An Image Processing Based System For Three Dimensional Sail Shape Analysis

by

Drew Scott Freides

Submitted to the Department of Ocean Engineering
in partial fulfillment of the requirements for the degrees of

Bachelor of Science

and

Master of Science in Naval Architecture and Marine Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1991

Author .....
Department of Ocean Engineering
May 10, 1991

Certified by .....
Jerome H. Milgram
Professor
Thesis Supervisor

Accepted by .....
A. Douglas Carmichael
Chairman, Departmental Committee on Graduate Students

An Image Processing Based System For Three Dimensional Sail Shape Analysis

by

Drew Scott Freides

Submitted to the Department of Ocean Engineering
on May 10, 1991, in partial fulfillment of the
requirements for the degrees of
Bachelor of Science
and
Master of Science in Naval Architecture and Marine Engineering

Abstract

A video based method for determining sail shapes and performance characteristics is presented. An image processing system was developed to record and measure sail shapes from video tape using a standard high quality video recorder, a frame grabber, and a personal computer. The shapes of the sails were recorded from a chase boat located close to the *MIT Rig Force Test Boat* sailing dynamometer while sailing upwind. The resulting data will be used to correlate the forces generated from the *MIT Rig Force Test Boat* sailing dynamometer with different sail configurations and shapes.

The results were compared to still photographs. The data calculated by the image processing system was found to be very accurate, insuring this to be an effective method to determine sail shapes.

Thesis Supervisor: Jerome H. Milgram
Title: Professor

Acknowledgments

I would like to sincerely thank my advisor, Prof. Milgram for his support throughout this project.

I would also like to thank Noah Eckhouse for helping me in the development of this video system. Without his computer software expertise this system would never have been functional.

I thank my lab mates, Don Peters, and Hasan Olmez, for their assistance, for answering my stupid questions, and for making this past year so enjoyable.

I finally thank my family for their encouragement, support, and motivation, without which this project would not have been possible.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The lack of an accurate method for measuring the shapes of sails has been a problem that has plagued the design and analysis of sails. In recent years, different groups have tried new approaches for determining sail shapes on a moving boat. This project consists of one attempt to accomplish this task in an efficient manner. A video image processing system was developed to determine sail shapes with a camcorder that has filmed the sails from a chase boat. The video system consists of a standard video recorder used in conjunction with a frame grabber/video windows card on a PC.

This thesis is divided into five parts. The first introduces sail shape analysis, and most of the reasons for designing this system. The second part explains the components needed to successfully operate it. The third chapter describes the proper filming procedures to obtain the necessary pictures. Chapter Four explains how to operate the sail shape analysis program, as well as discusses the calculations performed by the program to return the desired sail shape information. The last section of this thesis, Chapter Five contains the results of some testing along with a comparison with some still photographs.

Some of the sections of this thesis apply directly to the work done with the *MIT Test Boat*, whereas others are more general. Some components, such as the camera chosen and the frame grabber used, can be interchanged with different parts. Therefore if these components are substituted, the sections dealing with these parts would not be useful. The positions of the sail markings can also be altered, but then the

program will have to be changed to reflect these differences. This thesis is geared to the production and usage of this video system for the *MIT Test Boat.* It can be used to apply to other systems and boats, but alterations will have to be made.

1.1 Motivation for System

In the past few years sail design has progressed immensely. From the mid-1980s to the present, there has been far greater interest in sail design than ever before. Events such as the America's Cup, especially in 1983 and 1987, produced large improvements in not only the sails themselves, but also in the methods of designing, constructing, and testing them accurately. The design and construction of sails has become more of a science and less of an art.

Recently, there has been increasing attention given to the analytical design of yacht sails. Computer codes have been developed to try to solve both the design problem, calculating the shape needed to generate a given load distribution, and the analysis problem, determining the resulting load from a given shape. If one were to pick up any sailing magazine and read the sail company advertisements, almost every company claims to design their sails with computers. Programs claim to be capable of taking a certain load distribution, converting it to a sail shape, entering the stretch characteristics of the different materials used in the sail, and simulate *flying* that sail to determine its *flying* characteristics. The overall result is the supposed actual *sailing shape*, and the forces generated from this shape. This loop is then repeated until the desired results are achieved. The different sail companies also claim that their programs are extremely accurate and have produced very successful sail designs that have helped many boats win innumerable sailing championships.

However, how is the effectiveness of these programs gauged? On the performance of the boats? There are so many variables that produce success on any given day it is almost unimaginable. They can range from the crew, to the wind (hitting the windshifts correctly), to the design of the boat, to the design of the sails. Even if it is the sail design, just because the sails used are faster than those used previously,

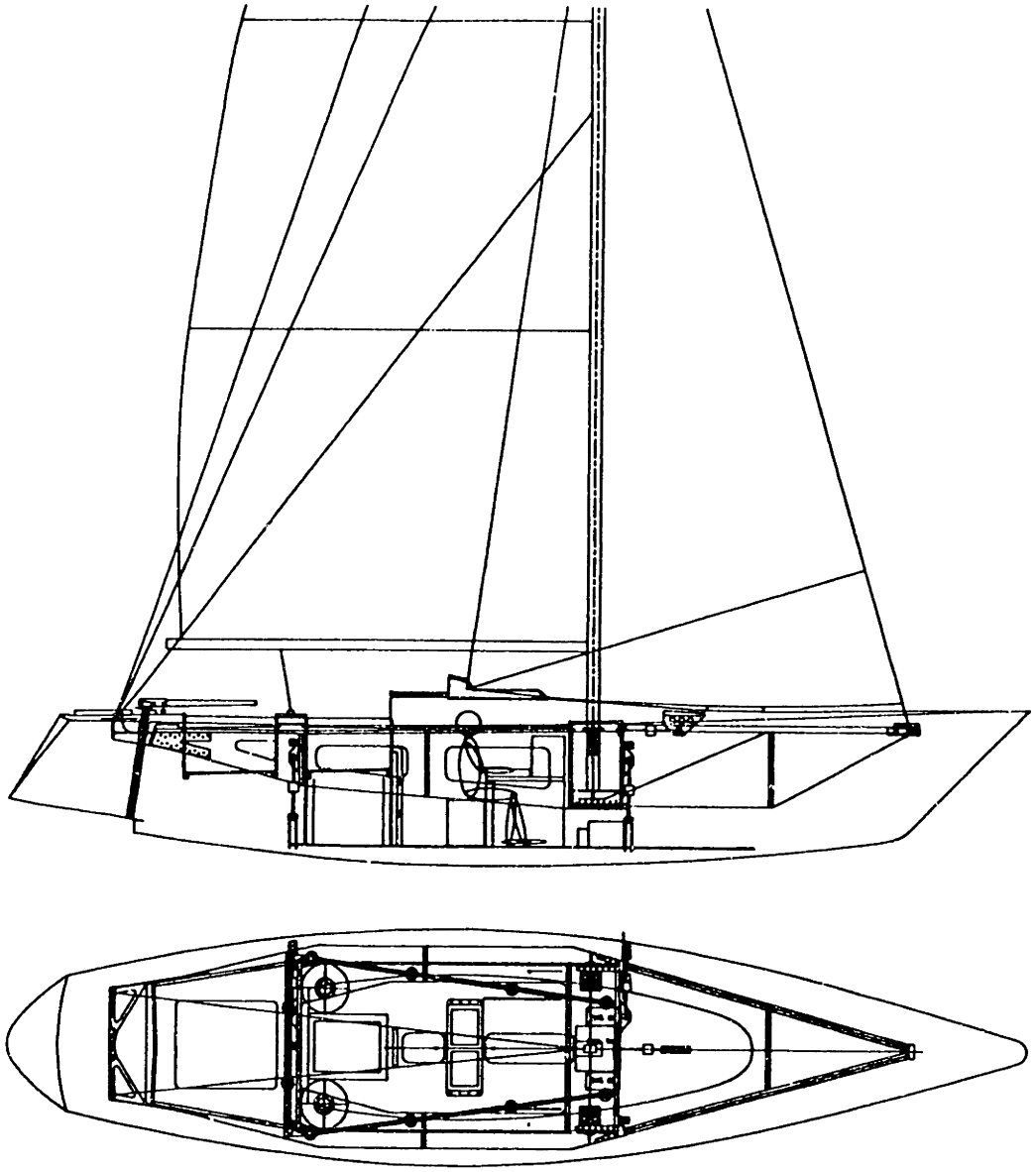

Figure 1-1: *MIT Sailing Dynamometer*

does not insure the programs are accurate. There have been so many advancements in the overall production of sails that the actual designed shape of the sail does not even have to have been changed to produce a significantly faster sail. A shape used five years ago could be very competitive even today, if today's materials and construction techniques are used. The sail would be built much lighter and be able to retain it's shape in a far greater wind range and for a longer period of time than a sail built five years ago. Excessive stretch can enormously distort a sail and hurt performance. These factors alone would produce a significantly faster sail. Therefore

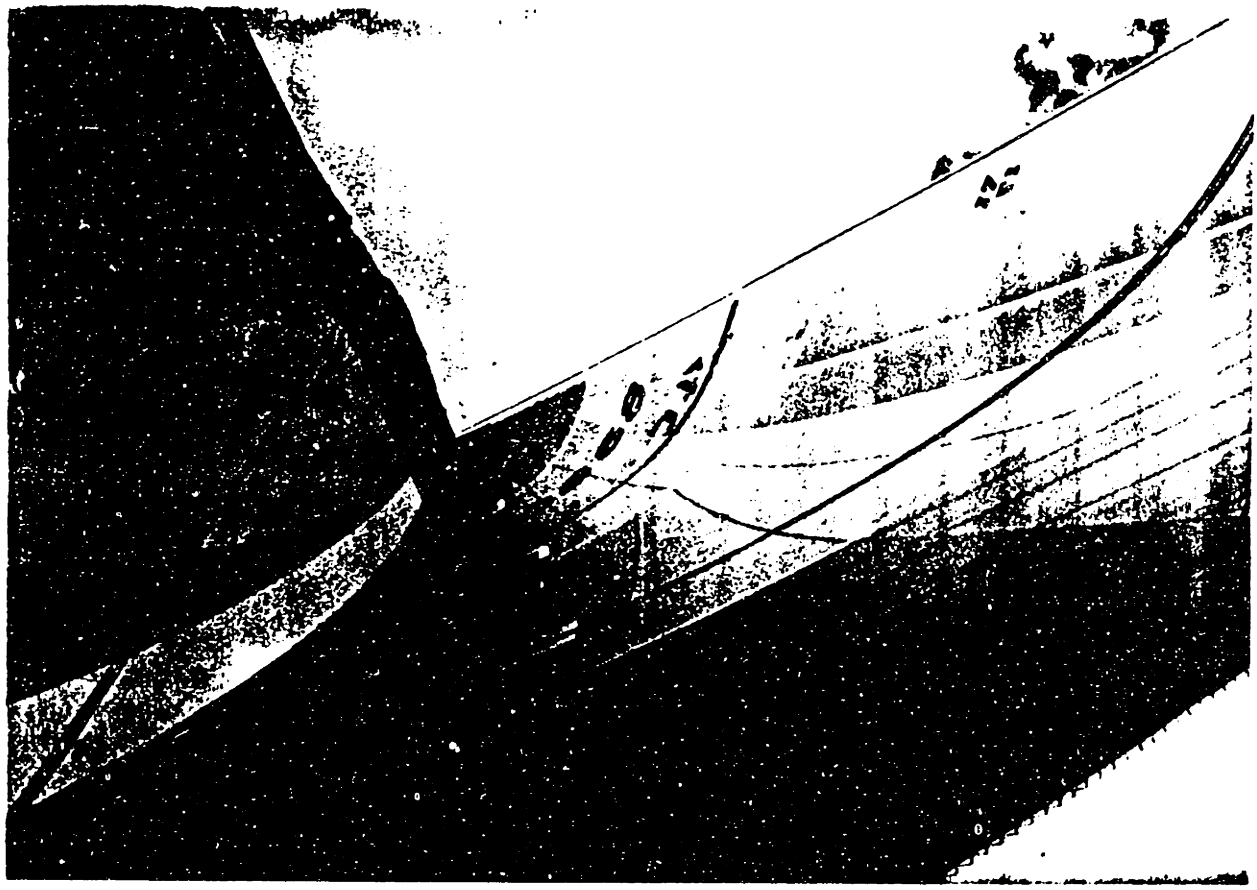

Figure 1-2: Still photograph (Courtesy Dave Hirsch of North Sails Inc.)

it is probably safe to say that this method of measuring the performance of sails is relatively inaccurate and error prone.

In this study, a unique vessel is used to attempt to answer these questions. The sailing yacht has been designed to directly measure the forces on the it's rig while sailing. This then gives the forces generated by the sails [3]. A picture of the boat, *The MIT Sailing Dynamometer* can be seen in Figure 1-1. To study the different sail shapes and their resulting forces, an accurate method must be used to record and store the sail shapes. It is very difficult to record and measure the shape of a sail on a moving boat. Direct measurement is just about impossible. However, this video system accomplishes the task, and enables the stored images to be digitized, therefore determining the exact shapes of the sails. The recorded shapes can then

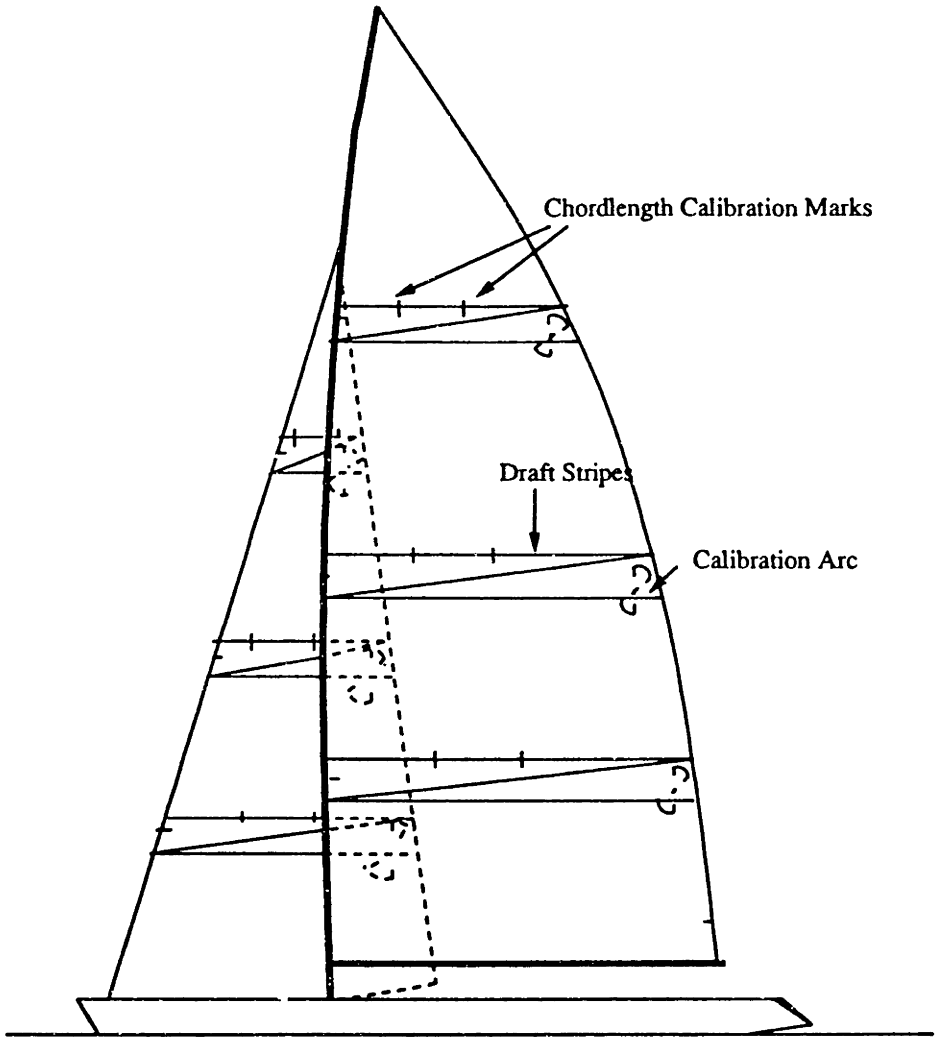

Figure 1-3: Sail Shape Stripes and Markings

be run through analytical sail design and analysis codes [2, 5], and the data can be compared to the actual forces measured on the *testboat.*

In the past, the most commonly used method of storing and calculating sail shapes is the use of still photographs, taken from either the deck or from other boats (see Figure 1-2). There have been many problems with this method. Firstly, the time delay created by the development of the film is frustrating. Secondly, getting the proper angle to minimize the distortion is hard, if not impossible at times. It is quite difficult to scramble around a boat while it is sailing (let alone racing), and get the

correct angles. Also, if the camera moves during the photograph, the picture may be incorrect. Therefore, this method has proven to be very error prone, and almost impossible for use while a boat is being raced.

Another image processing system was used before on the *MIT Sailing Dynamometer* with mediocre results. The system consisted of a two cameras mounted on the mast. One mounted at the position where the headstay meets the mast and the other mounted at the masthead. They were used to view the jib and main respectively [4]. This system recorded and stored the images successfully, but there has been doubt concerning the accuracy of the images. The digitized pictures yielded shapes that did not appear to effectively measure the shapes of the sails. The twist angles near the head of the sails appeared to be greatly exaggerated. Whether it was due to lens distortion, viewed angle, or a combination of both, is not known.

One of the attributes of the off-boat video image processing system is its flexibility in the viewing positions. An exact viewing position does not have to be maintained. As long as the correct position for the measurements is included in each pass by the chase boat, the frame that contains the data can be extracted. This enables the proper angles and positions to always be recorded.

Another attribute of this image processing system is the ability to use it to calculate the sail shapes of the competition's sails from positions and distances readily obtainable. Obviously, it would be quite difficult to board a competitor's yacht and film their sails. A problem that exists though, is the inability to obtain all the sail information that we are looking for. To get all of the data, certain stripes must be placed on the sails, as has been done on the *MIT Sailing Dynamometer*. These stripes and markings can be seen in Figure 1-3, and are explained in Section 2.3.

1.2 Describing Sail Shapes

Since the purpose of this project is to effectively determine sail shapes, the first thing that must be explained is how a specific sail shape is described. A sail acts much like a wing of a plane, so it would be fitting to describe it in much the same way. It

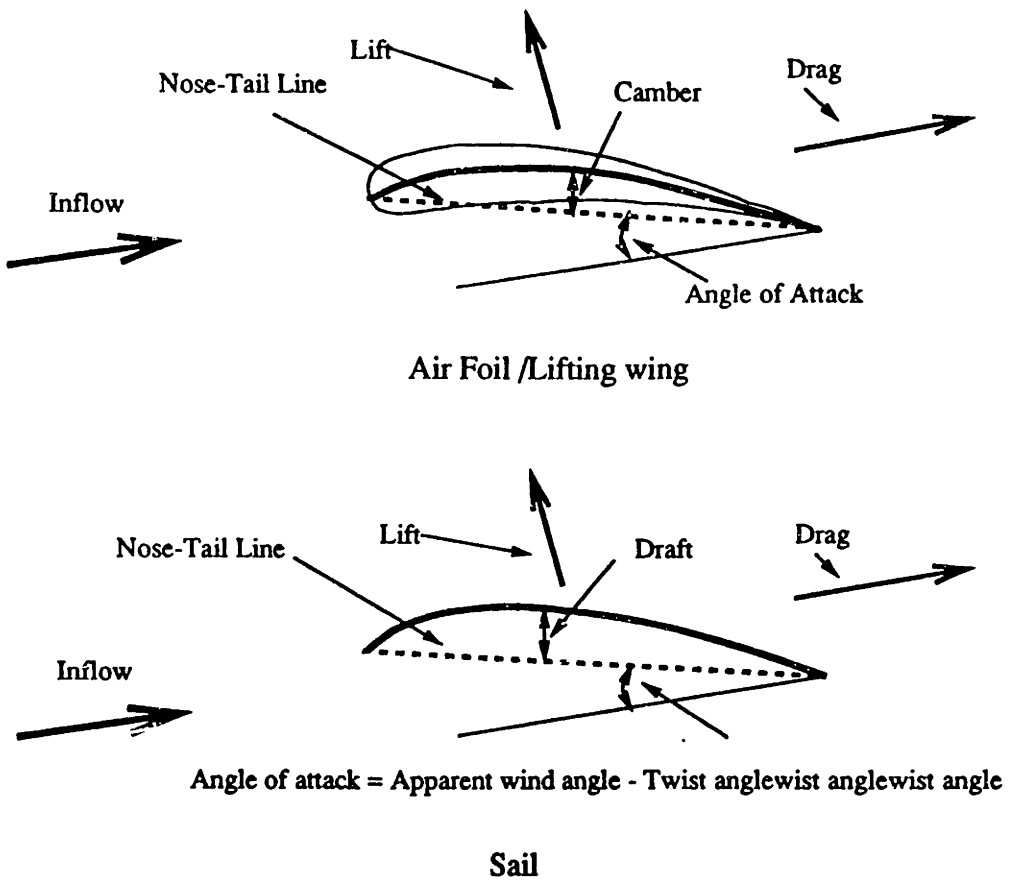

Figure 1-4: Comparison of a Wing and a Sail

produces lift, a force which acts perpendicular to the inflow, and drag, which acts in the direction of inflow. The two dimensional cross section of a wing is defined by an angle of attack and a camber, while the shape of a sail is defined by an angle of attack and a draft. The angle of attack is the angle between the line connecting the leading edge and trailing edge of the wing or sail (Nose-Tail line), while the camber or draft is the perpendicular distance from the nose-tail line to the surface of the wing or sail (See Figure 1-4).

The dimensions of a sail are described by the span, the length of the sail vertically,

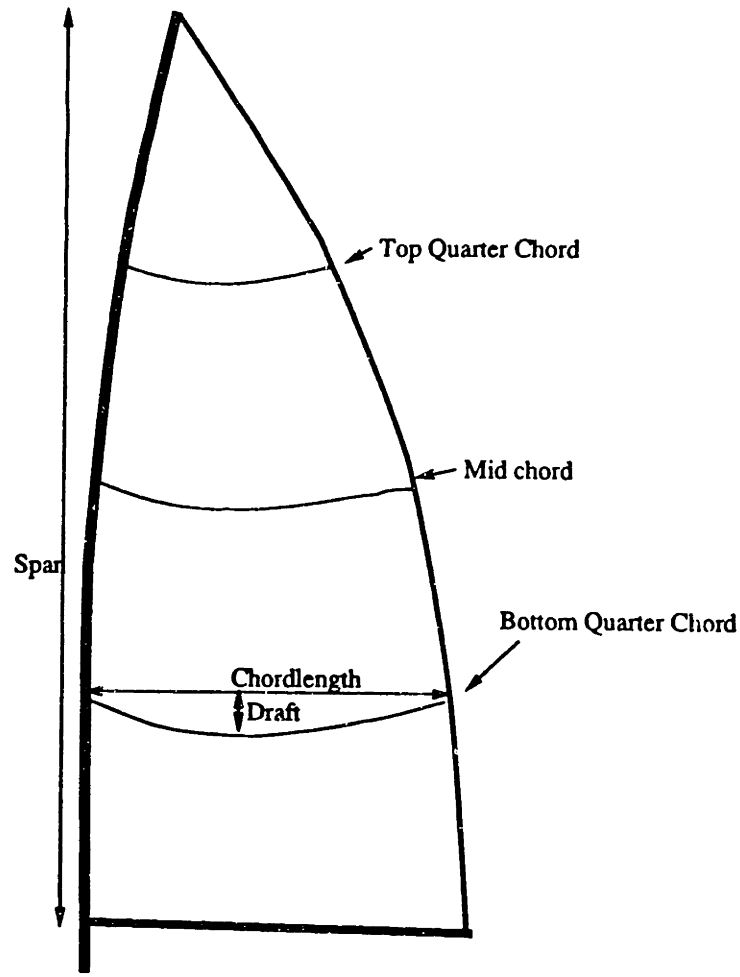

Figure 1-5: Sail Geometry

and the chord length, which is drawn perpendicular to the span. The chord lenth can be described at any height, but is normally given at four positions, the boom, the bottom quarter chord, the mid chord, and the top quarter chord. This can be seen in Figure 1-5. Instead of the angle of attack of a sail, the angular orientation of a sail is normally described by a twist angle. A twist angle is the angle formed by the nose-tail line and the centerline of the boat. This can be seen in Figure 1-6. The twist angles of a sail are normally given at different vertical positions along with the angle the boom makes with the centerline of the boat. The angle of attack of the sail

can then be calculated by subtracting the twist angle from the apparent wind angle.

The shape of a given sail depends upon many factors. First, there is the designed shape designed of the sail. This shape is put into the sail when it is built. It is the result of adjoining curved panels. This then changes when the sail is loaded with the force of the wind, due to the stretch of the materials used to construct the sail. The shape of the sail can also be adjusted somewhat by changing the the tension on different parts of the sail. Adjustments such as the cunningham, outhaul, halyard tension, sheet tension, mast bend, and boom vang, all effect the shape of a mainsail. Changing the positions of these controls can greatly effect the overall shape of a sail.

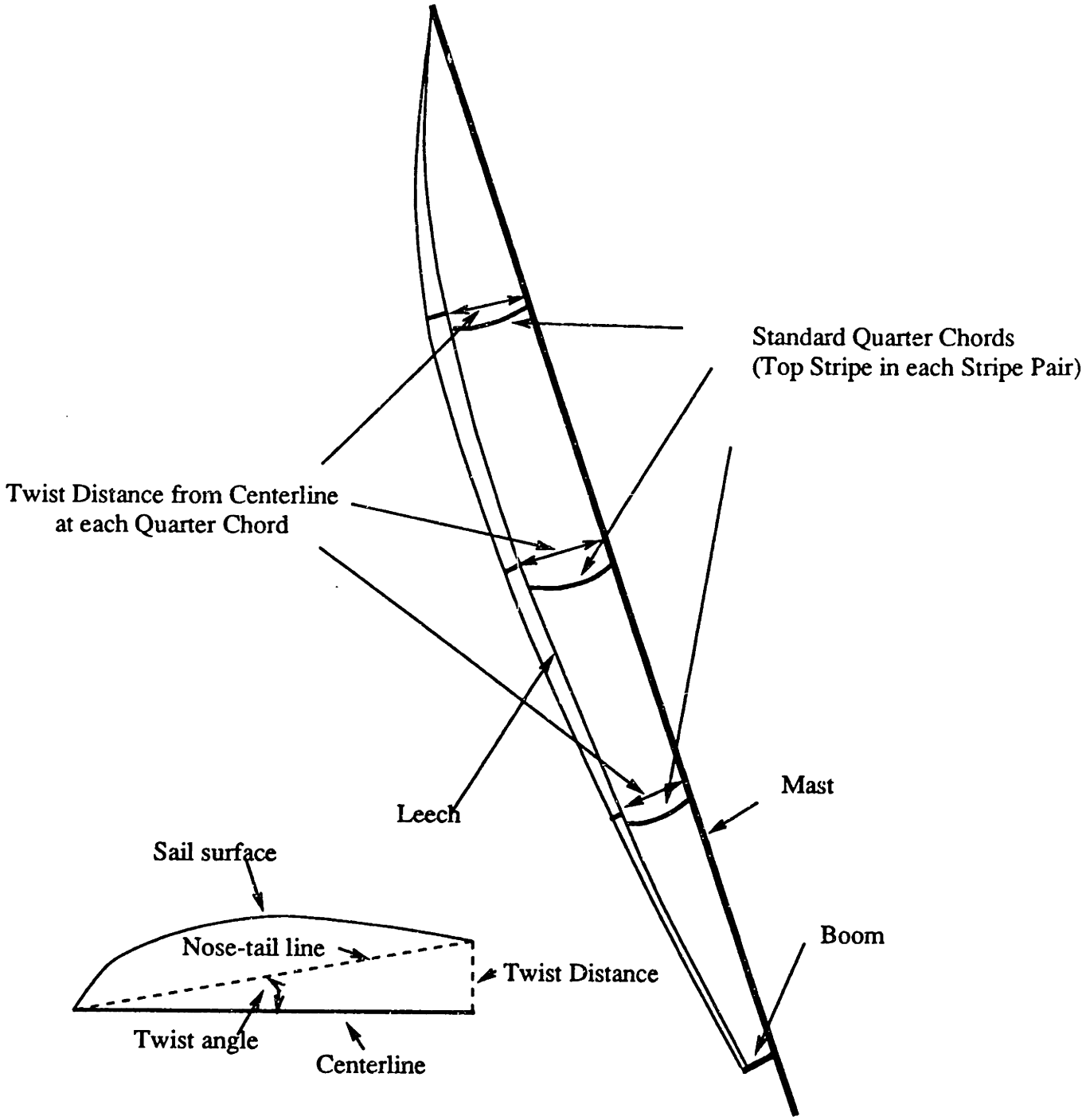

Figure 1-6: Sail Twist

Chapter 2

System Components

2.1 Necessary Sail Markings

This project attempts to determine three basic measurements. The first is the twist angle from centerline. The second is the maximum draft position, as a function of percentage aft from the leading edge of the sail. The third is the maximum draft itself (a length). To calculate these three measurements at the quarter chords, as well as the position of the boom, some necessary stripes and markings must be located on the sails (see Figure 1-3 for more details).

First, horizontal stripes must be located at the quarter chords of the sail (top quarter chord, mid chord, and bottom quarter chord). Next, a horizontal stripe must be located 30 inches below each of the quarter chords. These two horizontal lines make up each stripe pair. Then, a diagonal stripe, extending from the point where the top stripe (quarter chord) in each stripe pair intersects with the leech, to the position where the bottom stripe in each stripe pair meets the mast (see Figure 2-1). The diagonal stripe must be placed on the sail between each of the stripes of each stripe pair.

Now calibration, or scaling markings, must be located on the sail. On the leech of the sail, slightly below each quarter chord, arcs are placed (see Figure 2-2). These arcs enable a constant scaling distance when viewed at different angles vertically. Like the draft stripe pairs, the radius of each arc is 30 inches. For example, if the camera

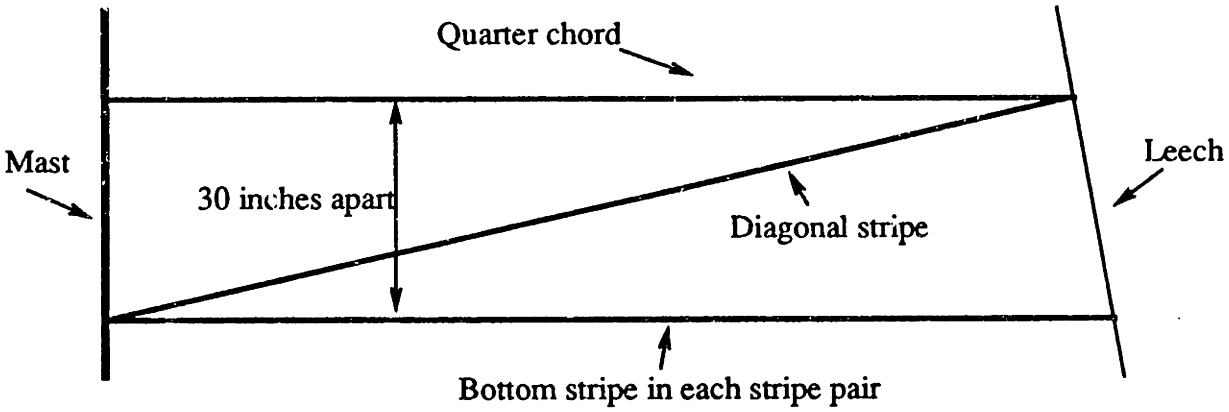

Figure 2-1: Draft Stripes

were at the same height as the stripe, then the vertical hash marks on the arcs would be used. If the camera were to be located at the same distance away vertically, as horizonally, then the hash marks located angle 45 degrees from vertical would be used (angles in between can use any position on arcs as long as the two correspond).

Chord length calibration marks are located on each quarter chord also 30 inches apart. A calibration mark must also be added is at the luff of the sail 15 inches below each quarter chord. This point is used as a scaling distance for draft information, because the draft is located somewhere between the leech and luff, and therefore a measurement is needed on the leech as well as the luff. The last calibration mark that must be attached to the sail is 30 inches above the clew of the sail, at the leech (see Figure 2-3). This mark is used as the scaling mark while sailing off the breeze for obtaining the boom angle from centerline. Upwind, the distance between the runner winches is used (36 inches). When the correct calibration marks are unavailable, other marks are available. As long as there are reference distances, such as the spreader lengths or other measurements on the the mast to serve as calibration lengths, the

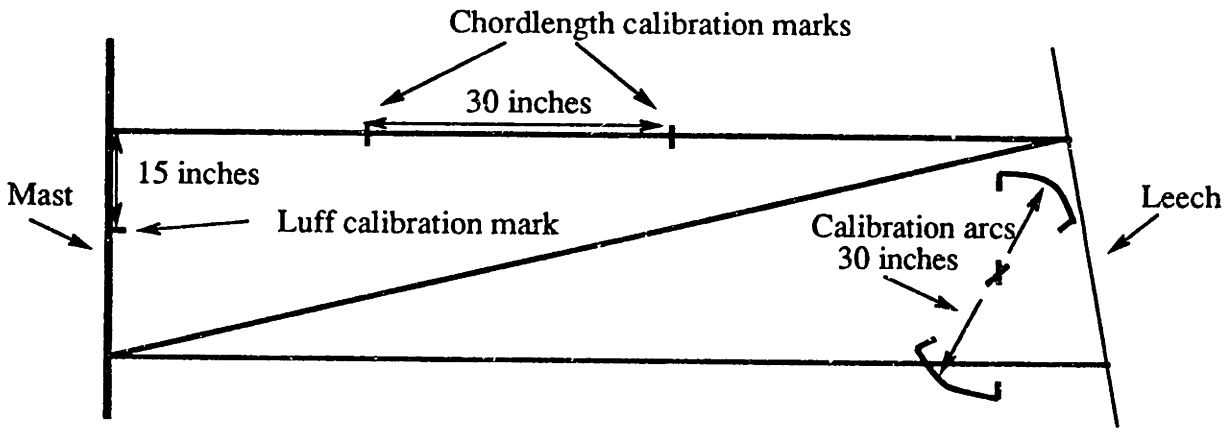

Figure 2-2: Calibration Marks

system can operate. Note that alterations must be made to the program if this is done.

2.2 Camera

To accomplish the difficult task of filming sails on the water an extremely high quality camera must be used. First of all, the video picture must be crystal clear when played in either the pause or slow motion frame by frame mode. Second of all, it must have a high shutter speed to insure clear images at all times. The camera will undoubtably be operated in rough conditions and will bounce around.

The camera chosen for this project is a *Canon A1 Mark II* Hi8 video camera (see Figure 2-4). This camera has been chosen for a number of reasons. First of all, a Hi8 camera was chosen for its improved image quality. A Hi8 recording has a resolution of 400 horizontal lines while a normal 8mm recording only has 250 lines. Second of all, the Canon camera was chosen for the numerous features it has that we need,

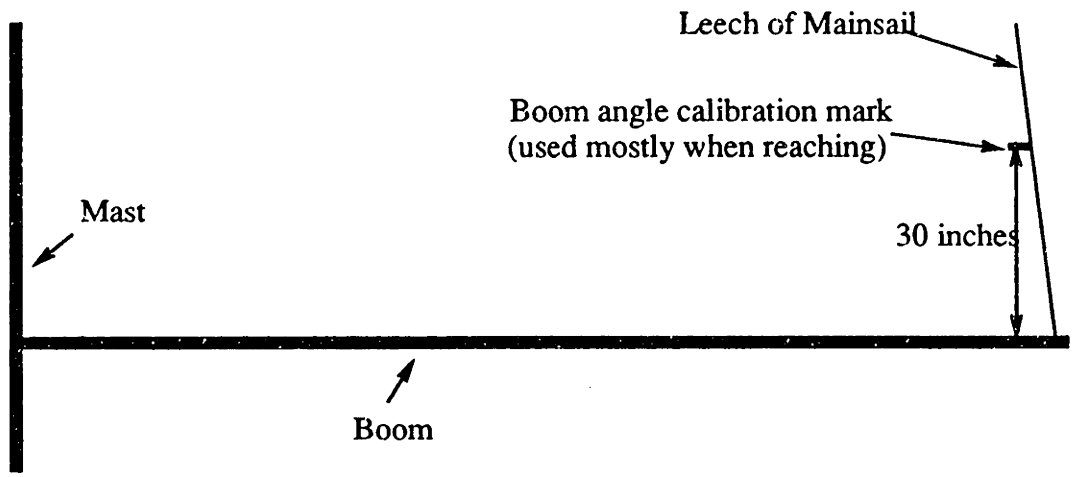

Figure 2-3: Boom Angle Calibration Mark

and because of its reputation for having the best image quality of any camera on the market. One of the special features this camera has that has proven to be essential is a super high shutter speed of 1/10000 of a second. When using this option, the camera can be used in very rough conditions. Even though the tape cannot be viewed in motion, due to the extreme movements of the camera, it can be viewed frame by frame with a crystal clear image. Other features of note, is the 10 to 1 zoom lens, the ability to record the time, and the clarity of the autofocus.

2.3 Computer

Once the recording has been made, it is viewed on a VGA monitor through a personal computer. One of the more difficult tasks in formulating this video system was finding the correct interface between the camera/player and the computer. The most common method for linking cameras to computers is through frame grabbers. Most frame grabbers operate with live video coming directly off a camera only, and therefore don't worry about synching up with video tape.

For this project though, a framer grabber must have the capability to synch up with video tape. While testing different frame grabbers it was found that most video

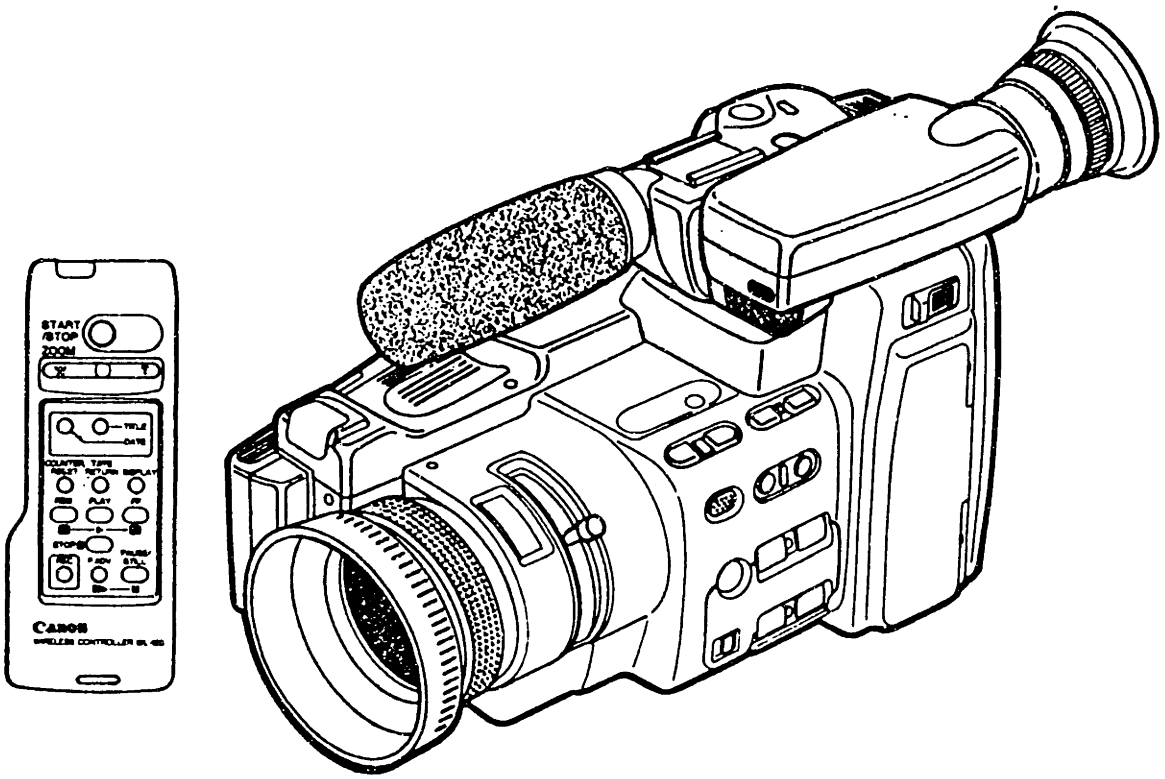

Figure 2-4: Video Camera used for Image Processing System

tapes are not precise in their frame rate. They vary slightly, throwing off most frame grabbers that attempt to capture frames at certain time intervals. Not only does the frame grabber have to synch properly, but it also has to be able to operate with the camera in the pause mode. Some frame grabbers were found to synch up properly, but would not produce a stable image when the camera was in the pause mode. This is due to the fact that some grabbers take two images and interface them together (blend every other horizontal pixel line).

After lengthy research, a video windows card, manufactured by New Media Graphics, was chosen as the link between the video camera/player and the computer. With New Media Graphics software, this board has functions similar to a frame grabber, and meets all of the specifications of this video system. The video windows card

mixes NTSC video with the computer's VGA graphics producing a composite display 640 pixels by 480 pixels on the monitor. This display contains the video signal in the background with an overlay that consists of the mouse driven sail analysis program.

The program enables sail shape data to be obtained for theoretical analysis (the program will be explained more in Chapters 3 and 4). The video windows card has features that allow the user to store and retrieve frames as well as the ability to freeze a live video signal, adjust the contrast, and zoom in on certain areas of the image if desired.

Chapter 3

Filming Procedures

3.1 Introduction

This chapter explains the necessary steps to obtain all of the pictures essential for sail shape analysis. The positions given in the various sections don't have to be maintained. One must make sure that while travelling in the vicinity of each position though, that there is constant filming to insure that the proper viewing location has been passed through and recorded. Each of the filming locations can be found on Figure 3-2. The diagram is not drawn to scale, but serves as a reference to see approximately the angle and distance needed to achieve the best results. The exact locations will be discussed in each section. Whenever possible, try to get the object that is being filmed to fill up as much of the screen as possible. The larger the object the better the resolution.

There are also some basics that must be covered concerning the camera operation. Firstly, the camera must be put into the manual mode. This is needed to make some necessary modifications to the camera's standard operating mode. Secondly, the shutter speed must be adjusted to 1/10000 of a second, so that when the camera shakes around (such as in the zoom mode), the shutter speed is fast enough to stop the frames from becoming blurred. The exposure can also be adjusted to make the picture slightly darker if desired. One must be careful not to overdue it and wash out the picture when adjusting this function. The date and time must also be displayed

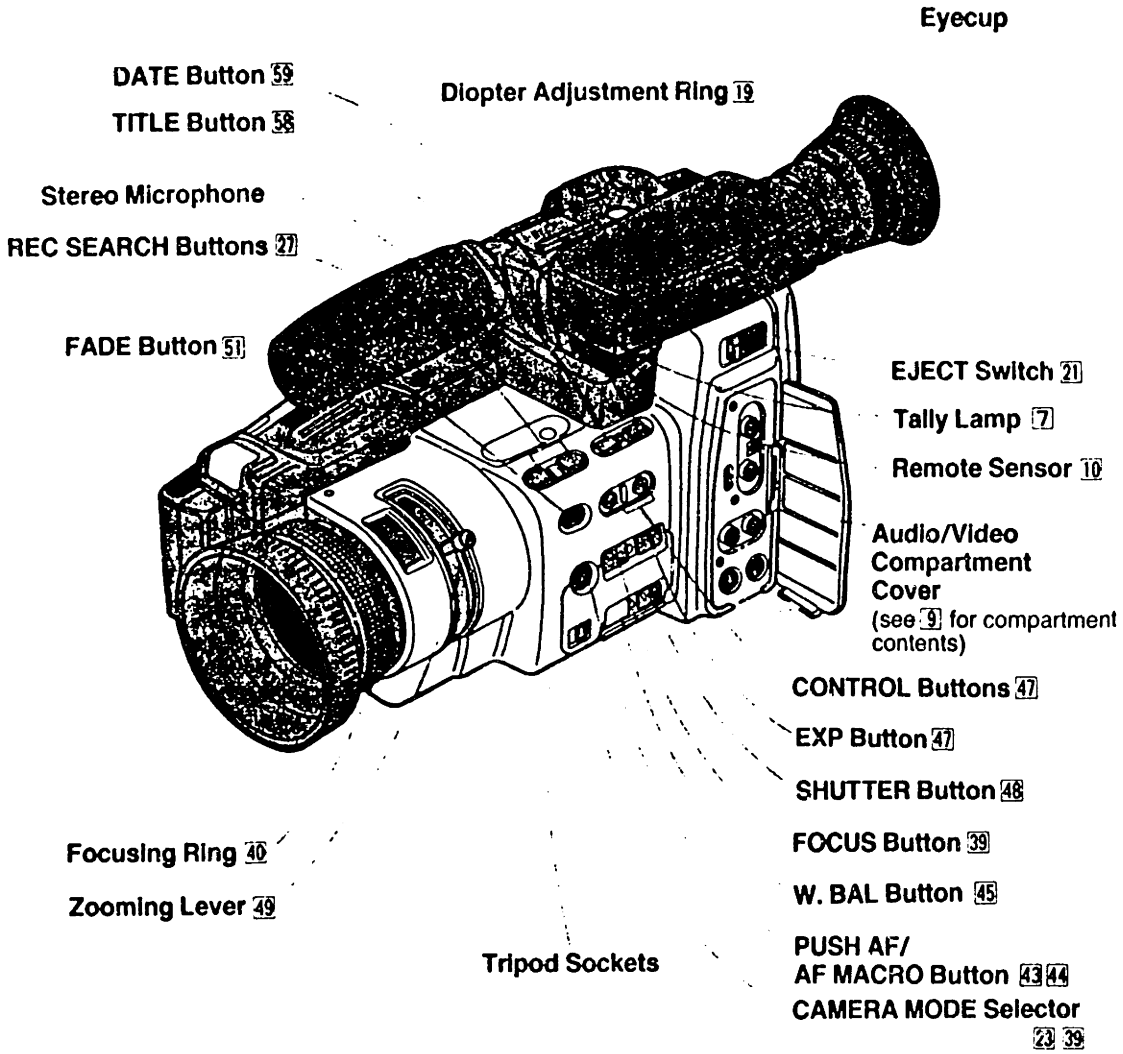

Figure 3-1: Function Buttons

(the time continuously) so that the frames can be correlated later to forces.

Every time the camera is shut off the time button must be pushed to display the time. The camera will remain in high shutter speed until adjusted again, so the shutter speed does not have to be altered each time the camera is shut off. Other than these functions, the camera should be operated in the automatic mode (all of the functions work in the auto mode even when the camera is switched to the manual mode, until they are adjusted). Figure 3-1 shows where some of the necessary buttons are located. To find out more about camera operation see the Canon Users Manual

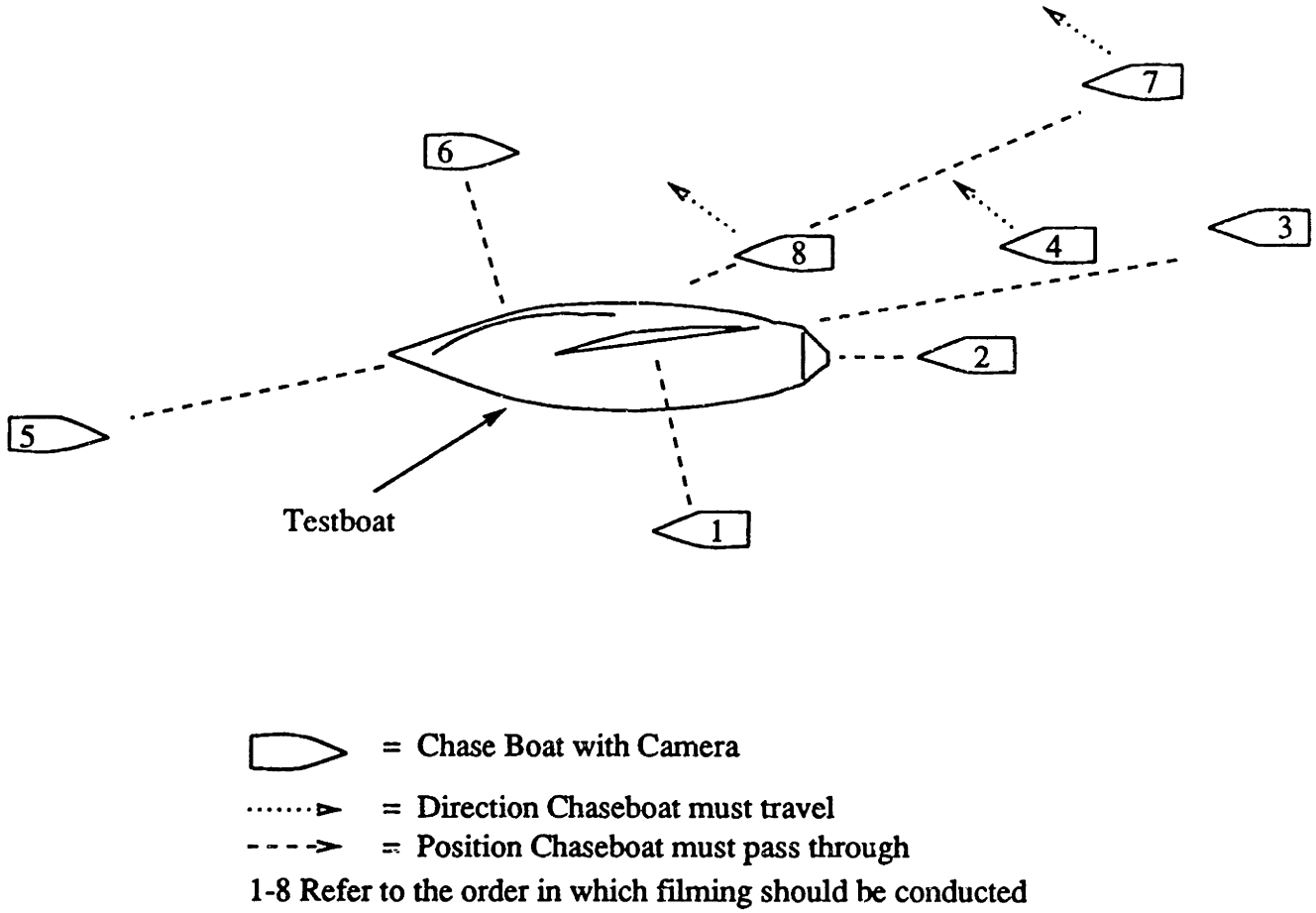

Figure 3-2: Filming Locations

[1].

3.2 Mainsail

3.2.1 Mainsail Chord Lengths

Locate the chase boat to windward of the sailing vessel, approximately perpendicular to the mainsail (see Figure 3-2 position 1). Get a closeup of each draft stripe pair to get the sailing chord lengths for the sail. Make sure that the entire quarter chord is included in the screen, yet attempt to make it fill as much of the screen as possible. Start from the top stripe pair, and continue to the middle pair, and then finish with

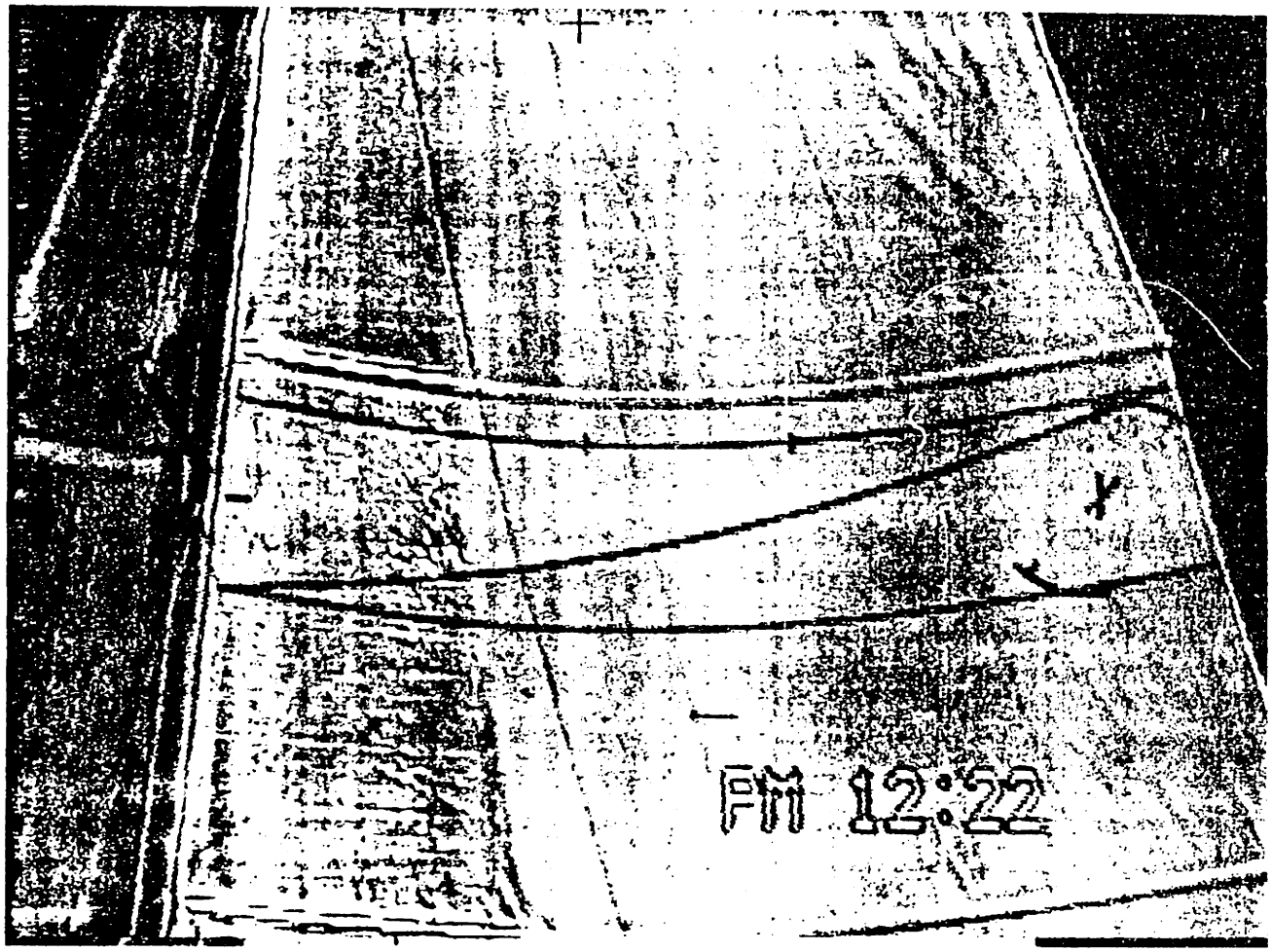

Figure 3-3: Mainsail Chord Length

the bottom stripe pair. The view seen through the camera should look similar to Figure 3-3. Note that if mast bend were to be studied at a later date, this picture could be used to determine the mast bend and its effects on sail shape.

3.2.2 Boom Angle

Locate the chase boat directly astern of the sailing vessel, and line up the mast with the center of the transom to get get the camera positioned directly on centerline. The boom position away from centerline can then be determined. The picture should be a

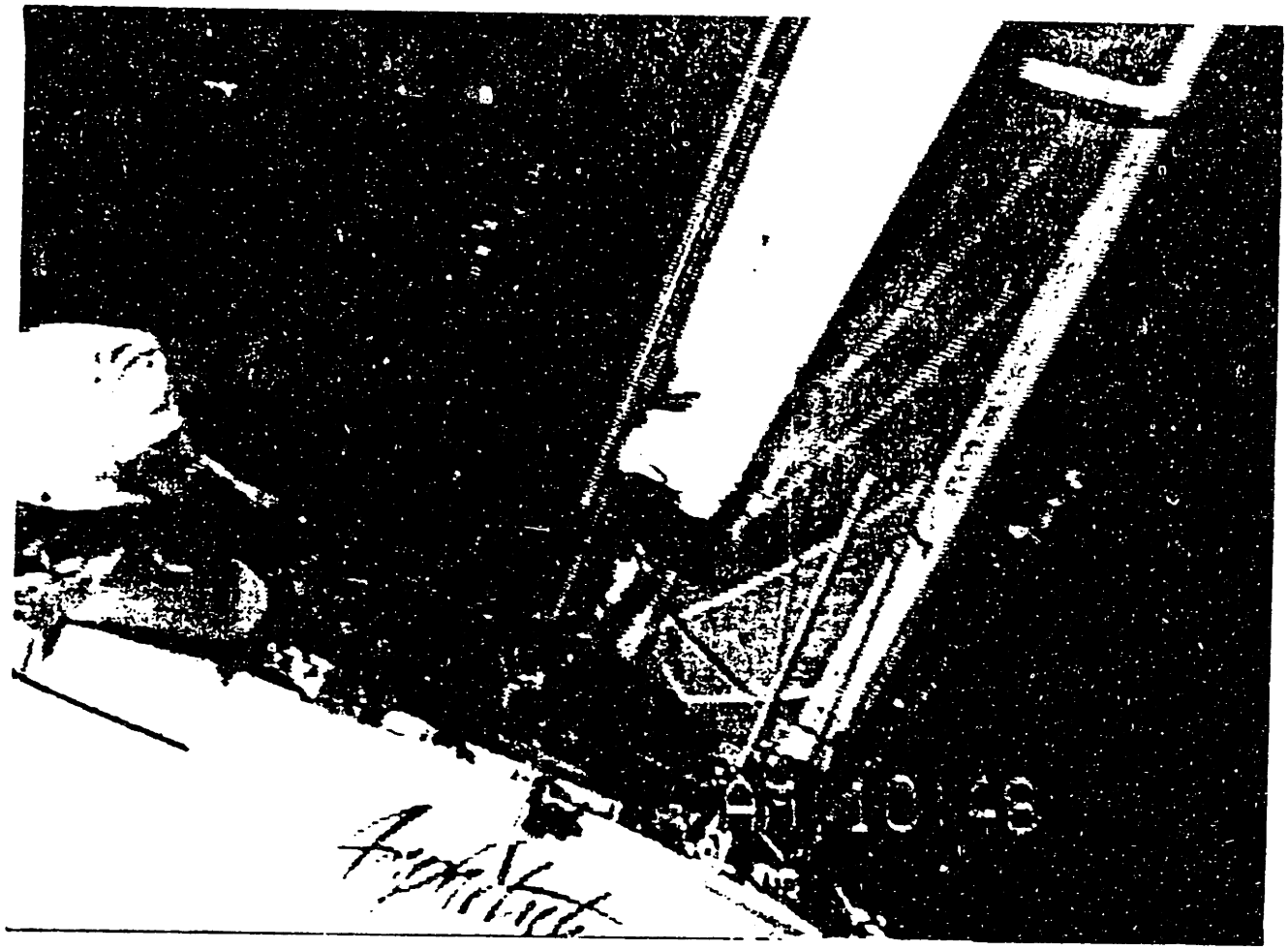

Figure 3-4: Boom Angle

closeup of the boom and the stern of the sailboat to increase the accuracy (see Figure 3-2 position 2). The view should look like Figure 3-4.

3.2.3 Mainsail Overall Twist

Locate the chase boat as far away from the sailing vessel as possible so that at maximum zoom, the mainsail fills entire picture. Line up with the end of the boom so that the twist offsets away from the boom can be measured from this picture (see Figure 3-2 position 3). The large distances are needed to reduce the vertical

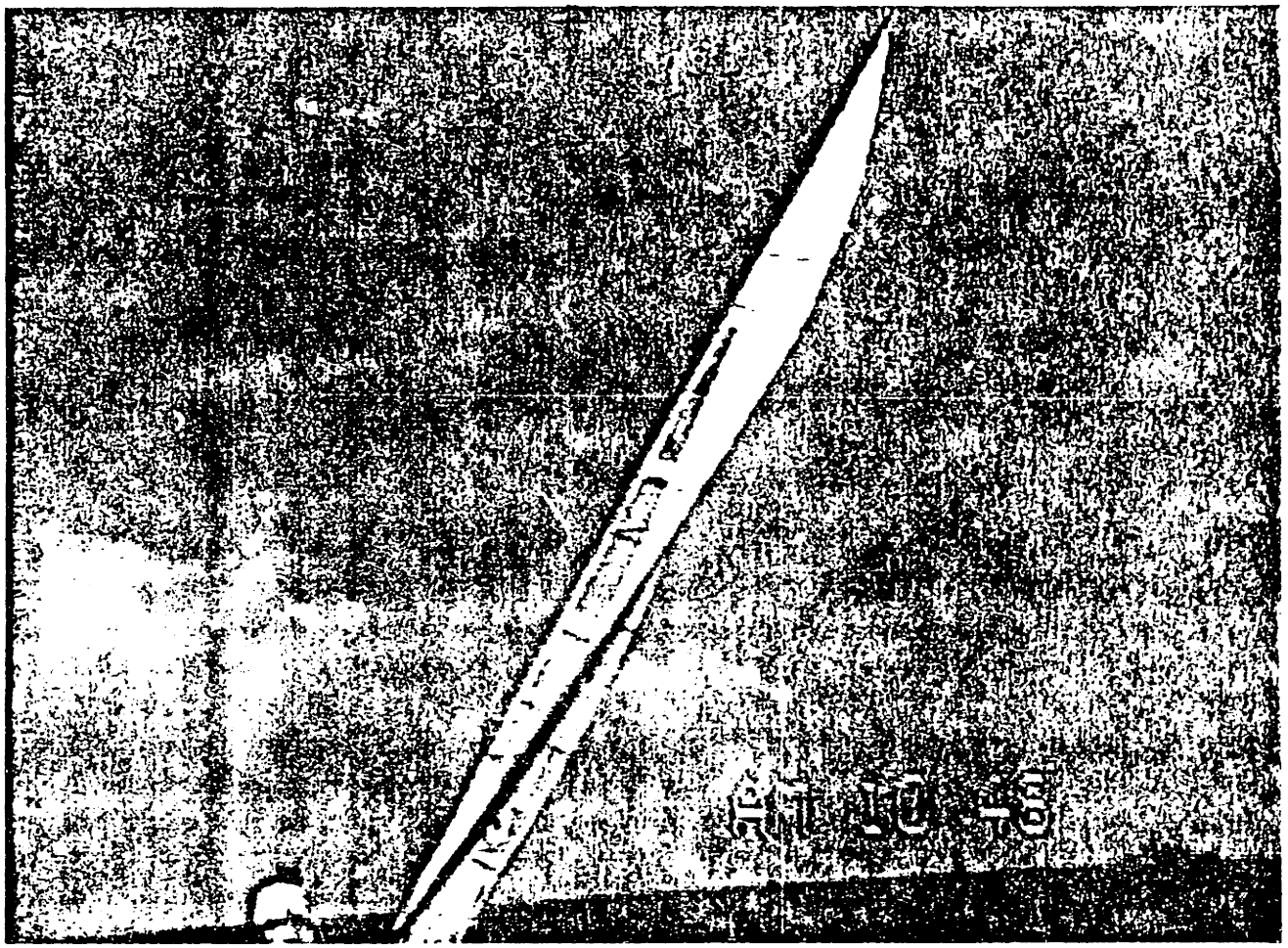

Figure 3-5: Overall Twist

angle to the upper stripes. This is because it has been found that it is hard to see the calibration arcs, which are used to compensate for vertical angle distortion (explained in detail in Chapter 4). Therefore instead of using the arcs during overall twist measurements, the distance between the stripes in each stripe pair is used. Make sure that the stripes can be seen clearly. The picture should be similar to Figure 3-5.

3.2.4 Mainsail Draft Data

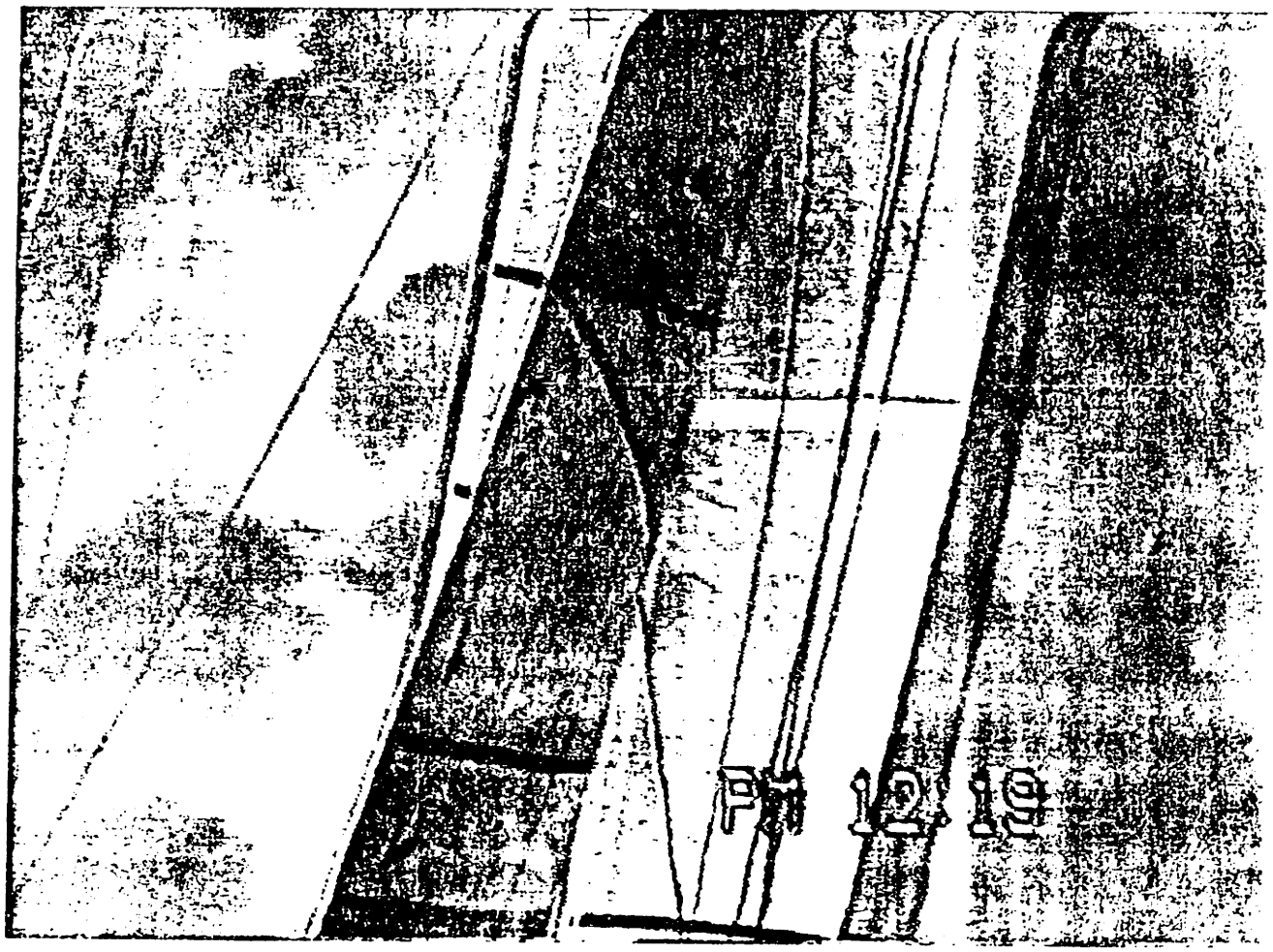

Figure 3-6: Draft Data

Locate the chase boat closer to the sailing vessel and now zoom into each stripe pair to get the draft data. First start with the bottom stripe pair (bottom quarter chord). Line up leech of the mainsail with the mast at the bottom stripe in the stripe pair. Try to fill up as much of the screen as possible with the sail, to again increase accuracy. As the chase boat moves slowly off to leeward (see Figure 3-2 position 4), the leech of the mainsail will cross the mast higher and higher up. Coordinate the filming of each stripe pair with this movement (as the leech crosses the mast at the lower stripe of each pair), to film the mid chord, and then the top quarter chord. Each stripe pair

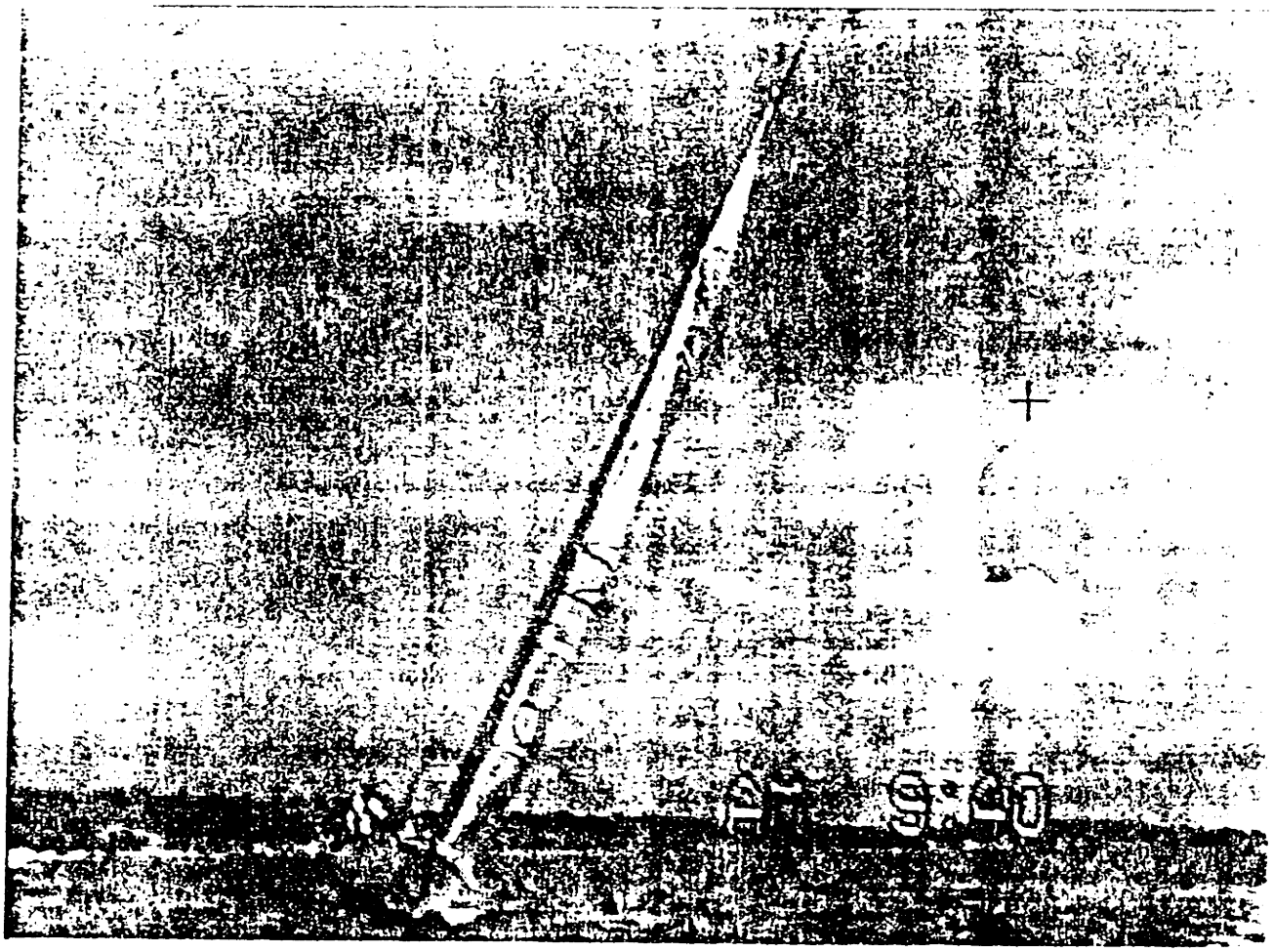

Figure 3-7: Leading Edge Position

should be filmed similar to Figure 3-6

3.3 Jib

3.3.1 Jib Leading Edge Position

The chase boat must be situated in front of the boat sailing, with tack of the jib approximately lined up with clew of the jib (see Figure 3-2 position 5). Again go back as far as possible so that when the camera is zoomed in all of the way, the jib

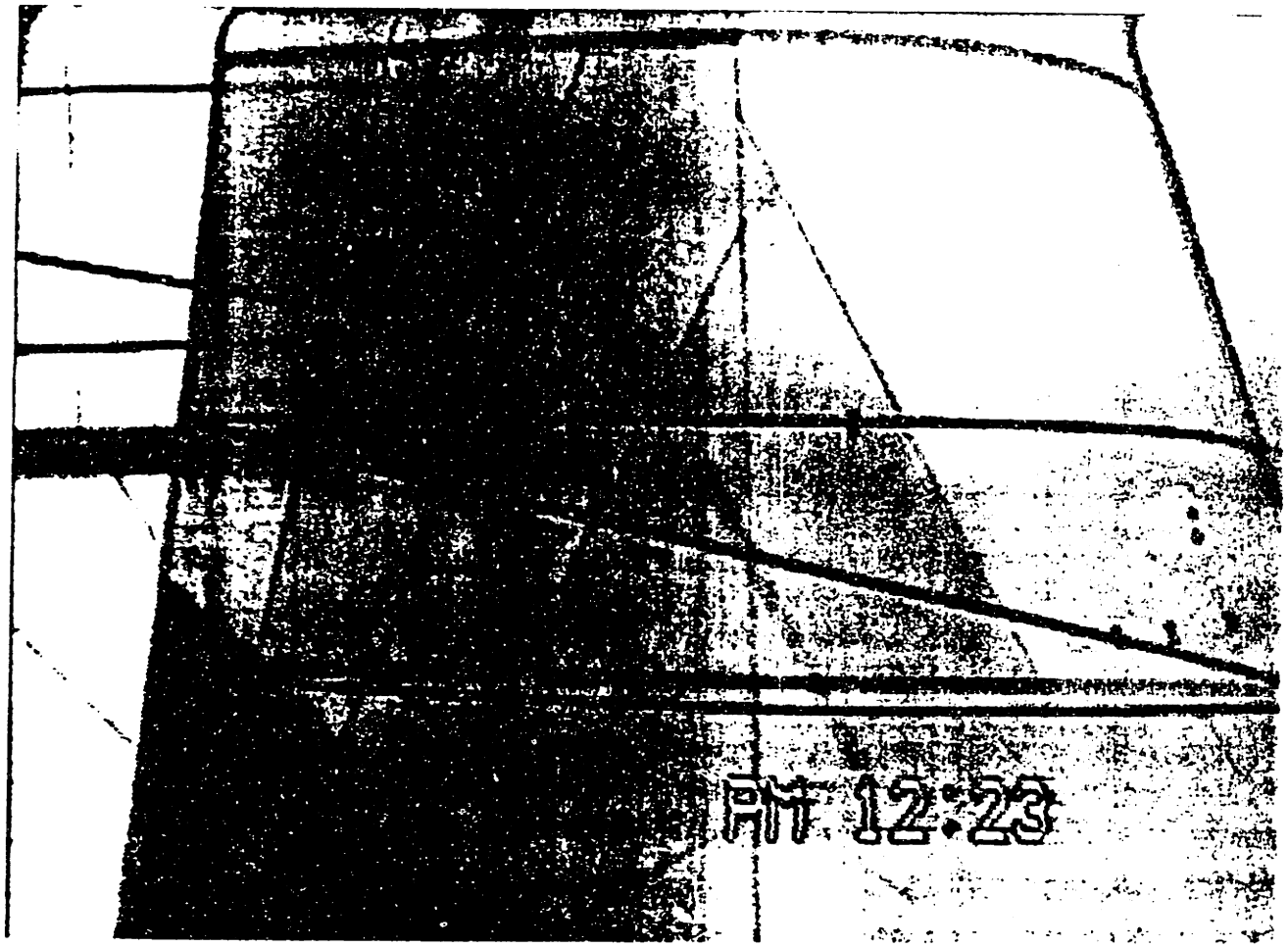

Figure 3-8: Jib Chord Length

luff fills the entire screen (make sure that the entire luff can be seen though). This view will enable the calculation of the luff sag (headstay sag) of the jib perpendicular to the plane of the sail. This will be used in the calculation of the twist, or angle of attack of the sail. The picture video taped should appear like Figure 3-7.

3.3.2 Jib Chord Lengths

The chase boat is located to leeward and in front of sailboat, approximately perpendicular to each chord of jib (see Figure 3-2 position 6). As the chase boat moves aft

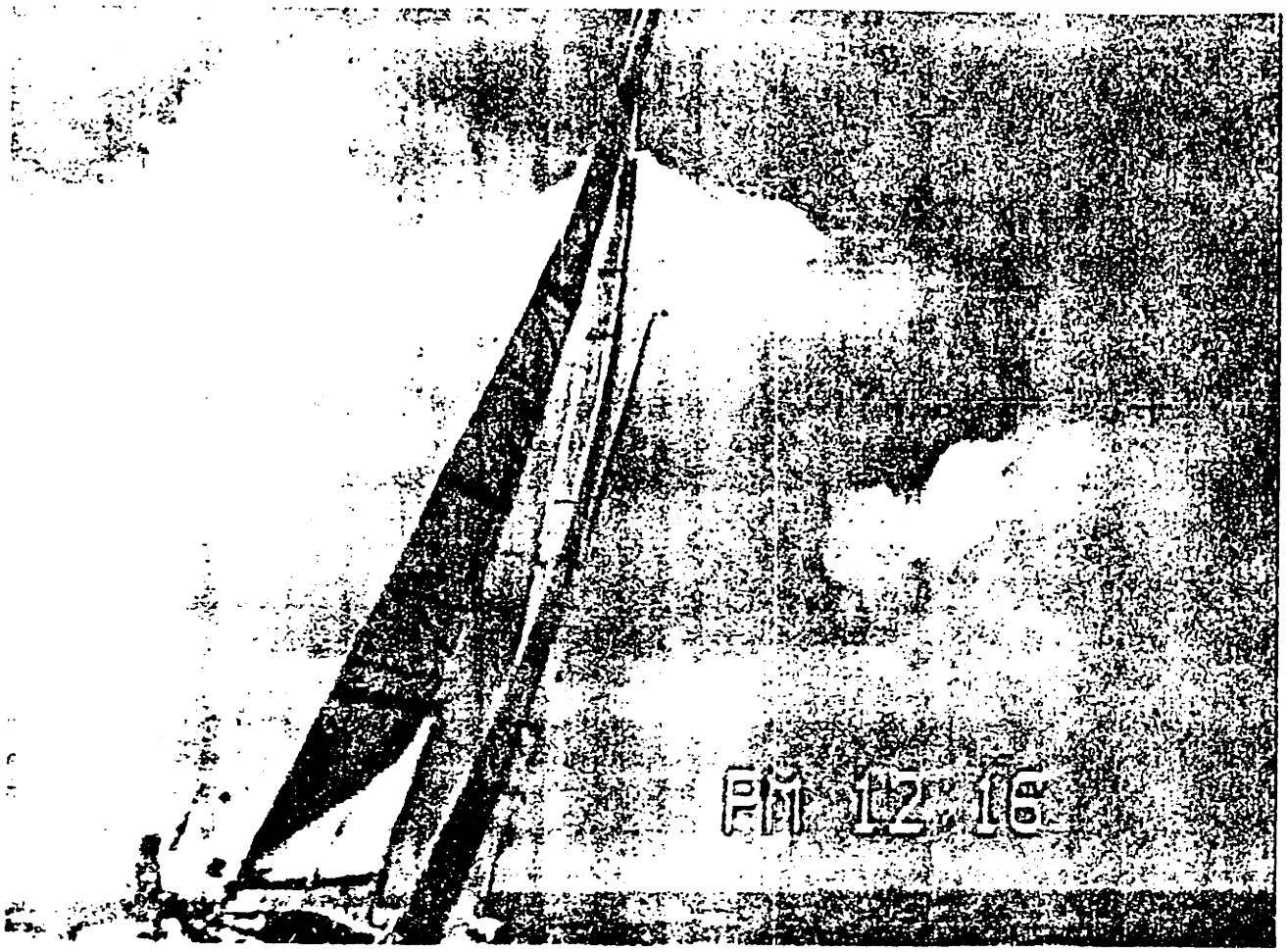

Figure 3-9: Jib Twist

with respect to the the sailboat, film from the top down. This is done because the top of the sail is twisted off more than the bottom, and to be perpendicular to the top quarter chord, one must be farther foward than the middle, and then bottom quarter chords. As was performed when filming the mainsail chord lengths, make sure to zoom in on each quarter chord to increase scaling accuracy. Each chord length picture should look similar to the picture in Figure 3-8.

3.3.3 Jib Overall Twist

Locate the chase boat on the leeward stern quarter of the sailing vessel. Go back as far as possible while zooming in on the sail all of the way to just fit head and clew of jib on screen (see Figure 3-2 position 7). It is imperative to be located far away to minimize the vertical angle distortion. With the jib, as with the main, at times it has been tough to see the calibration arcs clearly. If they cannot be seen, the distance between the stripes in each stripe pair must be used. These stripes are horizontal, not angled down as with the calibration arcs, so that the greater the distance viewed from, the smaller the vertical angle, and the lower the angle distortion.

Line up with tack and clew of the jib, and slowly move to leeward until you can see head. Make sure the head of the jib can be seen (clear of mainsail). Try to estimate the angle away from the tack-clew line of the jib when the optimum position (can see the head and clew of jib, and are located as close to centerline of sailboat as possible), and record on tape. This location enables the calculation of the twist offsets of the jib. The view seen from this location should resemble Figure 3-9. Note that unlike when attempting to determine the twist of the mainsail, we are unable to obtain the twist offsets from the plane formed from the heat, tack, and clew directly. Instead, the twist is calculated from a position slightly to leeward and corrected (see the Overall Sail Twist for the Jib section in Chapter 4).

3.3.4 Jib Draft Data

Situate the chase boat closer to the sailboat at approximately the same angle (see Figure 3-2 position 8). Zoom in all of the way to record draft data at each quarter chord. As with the mainsail, line up leech with the headstay (the mast with the mainsail), at the bottom stripe in the bottom stripe pair. The chase boat may have to travel aft with respect to the sailing vessel to achieve this position. As the chase boat slowly heads to leeward, the leech will cross the headstay higher and higher. As soon as the bottom quarter chord is filmed properly, position the camera on the mid chord, and then on the top quarter chord to coordinate with the chase boat's movement (there is little time between the mid chord and top quarter chord). Each stripe pair should be filmed similar to Figure 3-10.

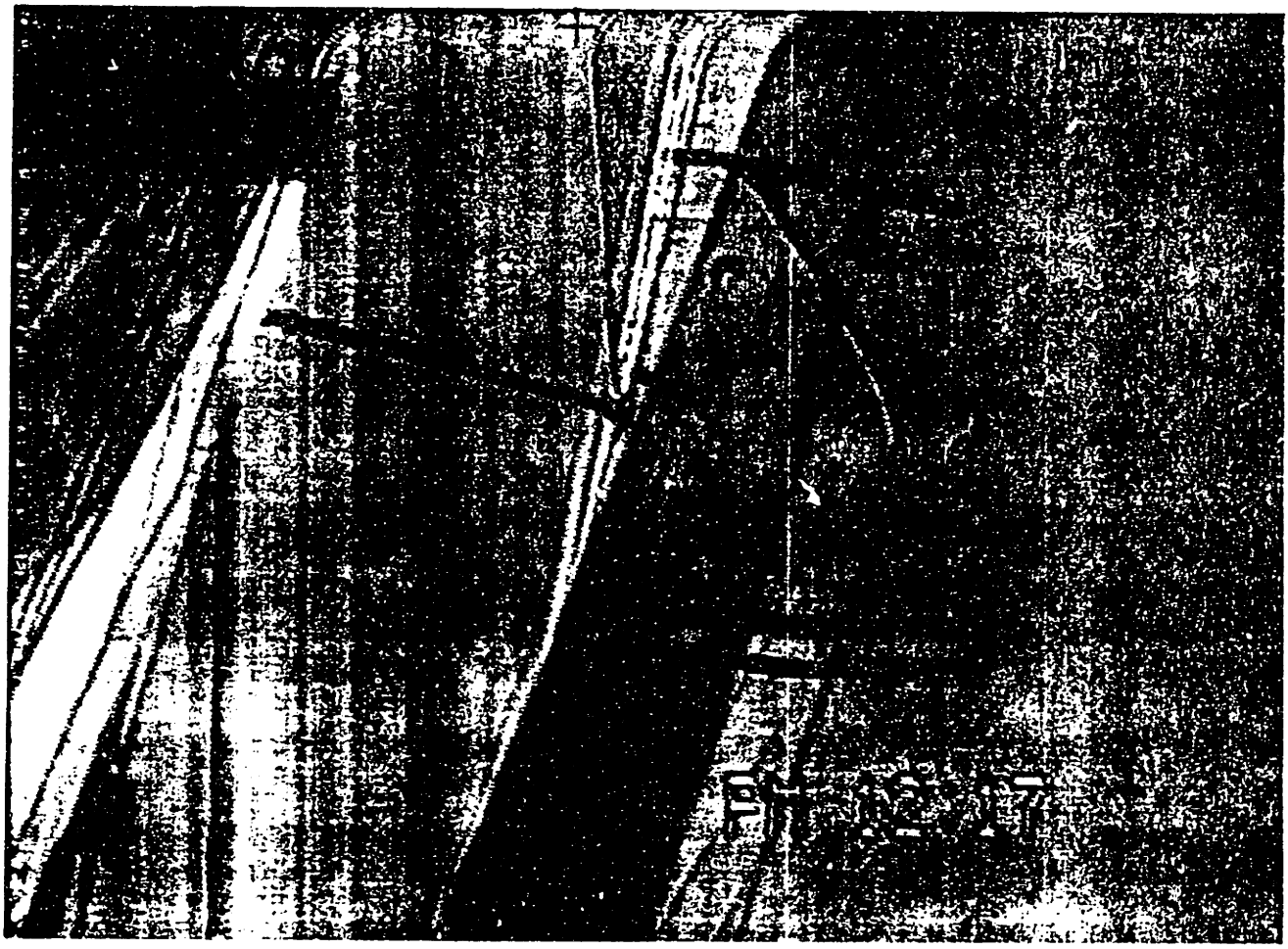

Figure 3-10: Draft Data

Chapter 4

Data Acquisition: Program Operation and Explanation

4.1 Introduction

Once the correct pictures of the sails have been filmed, the sail shape data must be collected and analysed. To accomplish this, as mentioned earlier, the video tape must be replayed through a computer containing a video graphics board/frame grabber onto a VGA monitor. To locate the frames which contain the correct viewing positions needed to obtain the sail shape data, the film can be stopped at any point by pressing the pause button. The easiest way to obtain the proper frame is to get the tape near the position of interest, and hit the pause button. Then the tape can be advanced frame by frame by pressing the *FADV.* button. A program written by Noah Eckhouse, enables one to locate the pixel positions of the calibration points and the sail shape data marks. The program then scales the sail shape data points to actual distances using the calibration information.

4.2 Calibration

The video windows card and video camera must first be calibrated to see the relationship between the number of pixels horizontally verses the number of pixels vertically

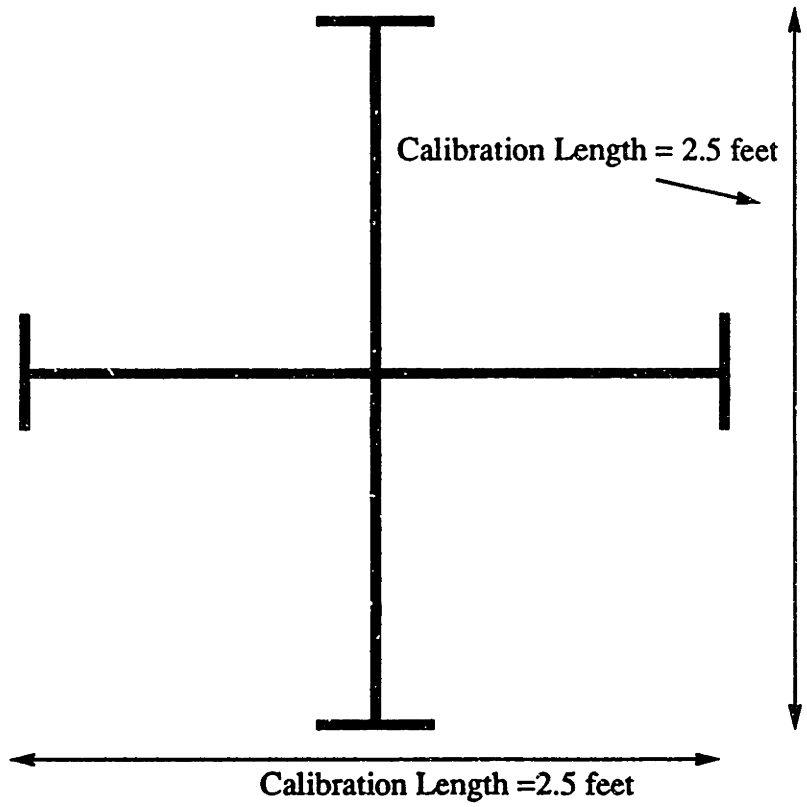

Figure 4-1: Calibration Mark

for a given distance. This was accomplished by creating crosshairs 30 inches by 30 inches with Autocad and a plotter, and measuring the pixel distances. The plot is similar to Figure 4-1. This was repeated at several distances to insure linearity. A function was then created to relate the x pixels to the y pixels (The given result is for the new Media Graphics Board used):

$$f(x) = .97 \tag{4.1}$$

This function will be used later to determine the pixel distances between given points.

4.3 Sail Shape Data Collection

This section describes how to operate the off-boat vision system computer program, and the computations that are carried out by the program to arrive at the desired results.

The first option, when running the program, is to decide which sail is to be analysed, main or jib. Then the chosen sail is digitized by following the directions on the screen (in conjunction with this chapter) and using the mouse as described on the screen and in the following pages.

4.3.1 Mainsail

The steps for digitizing the mainsail follow the order of the different filming positions (see Figure 3-2). The first position, located to windward of the sailing vessel, perpendicular to the mainsail, is used for chord length analysis. The second position, located behind the boat and directly on centerline enables boom angle calculation. The third location, positioned directly in line with the boom, enables the twist offsets from the boom to be calculated. The fourth, and final mainsail filming position, located on the leeward stern quarter (travelling in an arc to leeward), records the draft data needed for draft position analysis.

Mainsail Sailing Chord Lengths

Using the pictures obtained from position 1 (see Figure 3-2), the view of the sail will appear similar to Figure 4-2. Locate the mouse on the calibration points (points 1 and 2). The real distance apart of these points is 2.5 feet (whenever possible, this scaling distance has been used). The first computation for calculating the mainsail chord length is to convert the pixel distance between the calibration marks to a scaling ratio. The calibration pixel distance conversion is given by:

$$Pd = \sqrt{(Px_1 - Px_2)^2(.97)^2 + (Py_1 - Py_2)^2} \tag{4.2}$$

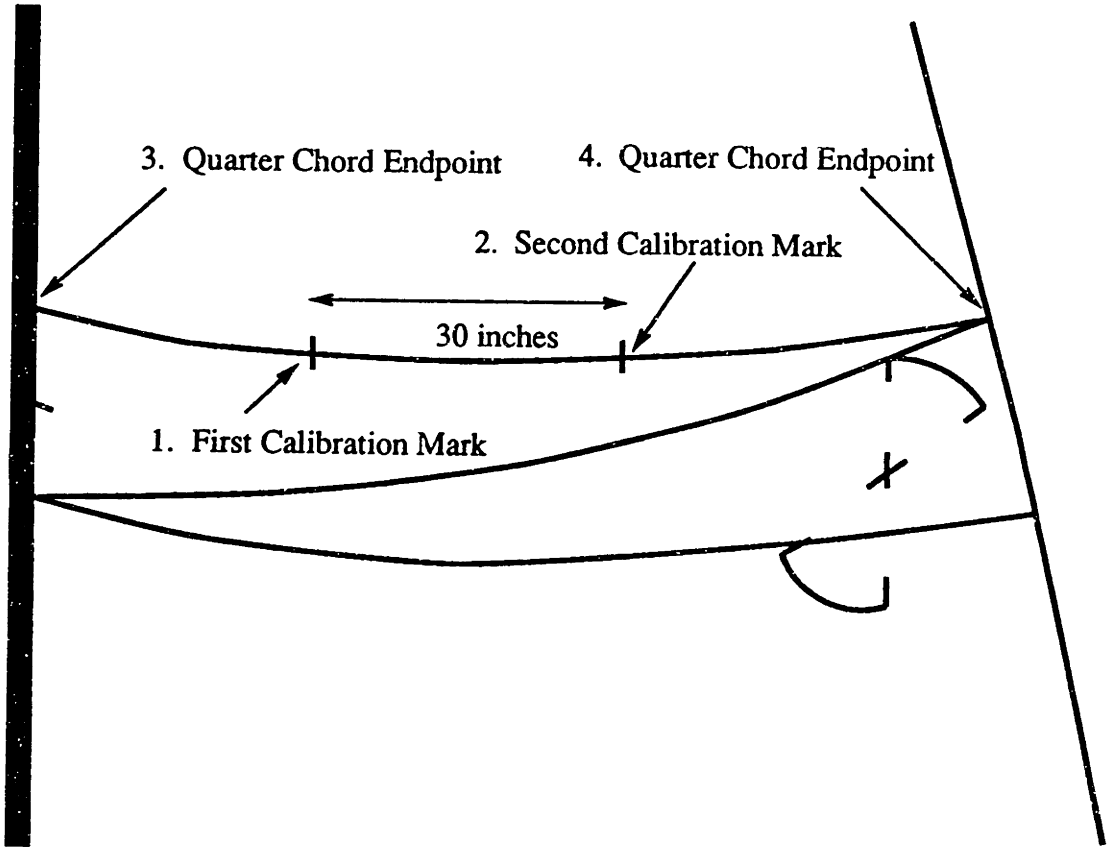

Figure 4-2: Mainsail Chord Length

$$dPy = \frac{2.5}{Pd} \tag{4.3}$$

Pd is the pixel distance between the two calibration marks, where Px and Py are the x and y positions of each point respectively (points 1 and 2). dPy is the ratio of the calibration distance (2.5 feet) to Pd, the pixel distance. Now that the calibration ratio has been calculated, the endpoints of quarter chord must be entered (points 3 and 4), and the actual chord length can then be determined. Note that the quarter chord is always the top stripe in each stripe pair. The chord length calculation is given by:

$$Cl = dPy\sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.4}$$

Cl is the sailing chord length and Px and Py are the x and y positions of each endpoint of the quarter chord (points 3 and 4).

This process is repeated for each of the quarter chords on the mainsail, starting at the top quarter chord and ending with the bottom quarter chord (each stripe pair has it's own frame). The top quarter chord, the mid chord, and the bottom quarter chord, are referred to as $Cl_{1,2,3}$ respectively. The length of each chord will be used to calculate the twist angles from centerline at each quarter chord.

Boomangle

Using the pictures obtained from position 2 (see Figure 3-2), which is located behind the boat directly on centerline, the boomangle can be calculated. The image from this position will appear similar to Figure 4-3. Again, the first step is to position the cursor on the calibration points. When sailing upwind, it has been observed that it is difficult at times to see the calibration mark on the leech of the sail located 2.5 feet above the boom. To correct this problem, the running backstay winches which happen to be located in line with the end of the boom, can be selected as a calibration distance (they are exactly 3 feet apart). When reaching, and the mark on the leech can be seen, the calibration mark above the leech is used in conjunction with the end of the boom (one of the sail measurement points).

Therefore as seen in Figure 4-3, the *U's* are the points used upwind. Points *1U* and *2U*, the centers of the port and starboard winches respectively, serve as the calibration points. When reaching the *R's* are used as calibration the points. Point *1R* is 2.5 feet up the leech of the mainsail, while point *2R* is at the end of the boom.

If the winches are used, the calibration distance of 2.5 feet used in the distance to pixel ratio equation (equation 4.6), is replaced with 3.0 (equation 4.7). The following expressions are then carried out to determine the calibration scaling:

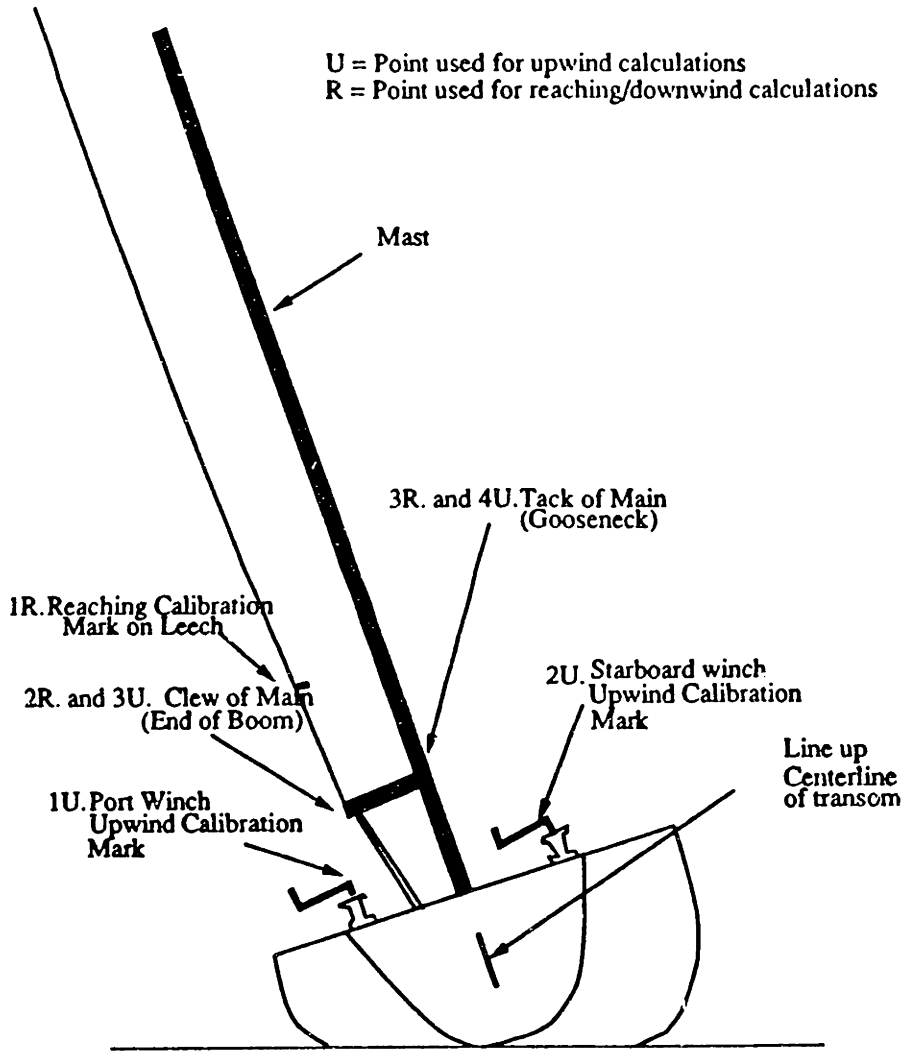

Figure 4-3: Boom Angle

$$Pd = \sqrt{(Px_1 - Px_2)^2(.97)^2 + (Py_1 - Py_2)^2} \tag{4.5}$$

$$dPy = \frac{2.5}{Pd} \tag{4.6}$$

or

$$dPy = \frac{3.0}{Pd} \tag{4.7}$$

Pd is again the pixel distance between the two calibration marks, whether it be the two winches or the mark on the leech and the end of the boom, and dPy is the

ratio of calibration distance to pixel distance, Pd. Throughout the program, Pd, dPy, Px, and Py, remain consistent. The subscripts of the x and y pixel positions always refer to the point number which can be found on the associated figure.

When sailing upwind and using the winches as the scaling points, input points for the boom angle, points $3U$ and $4U$ are located at the end of the boom and at the gooseneck respectively. The distance of the end of the boom off centerline is equal to BD from the following formula:

$$BD = dPy\sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.8}$$

If the calibration point on the leech is used instead, or the vessel is sailing off the wind, point $2R$, already input from calibrating, and point $3R$, located at the gooseneck, are used to determine the boom distance from centerline by substituting the following expression:

$$BD = dPy\sqrt{(Px_2 - Px_3)^2(.97)^2 + (Py_2 - Py_3)^2} \tag{4.9}$$

The boomangle, BA, is then calculated by using this distance and the boomlength, BL, with the simple formula:

$$BA = \sin^{-1}(\frac{BD}{BL}) \tag{4.10}$$

Mainsail Overall Sail Twist

The overall sail twist is calculated from a position located directly in line with the end of the boom. This is position 3 as seen in Figure 3-2. The view from this location should be similar to Figure 4-4. The first points to be digitized are the calibration points. The edges of the circular arcs may be used, but in many instances it has been found that it is hard to see them from this far away. An alternative that has worked much better is the trailing edges of the stripe pairs (at the leech), which are exactly the same distance apart. This has been found to not greatly effect the results, because when viewing from distances this large, the angle up is relatively small (this

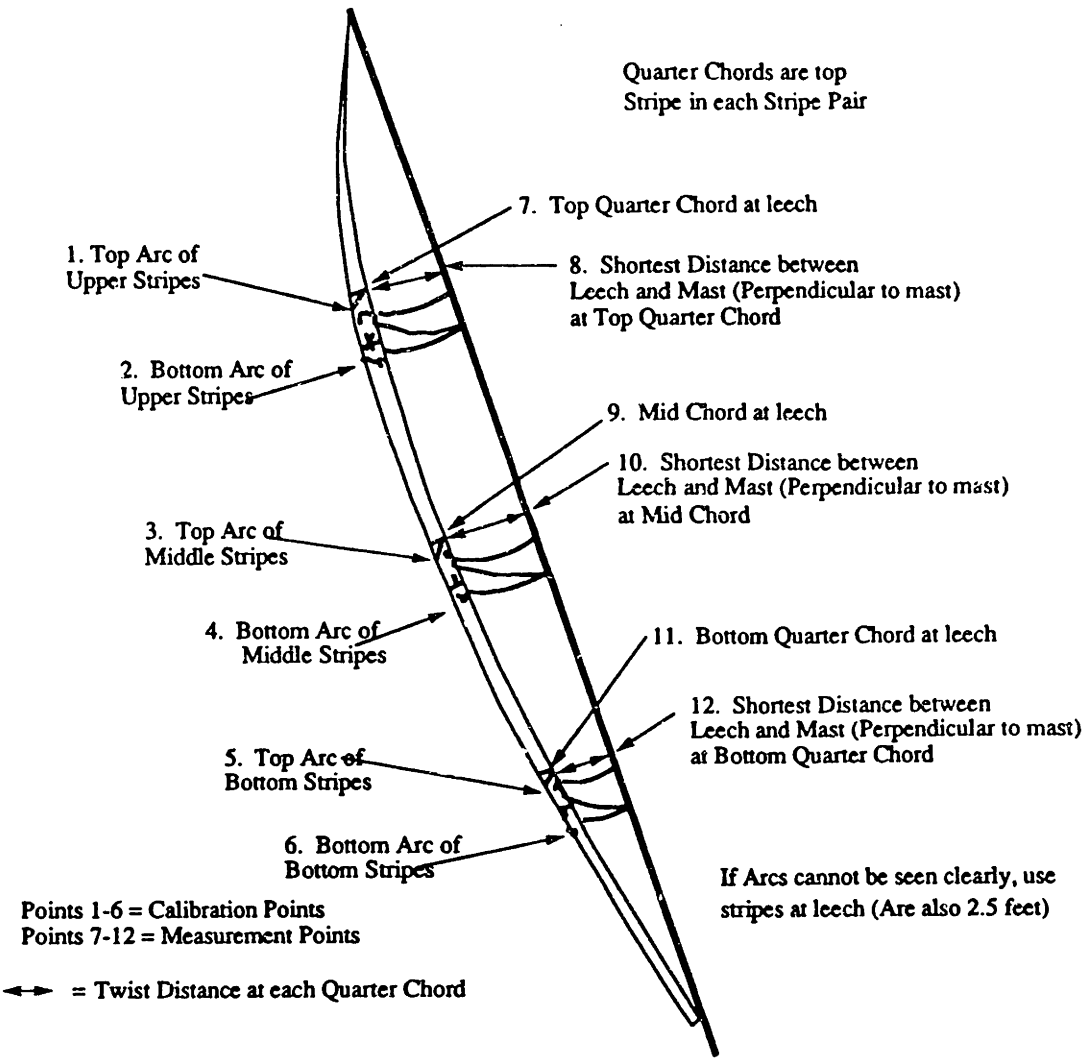

Figure 4-4: Mainsail Twist

is not the case when zooming in on each stripe at much closer distances). In any case, there are two calibration points for each quarter chord, which totals 6 points (as can be seen in Figure 4-4 as points 1-6). The pixel distances are again measured and ratios calculated:

$$Pd_1 = \sqrt{(Px_1 - Px_2)^2(.97)^2 + (Py_1 - Py_2)^2} \tag{4.11}$$

$$dPy_1 = \frac{2.5}{Pd_1} \tag{4.12}$$

$$Pd_2 = \sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.13}$$

$$dPy_2 = \frac{2.5}{Pd_2} \tag{4.14}$$

$$Pd_3 = \sqrt{(Px_5 - Px_6)^2(.97)^2 + (Py_5 - Py_6)^2} \tag{4.15}$$

$$dPy_3 = \frac{2.5}{Pd_3} \tag{4.16}$$

The subscripts 1,2, and 3, following dPy refer to the top, middle, and bottom, quarter chords respectively.

By using these calibration distances and the mouse to locate the perpendicular distance of each quarter chord to the mast (as seen in Figure 4-4 as points 7 through 12), the distance of each quarter chord from the plane of the boom can be calculated from the following formulas:

$$TD_1 = dPy_1\sqrt{(Px_7 - Px_8)^2(.97)^2 + (Py_7 - Py_8)^2} \tag{4.17}$$

$$TD_2 = dPy_2\sqrt{(Px_9 - Px_{10})^2(.97)^2 + (Py_9 - Py_{10})^2} \tag{4.18}$$

$$TD_3 = dPy_3\sqrt{(Px_{11} - Px_{12})^2(.97)^2 + (Py_{11} - Py_{12})^2} \tag{4.19}$$

$TD_{1,2,3}$ refer to the twist distances from the boom plane for the top, middle, and bottom stripe pairs respectively. Using these distances, along with the chord lengths previously calculated for each quarter chord, the twist angles from centerline for each quarter chord can then be calculated with the expressions:

$$TA_1 = \sin^{-1}(\frac{TD_1}{CL_1}) + BA \tag{4.20}$$

$$TA_2 = \sin^{-1}(\frac{TD_2}{CL_2}) + BA \tag{4.21}$$

$$TA_3 = \sin^{-1}(\frac{TD_3}{CL_3}) + BA \tag{4.22}$$

$TA_{1,2,3}$ refers to the twist angle of each stripe (top, middle, and bottom respectively). $Cl_{1,2,3}$ is the chord length of each corresponding quarter chord, while BA is the boom angle.

Mainsail Draft Data

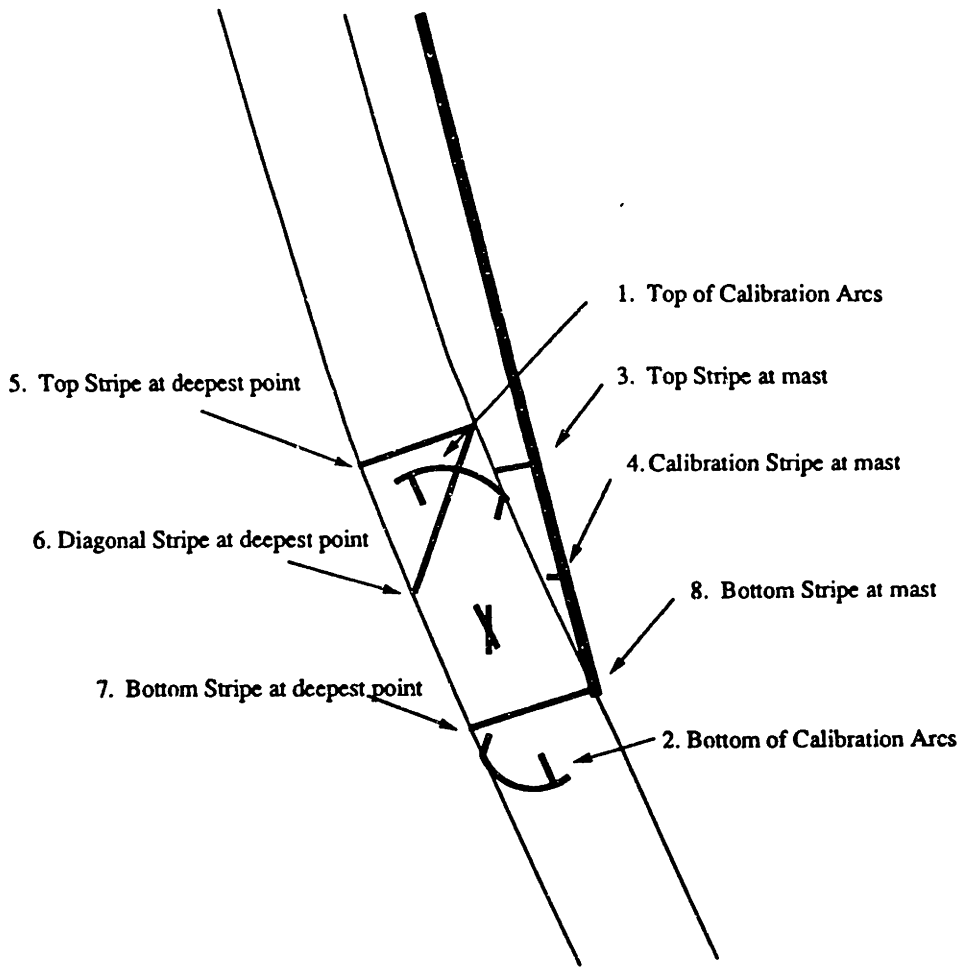

Figure 4-5: Mainsail Draft

With the chase boat located at position 4, as seen in Figure 3-2, the camera is zoomed in all the way to get a closeup view of each draft stripe pair. The picture will be similar to that seen in Figure 4-5. The first shot should be of the bottom quarter chord, and as the chase boat slowly heads off to leeward, the leech will cross the mast higher and higher up. As the bottom stripe from each pair crosses the mast, the draft data at that stripe can be obtained.

Since these shots are taken at close range, the arcs at the leech must used for

the calibration distance. The arcs are placed on the sails so that if the pictures are taken at different distances, and therefore the camera is angled at different angles up, positions on the arc can be chosen that are equidistant from the lens. For instance, if the stripe viewed is 35 feet up, and the pictures are taken from 35 feet behind the leech, then a position 45 degrees from vertical is used (the hash mark away from vertical).

As before, the calibration distances are the first inputs. Since the maximum draft is not at the leech (all of the previous distances have been from the leech), but somewhere near the middle of the sail, another calibration distance at the mast must be taken. As seen in Figure 4-5, points 1 and 2 give the calibration distance at the leech while points 3 and 4 yield the calibration distance at the mast (note that points 3 and 4 are only 1.25 feet apart). Therefore the calibration distance ratios can once again be calculated by:

$$Pd_1 = \sqrt{(Px_1 - Px_2)^2(.97)^2 + (Py_1 - Py_2)^2} \tag{4.23}$$

$$dPy_1 = \frac{2.5}{Pd_1} \tag{4.24}$$

$$Pd_2 = \sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.25}$$

$$dPy_2 = \frac{1.25}{Pd_2} \tag{4.26}$$

dPy_1 is the calibration ratio at the leech, while dPy_2 is the calibration ratio at the mast.

The purpose of the diagonal stripe is to locate the position of the maximum draft. When the leech is lined up with the mast, as viewed from astern of the boat, all the sail that can be seen is the sail behind the maximum draft position. The diagonal stripe starts at the top at the leech and ends at the bottom at the luff. At fifty percent aft, the stripe will be mid-way between the two parallel stripes. So therefore the ratio of the distance from the diagonal stripe to the bottom stripe, to the distance between the two horizontal stripes, yields the maximum fore/aft draft location. As seen in Figure 4-5, points 5,6, and 7, are the pixel positions needed to determine this

location by the following calculations:

$$R_1 = \sqrt{(Px_5 - Px_6)^2(.97)^2 + (Py_5 - Py_6)^2} \tag{4.27}$$

$$R_2 = \sqrt{(Px_6 - Px_7)^2(.97)^2 + (Py_6 - Py_7)^2} \tag{4.28}$$

$$DP = \frac{R_2}{R_1 + R_2} \tag{4.29}$$

R_1 is the top stripe to diagonal stripe pixel distance, while R_2 is the diagonal stripe to bottom stripe pixel distance. DP is the location of the maximum draft expressed as a percentage aft of the leading edge.

To get the actual maximum draft, a perpendicular distance must be determined at the point where the leech intersects with the mast (at the bottom stripe in the stripe pair). This is accomplished by locating the cursor at the point of maximum draft, point 7 (already input), and at the point where the leech intersects with the mast (point 8). This pixel distance is located DP aft of the mast. The formula used to calculate the maximum draft (using scaling at the leech and at the mast) is given by:

$$MD = [\sqrt{(Px_7 - Px_8)^2(.97)^2 + (Py_7 - Py_8)^2}][dPy_1 DP + dPy_2(1 - DP)] \tag{4.30}$$

MD is then the maximum draft in feet, located DP aft of the mast or leading edge of the sail. This same process is carried out for each draft stripe pair to determine the fore/aft shape of the sail at the three quarter chords (each stripe pair has its own frame). Therefore the maximum draft at the top, middle, and bottom quarter chords, $MD_{1,2,3}$, and their respective positions, $DP_{1,2,3}$ is determined.

4.3.2 Jib

As with the mainsail, the steps for digitizing the jib follow the order of filming, as described in Section 3 of Chapter 3, and Figure 3-2. The first position (labeled position 5 on Figure 3-2), located in front and to windward of the sailing vessel,

parallel to the clew-tack line, is used for leading edge position analysis. The second jib filming location (labeled as position 6 on Figure 3-2), positioned to leeward and perpendicular to the jib enables chord lengths to be determined. The third location (labeled as position 7 on Figure 3-2), is off the leeward stern quarter of the sailboat nearly parallel to the tack-clew line (similar to leading edge except opposite end of jib). This position records the frame that will be used for jib twist analysis. The fourth and final filming locating for the jib (labeled as position 8 on Figure 3-2), situated again on the leeward stern quarter (travelling in an arc to leeward), records the draft data needed for draft analysis.

Jib Leading Edge Location

Since it is almost impossible for the headstay to be perfectly straight, the headstay sag, perpendicular to the angle of attack of the jib must be determined. This is important because it describes where the leading edge of the jib is, and it effects the calculations needed to obtain the twist angles for the jib. Viewing the entire jib luff from position 5 in Figure 3-2, results in a picture similar to Figure 4-6.

The first points needed are the head and tack so that a line can be drawn between them by the computer to eventually obtain the headstay sag offsets. As seen in Figure 4-7, these are points 1 and 2. Points 3,4,5,6,7, and 8 are the calibration distances at each draft stripe pair (the stripes in each pair are located 2.5 feet apart). They are located where each stripe intersects with the headstay. As before, these are converted into 3 different pixel distance ratios:

$$Pd_1 = \sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.31}$$

$$dPy_1 = \frac{2.5}{Pd_1} \tag{4.32}$$

$$Pd_2 = \sqrt{(Px_5 - Px_6)^2(.97)^2 + (Py_5 - Py_6)^2} \tag{4.33}$$

$$dPy_2 = \frac{2.5}{Pd_2} \tag{4.34}$$

$$Pd_3 = \sqrt{(Px_7 - Px_8)^2(.97)^2 + (Py_7 - Py_8)^2} \tag{4.35}$$

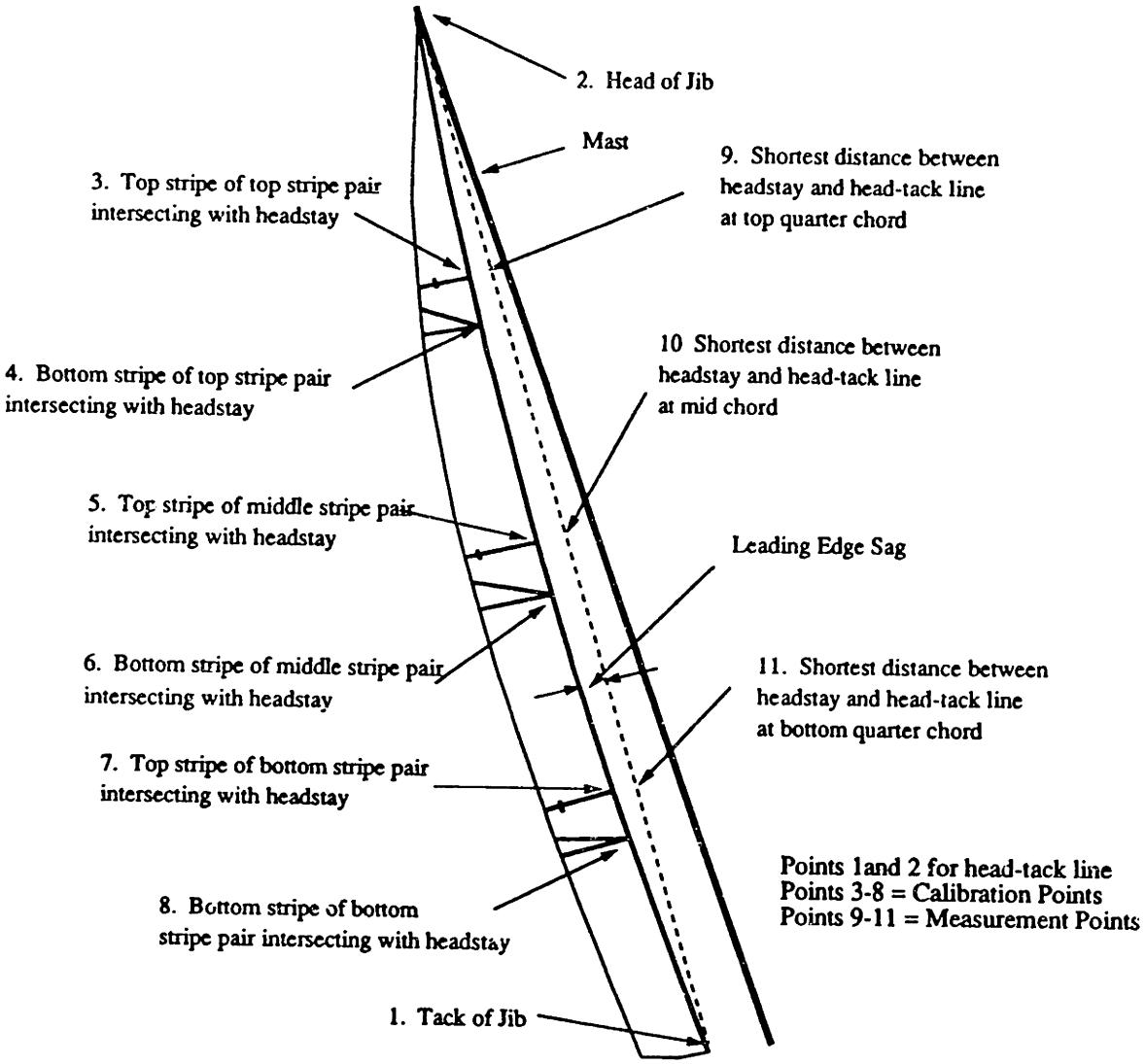

Figure 4-6: Jib Leading Edge Position

$$dPy_3 = \frac{2.5}{Pd_3} \tag{4.36}$$

The subscripts 1,2, and 3, following dPy again refer to the top, middle, and bottom, quarter chords respectively.

Points 9, 10, and 11, located on the head-tack line, give the perpendicular pixel distance of the top, middle, and bottom quarter chords respectively, from the headstay to the head-clew line. These measurements are converted to actual distances using the expressions:

$$HS_1 = dPy_1\sqrt{(Px_9 - Px_3)^2(.97)^2 + (Py_9 - Py_3)^2} \tag{4.37}$$

$$HS_2 = dPy_2\sqrt{(Px_{10} - Px_5)^2(.97)^2 + (Py_{10} - Py_5)^2} \tag{4.38}$$

$$HS_3 = dPy_3\sqrt{(Px_{11} - Px_7)^2(.97)^2 + (Py_{11} - Py_7)^2} \tag{4.39}$$

Where $HS_{1,2,3}$ refer to the headstay sag for the top, middle, and bottom draft stripes respectively. As mentioned before, this data will be stored and used for twist angle calculations.

Jib Sailing Chord Lengths

The process for obtaining the sailing chord lengths for the jib is exactly the same for the jib as for the main, except for the obvious difference that the sail must be viewed from the leeward side of the boat instead of the windward side. This location is shown as position 6 in Figure 3-2. It has been observed that because of the relatively small chord length and large amount of twist at the top quarter chord, the top stripe must be filmed when the chase boat is a good deal farther foward in relation to the sailboat, than the lower two draft stripes. This can be accomplished with the same filming method of top down, as was done with the main, just in this case, the chase boat will be moving slowly aft in relation to the sailing vessel. The picture yielded from this spot should appear to be similar to Figure 4-7. The same pixel locations are input in the same order as with the main, and the computations are carried out in the same manner. Points 1 and 2 (as seen in Figure 4-7), are the calibration mark s, and are converted to pixel distance ratios by the following equations:

$$Pd = \sqrt{(Px_1 - Px_2)^2(.97)^2 + (Py_1 - Py_2)^2} \tag{4.40}$$

$$dPy = \frac{2.5}{Pd} \tag{4.41}$$

Again, Pd is the pixel distance between the two calibration marks, and dPy is the ratio of the calibration distance (2.5 feet) to Pd, the pixel distance. From this, and points 3 and 4 (endpoints for chord), the actual chord length is given by:

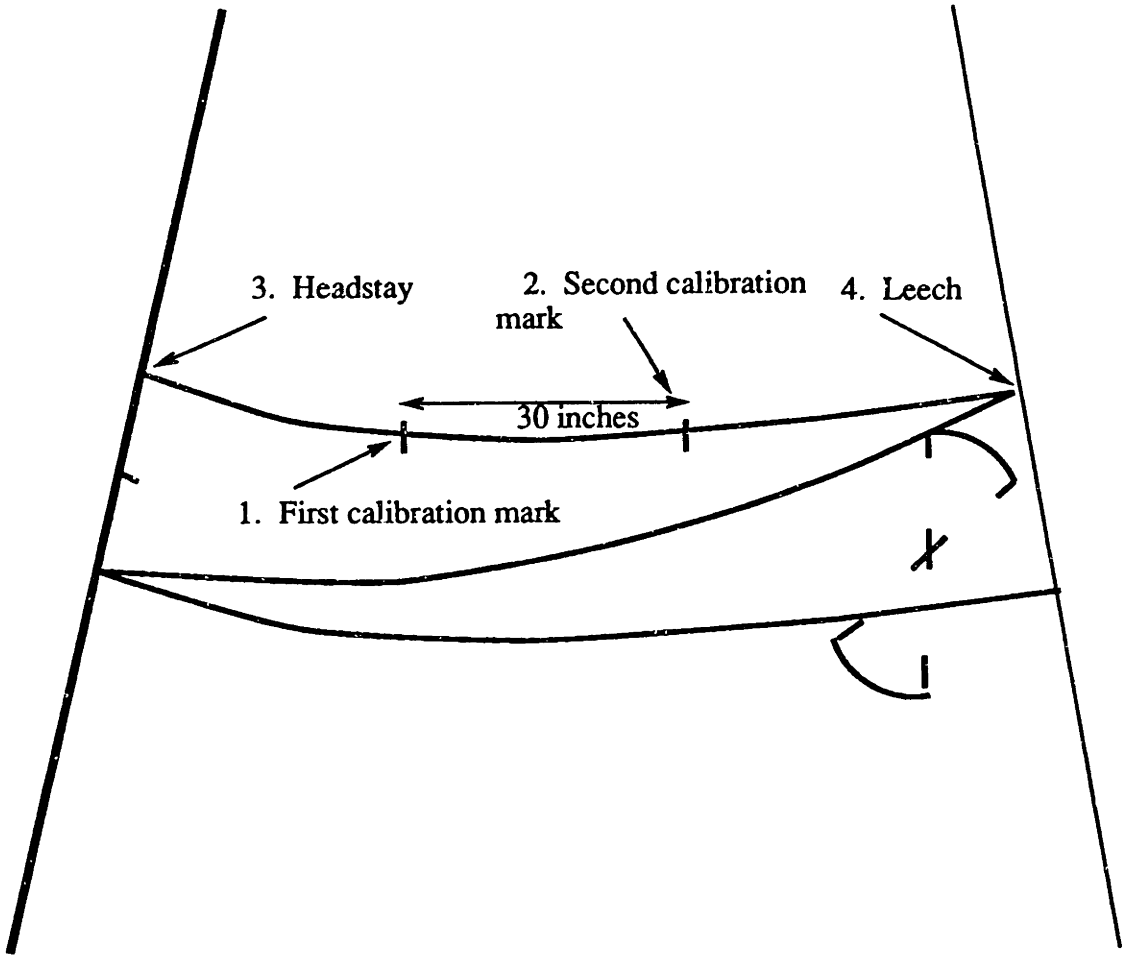

Figure 4-7: Jib Chord Length

$$Cl = dPy\sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.42}$$

This routine is repeated for each of the quarter chords on the mainsail, starting at the top quarter chord and ending with the bottom quarter chord (each stripe pair has it's own frame). The top quarter chord length, the mid chord length, and the bottom quarter chord length, are referred to as $Cl_{1,2,3}$. The length of each chord will be used to calculate the twist angles of the jib from centerline at each quarter chord.

Jib Overall Sail Twist

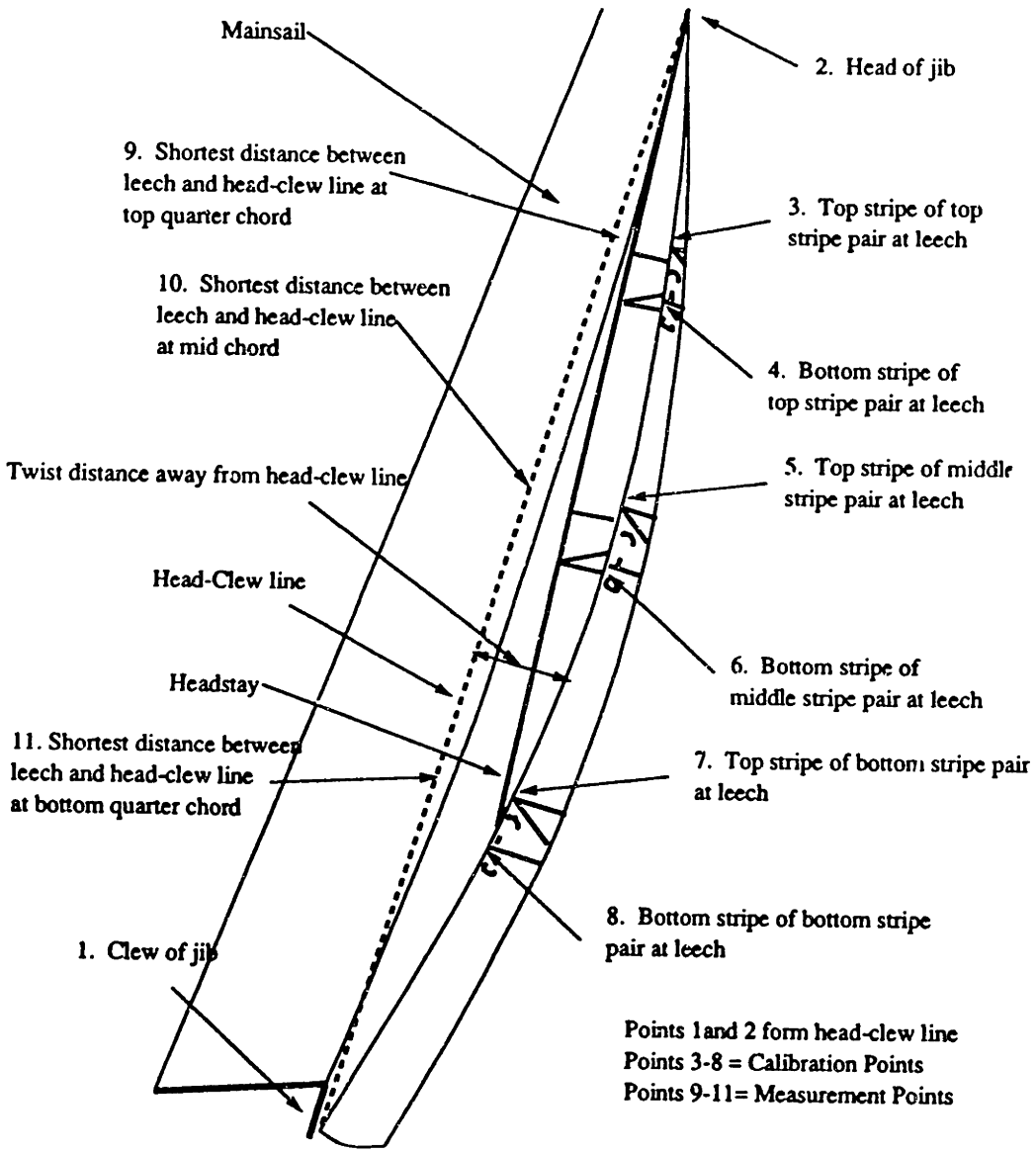

Figure 4-8: Jib Twist

The position of the clew of the jib when sailing upwind is almost always just about directly over the jib track. On the *MIT Sailing Dynamometer*, the jib tracks are located at a constant angle of 8.5 degrees from centerline. All of the jib twist distances are calculated from the plane intersecting the head, tack, and clew (which is angled 8.5 degrees from centerline).

The optimum location to determine the overall sail twist is at a position directly lined up with the clew and tack of the jib, so that the offsets can be measured

perpendicular to the plane of the sail. This was done with the mainsail, but with the jib, the upper portion of the sail cannot be see from this angle.

The solution chosen to remedy this problem is to view the sail from a position that is farther to leeward. The entire leech can then be seen. This position is seen as position 7 in Figure 3-2. The picture seen from this location is similar to Figure 4-8. The drawback to this approach is that the distance measured from the line connecting the head and the clew is not exactly equal to the perpendicular distance (it is off by the cosine of the angle away from the correct plane), as seen in Figure 4-9. The error has been estimated to be minimal. If the angle viewed at is 20 degrees from the tack clew line, which should be greater than the actual angle to see the head in most cases, the error is equal to about 6%. A correction factor of 5% has been added to the program to account for this angle distortion.

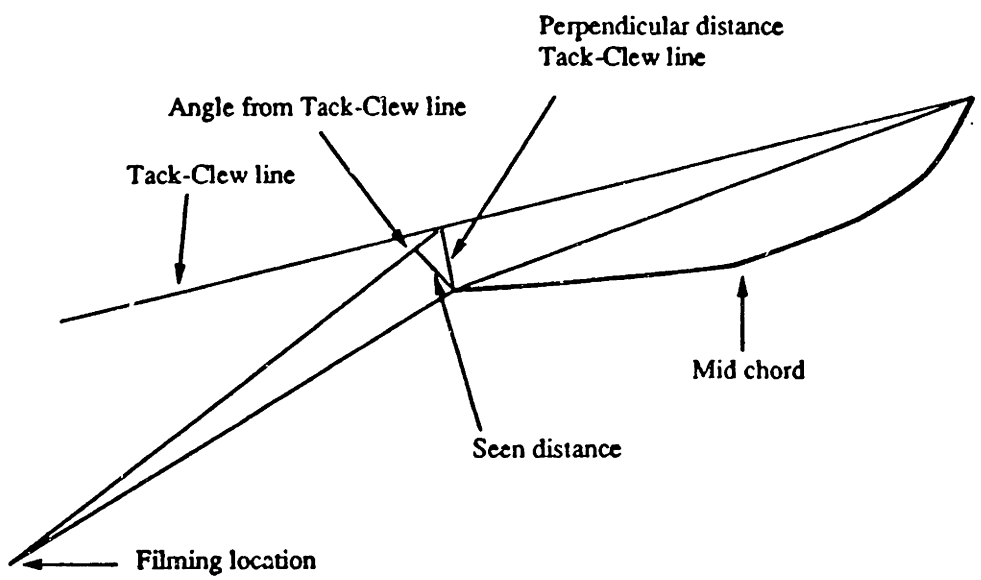

Figure 4-9: Viewed versus Actual Twist Offsets

The first two points needed for the calculation of the twist from the head/clew line, are obviously the head and the clew themselves, so that the line can be drawn by the computer (enables user to see line to obtain offsets from). The twist offsets

are then calculated in the same exact manner as with the leading edge or headstay sag offsets. The pixel distance ratios are calculated at each stripe pair using points 3 through 8, as seen in Figure 4-8. The expressions that compute these ratios are given by:

$$Pd_1 = \sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.43}$$

$$dPy_1 = \frac{2.5}{Pd_1} \tag{4.44}$$

$$Pd_2 = \sqrt{(Px_5 - Px_6)^2(.97)^2 + (Py_5 - Py_6)^2} \tag{4.45}$$

$$dPy_2 = \frac{2.5}{Pd_2} \tag{4.46}$$

$$Pd_3 = \sqrt{(Px_7 - Px_8)^2(.97)^2 + (Py_7 - Py_8)^2} \tag{4.47}$$

$$dPy_3 = \frac{2.5}{Pd_3} \tag{4.48}$$

The subscripts 1,2, and 3, following dPy again refer to the top, middle, and bottom, quarter chords respectively.

Points 9, 10, and 11, located on the head-clew line, give the perpendicular pixel distance of the top, middle, and bottom quarter chords respectively, to the head-clew line. These measurements are converted to actual distances using the expressions:

$$TD_1 = dPy_1\sqrt{(Px_9 - Px_3)^2(.97)^2 + (Py_9 - Py_3)^2} \tag{4.49}$$

$$TD_2 = dPy_2\sqrt{(Px_{10} - Px_5)^2(.97)^2 + (Py_{10} - Py_5)^2} \tag{4.50}$$

$$TD_3 = dPy_3\sqrt{(Px_{11} - Px_7)^2(.97)^2 + (Py_{11} - Py_7)^2} \tag{4.51}$$

Once $HS_{1,2,3}$ and $TD_{1,2,3}$ are determined, the twist angles for each quarter chord can be calculated. The following expressions calculate the the twist angle (TA) at each quarter chord from the gathered data:

$$TA_1 = \sin^{-1}(\frac{TD_1 - HS_1}{CL_1}) + 8.5 \tag{4.52}$$

$$TA_2 = \sin^{-1}(\frac{TD_2 - HS_2}{CL_2}) + 8.5 \tag{4.53}$$

$$TA_3 = \sin^{-1}(\frac{TD_3 - HS_3}{CL_3}) + 8.5 \tag{4.54}$$

$TA_{1,2,3}$ refers to the twist angles from centerline at the top quarter chord, middle chord, and bottom quarter chord respectively.

Draft Data

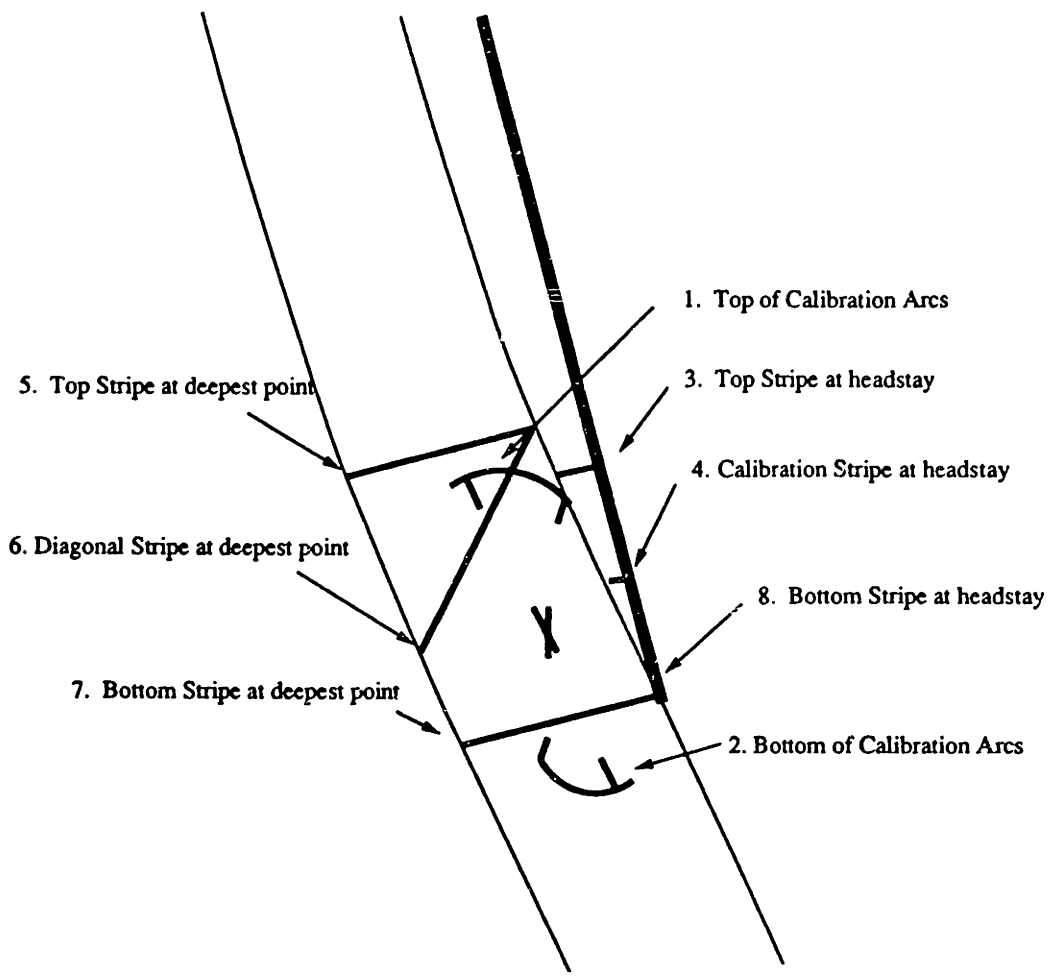

Figure 4-10: Jib Draft

The process for obtaining the draft data for the jib is exactly as with the mainsail. If more detailed information is desired than is covered in this section, see Subsection Draft Data in Section 4.3.1.

With the chase boat located at position 8, as seen in Figure 3-2, the camera should be zoomed in all the way to get a closeup view of each draft stripe pair of the jib. The picture should be similar to that seen in Figure 4-10. The first shot should be of the bottom quarter chord, and as mentioned earlier, as the chase boat slowly heads to leeward, the leech will cross the headstay higher and higher up. As the bottom stripe from each pair crosses the headstay, the draft data can be obtained. Since these shots are taken at close range, the arcs at the leech must again be used to determine the calibration distance.

Once again, the calibration distances are the first inputs. As seen in Figure 4-10, points 1 and 2 give the calibration distance at the leech while points 3 and 4 yield the calibration distance at the headstay (note that points 3 and 4 are only 1.25 feet apart). The calibration distance ratios are given by:

$$Pd_1 = \sqrt{(Px_1 - Px_2)^2(.97)^2 + (Py_1 - Py_2)^2} \tag{4.55}$$

$$dPy_1 = \frac{2.5}{Pd_1} \tag{4.56}$$

$$Pd_2 = \sqrt{(Px_3 - Px_4)^2(.97)^2 + (Py_3 - Py_4)^2} \tag{4.57}$$

$$dPy_2 = \frac{1.25}{Pd_2} \tag{4.58}$$

dPy_1 is the calibration ratio at the leech, while dPy_2 is the calibration ratio at the luff.

Using the diagonal stripe position, the draft position can then calculated. As seen in Figure 4-10, points 5,6, and 7, are the pixel positions needed to determine this location with the following expressions:

$$R_1 = \sqrt{(Px_5 - Px_6)^2(.97)^2 + (Py_5 - Py_6)^2} \tag{4.59}$$

$$R_2 = \sqrt{(Px_6 - Px_7)^2(.97)^2 + (Py_6 - Py_7)^2} \tag{4.60}$$

$$DP = \frac{R_2}{R_1 + R_2} \tag{4.61}$$

R_1 is the top stripe to diagonal stripe pixel distance, while R_2 is the diagonal stripe to bottom stripe pixel distance. DP is the location of the maximum draft expressed as a percentage aft of the leading edge.

The actual maximum draft measurement can be calculated from the perpendicular distance from the bottom stripe in each stripe pair to where the leech intersects with the headstay (at the bottom stripe in the stripe pair). This is accomplished by positioning the cursor at the point of maximum draft, point 7 (has already been entered), and at the point where the leech intersects with the headstay (point 8). This pixel distance is located DP aft of the mast. The following formula must be used to calculate the maximum draft (using scaling at the leech and at the luff):

$$MD = [\sqrt{(Px_7 - Px_8)^2(.97)^2 + (Py_7 - Py_8)^2}][dPy_1 DP + dPy_2(1 - DP)] \tag{4.62}$$

MD is then the maximum draft in feet, located DP aft of the headstay or leading edge of the sail. This same process is carried out for each draft stripe pair to determine the fore/aft shape of the sail at the three quarter chords (each stripe pair has its own frame). Therefore the maximum draft at the top, middle, and bottom quarter chords, $MD_{1,2,3}$, and their respective positions, $DP_{1,2,3}$ is determined.

Chapter 5

Results

After following the procedures described in this paper, this off-boat video image processing system (otherwise known as *The Offboat Vision System*), was successfully implemented. The results calculated appear to be accurate, when comparing them as best as possible to still photographs. Photographs taken from simliar angles, and analysed manually by using a ruler and dividers yielded similar results in all cases.

Still photographs were also taken from the deck to serve as a reference for accuracy. Figure 5-1 and Figure 5-2 are pictures of the mainsail, and Figure 5-3 and Figure 5-4 are pictures of the jib. The draft position and depth can be determined from Figures 5-1 and 5-3 for the mainsail and jib respectively. As can be seen from the photographs, all the stripes cannot entirely be seen. This is another draw back to using still photographs, as has been done in the past. Figures 5-2 and 5-4 were taken to serve as a check for the accuracy of the calculated twist offsets of the main and jib respectively. There is no accurate way to measure the twist from these photographs looking up at the sails. There is no reference to centerline, and therefore no method possible for determining the twist from centerline. In the past, sail designers and sailmakers have mainly been concerned with the draft and its fore/aft position, and still photographs met these needs. They don't enable one to measure the overall twist of the sail.

A sample running of *The Offboat Vision System* yielded the results in Tables 5.1 and 5.2.

Main	*Twist Angle*	*Draft/Chord Length*	*Draft Position*
Boom	1.75°		
Bottom Stripe	7.74°	.09	47%
Middle Stripe	13.80°	.11	53%
Top Stripe	21.35°	.12	51%

Table 5.1: Mainsail Output Data

Jib	*Twist Angle*	*Draft/Chord Length*	*Draft Position*
Foot	8.5°		
Bottom Stripe	14.65°	.15	48%
Middle Stripe	26.20°	.17	50%
Top Stripe	30.60°	.19	53%

Table 5.2: Jib Output Data

The video image processing system designed for this project has worked effectively. It is not the easiest nor the most efficient method for determining sail shapes, but it does offer a procedure to analyze sails that can be used to yield consistently accurate data. It does not offer real time sail shape analysis, but it does offer a method to store and retrieve sail shapes.

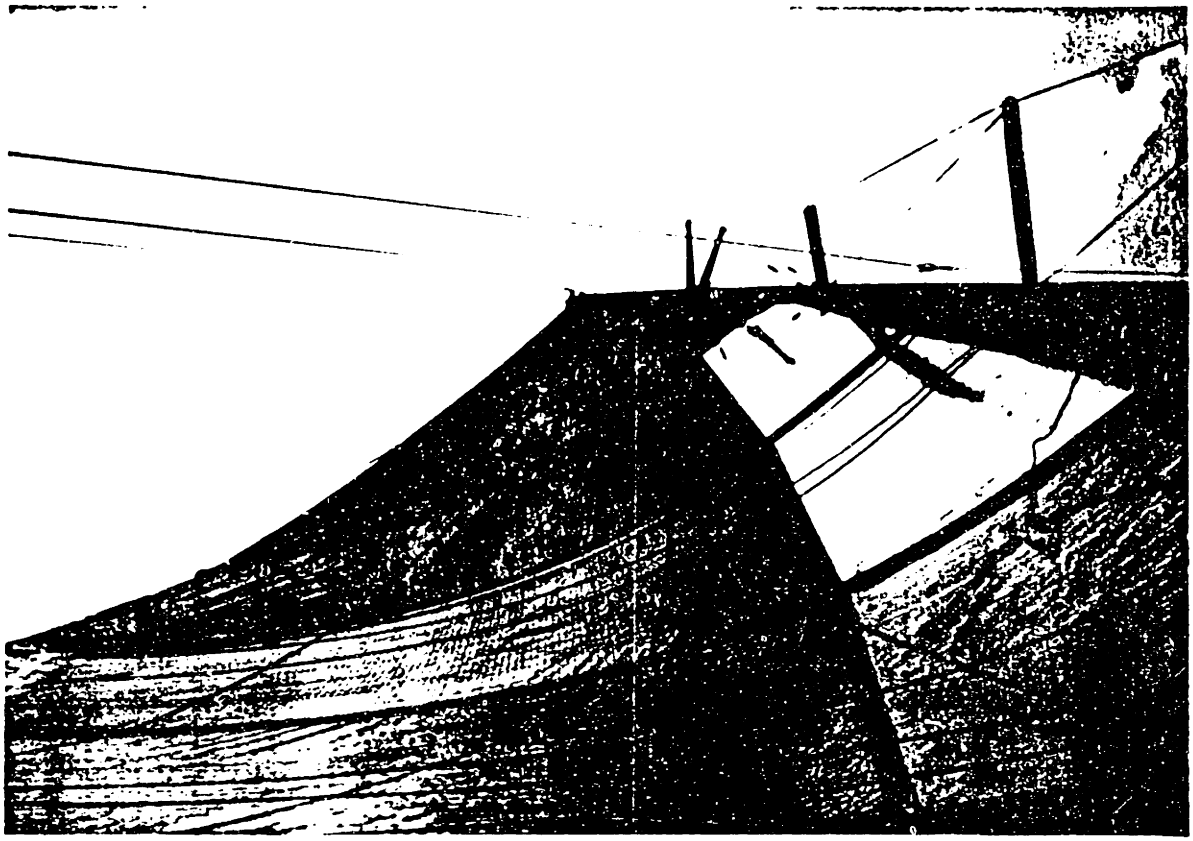

Figure 5-1: Mainsail Draft

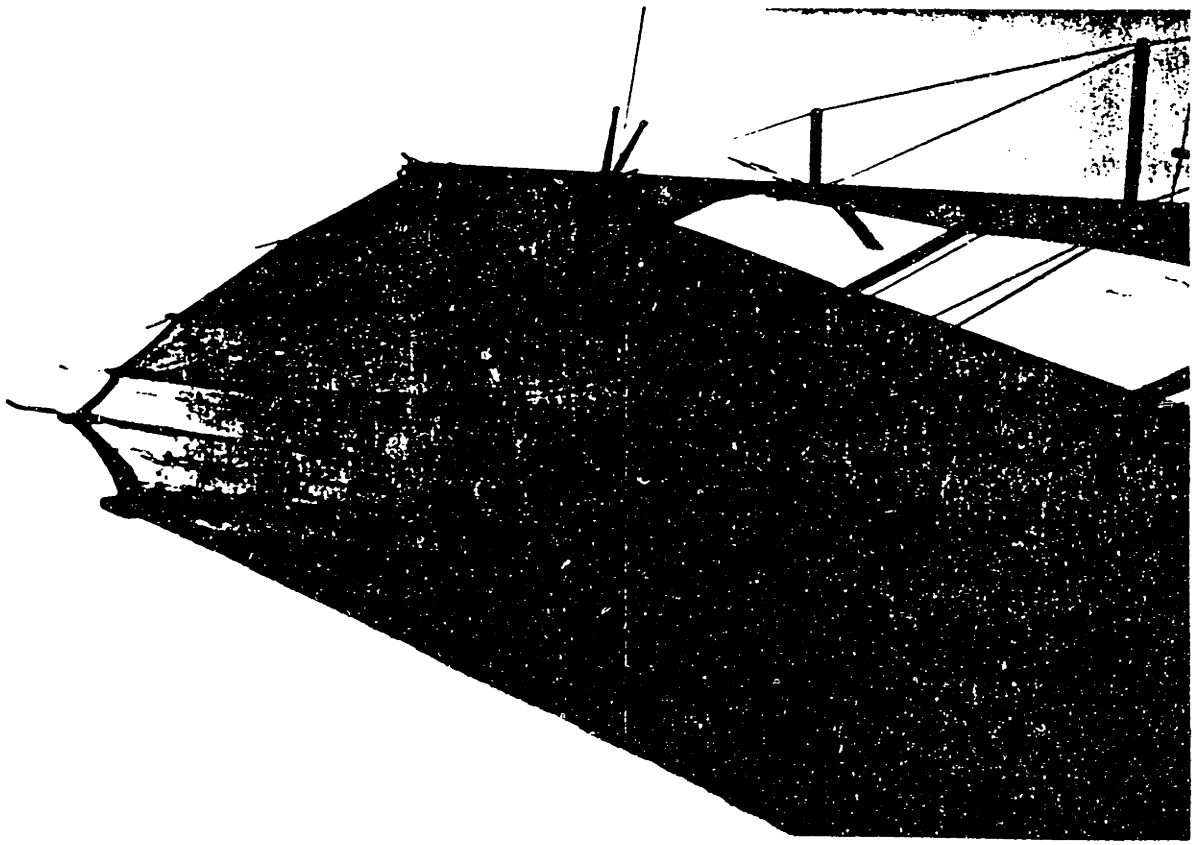

Figure 5-2: Mainsail Twist

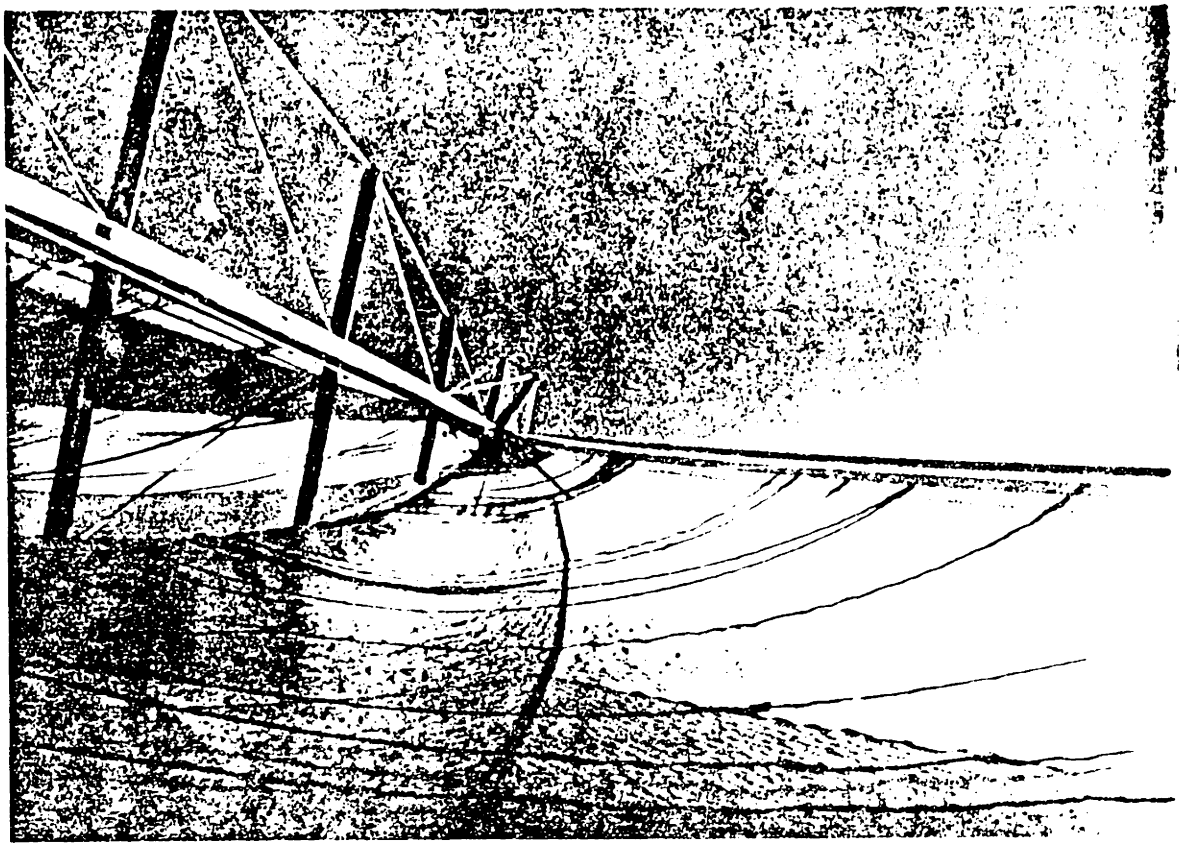

Figure 5-3: Jib Draft

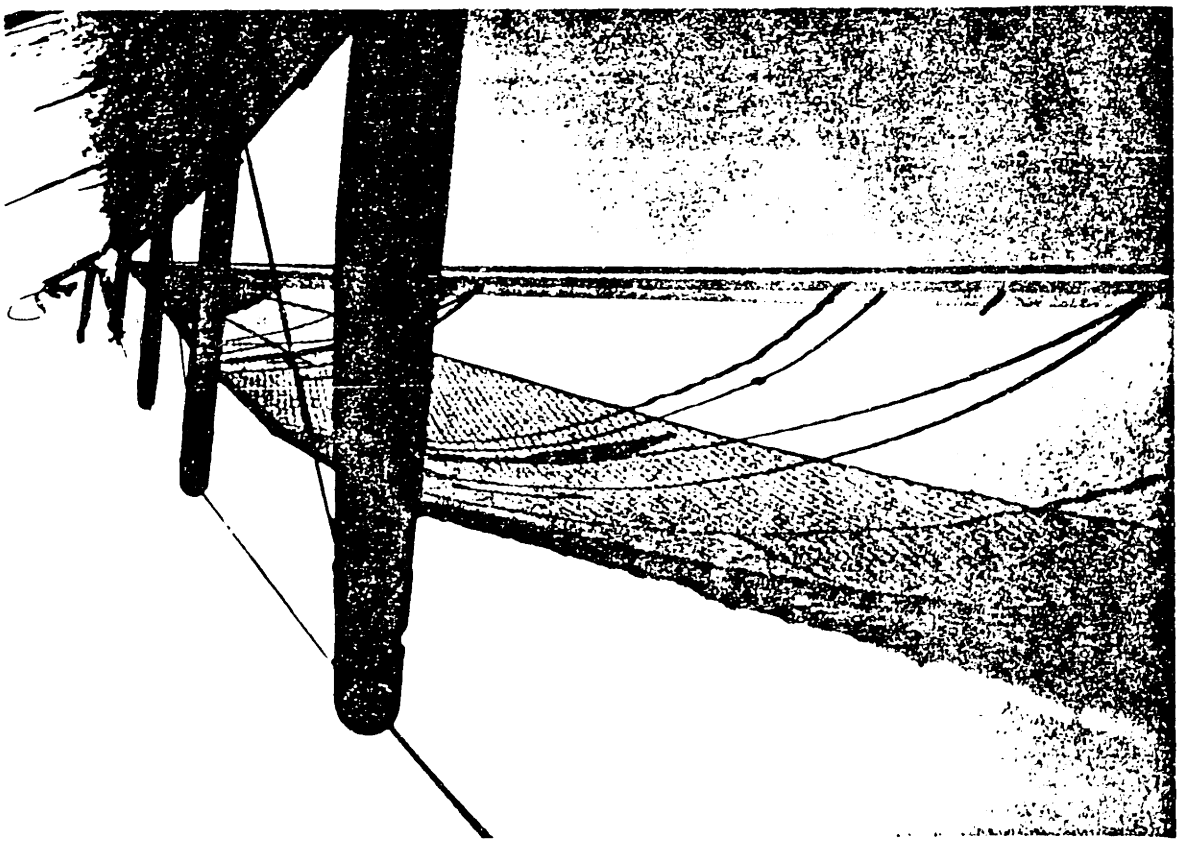

Figure 5-4: Jib Twist

Bibliography

[1] Canon Video Cameras. *Canon AF Mark II Users Manual.* Canon Incorporated, Japan, 1990.

[2] D.S. Greeley, K.L. Kirkman, A.L. Drew, and J. Cross-Whiter. *Scientific Sail Shape Design.* Proceedings of the Ninth Chesapeake Sailing Yacht Symposium, SNAME, 1989.

[3] J.S. Herman. *A Sail Force Dynamometer: Design, Implemenation and Data Handling.* S.M. Thesis, Department of Ocean Engineering, 1988.

[4] A.K. Klein. *A Comparison of Experimental and Theoreical Sail Forces.* S.M. Thesis, Department of Ocean Engineering, 1990.

[5] J.H. Milgram. *The Analytical Design of Yacht Sails.* SNAME Transactions, Volume 76, 1968.