len(cmlist[j]))
    y_list = []

    for x in x_list:
        y = cmlist[j][x]
        y_list.append(y)

    y_list = array(y_list)

    m,b = polyfit(x_list,y_list,1)
    error = (y_list - (m*x_list + b))**2
    ermedian = median(error) * 10

    g = 0
    for i in range(0,len(y_list)):
        if error[i] > ermedian:
            #del y_list[i]
            y_list = delete(y_list, [g])
            g = g-1
        elif error[i] < ermedian/100:
            y_list = delete(y_list, [g])
            g = g-1
        g += 1

    x_list = arange(len(y_list))
    m,b = polyfit(x_list,y_list,1)

    error = (y_list - (m*x_list + b))**2
    ermedian = median(error) * 5
##    print error
##    print ermedian
##    print y_list
##    print len(y_list)
    g = 0
    for i in range(0,len(y_list)):
        if error[i] > ermedian:
            #del y_list[i]
            y_list = delete(y_list, [g])
            g = g-1
        elif error[i] < ermedian/25:
            y_list = delete(y_list, [g])
            g = g-1
        g += 1

    x_list = arange(len(y_list))
    m,b = polyfit(x_list,y_list,1)



    bestfit = m*x_list + b
    ice_thick = (max(bestfit) - min(bestfit))/2
    string = '%s' % (j+1)
    stringice = '%1.2f' % (ice_thick)
    icerate = (max(bestfit) - min(bestfit))/(cnt/5)
    stringrate = '%1.3f' % (icerate)
    print 'The ice thickness for Position', string, 'is', stringice,
'cm'
    print 'The rate of ice thickness is ', stringrate, 'cm/hr'


    std_ice = array((y_list - bestfit)**2)
    std_value = sqrt((std_ice.sum())/(len(y_list)-2))
    std_str = '%1.2f' % (std_value)
    print std_value

    plot(x_list, y_list, 'bo', x_list, bestfit, '-k', linewidth=2)
    string = '%s' % (j+1)
    title('Ice Progression for Position ' + string + ' of Image (Jan
15)')
    xlabel('Time Progress')
    ylabel('Width (cm)')
    figtext(0.15,0.825, 'Ice Thickness = ' + stringice + ' cm',
color='red')
    figtext(0.15,0.725, 'Standard Deviation = ' + std_str, color='red')
    figtext(0.15,0.775, 'Rate of Increase = ' + stringrate + ' cm/hr',
color='red')

    savefig('E:\\Icing Event\\Figures\\jan15figposition' + string +
'.png')
    clf()
```

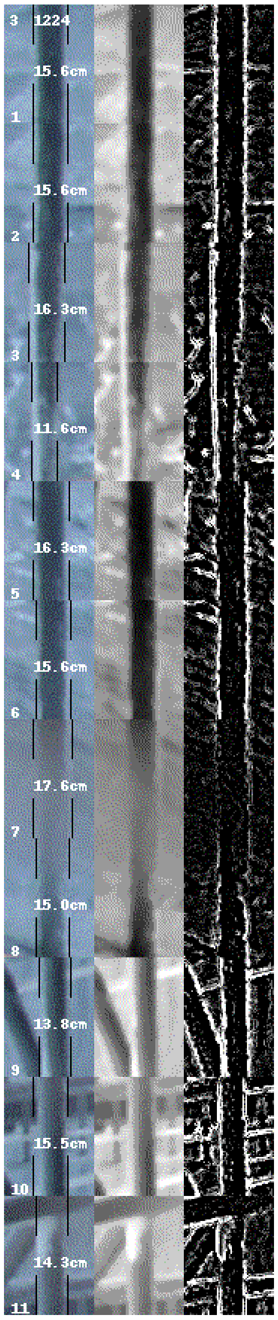
Appendix B

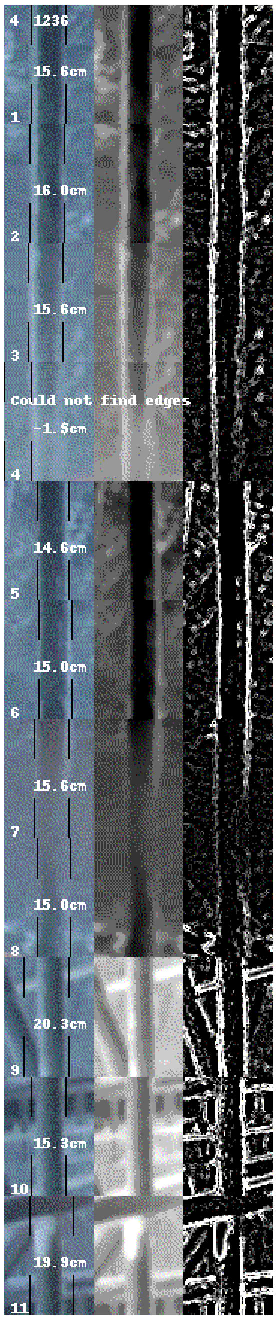
Sample Analysis Pictures for Icing Event (Dec. 29, 2006)

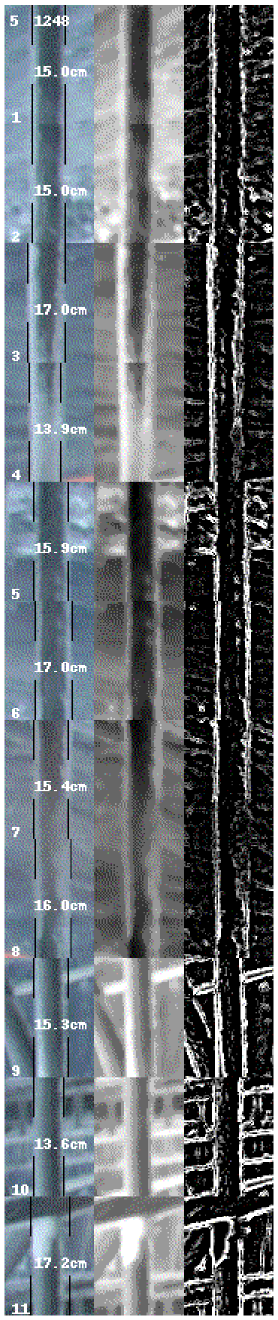
Positions 1 – 11

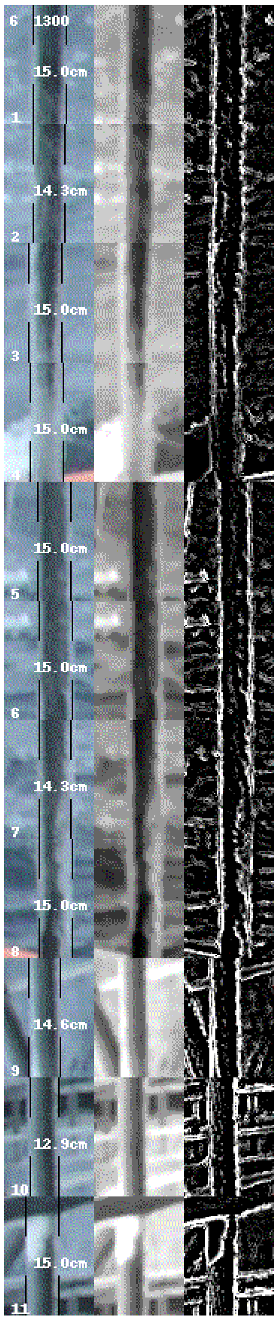


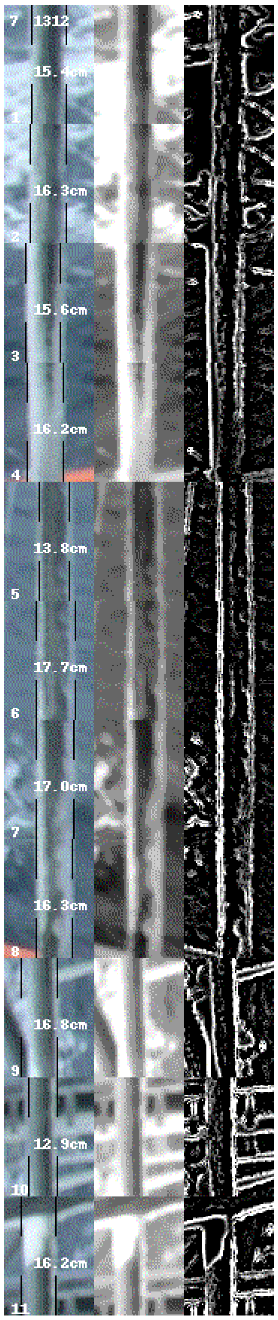


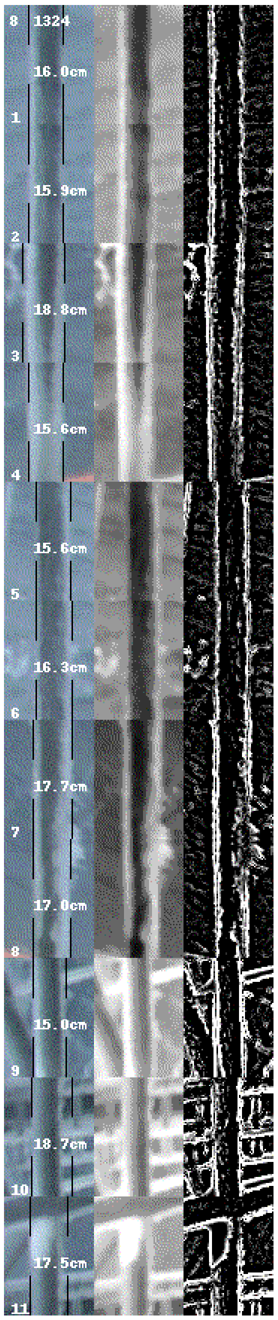


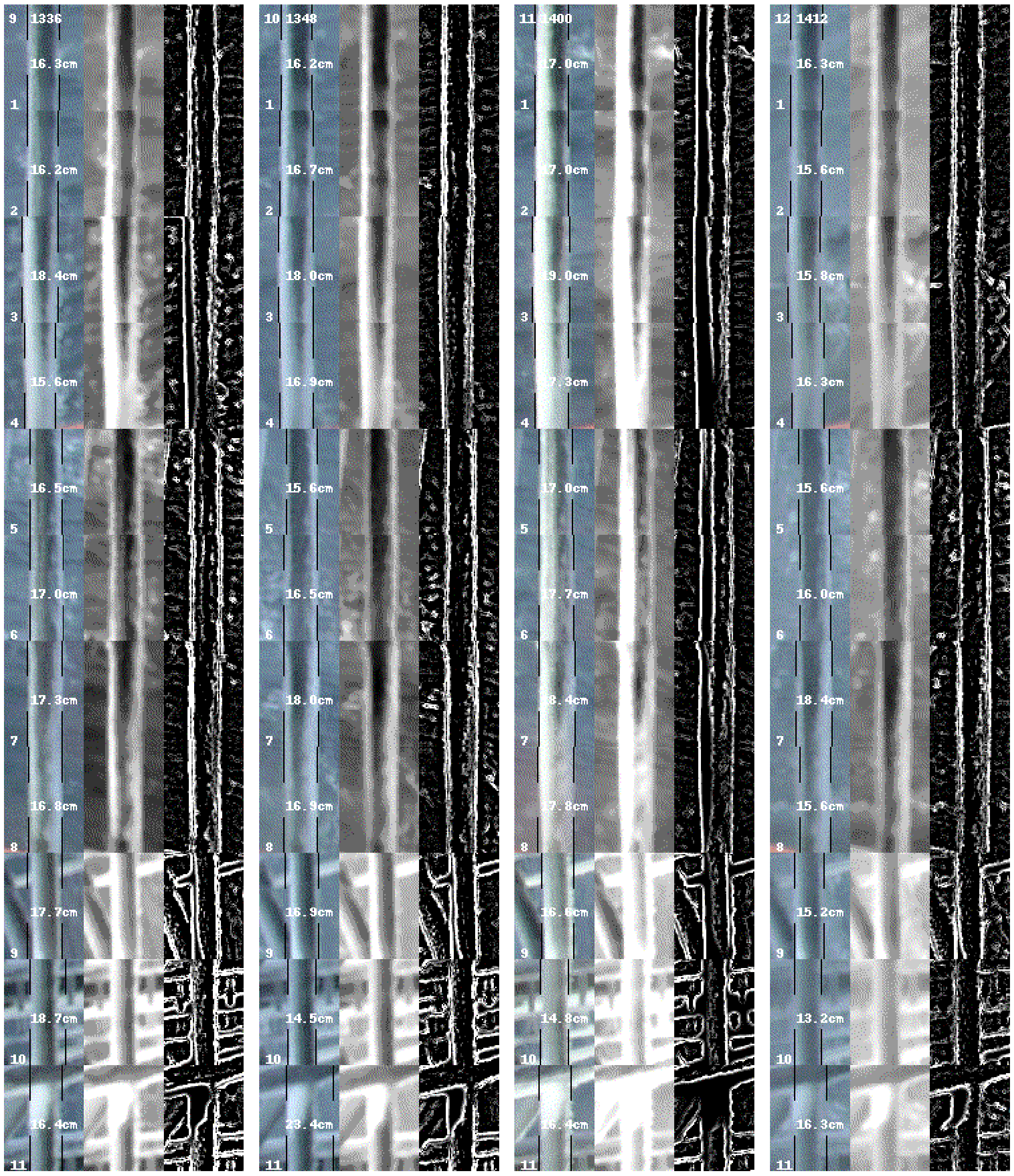


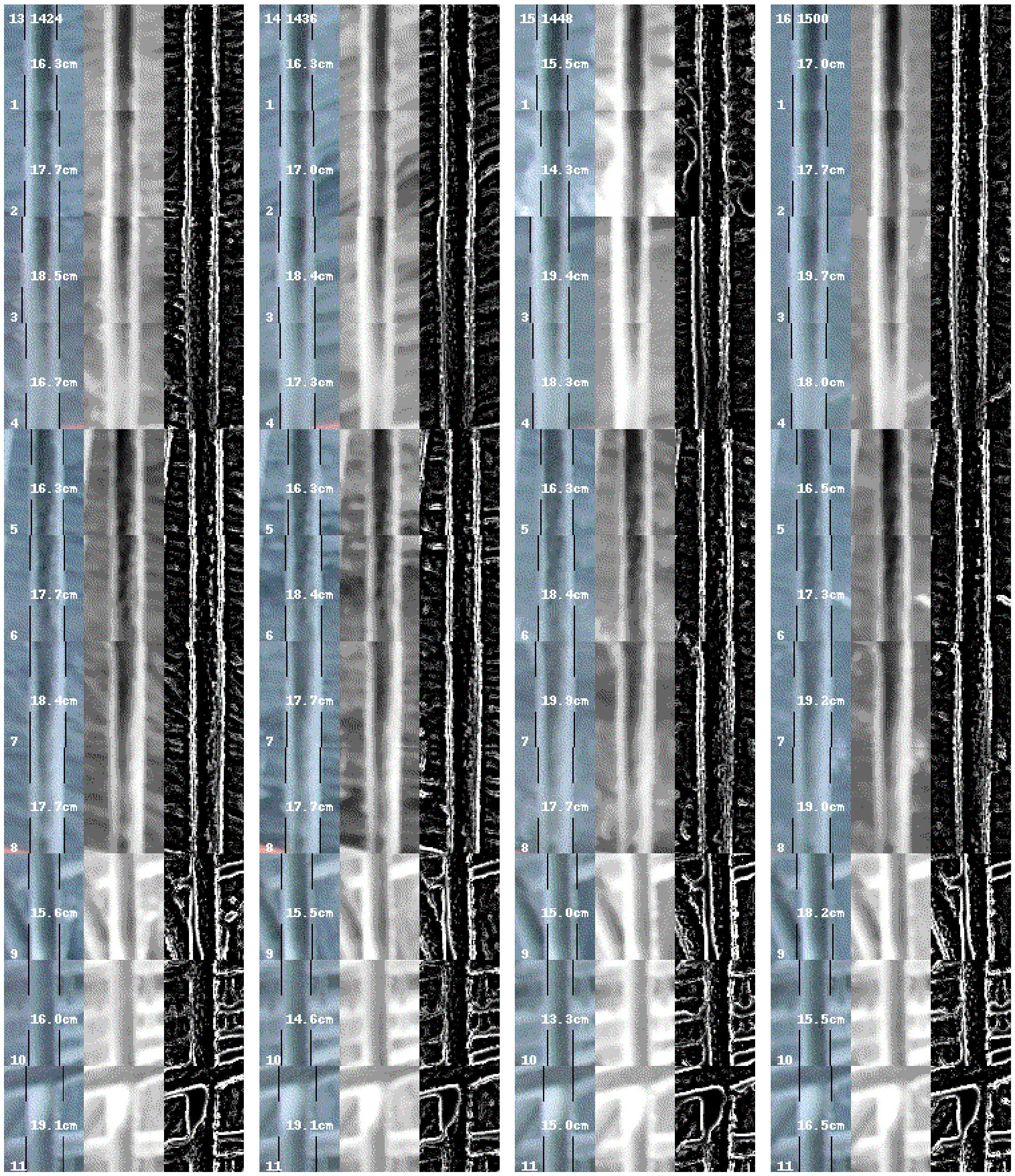

5
1248
15.0cm
1
15.0cm
2
17.0cm
3
13.9cm
4
15.9cm
5
17.0cm
6
15.4cm
7
16.0cm
8
15.3cm
9
13.6cm
10
17.2cm
11

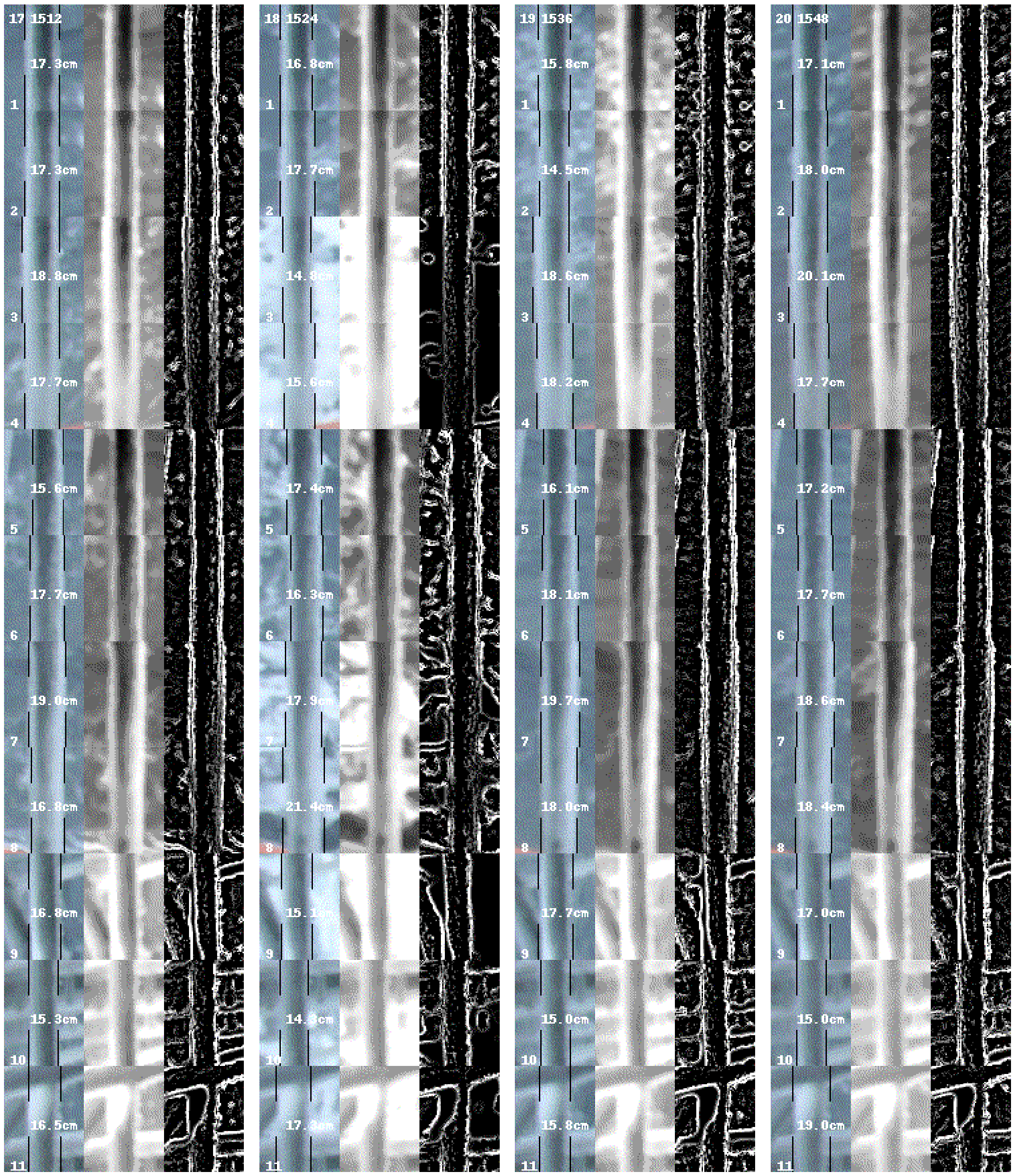

6
1300
15.0cm
1
14.3cm
2
15.0cm
3
15.0cm
4
15.0cm
5
15.0cm
6
14.3cm
7
15.0cm
8
14.6cm
9
12.9cm
10
15.0cm
11


7
1312
15.4cm
1
16.3cm
2
15.6cm
3
16.2cm
4
13.8cm
5
17.7cm
6
17.0cm
7
16.3cm
8
16.8cm
9
12.9cm
10
16.2cm
11

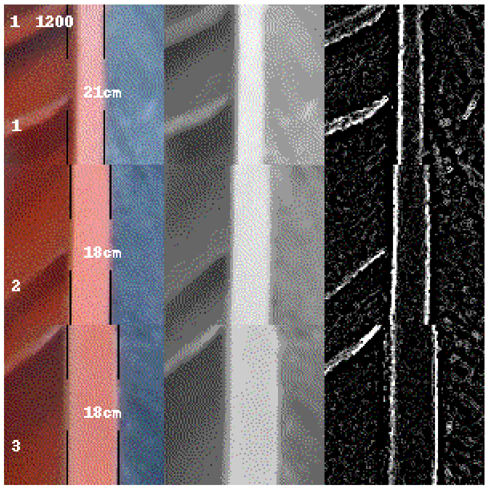

8
1324
16.0cm
1
15.9cm
2
18.8cm
3
15.6cm
4
15.6cm
5
16.3cm
6
17.7cm
7
17.0cm
8
15.0cm
9
18.7cm
10
17.5cm
11

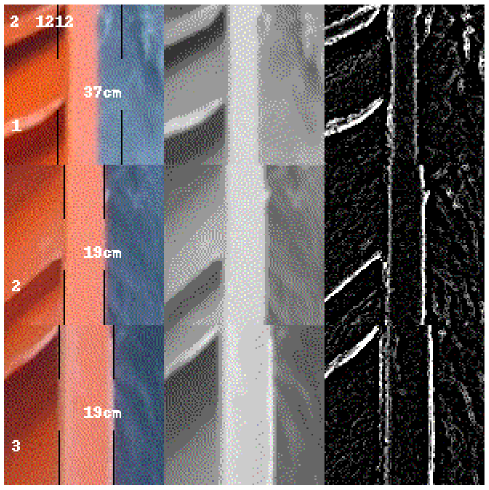

9 1336
16.3cm
1
16.2cm
2
18.4cm
3
15.6cm
4
16.5cm
5
17.0cm
6
17.3cm
7
16.8cm
8
17.7cm
9
18.7cm
10
16.4cm
11
10 1348
16.2cm
1
16.7cm
2
18.0cm
3
16.9cm
4
15.6cm
5
16.5cm
6
18.0cm
7
16.9cm
8
16.9cm
9
14.5cm
10
23.4cm
11
11 1400
17.0cm
1
17.0cm
2
19.0cm
3
17.3cm
4
17.0cm
5
17.7cm
6
18.4cm
7
17.8cm
8
16.6cm
9
14.8cm
10
16.4cm
11
12 1412
16.3cm
1
15.6cm
2
15.8cm
3
16.3cm
4
15.6cm
5
16.0cm
6
18.4cm
7
15.6cm
8
15.2cm
9
13.2cm
10
16.3cm
11

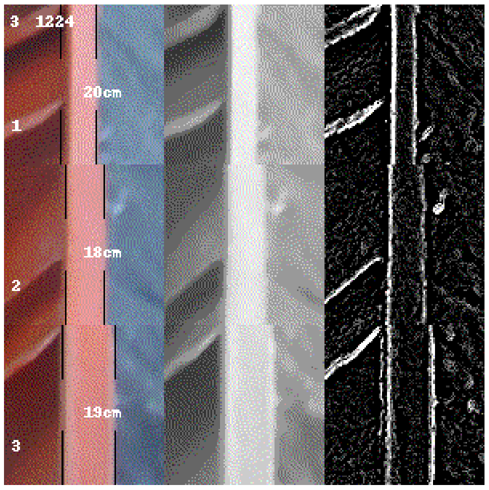

13 1424
16.3cm
1
17.7cm
2
18.5cm
3
16.7cm
4
16.3cm
5
17.7cm
6
18.4cm
7
17.7cm
8
15.6cm
9
16.0cm
10
19.1cm
11
14 1436
16.3cm
1
17.0cm
2
18.4cm
3
17.3cm
4
16.3cm
5
18.4cm
6
17.7cm
7
17.7cm
8
15.5cm
9
14.6cm
10
19.1cm
11
15 1448
15.5cm
1
14.3cm
2
19.4cm
3
18.3cm
4
16.3cm
5
18.4cm
6
19.9cm
7
17.7cm
8
15.0cm
9
13.3cm
10
15.0cm
11
16 1500
17.0cm
1
17.7cm
2
19.7cm
3
18.0cm
4
16.5cm
5
17.3cm
6
19.2cm
7
19.0cm
8
18.2cm
9
15.5cm
10
16.5cm
11

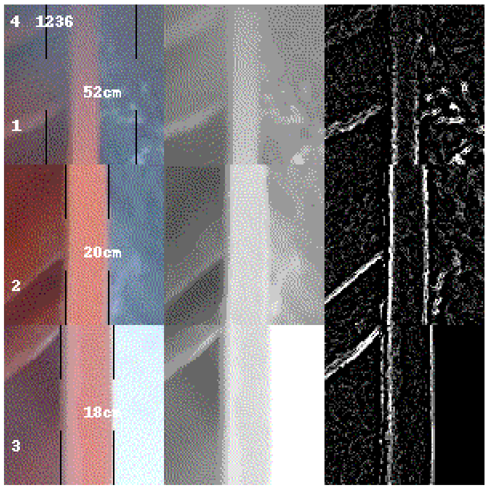

17 1512
17.3cm
1
17.3cm
2
18.8cm
3
17.7cm
4
15.6cm
5
17.7cm
6
19.0cm
7
16.8cm
8
16.8cm
9
15.3cm
10
16.5cm
11
18 1524
16.8cm
1
17.7cm
2
14.8cm
3
15.6cm
4
17.4cm
5
16.3cm
6
17.9cm
7
21.4cm
8
15.1cm
9
14.8cm
10
17.3cm
11
19 1536
15.8cm
1
14.5cm
2
18.6cm
3
18.2cm
4
16.1cm
5
18.1cm
6
19.7cm
7
18.0cm
8
17.7cm
9
15.0cm
10
15.8cm
11
20 1548
17.1cm
1
18.0cm
2
20.1cm
3
17.7cm
4
17.2cm
5
17.7cm
6
18.6cm
7
18.4cm
8
17.0cm
9
15.0cm
10
19.0cm
11

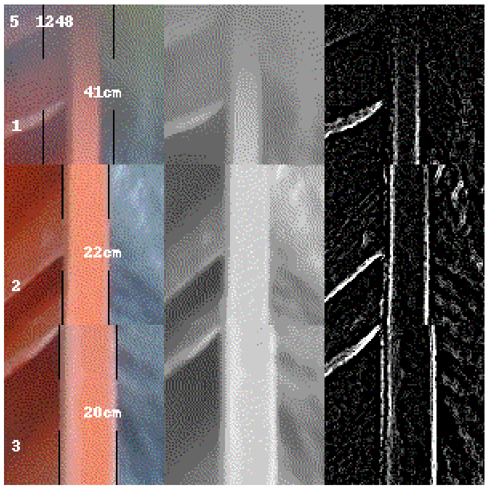
Positions 12 – 14

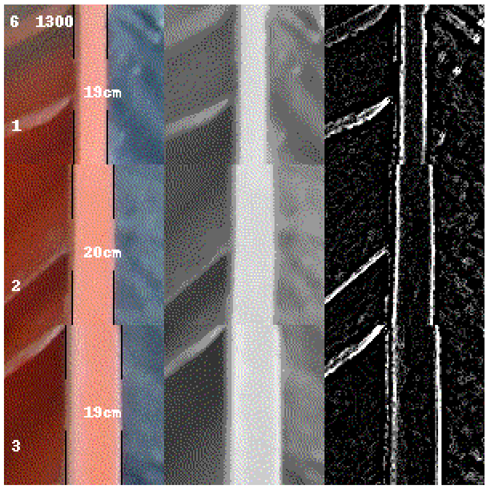


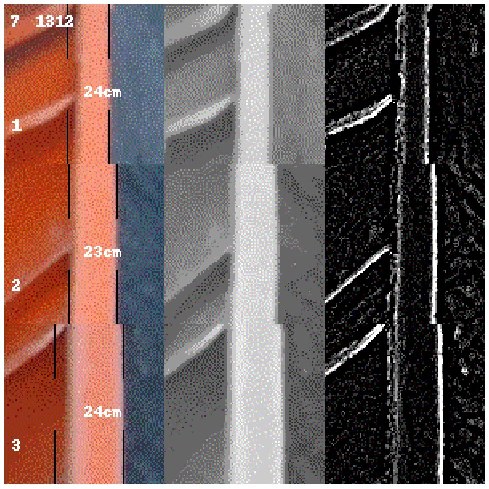


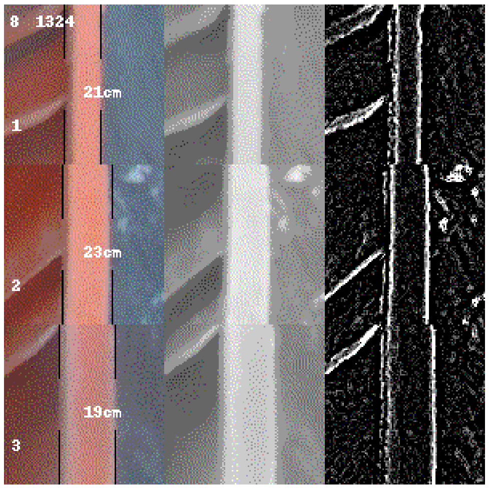


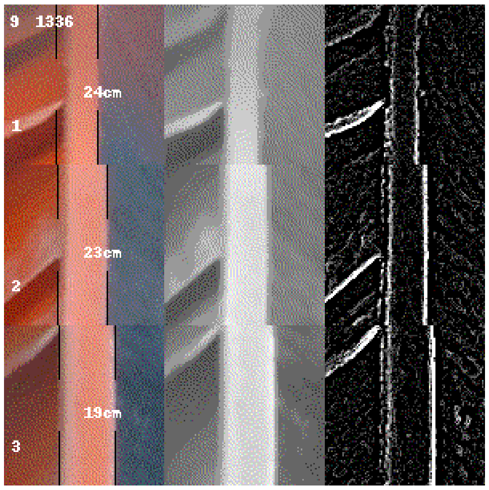


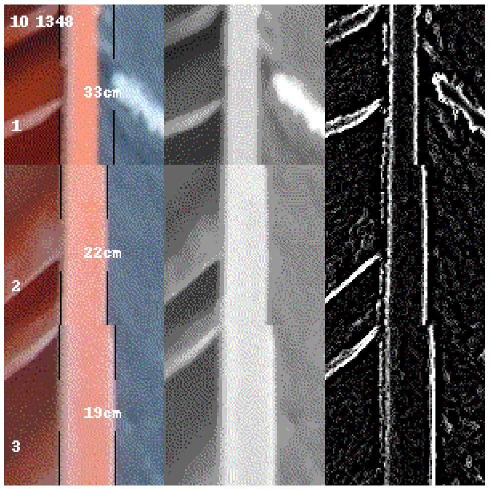


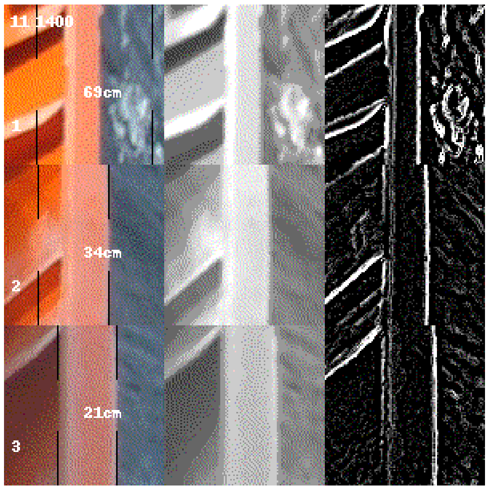


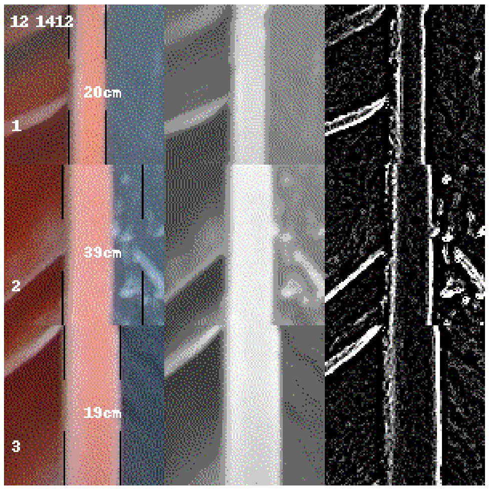

7 1312
24cm
1
23cm
2
24cm
3

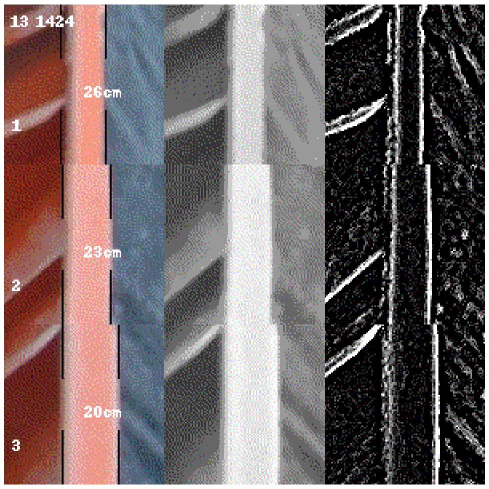
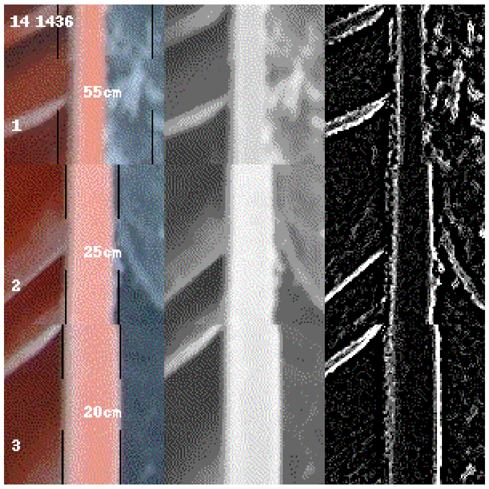
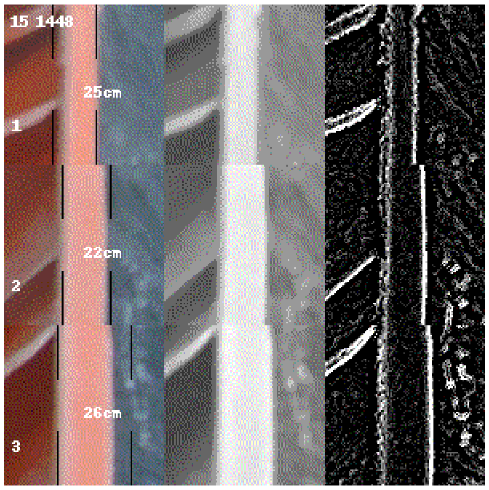
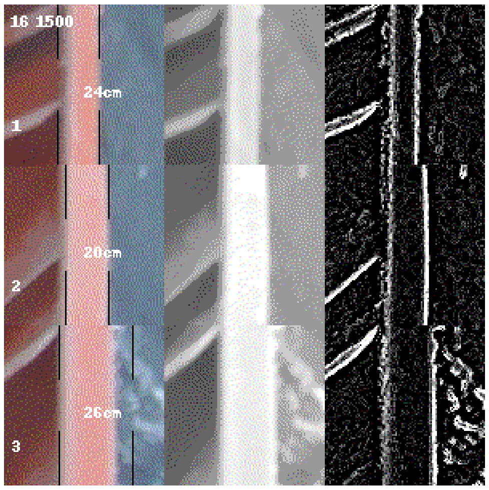
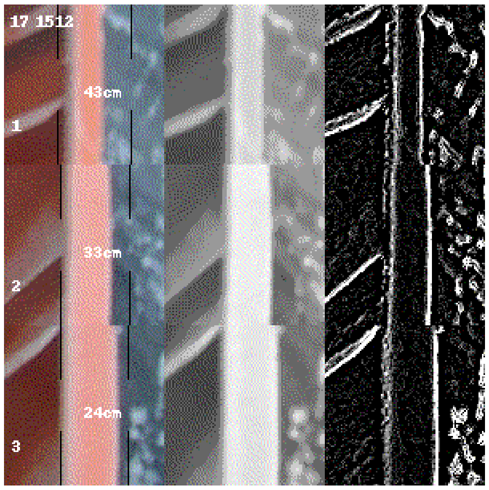
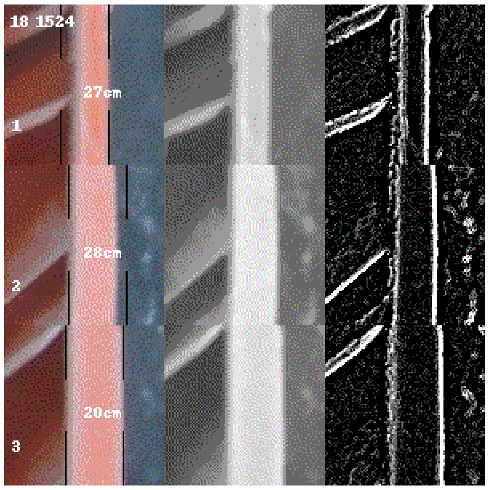

8 1324
21cm
1
23cm
2
19cm
3

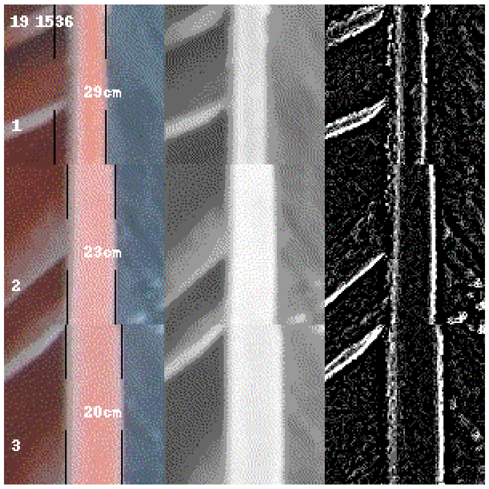

9 1336
24cm
1
23cm
2
19cm
3


10 1348
33cm
1
22cm
2
19cm
3

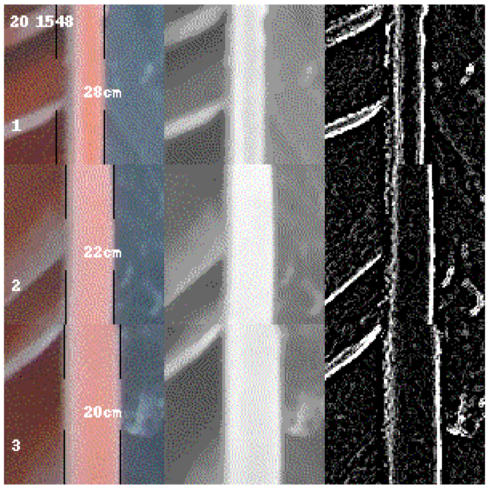

11 1400
69cm
1
34cm
2
21cm
3


12 1412
20cm
1
39cm
2
19cm
3


13 1424
26cm
1
23cm
2
20cm
3

14 1436
55cm
1
25cm
2
20cm
3

15 1448
25cm
1
22cm
2
26cm
3

16 1500
24cm
1
20cm
2
26cm
3

17 1512
43cm
1
33cm
2
24cm
3

18 1524
27cm
1
28cm
2
20cm
3

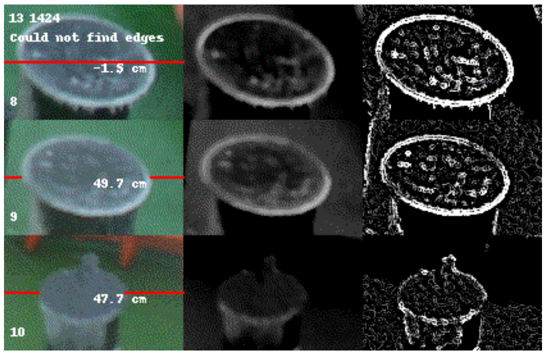


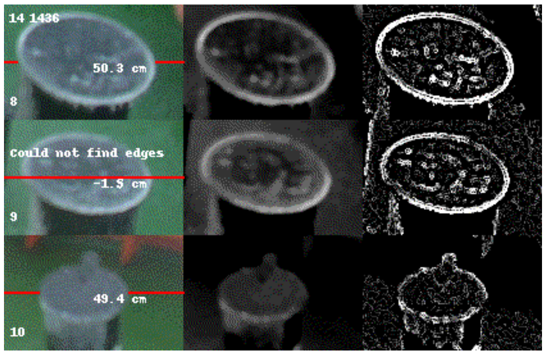
19 1536
29cm
1
23cm
2
20cm
3

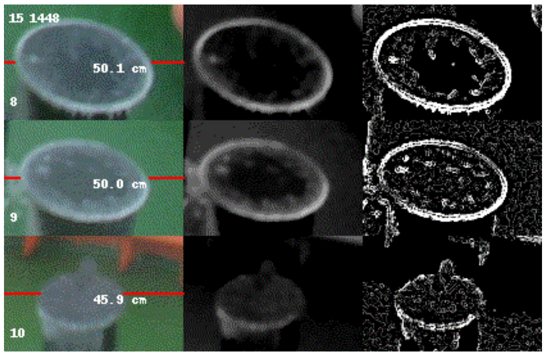


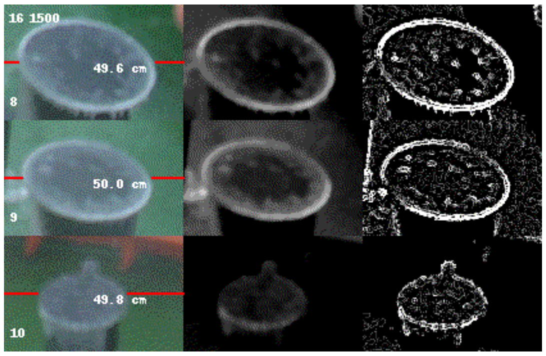
20 1548
28cm
1
22cm
2
20cm
3

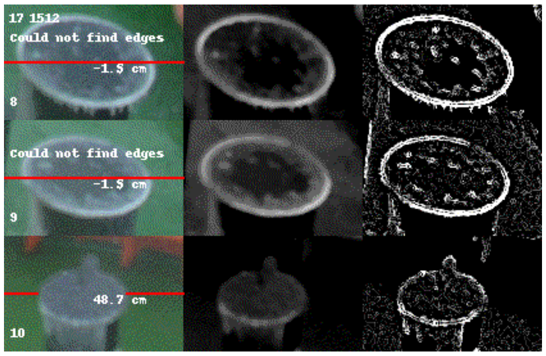
Positions 15 – 17

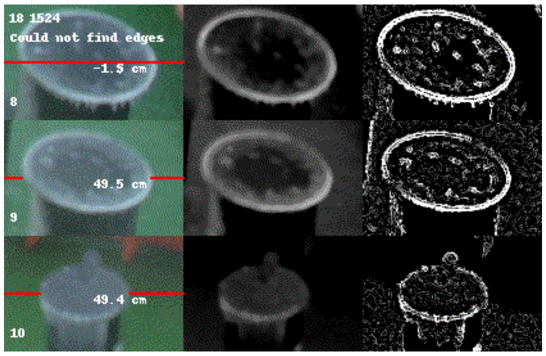


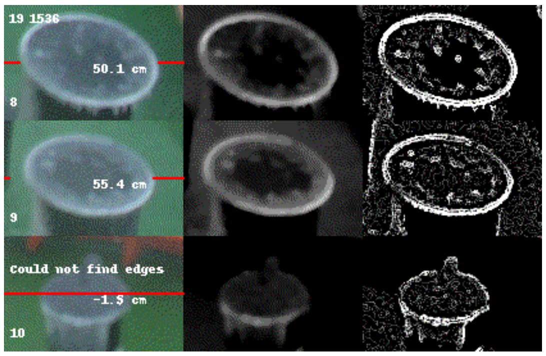


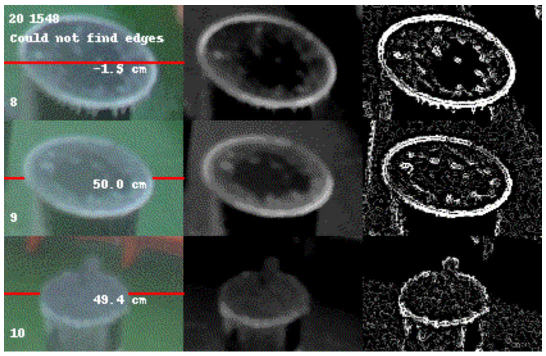


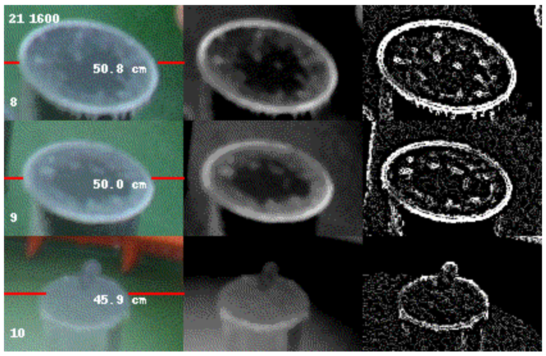


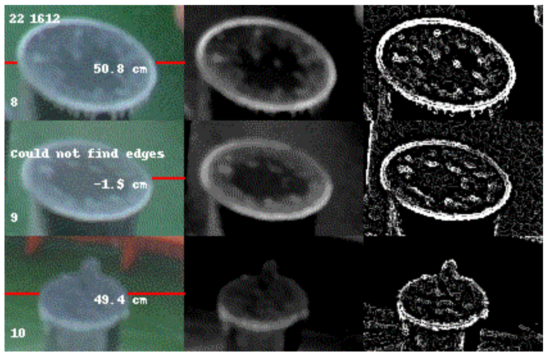


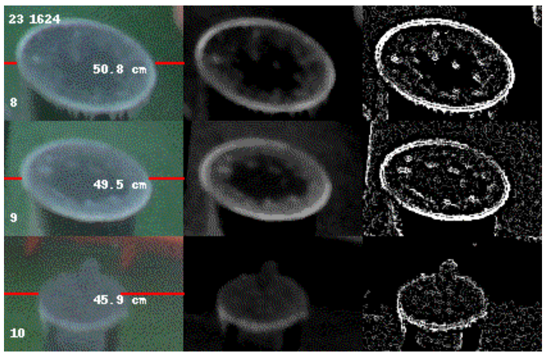


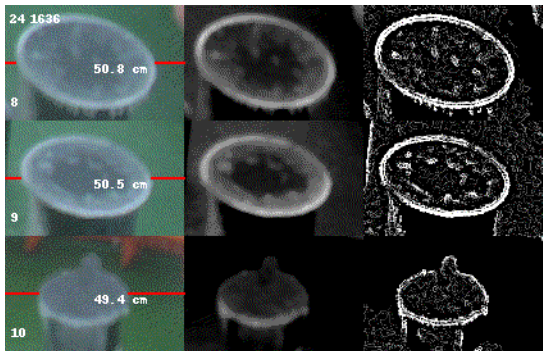


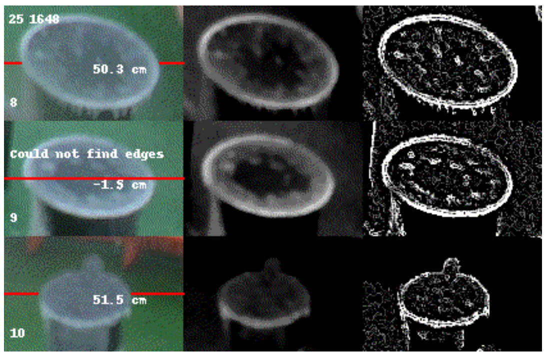


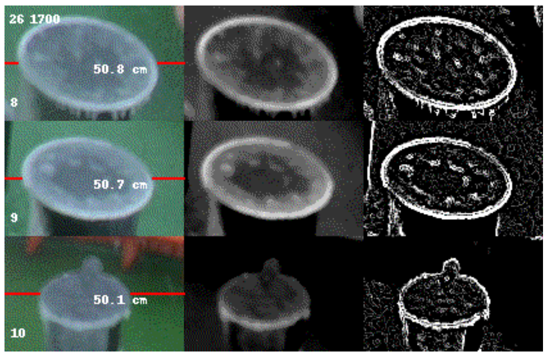

21 1600
50.8 cm
8
50.0 cm
9
45.9 cm
10

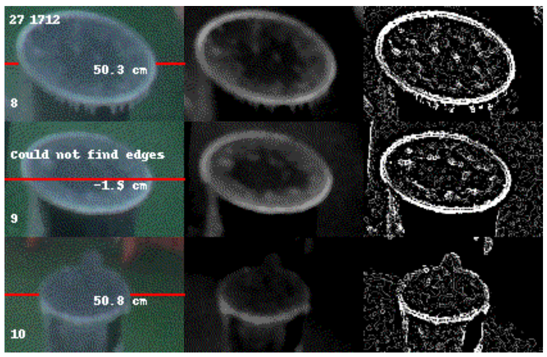

22 1612
50.8 cm
8
could not find edges
-1.$ cm
9
49.4 cm
10

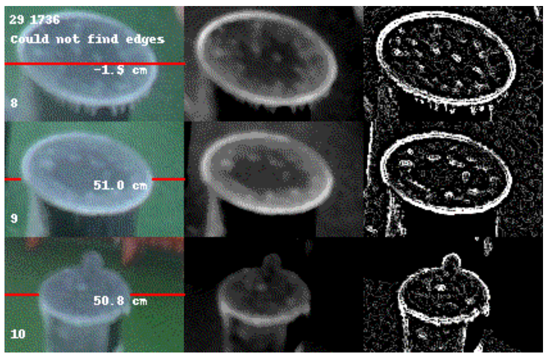

23 1624
50.8 cm
8
49.5 cm
9
45.9 cm
10

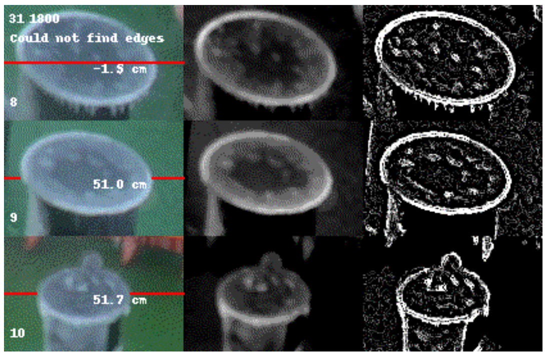

24 1636
50.8 cm
8
50.5 cm
9
49.4 cm
10


25 1648
50.3 cm
8
could not find edges
-1.$ cm
9
51.5 cm
10

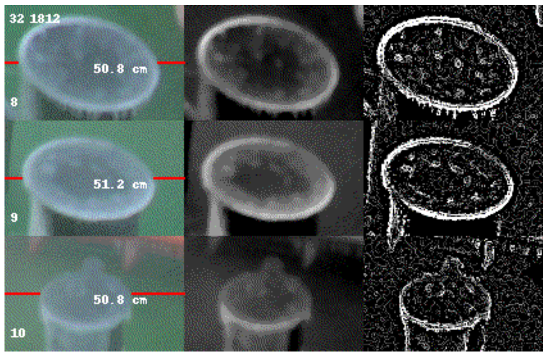

26 1700
50.8 cm
8
50.7 cm
9
50.1 cm
10


27 1712
50.3 cm
8
could not find edges
-1.$ cm
9
50.8 cm
10

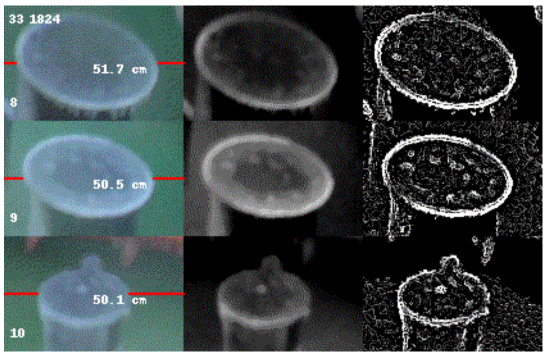

29 1736
could not find edges
-1.$ cm
8
51.0 cm
9
50.8 cm
10



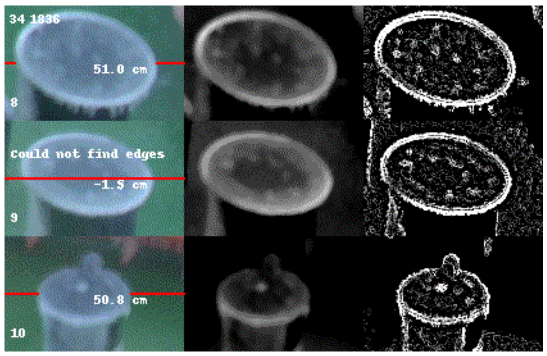
31 1800
could not find edges
-1.$ cm
8
51.0 cm
9
51.7 cm
10



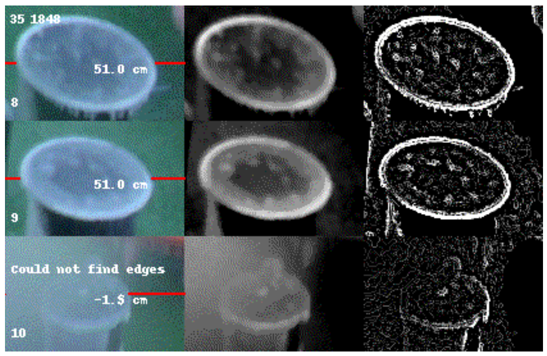
32 1812
50.8 cm
8
51.2 cm
9
50.8 cm
10



33 1824
51.7 cm
8
50.5 cm
9
50.1 cm
10



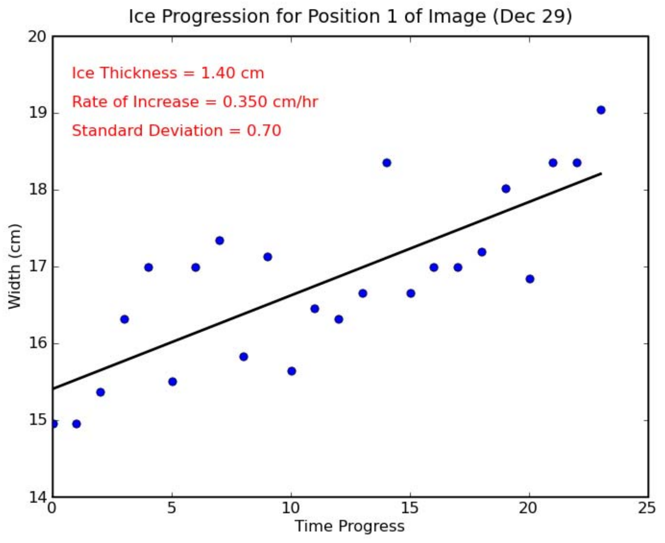
34 1836
51.0 cm
8
could not find edges
-1.$ cm
9
50.8 cm
10



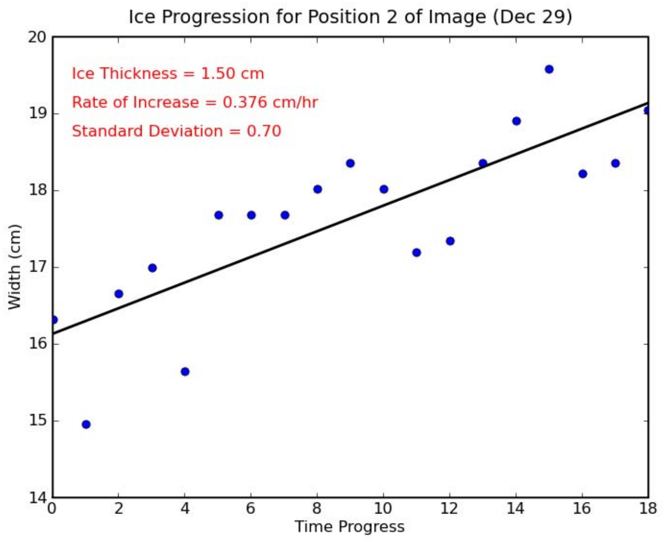
35 1848
51.0 cm
8
51.0 cm
9
could not find edges
-1.$ cm
10

Appendix C

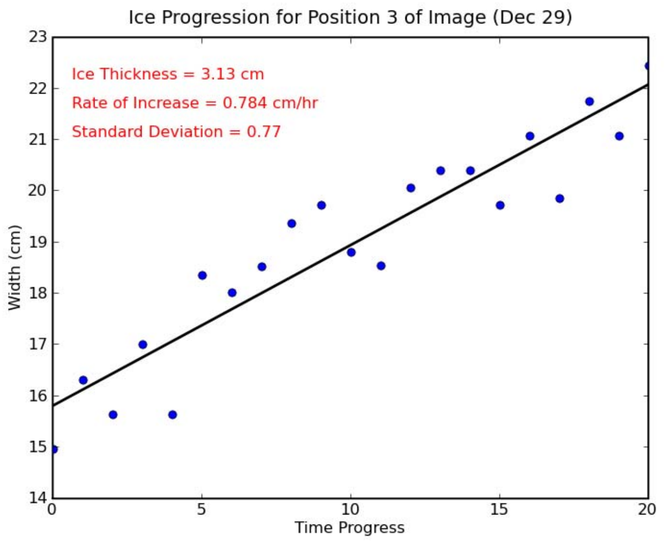
Icing Event Figures for Ice Accumulation



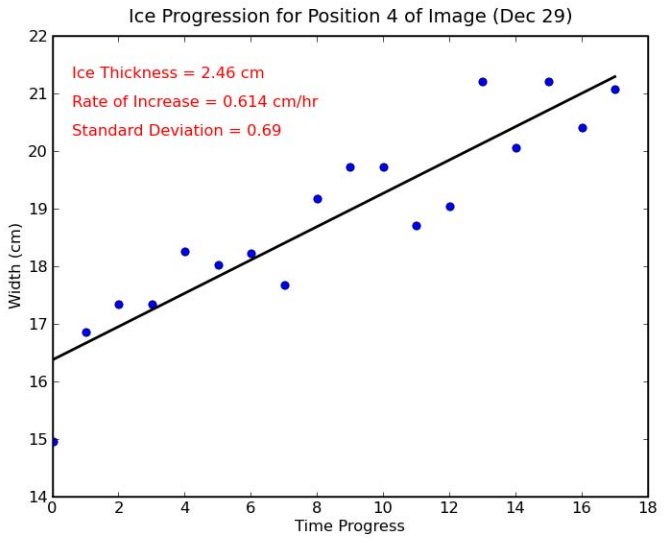
Ice Progression for Position 1 of Image (Dec 29)
Ice Thickness = 1.40 cm
Rate of Increase = 0.350 cm/hr
Standard Deviation = 0.70
Width (cm)
Time Progress

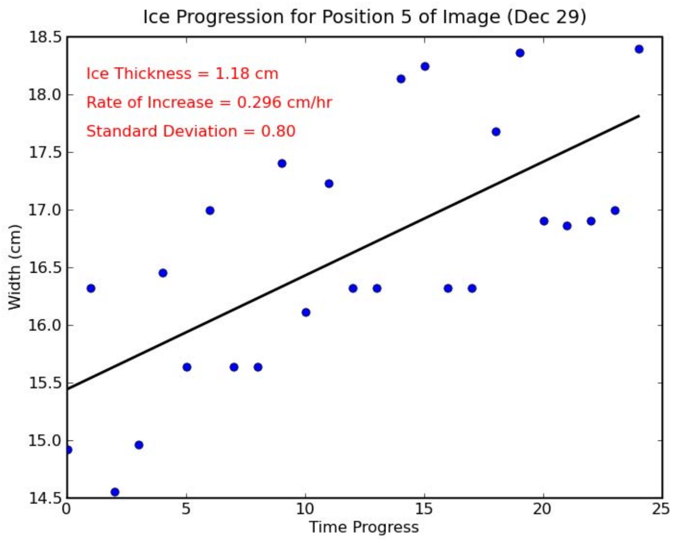


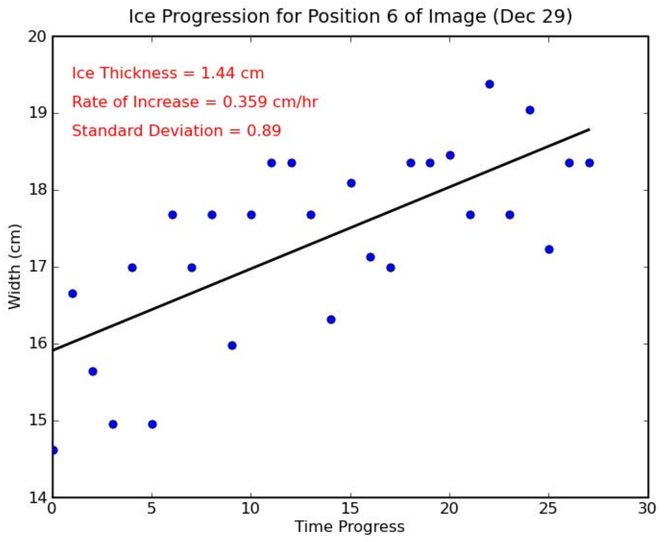
Ice Progression for Position 2 of Image (Dec 29)
Ice Thickness = 1.50 cm
Rate of Increase = 0.376 cm/hr
Standard Deviation = 0.70
Width (cm)
Time Progress

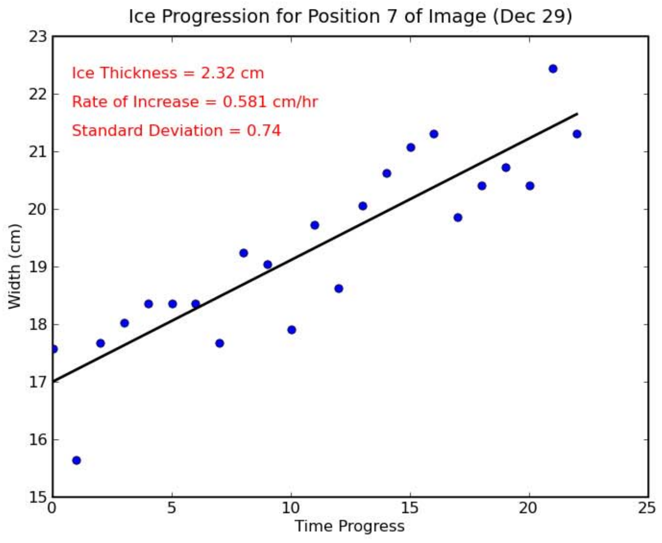


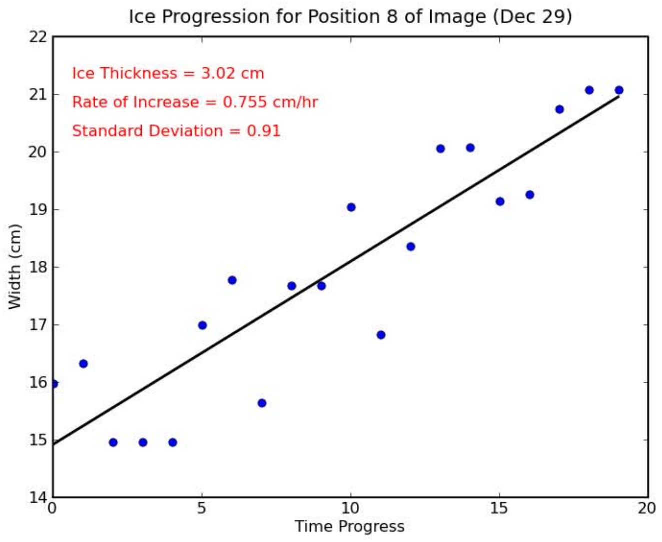
Ice Progression for Position 3 of Image (Dec 29)
Ice Thickness = 3.13 cm
Rate of Increase = 0.784 cm/hr
Standard Deviation = 0.77
Width (cm)
Time Progress

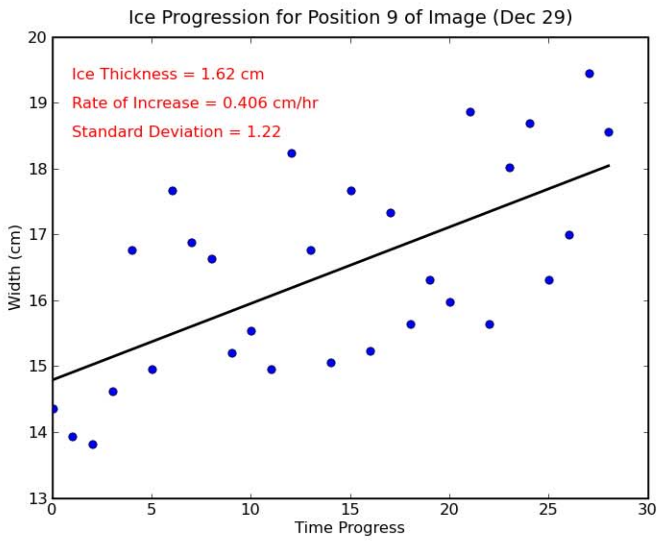

Ice Progression for Position 4 of Image (Dec 29)
Ice Thickness = 2.46 cm
Rate of Increase = 0.614 cm/hr
Standard Deviation = 0.69
Width (cm)
Time Progress

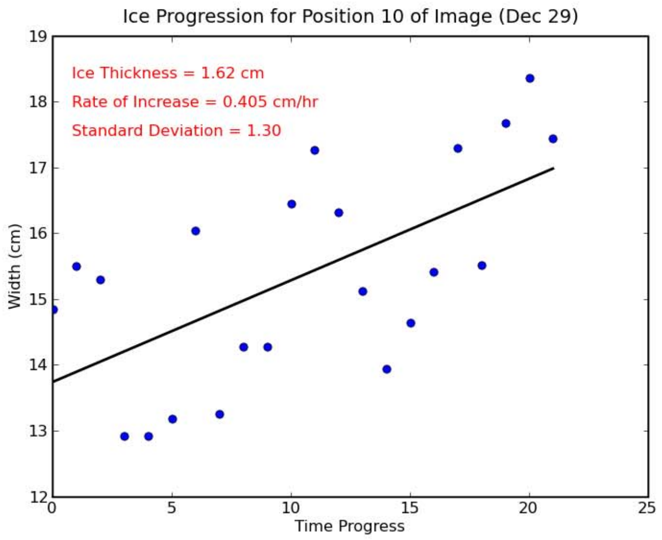

Ice Progression for Position 5 of Image (Dec 29)
Ice Thickness = 1.18 cm
Rate of Increase = 0.296 cm/hr
Standard Deviation = 0.80
Width (cm)
Time Progress

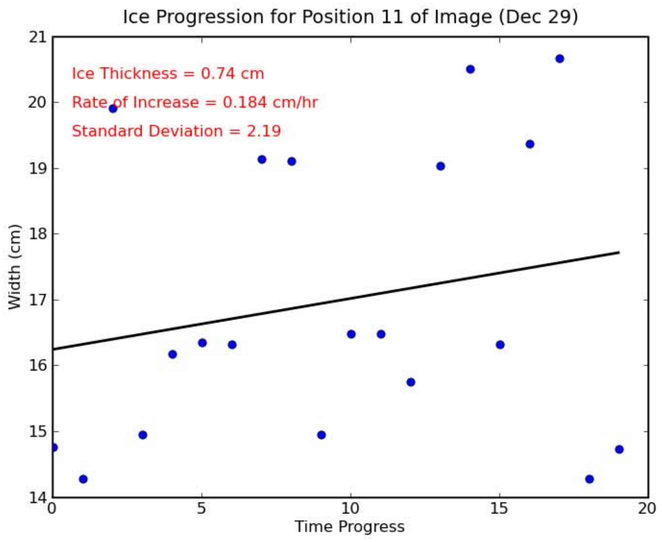

Ice Progression for Position 6 of Image (Dec 29)
Ice Thickness = 1.44 cm
Rate of Increase = 0.359 cm/hr
Standard Deviation = 0.89
Width (cm)
Time Progress

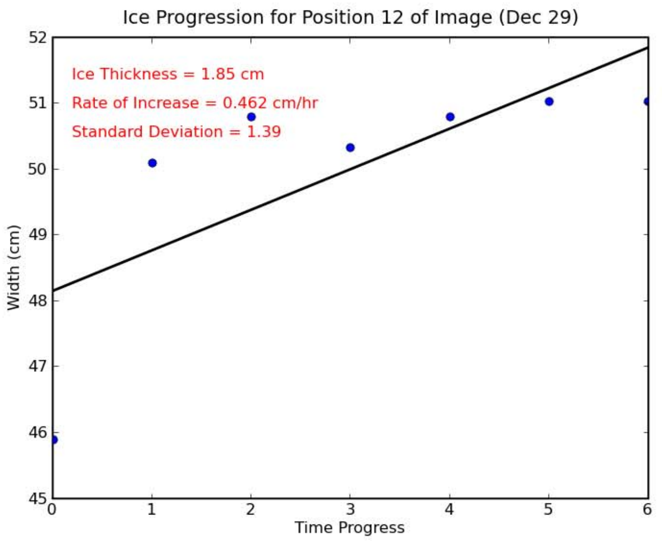

Ice Progression for Position 7 of Image (Dec 29)
Ice Thickness = 2.32 cm
Rate of Increase = 0.581 cm/hr
Standard Deviation = 0.74
Width (cm)
Time Progress

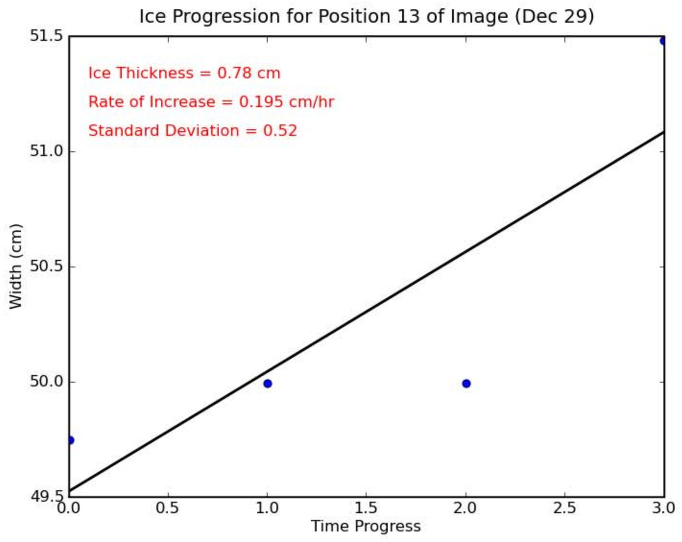

Ice Progression for Position 8 of Image (Dec 29)
Ice Thickness = 3.02 cm
Rate of Increase = 0.755 cm/hr
Standard Deviation = 0.91
Width (cm)
Time Progress

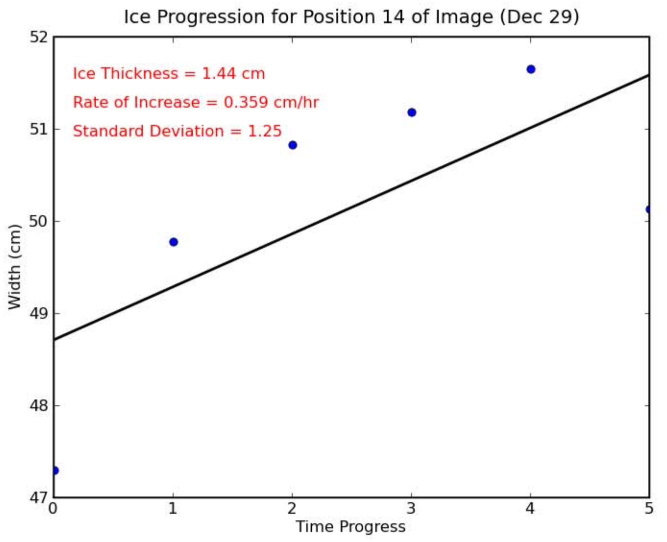

Ice Progression for Position 9 of Image (Dec 29)
Ice Thickness = 1.62 cm
Rate of Increase = 0.406 cm/hr
Standard Deviation = 1.22
Width (cm)
Time Progress

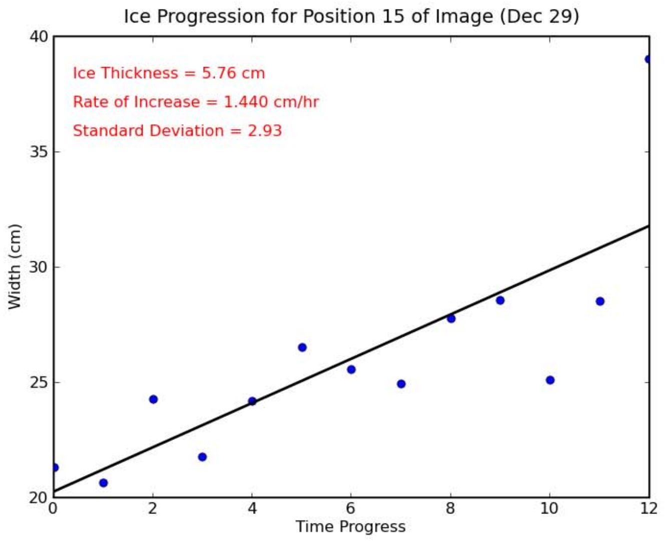

Ice Progression for Position 10 of Image (Dec 29)
Ice Thickness = 1.62 cm
Rate of Increase = 0.405 cm/hr
Standard Deviation = 1.30
Width (cm)
Time Progress

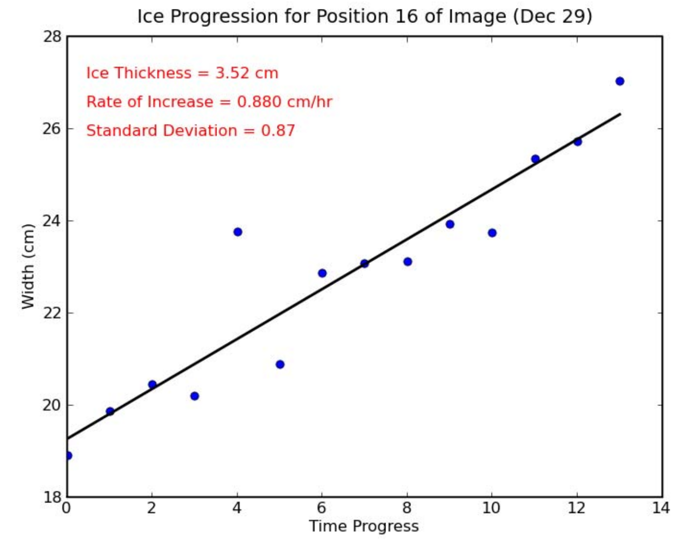

Ice Progression for Position 11 of Image (Dec 29)
Ice Thickness = 0.74 cm
Rate of Increase = 0.184 cm/hr
Standard Deviation = 2.19
Width (cm)
Time Progress

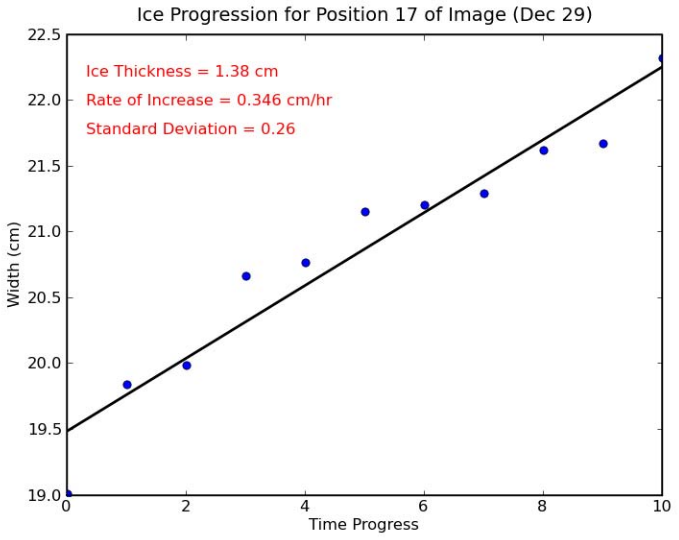

Ice Progression for Position 12 of Image (Dec 29)
Ice Thickness = 1.85 cm
Rate of Increase = 0.462 cm/hr
Standard Deviation = 1.39
Width (cm)
Time Progress


Ice Progression for Position 13 of Image (Dec 29)
Ice Thickness = 0.78 cm
Rate of Increase = 0.195 cm/hr
Standard Deviation = 0.52
Width (cm)
Time Progress


Ice Progression for Position 14 of Image (Dec 29)
Ice Thickness = 1.44 cm
Rate of Increase = 0.359 cm/hr
Standard Deviation = 1.25
Width (cm)
Time Progress


Ice Progression for Position 15 of Image (Dec 29)
Ice Thickness = 5.76 cm
Rate of Increase = 1.440 cm/hr
Standard Deviation = 2.93
Width (cm)
Time Progress


Ice Progression for Position 16 of Image (Dec 29)
Ice Thickness = 3.52 cm
Rate of Increase = 0.880 cm/hr
Standard Deviation = 0.87
Width (cm)
Time Progress


Ice Progression for Position 17 of Image (Dec 29)
Ice Thickness = 1.38 cm
Rate of Increase = 0.346 cm/hr
Standard Deviation = 0.26
Width (cm)
Time Progress