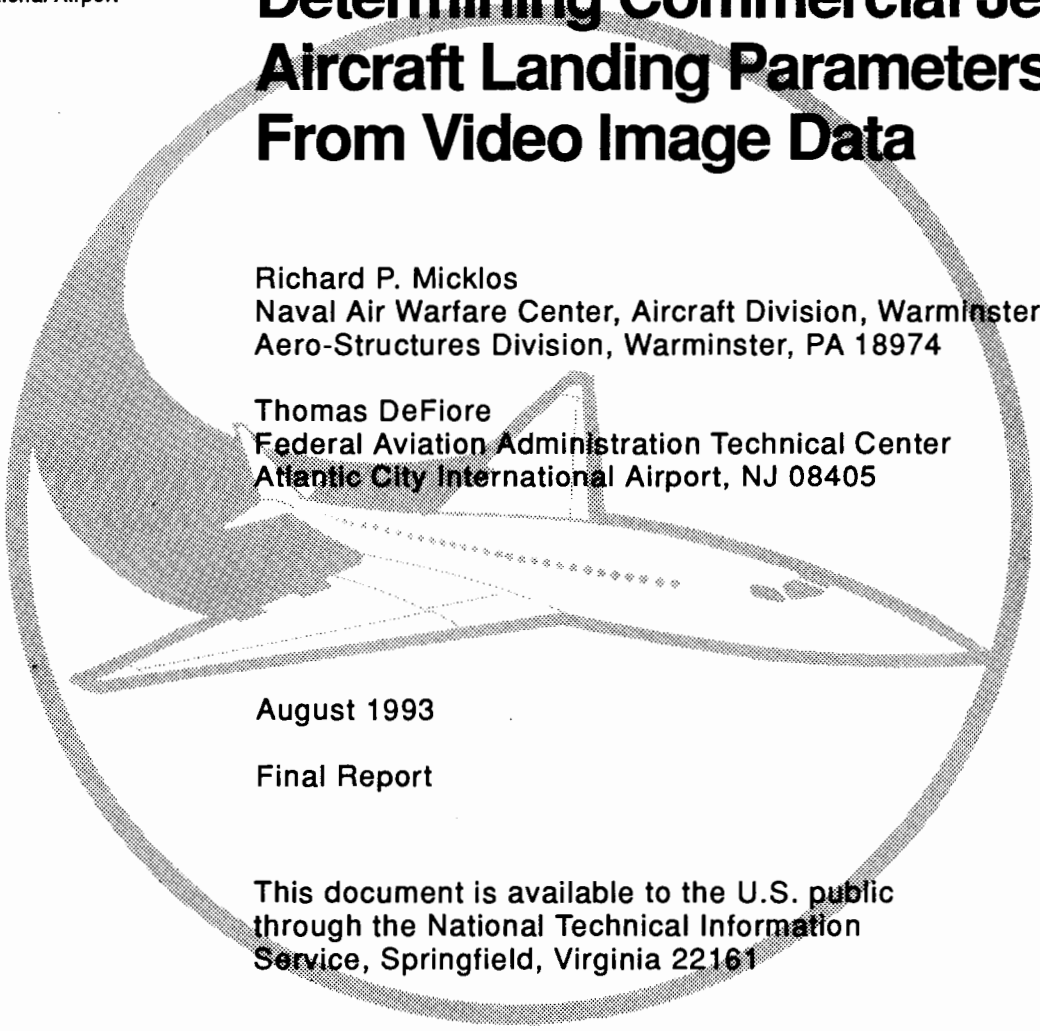
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FAA Technical Center
Atlantic City International Airport
N.J. 08405

Methods for Experimentally Determining Commercial Jet Aircraft Landing Parameters From Video Image Data

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As part of its Aging Aircraft Research Program the Federal Aviation Administration is establishing a passive system of measuring aircraft landing contact parameters at commercial airports. This research involves the broader application of recent US NAVY technology used to measure landing contact conditions of Navy carrier aircraft and develop/assess Navy landing loads design criteria. This technique is based on digitizing and analyzing high resolution video images recorded by cameras strategically stationed along the runway apron, and it does not require the installation of any instrumentation on the aircraft or changes to normal aircraft operating procedures. This report describes the application of the Navy's latest procedures for precisely determining the kinematics of typical commercial aircraft landings and provides the results of a demonstration survey conducted at the Federal Aviation Administration (FAA) Technical Center in June 1992. In addition, the proposed runway camera configuration for a production landing survey at a high volume airport is presented.

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TABLE OF CONTENTS

	PAGE
EXECUTIVE SUMMARY	ix
BACKGROUND	1
SYSTEM DEMONSTRATION	1
Data Collection Procedures	3
Naaldas Data Acquisition	4
NAALDAS MODIFICATIONS FOR COMMERCIAL OPERATIONS	5
Data Acquisition System	5
Data Analysis System	6
Image Analysis Procedures	6
Naaldas Data Analysis	8
SCALE FACTOR DETERMINATION	10
CALCULATION OF THE ANGLE BETWEEN AIRCRAFT CENTER LINE AND RUNWAY CENTER LINE	14
SINK SPEED CALCULATION	15
HORIZONTAL VELOCITY CALCULATION	16
POSITION AND ATTITUDE DETERMINATION	18
Off Center Distance	18
Touchdown Distance to Runway Threshold	18
Roll Angle	19
Pitch Angle	19
Aircraft Flight Path Angle	20
Yaw Angle	20
CONCLUSIONS	21
REFERENCES	22

APPENDICES

A - Landing Loads Survey Definitions

B - Aircraft Dimensional Input Requirements for Landing Loads Surveys

C - List of Symbols

LIST OF FIGURES

		PAGE
1.	FAA TECHNICAL CENTER, RUNWAY 13, SURVEY EQUIPMENT LOCATION	23
2.	FAA TECHNICAL CENTER, RUNWAY 31, SURVEY EQUIPMENT LOCATION	24
3.	FAA LANDING LOADS DATA COLLECTION PROGRAM, FIELD CAMERA SETUP	25
4.	FAA LANDING LOADS DATA COLLECTION PROGRAM RUNWAY EQUIPMENT DIAGRAM	26
5.	FAA LANDING LOADS DATA COLLECTION PROGRAM, REMOTE STATION EQUIPMENT	27
6.	FAA LANDING LOADS DATA COLLECTION PROGRAM, FAA TECHNICAL CENTER B-727-100 LANDINGS, NUMBER OF LANDINGS VERSUS AVG. SINKING SPEED	28
7.	FAA LANDING LOADS DATA COLLECTION PROGRAM, FAA TECHNICAL CENTER B-727-100 LANDINGS, NUMBER OF LANDINGS VERSUS ENGAGING SPEED	29
8.	LANDING LOADS DATA COLLECTION PROGRAM, FAA TECHNICAL CENTER B-727-100 LANDINGS, NUMBER OF LANDINGS VERSUS PITCH ATTITUDE	30
9.	LANDING LOADS DATA COLLECTION PROGRAM FAA TECHNICAL CENTER B-727-100 LANDINGS, NUMBER OF LANDINGS VERSUS ROLL ANGLE	31
10.	TYPICAL CONFIGURATION OF CAMERA, AIRCRAFT AND RUNWAY	32
11.	DEFINITION OF ANGULAR RELATIONSHIPS	33
12.	PROJECTION OF 1/2 SCALE FACTORS	34
13.	CORRECTION FOR SCALE FACTORS FOR SPECIFIC IMAGE FEATURES	35
14.	CALCULATION OF ANGLE Φ	36
15.	OFF CENTER DISTANCE DIAGRAM	37
16.	DETERMINATION OF DISTANCE FROM RUNWAY THRESHOLD	38

LIST OF TABLES

		PAGE
1.	FAA VIDEO SYSTEM EVALUATION, STATISTICAL SUMMARY OF ALL B-727-100 EVENTS	39
2.	FAA VIDEO SYSTEM EVALUATION, STATISTICAL SUMMARY OF ACTUAL B-727-100 TOUCHDOWNS	40
3.	FAA VIDEO SYSTEM EVALUATION B-727-100 DATA SUMMARY	41

EXECUTIVE SUMMARY

As part of its Aging Aircraft Research Program the Federal Aviation Administration is establishing a passive system of measuring aircraft landing contact parameters at commercial airports. This research involves the broader application of recent US NAVY technology used to measure landing contact conditions of Navy carrier aircraft and develop/assess Navy landing loads design criteria. This technique is based on digitizing and analyzing high resolution video images recorded by cameras strategically stationed along the runway apron, and it does not require the installation of any instrumentation on the aircraft or changes to normal aircraft operating procedures. This report describes the application of the Navy's latest procedures for precisely determining the kinematics of typical commercial aircraft landings and provides the results of a demonstration survey conducted at the Federal Aviation Administration (FAA) Technical Center in June 1992. In addition, the proposed runway camera configuration for a production landing survey at a high volume airport is presented.

BACKGROUND

The Aerostructures Division of the Naval Air Warfare Center, Aircraft Division, Warminster has developed and maintains a state of the art capability to determine aircraft landing parameters. The purpose of this effort is to collect typical usage data which will allow the assessment of the adequacy of current structural design specifications, compare design criteria to actual operational usage, validate fatigue analysis and assess fleet operations. This system allow the NAVY to periodically collect data on operational aircraft flown by fleet pilots in the normal aircraft operating environment. The parameters measured include horizontal velocity, sink rates, aircraft attitude and rates of change of those attitudes at touchdown. Additional information on prevailing winds, atmospheric conditions and aircraft weight are also collected.

A technique, which has been used for over thirty years, consists of the collection of photographic images of aircraft landings on 70mm photographic film. Recent advancements in video technology have permitted the introduction of high resolution video cameras, coupled with computer controlled image processing technology, to duplicate the performance of the 70mm system. The 70mm film system is now being replaced by a video landing loads system, which is known as the Naval Aircraft Approach and Landing Data Acquisition System (NAALDAS). The application of video technology permits remote operation and automated image processing, eliminates film handling and processing, increases system flexibility, reduces system size and power requirements, and enhances operator safety. These improvements make practical the use of this technique to collect landing parameters on commercial airfields. The application of these procedures is described in this report.

Aircraft motions are calculated from the detailed analysis of image features combined with information on the locations of the camera and touchdown point and the time interval between successive images. No special aircraft instrumentation is required, nor are special procedures required by the pilots. In many cases, pilots are not aware the survey is being conducted. Typically, over 1000 landings are recorded during a landing survey.

A demonstration of this technology was performed at the Federal Aviation Administration Technical Center, Atlantic City International Airport, N.J. in June of 1992. The results of this demonstration are included in this report.

SYSTEM DEMONSTRATION

The Naval Aircraft Approach and Landing Data Acquisition System was demonstrated at the Federal Aviation Administration Technical Center during the week of 22 June 1992. The system was in its normal single camera configuration.

Preliminary surveying of the runway touchdown areas, calibration target locations and camera locations on all four runways, 13/31 and 4/22 had been performed during an earlier trip to the Technical Center. During this demonstration, data was collected at both ends of runway 13/31, the airport's main runway. The locations of the camera and calibration targets are detailed in figures (1) and (2).

This demonstration consisted of recording a series of touch and go landings performed by the Federal Aviation Administrations' Boeing 727-100 aircraft. Other targets of opportunity were also recorded. It quickly became apparent that the wide dispersion of touchdown points associated with commercial aircraft landings could not be adequately covered by the limited field of view of the NAALDAS system. While it could successfully record and analyze landings that occurred within the camera's field of view, the percentage of such landings was less than 20%. Even when the test pilot was attempting to land within the camera's field of view, only 50% of the landings actually touched down in that location. However, those landings which passed thru the camera system's field of view but did not touch down were processed to determine the aircraft's horizontal velocity, attitude and sinking speeds. This was done by introducing a relative touchdown point in the image sequence to trigger the software to perform the necessary calculations. The software was written to calculate landing parameters based on data from the last 0.5 seconds prior to touchdown.

Statistical information on the principal landing parameters from all B-727-100 events are provided in table (1). Table (2) provides the same data for all the actual B-727-100 touchdowns observed during this demonstration. These non-touchdown events are identified on the B-727-100 summary table, table (3) which lists the individual landing parameters for each event. Appendix A lists the definitions and symbols associated with the various landing parameters determined from landing survey data.

The purpose of this demonstration survey was to verify the feasibility and suitability of the recording system to collect data at the lower sink speeds associated with commercial operations. A future demonstration of this system, modified to a four camera configuration to provide extended coverage of a 2000 ft. touchdown area, will be performed. This future test will include comparisons of landing parameters determined with the video system to data collected by laser tracking equipment at the technical center. Systems testing which was performed at a naval activity, and documented in reference (a), demonstrated the performance and accuracy of NAALDAS in collecting military aircraft landing data.

This demonstration at the Federal Aviation Administration Technical Center documents that the technology used in NAALDAS is capable of measuring and analyzing commercial aircraft landings. The system needs to be modified to develop a multiple camera configuration of NAALDAS to increase its effectiveness in collecting data while covering the entire 2000 foot touchdown area on a commercial runway.

DATA COLLECTION PROCEDURES

The procedures described in this section were developed to record landing parameters for carrier landings. The Naval Aircraft Approach and Landing Data Acquisition System (NAALDAS) was developed to incorporate video technology to modernize and automate these procedures. The modifications required for NAALDAS to collect data on commercial aircraft operations are described.

The current procedures uses one camera to collect the required images. NAALDAS was optimized to collect landing parameters for shipboard carrier landings and Navy field carrier practice landings. The typical runway on a carrier is less than eight hundred feet long, 120 feet wide. Four arresting gear cables, which engage the aircraft's arresting hook to stop the aircraft, are located within a 120 ft length, centered 300 ft from the stern of the ship. The pilots follow a prescribed glide slope which is established to guide the pilot to land in the center of the arresting gear area. Since no flare is permitted, the glide slope is maintained to deck contact. This reduces the dispersion of landing touchdown points caused by flared landings during normal land based operations.

The camera is located approximately 60 ft off the center line of the runway, approximately 250 ft away from the expected touchdown point. This results in approximately a 13 degree angle between the camera lens center line and the runway center line. This location provides a near head on view of the aircraft to determine roll attitude, yaw angle and off center touchdown distance. It does require that aircraft horizontal velocity be resolved from two components, motion perpendicular to the image plane and motion across the image plane. Considerable geometric analysis was required to account for the image foreshortening caused by this configuration. The current analysis computer program, Landings I, performs these calculations. The geometric information on the surveyed aircraft required as input to the analysis program is described in appendix B.

It is the limited dispersion of the touchdown point during carrier landings that makes the current NAALDAS configuration successful. The landing flare which reduces aircraft sink rates during normal landings generates the wide dispersion of expected aircraft touchdown points. To cover this large touchdown area, a four camera system will be required. These cameras will be located 500 ft apart, to cover the expected touchdown area.

The accuracy of these techniques is directly related to the range of the camera from the actual touchdown point. The accuracy is also related to the field of view of the lens, which directly effects the size of one resolution element of the film (or one pixel in the video system). These requirements conflict with the desire to make the field of view as large as possible to minimize the number of cameras required to cover the touchdown area. These considerations led to the current 25 degree field of view used for recording carrier landings. The size of jet commercial aircraft indicates that a larger field of view will be acceptable.

Another modification to these procedures will be required by the lower sink rates of commercial aircraft. The existing system is required to monitor landing sink speeds up to 25 ft/sec. Typical carrier landings occur in the range of 10 to 15 ft/sec. The typical commercial landing sink speed is expected to be in the range of one to five ft/sec. The smaller relative motions associated with these sink rates will require more precise measurements of vertical position or measurement over longer time intervals. NAALDAS accuracy increases with increasing sink rates; it is these higher sink rate landings which are the extremes of the design values.

NAALDAS DATA ACQUISITION

This portion of NAALDAS consists of a frame grab, charged coupled device (CCD) video camera, laser disk video recorder, and portable computer to control and operate the system. The system runs on 110 volt 60 Hertz, alternating current, weighs 500 pounds and is packaged in five shipping containers that can be fitted on two pallets.

The key technical development in NAALDAS was the design and manufacture of video camera which emulates a "Frame Grab" video camera. In standard video cameras, the image is split into two parts called fields. Each field consists of a series of horizontal lines. Every other horizontal line is collected and processed as one field, then the alternate horizontal lines are scanned as the second field. These two fields, referred to as odd and even, are combined to generate one video frame (total image). These video fields are separated by 1/60th of a second. The human eye integrates the fields, and the changes in image feature location are not apparent until an attempt is made to stop action. When the image is stopped, the relative motion which occurred between the fields causes the image to be blurred. This makes it difficult to resolve the image feature location accurately. The NAALDAS camera collects the two fields but eliminates the time delay between them. Thus the NAALDAS camera can resolve vertical positions to twice the accuracy of the standard video camera. It is this increased vertical resolution which makes NAALDAS practical.

When operating at a commercial airport, the data recording equipment is located in a vehicle stationed in an acceptable location approximately 300 ft back from the runway center line. The vehicle must be environmentally controlled. The laser disk recorder has been installed in a shock mounted, electromagnetic interference (EMI) protective enclosure and the computer has been ruggedized and EMI protected for use in this environment. All the interconnecting cabling and mounting hardware are included in the system.

The system is calibrated during a runway shutdown period by placing temporary targets at known locations in the camera's field of view and recording these images as a calibration sequence. This sequence is processed to generate a transformation matrix to relate image measurements to the runway.

When an aircraft is near the runway threshold, the cameras are activated and video images are recorded on laser disks. Approximately 40 landings are stored on one disk. An identity number is assigned to the disk and an event number to each video sequence. Additional data such as aircraft type, wind direction, aircraft identification numbers are recorded on the computer hard disk for future analysis.

The video camera is remotely operated from the equipment vehicle. Contact is maintained with the control tower at all times, to acquire additional information and for the safety of both personnel and equipment. There is no requirement to place personnel at the camera site on the runway apron. There is no post processing required of the video disks. This eliminates the time and cost required to perform film processing with the prior 70mm film system.

The output of the data acquisition subsystem consists of the video disks and data files associated with them. These are subsequently processed using the data analysis subsystem.

NAALDAS MODIFICATIONS FOR COMMERCIAL OPERATIONS

DATA ACQUISITION SYSTEM

The need to successfully record commercial aircraft landings has generated a requirement to expand the camera coverage area to over 2000 feet of runway. This has driven the design of a four camera configuration for the commercial application of the NAALDAS. This proposed configuration is shown in figure (3). The four cameras are spaced along the edge of the runway and provide coverage over a distance of two thousand feet measured along the runway centerline. The camera's fields of view overlap to provide continuous coverage of the touchdown area. The cameras are powered by small portable generators, each generator supporting two cameras.

The FAA camera system is based on the NAALDAS camera design but incorporates a fiber optic transmitter, fiber optic receiver and power supply. These changes are necessary to reduce signal degradation over the longer transmission distances of the extended touchdown zone. The receiver allows the cameras to use a common sync signal to establish a single reference time for each unit.

The camera video signals are transmitted over fiber optic cables to the control station. Each incoming video signal is monitored at the control station, with the operator selecting the camera image to be recorded. The overlapping camera's fields of view allow sufficient time for the operator to switch recording between the cameras as the target aircraft passes through a camera's field of view. The camera signals are synchronized using a signal provided from the control station. This signal is also transmitted using fiber optic cables. The interconnections between the cameras, generators and control station are described in figure (4).

These system modifications require the introduction of additional hardware at the camera control station. Fiber optic receivers and transmitters are needed to transmit signals through the fiber optic cabling. A series of video monitors are used to monitor the video output of the cameras. An electronic digital color quad unit is used to select and identify the video image to be recorded. The image signal must be identified with its camera so the proper geometric and calibration constants are used in the subsequent image analysis. Additional hardware is used to provide the synchronization signal to the camera system. Modifications, shown in figure (5), will provide NAALDAS with the flexibility to collect video images from which landing parameters for commercial flight operations can be calculated.

DATA ANALYSIS SYSTEM

The modified camera configuration required for the expanded runway coverage area for commercial airports does not affect the analysis station hardware and software. Minor modification of the analysis procedures may be required to assure that the proper calibration sequence is used when a touchdown sequence passes through the field of view of multiple cameras. The existing software analysis package which uses the output of NAALDAS as its input, is directly applicable, requiring only the generation of an input file of selected commercial aircraft dimensions for use in data analysis.

Additional software capability may be required to process long duration single gear ground contact events and also multiple touchdown events caused by aircraft bouncing. Both these events are extremely rare in naval service but are much more likely at commercial airports.

IMAGE ANALYSIS PROCEDURES

The determination of aircraft landing parameters consists of measuring the position of aircraft features in the image and establishing the changes in position of those features in successive images. The measured image locations are corrected for camera location and attitude. A mathematical curve is then fitted through these points. These curves are differentiated to provide velocities. The reported velocities are calculated for one time increment prior to aircraft touchdown.

To begin the analysis procedure, the relationship between physical positions on the aircraft must be established. The span between main landing gear, wing tips or the outer edges of flaps are used for most aircraft. These known dimensions, modified for camera viewing location and angle, establish the "yardstick" used for measuring relative positions in the film frame. These "yardsticks" are referred to as "scale factors" in the analysis software. Since the relative position of the aircraft to the camera changes in each film frame, new scale factors must be calculated for each frame.

The measurements made in each image must be referenced to some invariant reference point in the film image plane. That reference point for the analysis system is a horizontal plane, which is perpendicular to gravity. The height of this plane is a known distance above (or below) the camera lens center line. The 70mm film system required that the camera/lens line of sight be level relative to the gravity vector. The video system eliminates the need to precisely level the camera, however, calibration targets located at surveyed positions and known heights are recorded and this information is used to convert the positions in the video image plane to the horizontal reference plane used in the analysis. A spatial conversion matrix is generated by the software in the video system from the calibration target positions, their image locations and the known inputs of camera location.

The current configuration of the analysis software accepts position information on the following aircraft features.

The vertical and horizontal location of the reference point.
The horizontal positions of the selected scale factor, currently wing span, outer span of main flaps or span of main landing gear wheels.
The horizontal and vertical location of the port main landing gear wheel
The horizontal and vertical location of the nose landing gear wheel
The vertical location of the starboard main landing gear wheel

These points can be modified, particularly when selecting scale factors. The selection of scale factor depends on the actual recorded image. The use of the largest image feature visible in the entire sequence is preferred.

The change in the calculated scale factor between successive frames is used to determine the range of the aircraft from the camera. This information, corrected for camera and aircraft orientation, determines the aircraft's horizontal speed.

The change of landing gear wheel height above (or below) the reference plane establishes the sinking speed of those wheels and of the aircraft. Separate sink speeds are determined for the port, starboard and nose landing gear. For commercial aircraft landing gear, this speed would be for one wheel truck associated with one strut assembly. This calculation requires the application of the specific scale factor for the image being analyzed, as well as the associated geometric corrections.

Also reported is an average sink speed for the aircraft which is the average value for both main landing gear. This is an approximation of the motion of the aircraft's center of gravity. The difference in vertical height of the main landing gear is used to determine the roll attitude of the aircraft. The rate of change of this difference is used to calculate aircraft roll rate.

Similarly, the horizontal and vertical position of the nose landing gear is compared to the position of the midpoint between the main landing gear to calculate aircraft pitch attitude and yaw attitude. The relationship between the nose gear, main gear and aircraft pitch reference axis must be known to perform this calculation. Again the rate of change of these differences is used to determine pitch rate and yaw rate.

Since this system precisely measures range in the camera's field of view, it can provide information on the aircraft touchdown point, such as touchdown distance from runway threshold and distance left or right of runway center line. By comparing values of sinking speed and horizontal speed, aircraft glide slope angle can be determined. An alternate procedure for determining glide slope is available. This consists of determining aircraft height above the reference plane at a fixed reference distance from the camera and the distance of touchdown point down the runway from that referenced position.

The parameters reported are calculated for one frame prior to impact. If the port landing gear impacts the runway two frames prior to the starboard wheel, the reported value for average sink speed is provided for the same frame as that of the port wheel.

The aircraft feature positions measured for successive frames are processed through a curve fitting routine to establish a position versus time regression curve. A minimum of twelve positions are used in the curve fitting operation. This time-position curve is differentiated and evaluated at time T=0 to provide velocity information. For sink speed calculations, a second order curve is fitted to allow for the determination of vertical acceleration.

NAALDAS DATA ANALYSIS

This NAALDAS subsystem is the data reduction portion of NAALDAS. It consists of a "Sun" computer work station with an image processing board installed, a laser disk player, computer monitor, high resolution monitor and associated power regulator and cables. This equipment is designed for operation in a normal laboratory environment and operates on 110 volt, 60 hertz alternating current.

The combination of the laser disk video recorder, image processing capability and high resolution monitor, along with the system's software, allows the operator to automatically track image features (such as a wheel or a wing tip,) through a landing sequence. By positioning "windows" over the initial image feature in a track sequence, the operator sets up the system to track that feature through the entire sequence. Multiple image features can be tracked simultaneously using multiple windows. The operator has the capability to select image threshold levels, various image enhancement formats as well as the type of tracking (edge or centroid) being used. These selections allow the system to automatically track the image, eliminating the errors in data reduction inherent in manual tracking

procedures. The centroid tracking algorithm enables the system to locate image features to sub-pixel accuracy.

The analysis system allows the operator to review the video images during the analysis process. The system can display the calculated track points and overlay those points on the video image. This allows the operator to review the track data for accuracy and to retrack questionable points which may have been influenced by contrast, lighting or background variations. Permanent visual records of the video image and track points are saved.

Once the image sequence has been tracked, the software transforms the pixel information to a digital format compatible with the existing landing parameter analysis software. This software takes image position information, determines the change in image feature position of successive frames and generates position time curves for the feature. Currently, both linear and second order curve fit routines are used in the analysis.

NAALDAS has been designed to measure aircraft sink speeds to $\pm$ 0.1 Ft/Sec. and engaging speed at touchdown within $\pm$ 0.5 knots. These accuracy were based on the higher sink rates and smaller image sizes associated with Naval fighter/attack aircraft. With the larger targets provided by commercial aircraft, similar accuracy should be attained, even at larger camera to touchdown distances. The actual accuracy of NAALDAS in this application will be tested against the FAA laser tracking system when the multiple camera configuration is demonstrated at the Technical Center.

After all of the landing sequences are completed, a second software package calculates statistical information on the distribution of the measured landing parameters. This includes calculating the Mean, Standard Deviation, Skewness and Kurtosis of the distribution of each landing parameter.

As an example of the type of data derived from this system, histograms generated from the FAA Boeing 727 landings recorded during the demonstration survey are included as figures 6, 7, 8 and 9 of this report. These histograms present data on average sink speed, engaging speed, pitch angle and roll angle respectively. The horizontal velocity of the aircraft is reported as engaging speed, (closure speed with the camera) since accurate information on the prevailing wind was not recorded. The aircraft's approach speed is calculated as from the engaging speed and component of wind parallel to the runway. The negative values of sink speed reported in figure 6 come from aircraft landings which did not touchdown in the camera's field of view. With the pilot flaring the aircraft for landing, coupled with the influence of ground effect phenomenon, the aircraft rose as it passed through the field of view. This is readily apparent from a visual inspection of the video sequences and the analysis software properly interpreted this as a negative sink speed.

SCALE FACTOR DETERMINATION

The key factor in determining landing parameters from image data is the determination of the scale factor. The scale factor serves as the yardstick when measuring dispacements in the image from the reference point and establishes the range of the image feature from the camera. The scale factor is based on the ratio of a known real world dimension on the target object and its apparent size in the image. This ratio also depends on the focal length of the lens system being used and the distance from the camera.

(Image Size / Lens Focal Length) = (Object Dimension / Range from Camera)

Of course, the object dimension must be corrected for the foreshortening caused by the orientation of the camera with respect to the flight path of the aircraft. An additional correction is included to account for the aircraft's roll angle. A typical camera installation is shown in figure (10).

Derivation of the scale factor is as follows:

Let S designate a known aircraft dimension which is visible in the image, such as the distance between the wing tips or landing gear struts. (See figure 10.)

Let Θ designate the angle between the camera lens center line and the runway center line. (See Figure 11.)

Let $\alpha 1$ designate the angle between the lens center line and the line of sight to the port wing tip (or other selected image feature). (See Figure 11.)

Let $\alpha 2$ designate the angle between the lens center line and the line of sight to the starboard wing tip (or other selected image feature). (See Figure 11.)

S/2 is the distance from the wing tip to the aircraft fuselage center line. Each side of the scale factor must be calculated separately because of the angular distortion involved. (See Figure 10.)

X1 is the horizontal distance measured on the image plane from image of the port wing tip (or other selected image feature) to the center of the image at the lens axis. (See Figure 10.)

X2 is the horizontal distance measured on the image plane from the image of the starboard wing tip (or other selected image feature) to the center of the image at the lens axis. (See Figure 10.)

F is the lens focal length.

SF is the scale factor for a particular image.

Φ is the angle between the runway center line and the center line of the aircraft's fuselage. (See Figure 11.)

The dimension (X2-X1) corresponds to the angle ($\alpha 2 - \alpha 1$), the actual angle established by the aircraft object feature, distorted by the aircrafts angle with the runway and the camera's angle to the runway. (See Figure 11.)

The length of the partial scale factors, S/2, on each side of the aircaft, must be projected onto a plane parallel to the image sensor in the camera.

The total scale factor is the sum of both partial scale factors, S/2 (port wing tip) and S/2 (starboard wing tip).

$$SF\ (total) = S/2\ (pwt) + S/2\ (swt) \tag{1}$$

The plane parallel to the image sensor crosses the lens center line at the point N of figure 11.

The angle established by the line of sight of the wing tips with the plane parallel to the image plane is labeled $\Gamma 1$ for the port wing tip and $\Gamma 2$ for the starboard wing tip. From the right triangle defined by the Focal Point Node, Point N and the projection of the wing tip on the parallel plane (See Figure 11.)

$$\Gamma 1 = 180 - 90 - \alpha 1 = 90 - \alpha 1 \tag{2}$$

$$\Gamma 2 = 180 - 90 - \alpha 2 = 90 - \alpha 2 \tag{3}$$

Projecting the lens axis to intersect with the aircraft fuselage center line establishes the triangle JKL. Since the angles Φ and Θ are known, the angle β at point K can be established as follows:

$$180 = \beta + \Phi + (180 - \Theta) \tag{4}$$

$$\beta = \Theta - \Phi \tag{5}$$

From the known value of β, we can calculate the value of the angle δ for the right triangle KMN.

$$180 = \beta + 90 + \delta \tag{6}$$

$$\delta = 90 - \beta = 90 - (\Theta - \Phi) \tag{7}$$

From this relation we establish that the angle Σ equals β

$$90 = \Sigma + \delta \tag{8}$$

$$\Sigma = 90 - PSI = 90 - (90 - \beta) = \beta \tag{9}$$

We can now solve for the angle Ω, the last angle in the triangle established by the length of the port scale factor S/2 and its projection in the plane parallel to the image plane.

$$180 = \Omega 1 + \Sigma + (180 - \Gamma 1) \quad (10)$$

$$\Omega 1 = \Gamma 1 - \Sigma = 90 - \alpha 1 - \Theta + \Phi \quad (11)$$

Using the law of sines, we can solve for the projected length of the port scale factor as follows: (See Figure 12.)

$$[(S/2)/ \sin(180 - \Gamma 1)] = (\text{Proj } S/2)/\sin(\Omega 1) \quad (12)$$

$$\text{Proj } S/2 \text{ (port wing tip)} = (s/2) \sin(\Omega 1) / \text{Sin}(180 - \Gamma 1) \quad (13)$$

Using the same reasoning, we can solve for the projected length of the starboard scale factor as follows: (See Figure 12.)

$$(S/2)/ \sin(180 - \Gamma 2) = (\text{Proj } S/2)/ \sin(\Omega 2) \quad (14)$$

where $\Omega 2 = \Gamma 2 - \Sigma = 90 - \alpha 2 - \Theta + \Phi$

$$\text{Proj } S/2 \text{ (stbd wing tip)} = (s/2) \sin(\Omega 2) / \sin(180 - \Gamma 2) \quad (15)$$

Substituting the quantities directly measurable from the image or initial set up into the equations, we find the following:

$$\text{Proj } S/2 \text{ (swt)} = S/2[\sin(90 - \alpha 2 - \Theta + \Phi)]/ \sin(90 + \alpha 2) \quad (16)$$

$$\text{Proj } S/2 \text{ (pwt)} = S/2[\sin(90 - \alpha 1 - \Theta + \Phi)]/ \sin(90 + \alpha 1) \quad (17)$$

Recalling that the cos (a) = sin (90 - a)

$$\text{Proj } S/2 \text{ (swt)} = (S/2)[\cos(\alpha 2 + \Theta - \Phi)]/ \cos(\alpha 2) \quad (18)$$

$$\text{Proj } S/2 \text{ (pwt)} = (S/2)[\cos(\alpha 1 + \Theta - \Phi)]/ \cos(\alpha 1) \quad (19)$$

We now sustitute the identity COS (A + B) = COS A * COS B - SIN A * SIN B where A = $(\Theta - \Phi)$ and B = α.

$$\text{Proj } S/2 \text{ (swt)} =$$

$$(S/2)[\text{COS}(\Theta - \Phi) * \text{COS}(\alpha 2) - \text{SIN}(\Theta - \Phi) * \text{SIN}(\alpha 2)] / \text{COS}(\alpha 2) \quad (20)$$

$$\text{Proj } S/2 \text{ (pwt)} =$$

$$(S/2)[\text{COS}(\Theta - \Phi) * \text{COS}(\alpha 1) - \text{SIN}(\Theta - \Phi) * \text{SIN}(\alpha 1)]/\text{COS}(\alpha 1) \quad (21)$$

By dividing through by the denominator in both cases, these reduce to

$$\text{Proj } S/2 \text{ (swt)} = (S/2)*[\text{COS}(\Theta - \Phi)- \text{SIN}(\Theta - \Phi)*\text{TAN}(\alpha 2)] \quad (22)$$

$$\text{Proj } S/2 \text{ (pwt)} = (S/2)*[\text{COS}(\Theta - \Phi)- \text{SIN}(\Theta - \Phi)*\text{TAN}(\alpha 1)] \quad (23)$$

Returning to Figure 11, the value of TAN ($\alpha 1$) = X1 / F where F is the focal length of the optical system. TAN ($\alpha 2$) = X2/F. Therefore,

$$\text{Proj } S/2 \text{ (swt)} = (S/2)*[\text{COS}(\Theta - \Phi)-(X2/F)*\text{SIN}(\Theta - \Phi)] \quad (24)$$

$$\text{Proj S/2 (pwt)} = (S/2)*[\cos(\Theta - \Phi) - (X1/F)*\sin(\Theta - \Phi)] \quad (25)$$

Restating equation (1) the total scale factor

$$SF(\text{total}) = \text{Proj S/2(pwt)} + \text{Proj S/2(swt)}$$

Thus

$$SF = S*[2F*\cos(\Theta - \Phi) - (X1+X2)*\sin(\Theta - \Phi)]/(2*F) \quad (26)$$

Returning to figure 11, F is the known camera focal length, Θ is the known camera set up angle with the runway center line, while X1 and X2 are values read off the image.

Only Φ is not directly available to perform the scale factor calculation. For an initial estimate of SF, it is reasonable to assume Φ is Zero. The value of Φ is iteratively calculated, using a scale factor based on the initial estimate of Φ. A detailed description of the calculation of Φ is provided in section 10 of this report. If the calculated value varies by more than 0.001 radians, the calculated value is substituted for the estimated value and the process is repeated until the calculated and estimated values of Φ converge to 0.001 radians.

The above equation is modified to account for roll attitute of the aircraft by dividing it by the cosine of the angle established from the difference in vertical height of the main landing gear measured to the horizontal reference line. The roll correction is derived as follows:

$$Y(\text{port wheel}) = SF*(Y \text{ port wheel position} - Y \text{ reference position}) \quad (27)$$

$$Y(\text{stbd wheel}) = SF*(Y \text{ stbd wheel position} - Y \text{ reference position}) \quad (28)$$

Note: the quanities within the parenthesis are image measurements

$$\text{Roll Angle} = \arcsin((Y(\text{port wheel}) - Y(\text{stbd wheel})) / \text{Tread}) \quad (29)$$

where "Tread" is the actual horizontal distance between the main landing gear wheels on the aircraft.

This correction is applied by dividing the equation for the scale factor SF by the cosine of the Roll Angle.

$$SF' = SF/\cos(\text{roll angle}) \quad (30)$$

The computer then redefines the value of SF' as SF.

CALCULATION OF THE ANGLE BETWEEN AIRCRAFT CENTER LINE AND RUNWAY CENTER LINE

The calculation of the angle Φ is an iterative process, beginning with the calculation of the scale factor for a Φ angle of Zero. The resulting scale factor is used to calculate an aircraft attitude. That attitude is examined and a Φ angle derived. This Φ angle is now used to calculate a new scale factor. Again the aircraft attitude and a new Φ value is calculated. This process is continued until the Φ values used in the scale factor calculation and from the attitude calculation agree within 0.001 Radians.

The key to this calculation is determining the relative horizontal positions of the nose landing gear and both the main landing gears. The scale factor SF calculated in the previous section of this report is strictly applicable only at the distance of the midpoint of the wheel span. The actual positions of the nose and main wheels are at a slightly different ranges from the camera than the midpoint of the wheel span. To accurately account for these variations, a separate value of scale factor is calculated for each wheel position. Figure 13 describes the derivation of the corrections used to calculate the individual wheel scale factors.

The scale factor for the nose wheel is calculated as follows:

$$SF(nose) = SF4 = SF - B * \cos(\Theta - \Phi)/F \qquad (31)$$

where SF is the previously calculated Scale Factor and B is the distance between the nose wheel and midpoint of the main wheels measured along the aircraft center line. F is camera system Focal Length. Θ and Φ are the camera set up angle and aircraft center line to runway center line angles respectively.

The scale factor for the port wheel is calculated as follows:

$$SF(port) = SF1 = SF - S * \sin(\Theta - \Phi)/(2F) \qquad (32)$$

where S is the full size dimension on the aircraft of the span used for the scale factor. Similarly, the starboard scale factor is calculated from:

$$SF(starboard) = SF2 = SF + S * \sin(\Theta - \Phi)/(2F) \qquad (33)$$

These corrected scale factors are used in the iterative calculation of Φ.

These modified scale factors, (SF1, SF2 and SF4) are used along with the measured image positions of the port wheel (X1), starboard wheel (X2), and nose wheel (X4) to calculate the angle of the aircraft center line to the camera lens center line. See Figure 14.

The horizontal distance of the port, starboard and nose wheels from the center line of the lens axis are given by:

$$DX1 = SF1 * X1 \tag{34}$$

$$DX2 = SF2 * X2 \tag{35}$$

$$DX4 = SF4 * X4 \tag{36}$$

To determine the angle of the aircraft center line from the camera lens center line, it is necessary to calculate the distance D for the center of the main wheel span. This is done as follows:

$$D = (DX1 + DX2)/2 \tag{37}$$

Knowing the distance between the center of the main wheels and the nose wheel B, we can now calculate $(\Theta - \Phi)$ from the equation

$$\text{Sin } (\Theta - \Phi) = (DX4-D)/B \tag{38}$$

$$\Phi = \Theta - \text{ARCSIN } [(DX4-D)/B] \tag{39}$$

It is this calculated value of Φ which is compared to the assumed value of Φ in the iterative process. This iteration is repeated until the difference between the values used is less than 0.001 radians.

SINK SPEED CALCULATION

Sink Speed is calculated for the port, starboard and nose landing gear. In addition, an average sink speed for the mid point of the span of the main landing gear wheels is calculated. Sink Speed is calculated from the vertical position of each wheel determined from the image data. Vertical acceleration is calculated from the average sink speed equation. A sequence of vertical positions are taken for each image feature (bottom of wheel). These positions are the last positions prior to the wheel touchdown point. The touchdown image is not used. From this image data, a vertical position versus time curve is described.

An empirical formula is fitted to these data by a modified method of least squares. The sequence of measured feature heights are used to generate a series of simultaneous equations of the form:

$$h = a + b(T) + c(T)^2 \tag{40}$$

These equations will fit a smooth curve through the space time data and produce a reasonably accurate result. The difference in the original

measured heights and the calculated h from the fitted equation is calledthe residual. The principle of least squares states that the best second-degree parabola fit is that which minimizes the sum of the squares of the residuals. Applying the method of least squares to the residual equations generates a series of three normal equations of the form:

$$N * A + B * \Sigma T + C * \Sigma T^2 = \Sigma H \quad (41)$$

$$A * \Sigma T + B * \Sigma T^2 + C * \Sigma T^3 = \Sigma (H*T) \quad (42)$$

$$A * \Sigma (T^2) + B * \Sigma T^3 + C * \Sigma T^4 = \Sigma (H*T^2) \quad (43)$$

N = number of points in the analysis

This set of equations is solved by application of Cramer's rule to the matrix representation of these equations. The inverse matrix and determinant are found for the coefficient matrix. This results in three algebraic expressions for the values of A, B & C.

A separate equation $Y = A + B(T) + C(T^2)$ is calculated for each of the landing gear wheels as well as for the average position of the main wheels. These equations are differentiated once and evaluated at T = 0. The resulting slope of the position time equation is reported as the sink speed for that feature. The average sink speed curve is differentiated a second time to determine the vertical acceleration of the aircraft. Again the value of acceleration is determined at T = 0.

HORIZONTAL VELOCITY CALCULATION

The horizontal velocity of the aircraft consists of two components. One is the motion of the aircraft perpendicular to the image plane and the other is the horizontal motion of the aircraft across the image. These two components are caused by the offset location of the camera with respect to the runway center line. The vector sum of these components is the horizontal speed calculated by the analysis program. The analysis program refers to this resultant as the aircraft's engaging speed, Ve.

Determination of the velocity component perpendicular to the image frame is based on the previously calculated scale factor which establish the range of the object from the camera. The equation used is

$$\text{Range} = \text{Focal length} * [SF/(X1-X3)] \quad (44)$$

where SF is the foreshortened scale factor and X1 - X3 is the dimension of the image feature (such as wing tips) in the image.

This range information is used to generate a position/time regression curve. The curve is then differentiated and evaluated at T = 0.

$$Vy = d/dt\ [A + B*T + C*(T^2)] \tag{45}$$

The component of horizontal velocity across the image is calculated by comparing the horizontal position of an image feature between successive image frames.

$$(SF*X1)\ (\text{at } T) - (SF*X1)\ (\text{at } T') = \text{horizontal motion} \tag{46}$$

where the scale factors used are those associated with each individual image.

These horizontal positions are used to generate a regression curve of horizontal position versus time. The curve is then differentiated and evaluated at T = 0.

$$Vx = d/dt\ [A + B*T + C*(T^2)] \tag{47}$$

The reported horizontal velocity is the vector sum of these velocities, Vx and Vy.

$$Ve = SQRT\ (Vx^2 + Vy^2) \tag{48}$$

POSITION AND ATTITUDE DETERMINATION

This section describes the procedures used to calculate the target aircraft's touchdown point on the runway as well as its pitch and roll attitude.

OFF CENTER DISTANCE

The key image measurement for the calculation of aircraft off-center distance is the horizontal position of the port main landing gear, this position is designated X3 in the analysis program. Off-center distance is the horizontal distance from the center of the aircraft's main landing gear to the runway center line (See Figure 15). Note that the value of X3 may be identical to X1, the port scale factor position, if the wheels are used as scale factors. The equation used is as follows:

$$\text{Off-Center Distance} = \eta - R - (\text{TREAD}/2) * \cos \Phi \qquad (49)$$

where $R = T * \sin(\Theta + \Phi)$; $T = C / \cos \Phi$; and $C = SF * F$

F is the lens focal length, SF is the appropriate scale factor for the image feature being tracked.

The horizontal positions from the twelve images prior to touchdown are used to generate a regression curve of position versus time in a manner identical to that used to calculate sink speed. This curve is also differentiated and evaluated at T = 0 to provide an off-center rate of change.

The value of the regression curve at T = 0 is compared to the known perpendicular distance of the camera to the runway center line to determine the off-center position at touchdown.

TOUCHDOWN DISTANCE FROM RUNWAY THRESHOLD

In a manner similar to that used to calculate the aircraft's horizontal velocity parallel to the camera lens axis, the Scale Factor is used to determine the range of the aircraft from the camera. This information is used to calculate the distance the aircraft lands from the camera. The range information is used to generate a regression curve which is evaluated at T = 0. This result is compared to the known geometry of the camera set-up and the distance from the runway threshold to the aircraft's touchdown point is determined (See Figure 16). The equation used in this calculation is:

$$A = \text{Scale Factor} * \text{Focal Length} \quad (50)$$

$$A' = A / \cos (\varepsilon) \quad (51)$$

$$G - \text{Runway Threshold Distance} = \text{SQRT} (A'^2 - (\eta - \text{OFFCEN})^2) \quad (52)$$

$$\text{Runway Threshold Distance} = G - \text{SQRT} (A'^2 - (\eta - \text{OFFCEN})^2) \quad (53)$$

where G is the measured distance from the camera location to the runway Threshold measured down the runway center line. η is the distance from the camera location measured perpendicular to the runway center line.

ROLL ANGLE

Roll angle is calculated at the aircraft's touchdown point and is calculated from the difference in vertical heights measured for the port and starboard main landing gear wheels. This difference is compared to the known dimension between the main wheels. The equation used is

$$\text{Roll Angle} = (Yp-Ys)/(\text{Tread}) \quad (54)$$

where Tread is the distance between the main wheels with the wheels in the fully extended position.

Again, these positions are used to generate a roll angle vs. time regression curve and this curve is evaluated at T = 0 to determine roll angle. This equation is differentiated and evaluated at T = 0 to determine the aircraft's roll rate at touchdown.

PITCH ANGLE

The key to the calculation of Pitch Angle is knowing the distance from the nose and main landing gear wheels to the fuselage reference line when the aircraft landing gear struts are fully extended. This establishes the natural pitch angle of the aircraft. Knowing the aircraft's natural pitch and the measured vertical position of the main landing gear wheels, the aircraft's pitch attitude is determined from the equation:

$$\text{Pitch Angle} = \mu + \text{arc sin} (\Delta h/x) \quad (55)$$

where:

Δh is the difference in vertical height of the main and nose gear axles.
x is the wheelbase between the nose and main landing gear axis.
μ is angle of the line through the center line of the main and auxiliary gear axles, when fully extended, to the aircraft reference line .

AIRCRAFT FLIGHT PATH ANGLE

The angle between the runway centerline and the aircraft flight path is defined as the FLIGHT PATH ANGLE. It is defined by the equation

FPA = TAN (OFF CENTER RATE / VETDnew) where (56)

OFF CENTER RATE is the rate of change of off center distance (defined from the runway centerline) and VETDnew is the horizontal velocity of the aircraft parallel to the runway centerline. VETDnew is calculated from the rate of change of the aircraft's distance from the runway threshold. The RUNWAY THRESHOLD DISTANCE calculated for each successive image is processed by a linear curve fitting routine to calculate VETDnew.

YAW ANGLE

Yaw angle is defined as the angle between the aircraft flight path and the aircraft fuselage centerline. Since FPA is the angle between the Aircraft flight path and the runway centerline, and Φ is defined as the angle between the aircraft fuselage centerline and the runway centerline, then YAW angle can be calculated from the equation

$$YAW = \Phi - FPA \quad (57)$$

CONCLUSIONS

1) That the requirements of the Federal Aviation Administration to collect landing performance data on commercial jet aircraft can be met by the Naval Aircraft Approach and Landing Data Acquisition System (NAALDAS). A future demonstration of the modified system will be scheduled to verify this conclusion. The modified system should be tested at the Federal Aviation Administration Technical Center to permit the Technical Center's laser tracking system to verify the landing parameters determined by NAALDAS.

2) The enhancements and modifications needed to apply NAALDAS to commercial use are low risk, and involve a broader application of existing technology.

3) That NAALDAS can be configured to meet all existing Federal Aviation Administration safety and operational restrictions. It is the first system capable of conducting the number and variety of landing surveys required to establish a meaningful data base on the landing performance of commercial jet aircraft.

4. After successful demonstration at the Federal Aviation Administration Technical Center, an operational survey should be performed at a major commercial airport. This initial survey should identify any operational or procedural problems in performing surveys in a "real world" environment.

REFERENCES

Technical Report: NAWCADWAR 93004-60, Naval Aircraft Approach and Landing Data Acquisition System (NAALDAS), Video Landing System Land Based Evaluation, 15 April 1993.

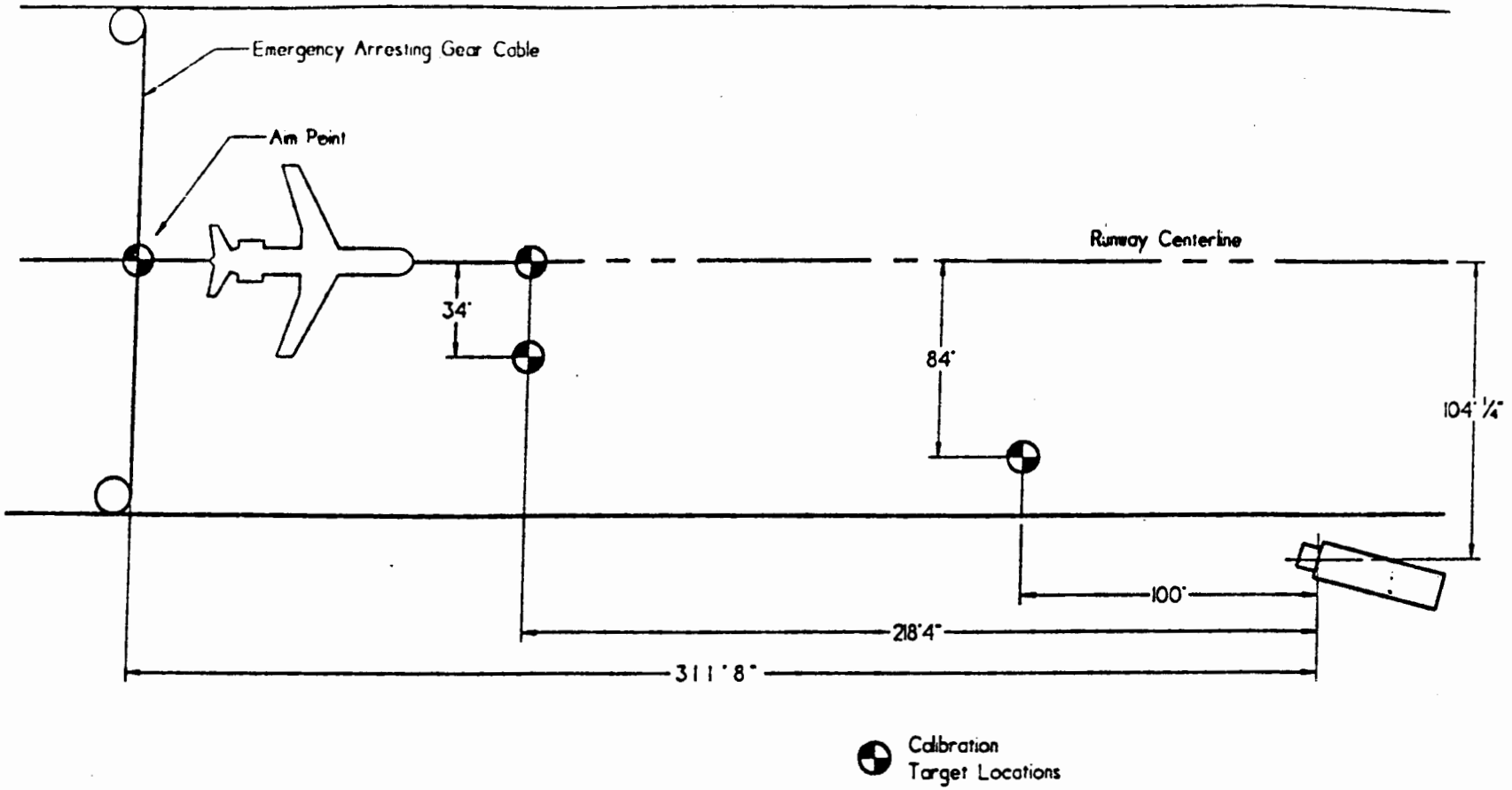


FIGURE 1, FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER RUNWAY 13, SURVEY EQUIPMENT LOCATION

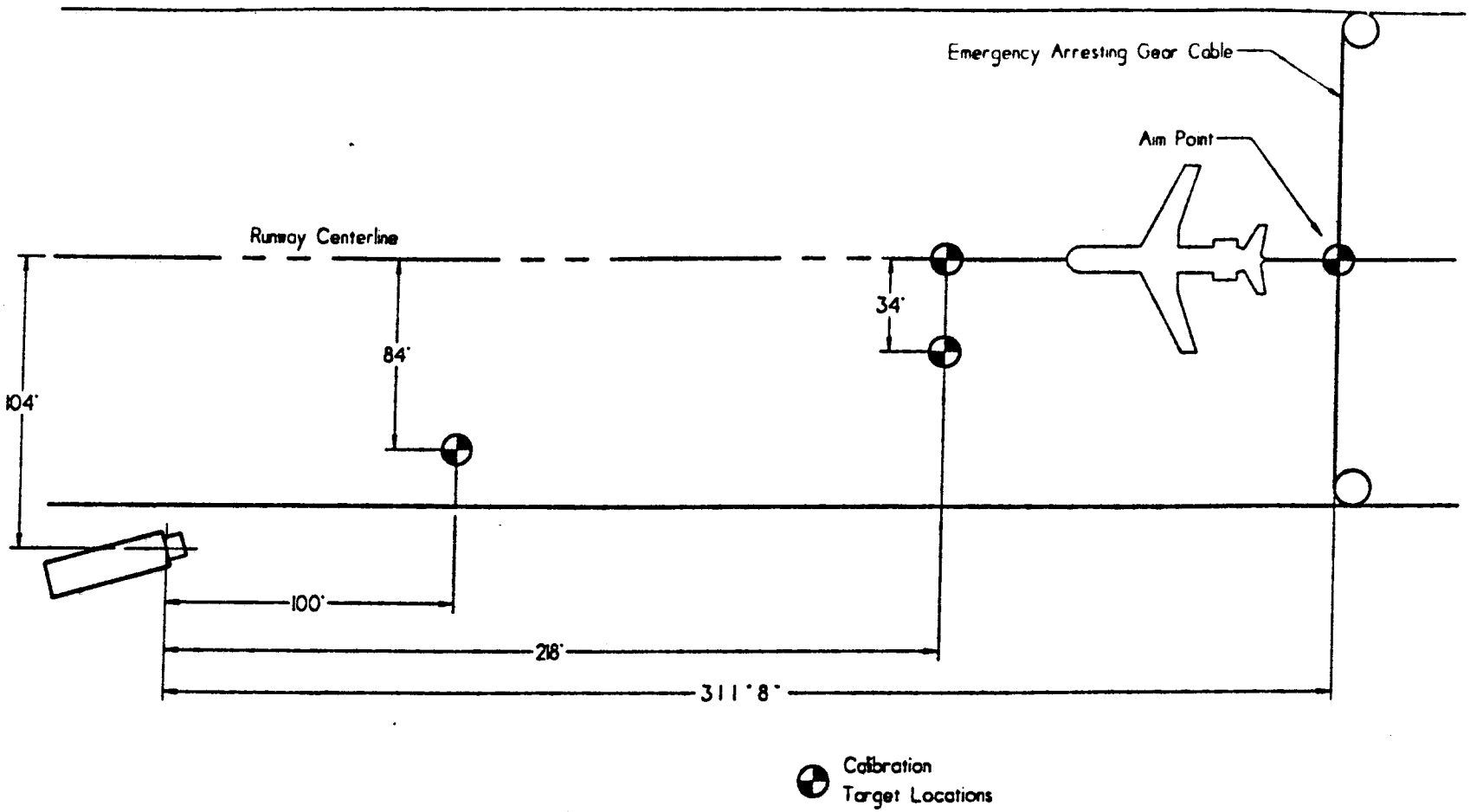


FIGURE 2, FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER RUNWAY 31, SURVEY EQUIPMENT LOCATION

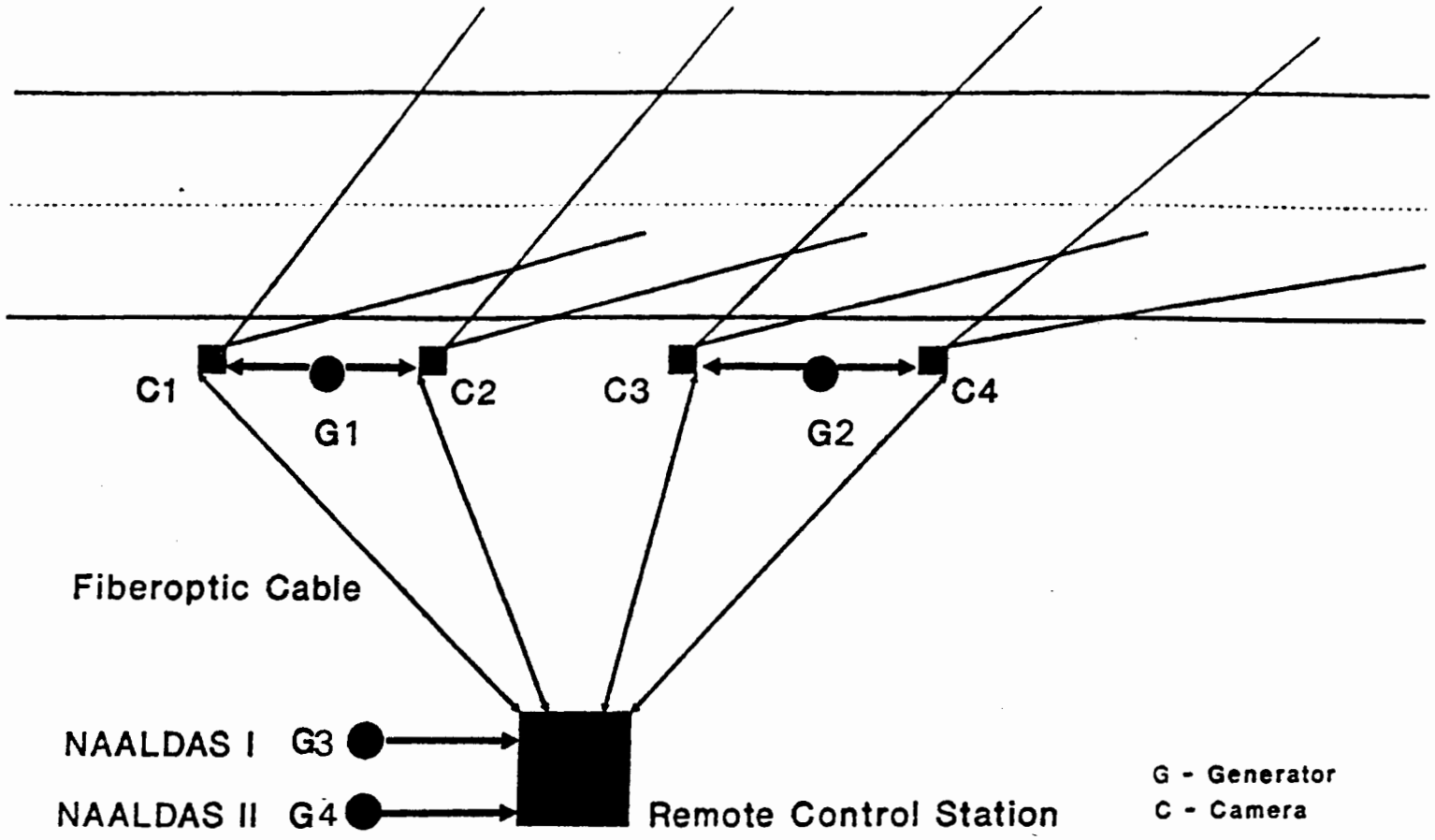


Figure 3. FAA LANDING LOADS DATA COLLECTION PROGRAM FIELD CAMERA SETUP

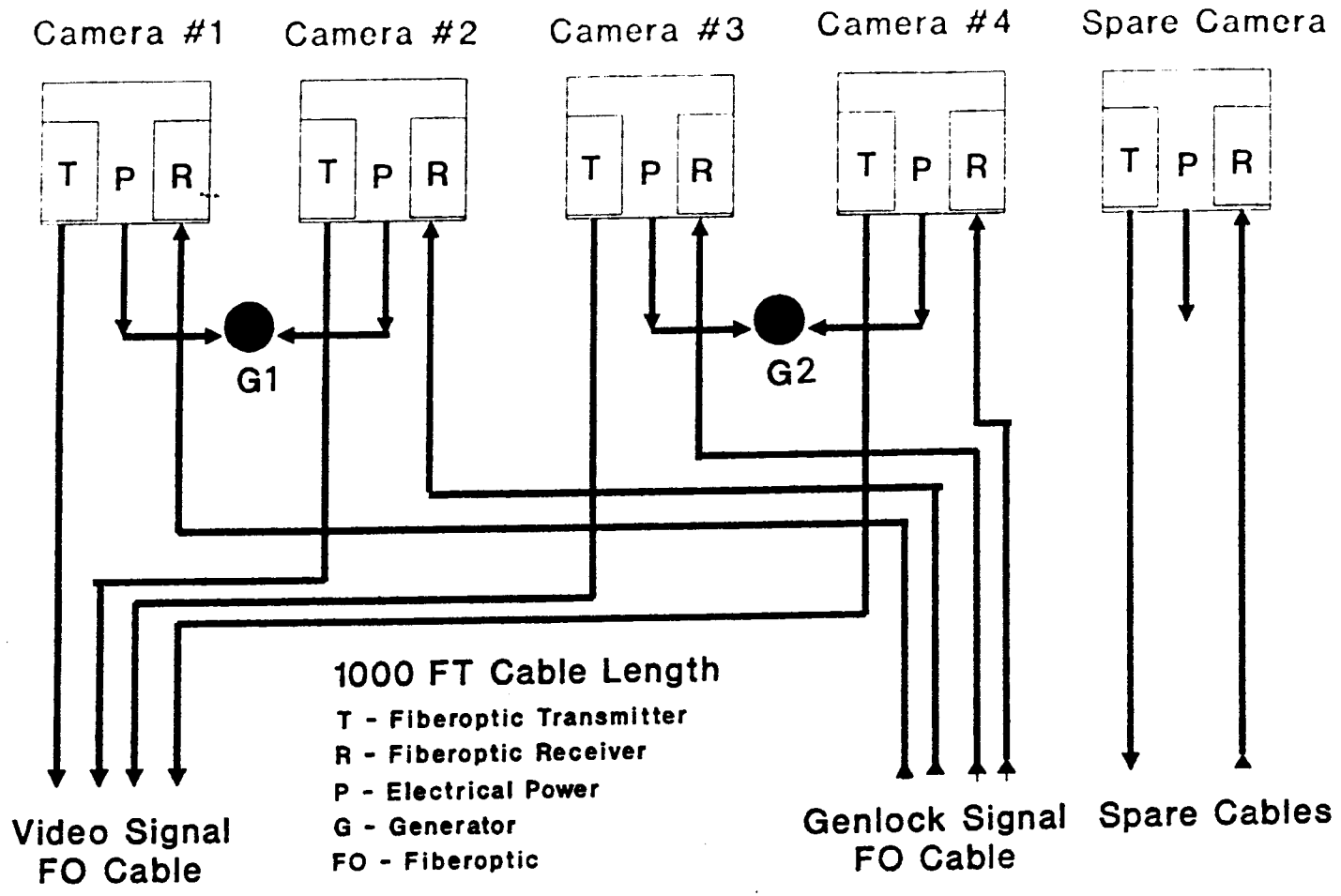


FIGURE 4. FAA LANDING LOADS DATA COLLECTION PROGRAM
RUNWAY EQUIPMENT DIAGRAM

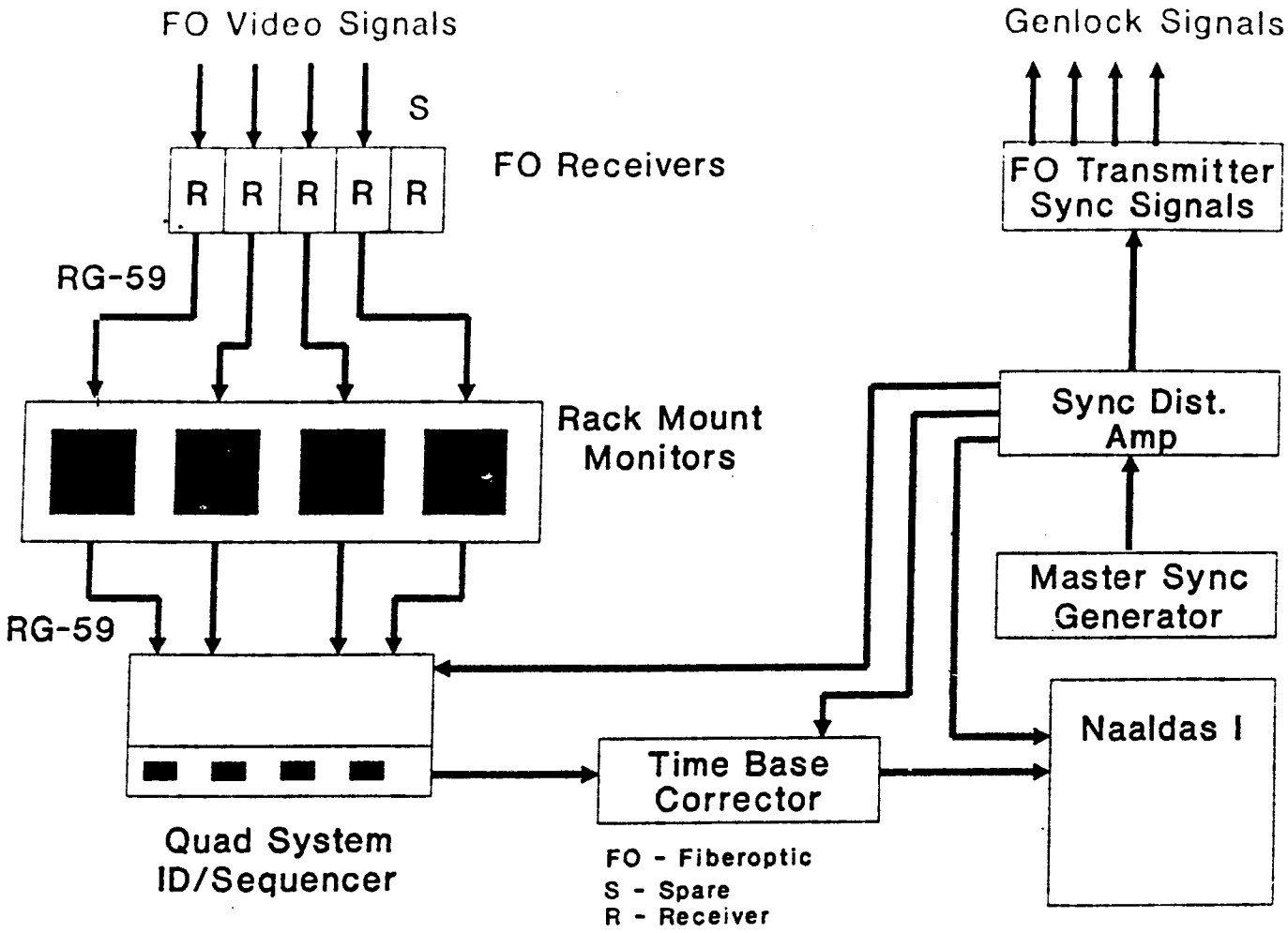


FIGURE 5. FAA LANDING LOADS DATA COLLECTION PROGRAM REMOTE STATION EQUIPMENT

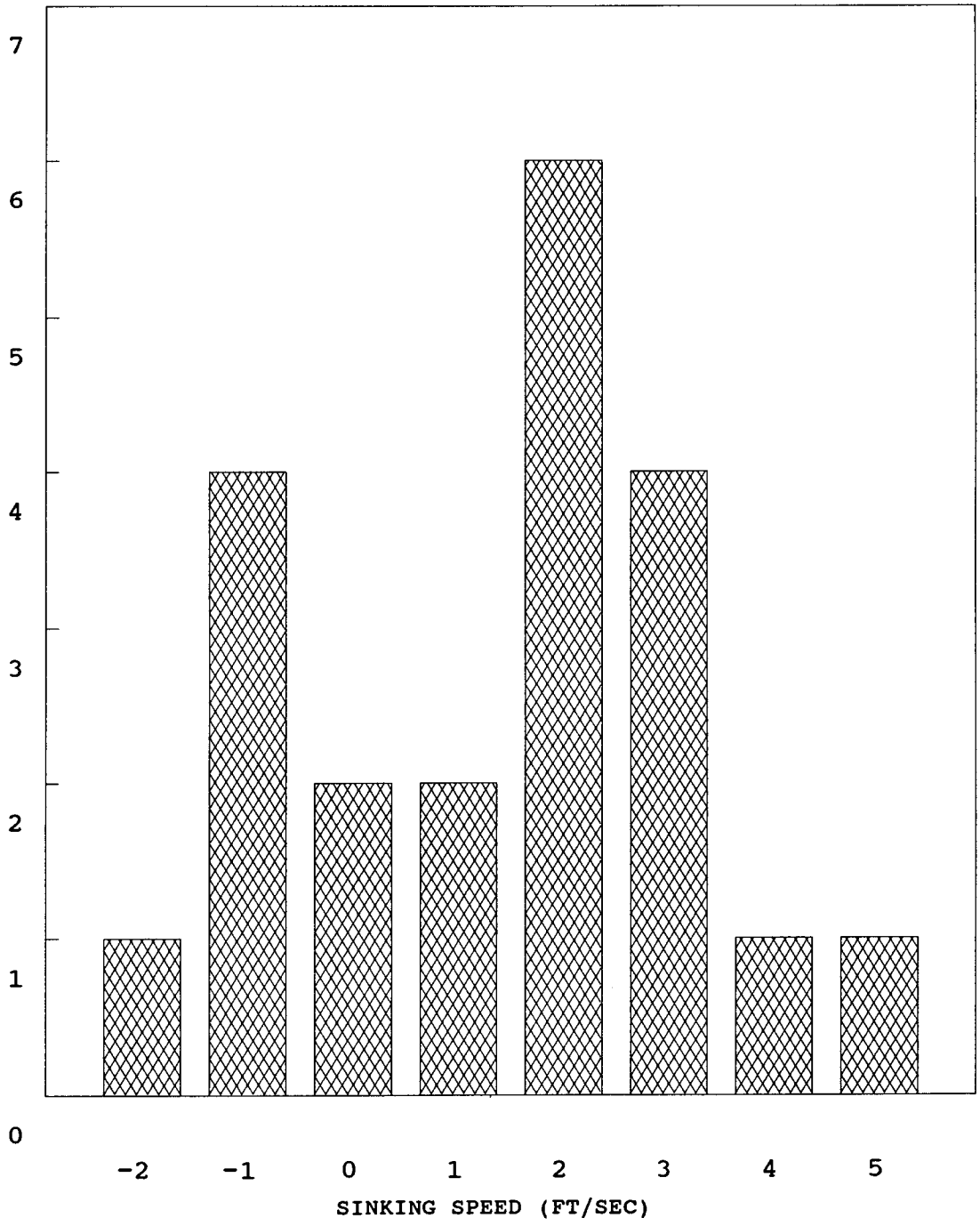


FIGURE 6. LANDING LOADS DATA COLLECTION PROGRAM FAA TECHNICAL CENTER B-727-100 LANDINGS NUMBER OF LANDINGS VERSUS SINK SPEED

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

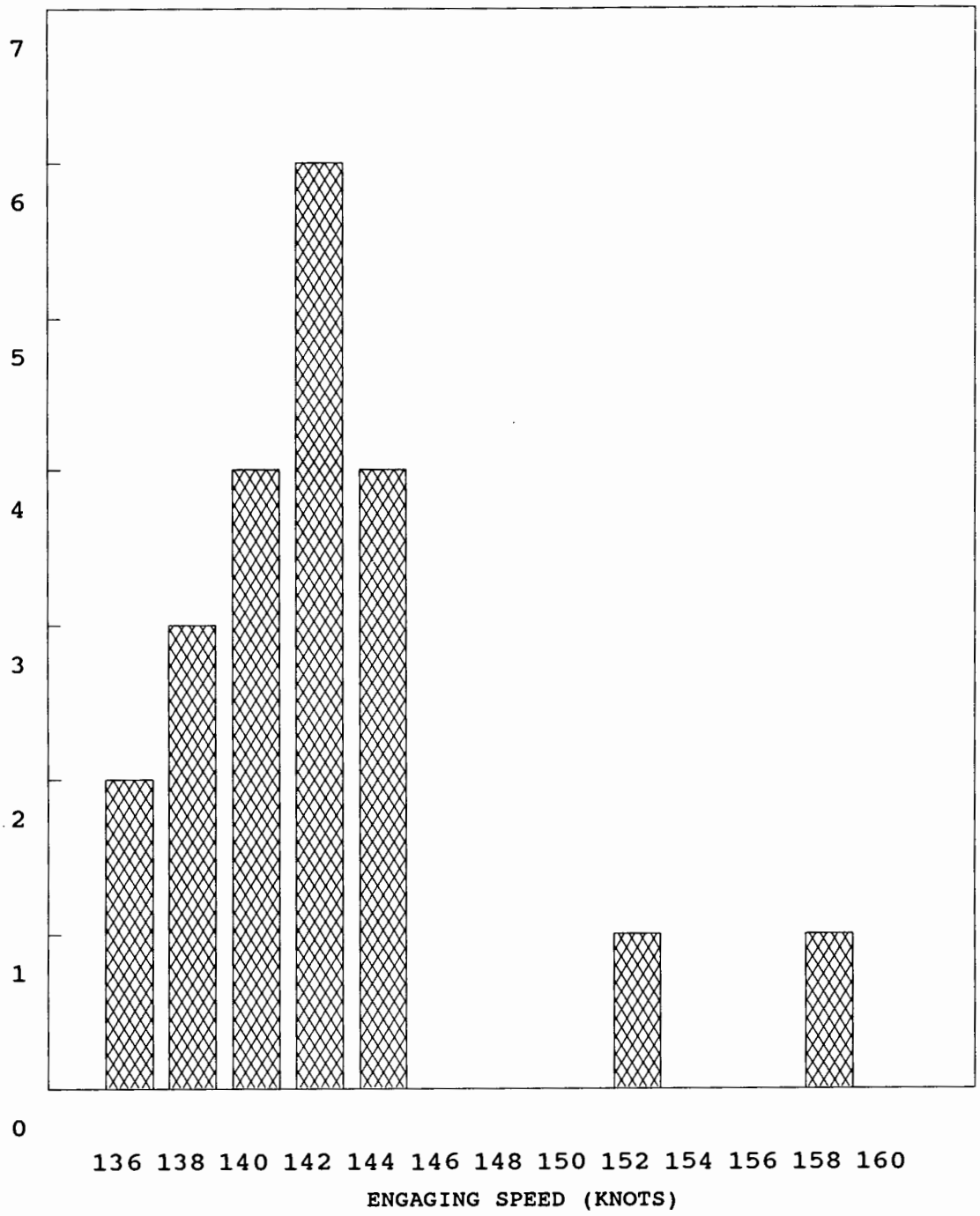


FIGURE 7. LANDING LOADS DATA COLLECTION PROGRAM FAA TECHNICAL CENTER B-727-100 LANDINGS NUMBER OF LANDINGS VERSUS ENGAGING SPEED

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

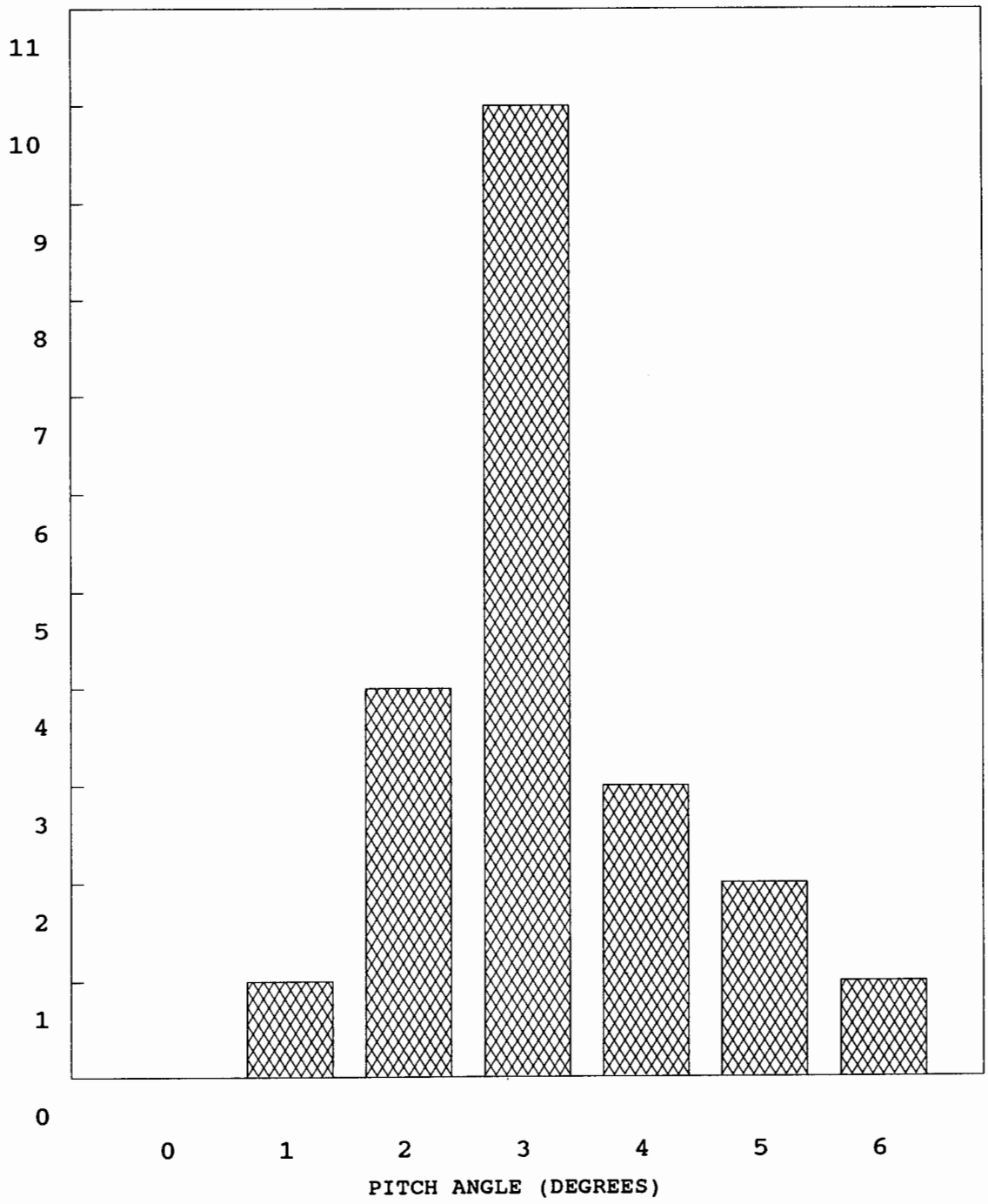


FIGURE 8. LANDING LOADS DATA COLLECTION PROGRAM FAA TECHNICAL CENTER B-727-100 LANDINGS NUMBER OF LANDINGS VERSUS PITCH ATTITUDE

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

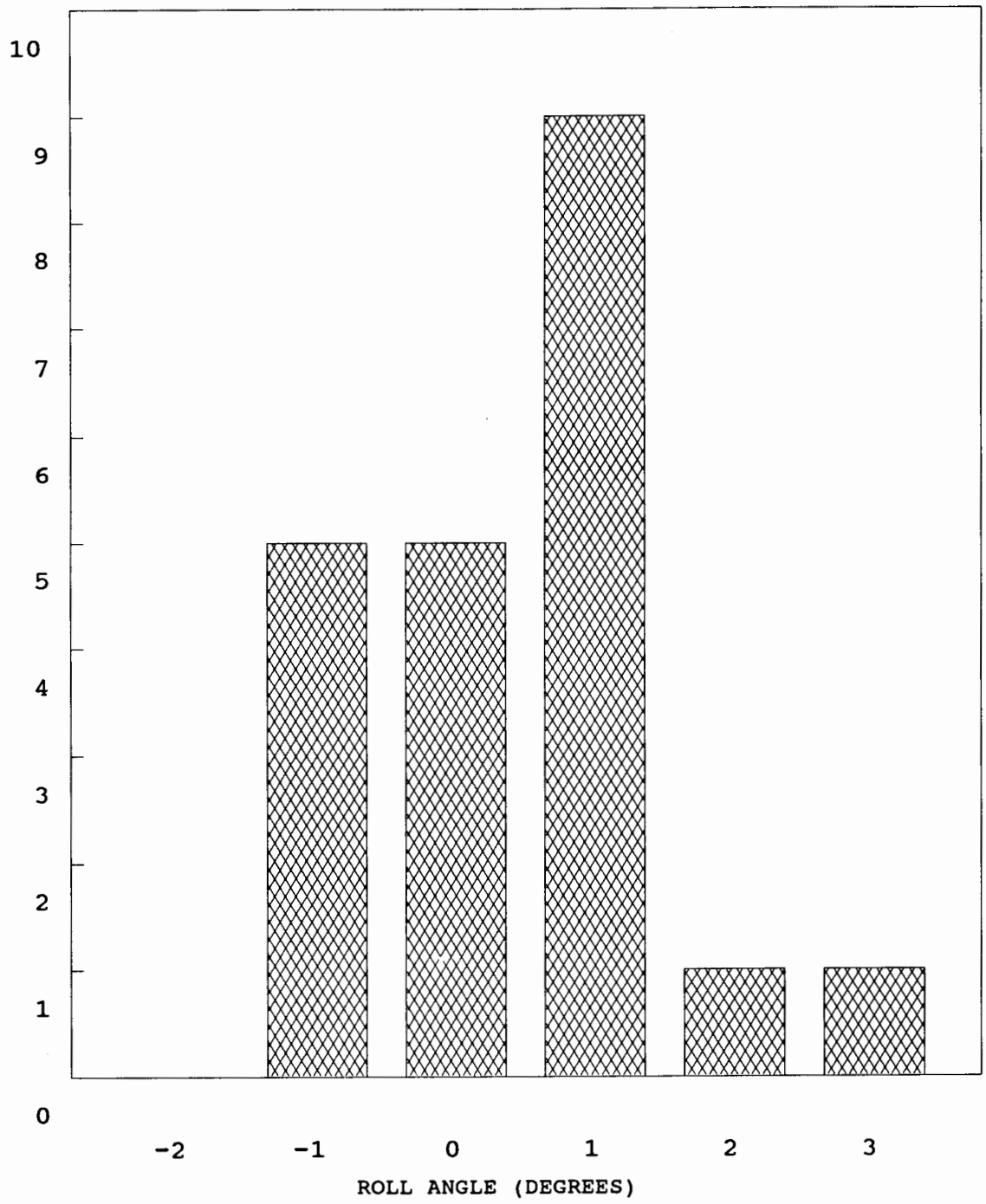


FIGURE 9. LANDING LOADS DATA COLLECTION PROGRAM FAA TECHNICAL CENTER B-727-100 LANDINGS NUMBER OF LANDINGS VERSUS ROLL ANGLE

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

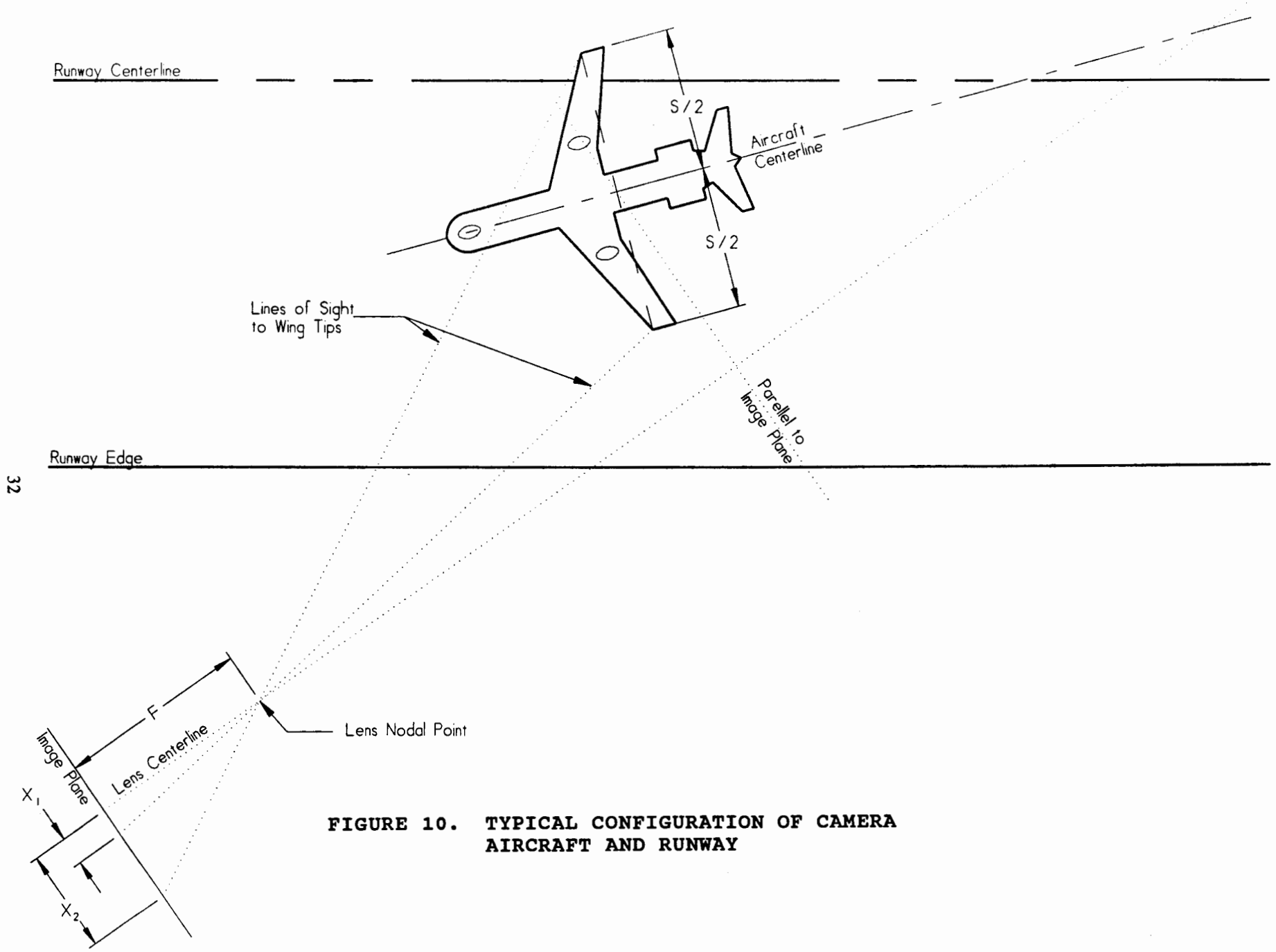


FIGURE 10. TYPICAL CONFIGURATION OF CAMERA AIRCRAFT AND RUNWAY

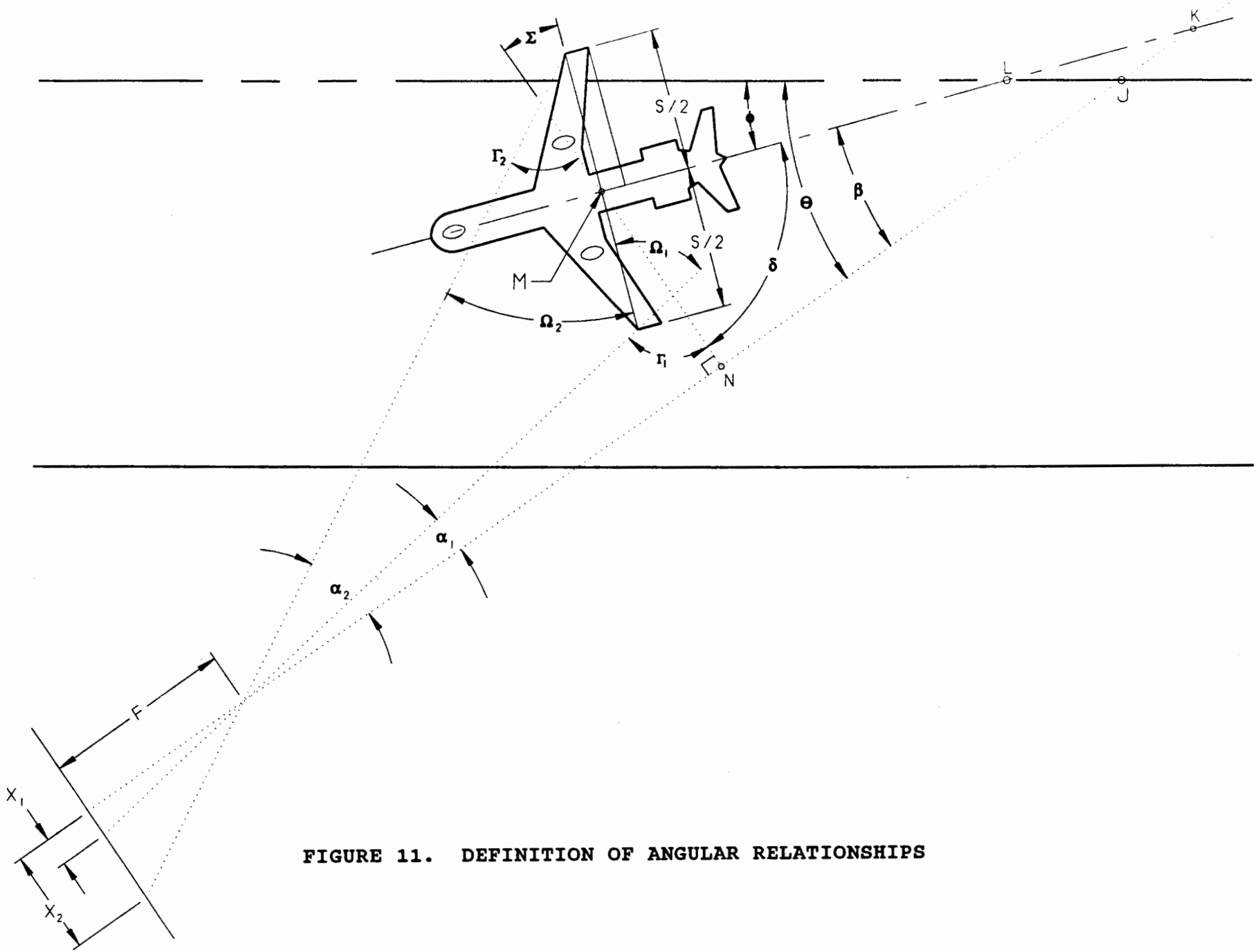


FIGURE 11. DEFINITION OF ANGULAR RELATIONSHIPS

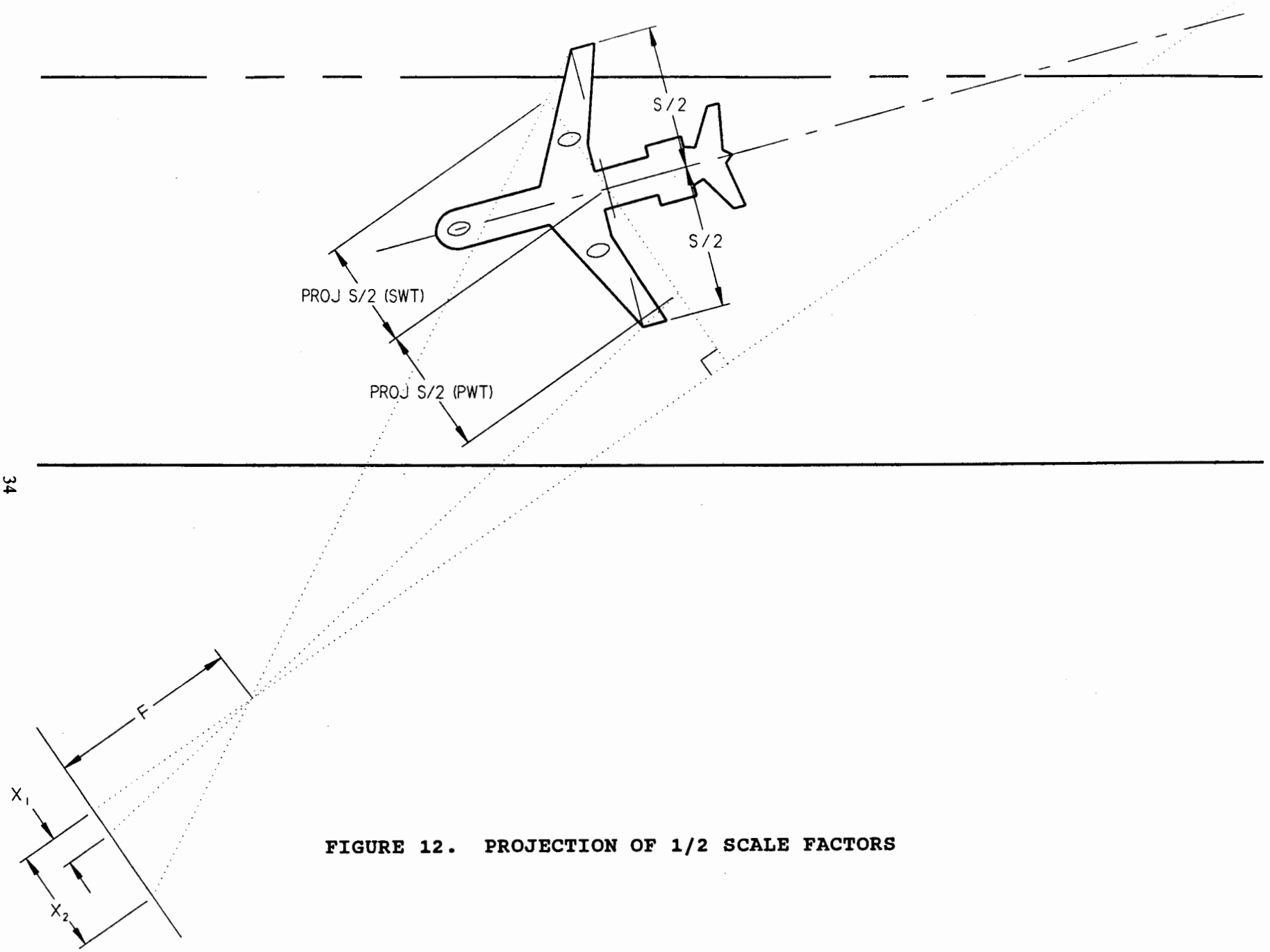


FIGURE 12. PROJECTION OF 1/2 SCALE FACTORS

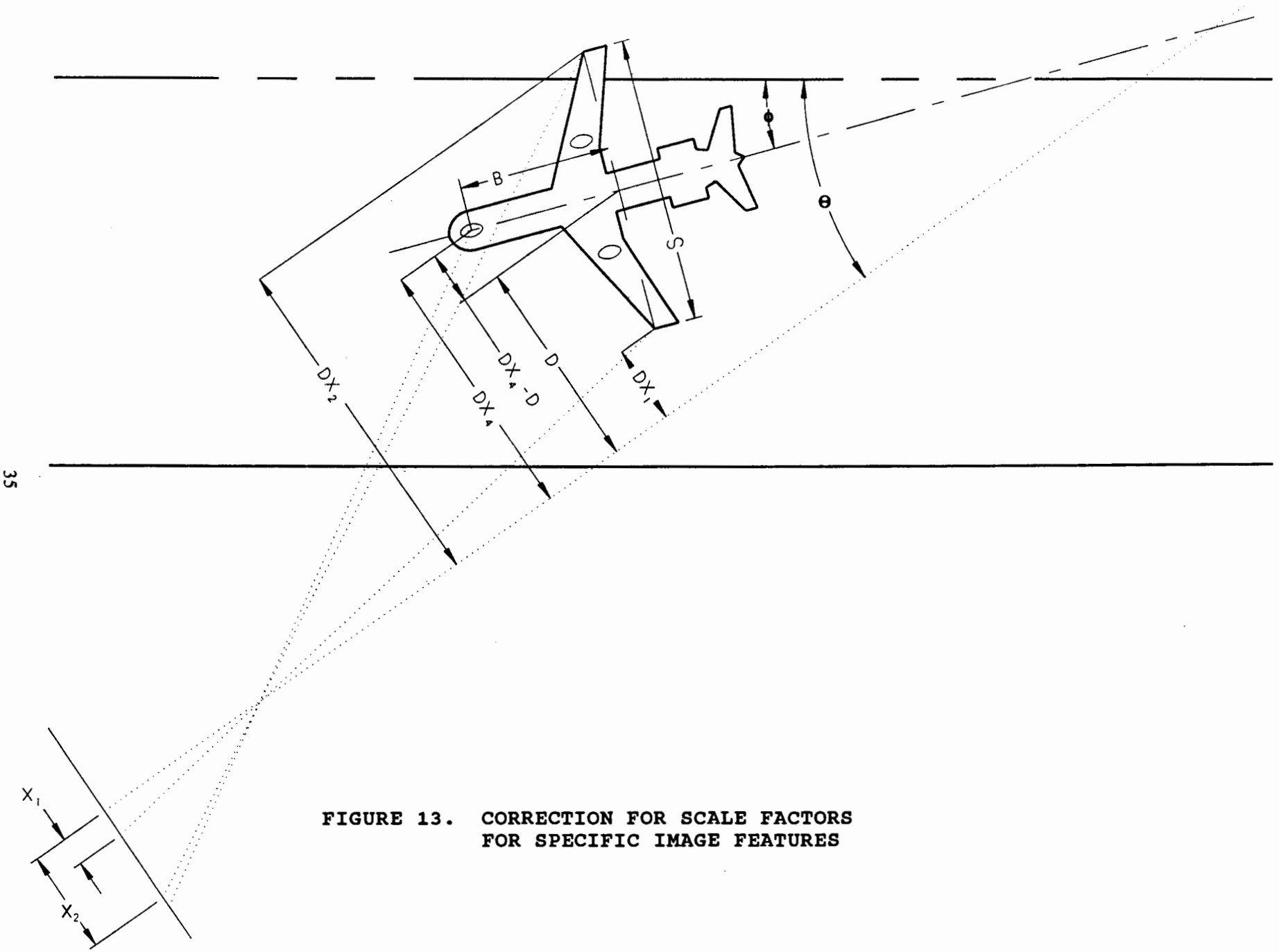


FIGURE 13. CORRECTION FOR SCALE FACTORS FOR SPECIFIC IMAGE FEATURES

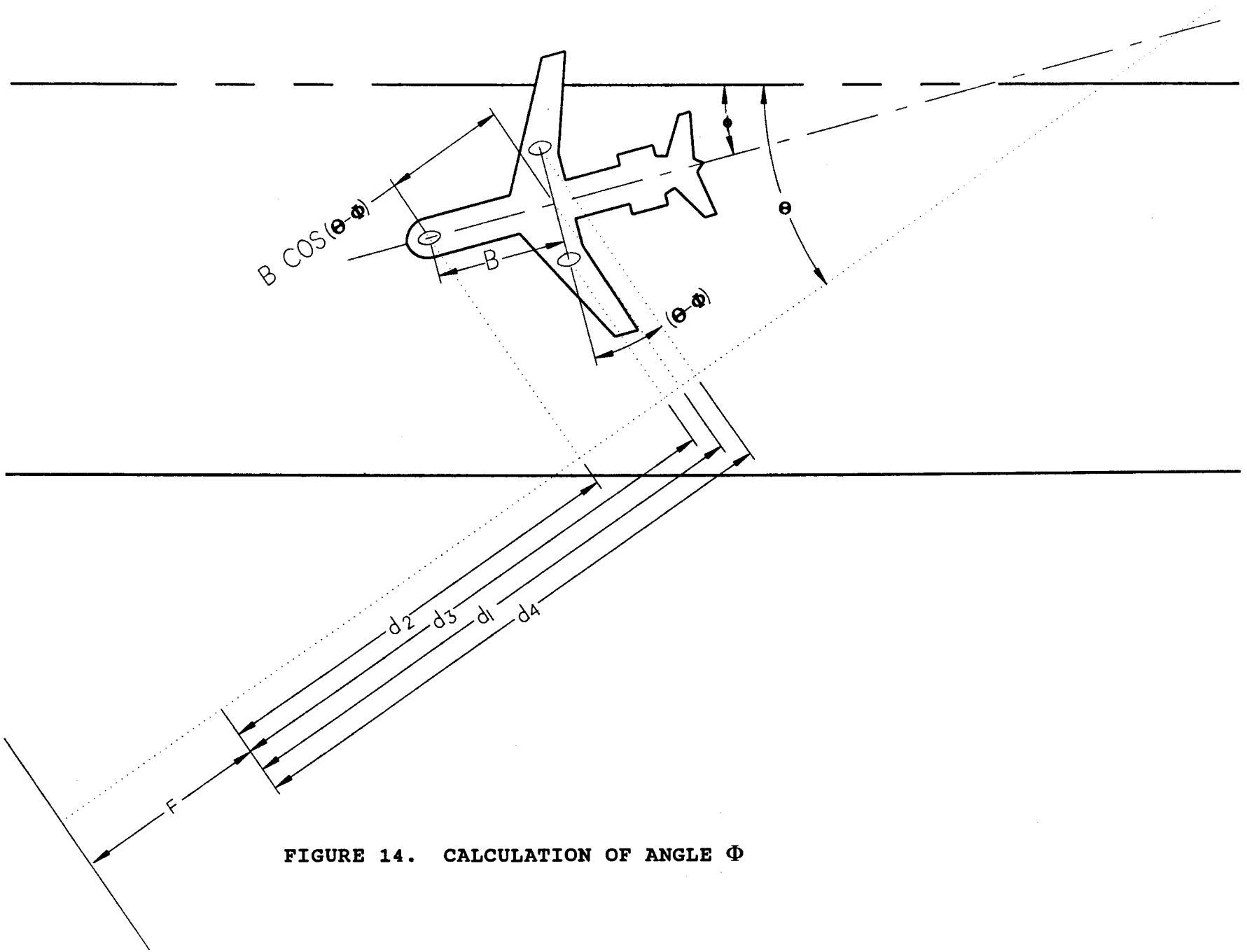


FIGURE 14. CALCULATION OF ANGLE Φ

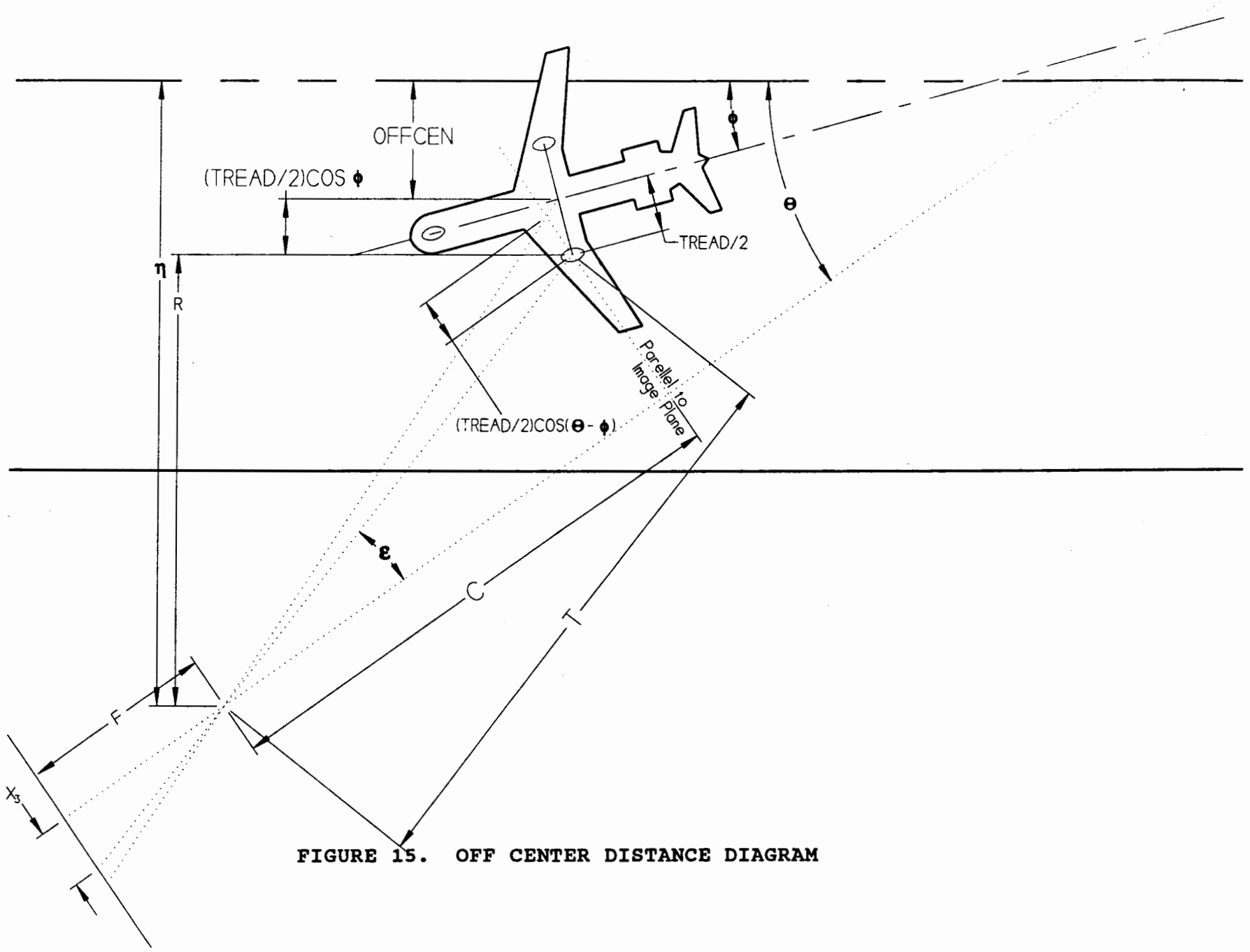


FIGURE 15. OFF CENTER DISTANCE DIAGRAM

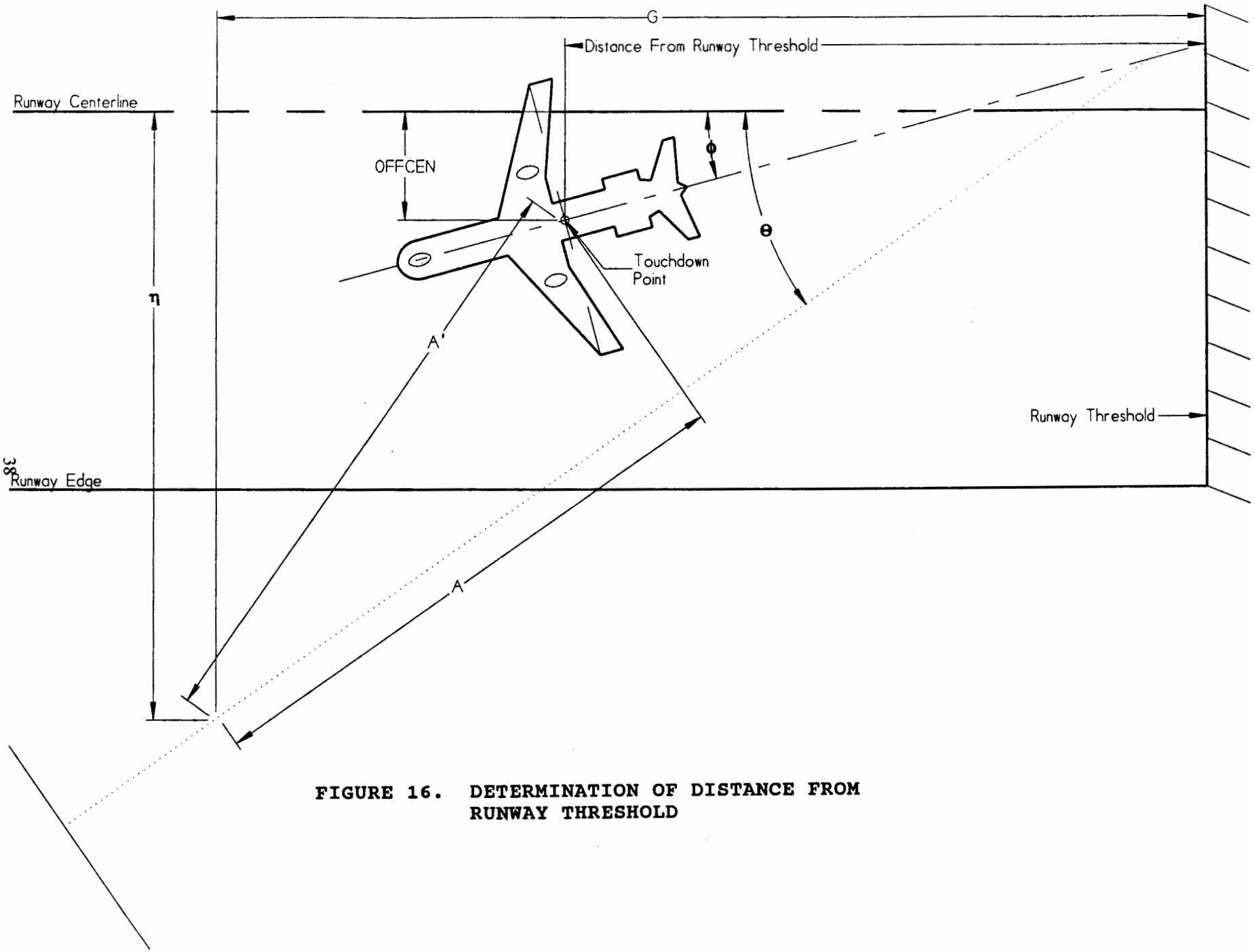


FIGURE 16. DETERMINATION OF DISTANCE FROM RUNWAY THRESHOLD

TABLE 1: FAA VIDEO SYSTEM EVALUATION STATISTICAL SUMMARY OF ALL B-727-100 EVENTS

PARAMETER	NUMBER OF LANDINGS	MEAN	STANDARD DEVIATION
SINKING SPEEDS			
PORT WHEEL	21	1.7	1.67
STBD WHEEL	21	1.6	2.30
AVG MAIN WHEELS	21	1.6	1.81
NOSE WHEEL	19	3.0	2.19
ENGAGING SPEED	21	142	4.68
PITCH td	21	3.2	1.01
ROLL td	21	0.2	1.06
PITCH RATE	19	1.90	1.69
ROLL RATE	21	0.1	4.82
OFFCENTER DISTANCE	21	-1.3	2.80
RUNWAY THRESHOLD TO TD DISTANCE	21	1563	93
WEIGHT	21	126624	9315
INSTANTANEOUS GLIDESLOPE	21	0.5	0.39
PHI TD	21	0.1	1.69
F.P.A.	21	-0.2	0.86
YAW	21	0.1	1.99

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA Test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

TABLE 2: FAA VIDEO SYSTEM EVALUATION
STATISTICAL SUMMARY OF ACTUAL B-727-100 TOUCHDOWN

PARAMETER	NUMBER OF LANDINGS	MEAN	STANDARD DEVIATION
SINKING SPEEDS			
PORT WHEEL	12	2.0	1.29
STBD WHEEL	12	2.5	1.78
AVG MAIN WHEELS	12	2.3	1.29
NOSE WHEEL	12	3.6	1.92
ENGAGING SPEED	12	143	5.88
PITCH td	12	3.3	1.26
ROLL td	12	0.6	0.92
PITCH RATE	12	1.68	1.23
ROLL RATE	12	-1.7	4.68
OFFCENTER DISTANCE	12	-2.0	2.80
RUNWAY THRESHOLD TO TD DISTANCE	12	1538	97
WEIGHT	12	123533	7774
INSTANTANEOUS GLIDESLOPE	12	0.5	0.38
PHI TD	12	0.7	1.86
F.P.A.	12	-0.2	0.91
YAW	12	0.9	1.98

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA Test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

TABLE 3: FAA VIDEO SYSTEM EVALUATION B-727-100 DATA SUMMARY

EVENT NO	TIME (LOCAL)	APPROACH SPEED (KNOTS)	NOSE SINKING SPEED (FT/SEC)	PORT SINKING SPEED (FT/SEC)	STBD SINKING SPEED (FT/SEC)	AVG SINKING SPEED (FT/SEC)	OFF CENTER DISTANC (FEET)	PITCH ANGLE (DEG)	ROLL ANGLE (DEG)	YAW ANGLE (DEG)	PHI ANGLE (DEG)	FPA ANGLE (DEG)	GLIDE SLOPE ANGLE (DEG)	PITCH RATE (DEG/SEC)	ROLL RATE (DEG/SEC)	THRESHOLD TOUCHDOWN DISTANCE (FEET)	LANDING WEIGHT (LBS)	TOUCHDOWN IN FIELD OF VIEW
19	11:42	143.9	3.20	1.00	3.90	2.5	-1	3.0	1.0	0.9	0.9	-0.1	0.56	0.80	-8.81	1574	125000	YES
21	11:53	141.1	2.20	1.00	1.21	1.1	-2	2.4	0.8	0.3	1.5	1.1	0.27	1.14	-0.64	1631	123000	YES
22	11:58	140.1	4.50	2.70	2.30	2.5	-3	1.0	0.0	2.3	2.4	0.0	0.61	2.13	1.10	1632	122500	YES
24	12:08	138.0	5.10	3.10	3.90	3.5	-1	2.0	2.6	3.6	1.8	-1.8	0.85	1.73	-2.29	1637	120000	YES
26	12:14	139.0	4.80	3.20	3.00	3.1	-3	2.3	0.6	3.5	3.1	-0.5	0.75	1.83	0.56	1629	119000	YES
29	12:25	141.5		3.90	4.30	4.1	-3	3.5	0.8	1.4	0.0	-1.4	0.98		-1.23	1641	116500	NO
32	12:32	157.4	0.56	2.40	3.85	3.1	-8	4.0	0.6	1.4	0.0	-1.4	0.67	2.04	-4.45	1491	114800	YES
33	12:37	138.0		-2.27	-1.95	-2.1	-3	2.8	-1.0	0.1	0.0	-0.1	0.52		-1.00	1643	114000	NO
34	12:40	136.3	3.00	2.40	-0.70	0.8	-6	3.2	0.6	3.0	3.9	0.9	0.2	2.34	9.46	1543	113500	YES
35	12:45	151.4	8.37	4.20	5.73	5.0	-2	3.3	0.4	1.3	0.0	-1.5	1.12	3.89	-4.52	1516	113000	YES
41	10:32	140.2	2.76	0.45	2.54	1.4	-0.1	3.3	-1.3	-2.0	-0.8	1.3	0.59	6.74	-5.50	1387	141000	NO
42	10:36	139.4	3.50	2.10	1.50	1.8	4	3.6	1.0	-2.8	-0.3	-0.2	0.44	1.86	1.92	1611	140500	NO
43	10:50	140.8	4.70	3.00	1.40	2.2	1	3.0	-1.0	-0.7	-1.4	-0.7	0.52	2.72	4.91	1614	138500	NO
44	10:55	144.0	1.68	1.50	2.56	2.0	3	5.9	1.7	-3.2	-2.5	0.7	0.48	-0.37	-3.24	1381	137200	YES
441	10:55	144.2	-1.90	-0.42	-1.40	-0.9	2	3.3	-1.3	-2.2	-2.4	-0.2	-0.22	-1.07	3.09	1618	137200	NO
46	11:08	141.5	3.95	-0.32	2.39	1.0	0	3.9	-0.3	-1.7	-2.2	-0.5	0.8	3.15	-8.30	1398	135000	YES
48	11:14	144.6	0.53	-0.42	-2.63	-1.5	1	3.2	0.0	-2.4	-1.9	0.5	-0.36	2.22	6.78	1614	134000	NO
52	11:28	141.3	2.51	3.06	2.97	2.3	-2	3.1	0.0	0.0	0.0	0.0	0.72	-0.54	0.26	1627	131500	YES
56	11:40	142.5	0.04	0.35	-2.14	-0.9	0	3.2	1.1	0.9	0.0	-0.9	-0.21	1.00	7.62	1620	130000	NO
58	11:47	137.0	3.02	0.29	-0.60	0.1	1	4.9	-1.2	-0.4	0.0	0.4	0.03	3.14	1.08	1395	127900	YES
59	11:54	141.3	3.84	3.36	1.93	2.6	-4	1.9	-1.4	-0.6	0.0	0.6	0.63	1.28	4.37	1625	125000	NO

These data are not to be considered typical of commercial aircraft operations. They were performed by an FAA Test pilot who employed atypical procedures while attempting to touchdown within the camera field of view.

APPENDIX A

LANDING LOADS SURVEY DEFINITIONS

SINK SPEED - V_V - The sink speed of the aircraft landing gear wheel just prior to touchdown. Sink speed is reported for each landing gear individually; that is for the port, starboard and nose wheels just prior to individual runway contact. In addition, the average sink speed of the aircraft main landing gear is calculated just prior to touchdown of the first main landing gear wheel. Sink speed is determined from image data.

The symbols used to identify aircraft sink speed are as follows:

V_{V_a} - average sink speed

V_{VS} - sink speed of the starboard main wheel

V_{VP} - sink speed of the port main wheel

V_{VN} - sink speed of the nose landing gear

The values of aircraft sink speed are reported in feet per second (ft/sec).

WING LIFT FACTOR - K_{le} - The Wing Lift Factor is calculated from the derivative of the aircraft average sink speed. It is calculated just prior to the touchdown of the first main landing gear. A value of 1.0 for the wing lift factor indicates that a constant sink speed is being maintained. If the value of K_{le} is greater than 1.0, this indicates that the sink speed is decreasing and the wing lift is greater than 1.0 G. Conversely, if the value is less than 1.0 then the sink speed is increasing and the lift being generated is less than 1.0 G.

The value of Wing Lift Factor is calculated from the equation

$$K_{le} = (2 * C / 32.2) + 1.0$$

where the value of 2*C is the second derivative of the regression curve of the aircraft vertical position with respect to time, evaluated at touchdown (t=0). The regression curve is that calculated for the average vertical position of the aircraft main landing gear and has the form of the equation

$$\text{Position} = A + Bt + Ct^2$$

The symbol for Wing Lift Factor is Kle.

This quantity is dimensionless.

ENGAGING SPEED - Ve - The Engaging Speed is the speed with which the aircraft closes on the runway. Engaging speed is calculated from image measurements.

The symbol for ENGAGING SPEED is Ve

The value of Engaging Speed is reported in Knots .

APPROACH SPEED - Vp'af - The value of Approach Speed reported is the algebraic sum of engaging speed and component of the prevailing wind parallel to the center line of the runway.

The symbol for approach speed is Vp'af.

The value of approach speed is reported in Knots.

AIRCRAFT PITCH ANGLE - Θp - The aircraft pitch angle measured between the aircraft reference line and a line parallel with the runway. Positive values of pitch angle are reported for an aircraft exhibiting a nose up attitude. Pitch Angle is determined from image data.

The symbol used for PITCH ANGLE is Θp.

The value of this quantity is reported in both Degrees and Radians.

The value of pitch angle is reported at two locations; just prior to first wheel touchdown and as the aircraft flies over the runway threshold.

SUBSCRIPTS: R - Over Runway Threshold

td - at touchdown

AIRCRAFT ROLL ANGLE - Θr - The aircraft roll angle is measured between the aircraft reference line and a line parallel with the runway center line. Positive values of roll angle are reported for an aircraft whose starboard wing is down. Roll Angle is determined from image data.

The symbol used for ROLL ANGLE is Θr.

The value of this quantity is reported in both Degrees and Radians.

The value of roll angle is reported at two locations; just prior to first wheel touchdown and as the aircraft flies over the runway threshold.

SUBSCRIPTS: R - Over Runway Threshold

td - at touchdown

AIRCRAFT PITCH RATE - $\dot{\Theta}p$ - The aircraft pitch rate is calculated from the film data. It is reported just prior to the touchdown of the first main wheel. Positive values of this variable indicates that the aircraft nose is pitching down. This rate is determined with respect to the runway.

The symbol used for this Quantity is $\dot{\Theta}p$.

The value of this quantity is reported in both Degrees per second (deg/sec) and Radians per second (radians/sec).

AIRCRAFT ROLL RATE - $\dot{\Theta}r$ - The aircraft roll rate is calculated from the film data. It is reported just prior to the touchdown of the first main wheel. Positive values of this variable indicates that the aircraft is rolling to port. This rate is determined with respect to the runway.

The symbol used for this Quantity is $\dot{\Theta}r$.

The value of this quantity is reported in both Degrees per second (deg/sec) and Radians per second (radians/sec).

AIRCRAFT OFF CENTER LINE DISTANCE - Y - This is the perpendicular distance measured between the aircraft center line and the center line of the runway. This value is calculated from film data just prior to first main wheel touchdown. Positive values of this quantity indicate that the aircraft landed on the port side of the runway center line.

The symbol for this quantity is Y.

The value of this quantity is reported in Feet (ft).

DISTANCE FROM RUNWAY THRESHOLD TO FIRST MAIN WHEEL TOUCHDOWN - Xw - The distance between the runway threshold and the point of first main wheel touchdown is determined from image data.

The symbol for this quantity is Xw.

The value of this quantity is reported in Feet (ft).

AIRCRAFT INSTANTANEOUS GLIDE SLOPE ANGLE - ßvv - This angle is determined just prior to first main wheel touchdown. The value of average sink speed (Vva) and engaging speed (Ve) are used to define the instantaneous glide slope. These values are entered into the equation:

$$\beta vv = \arctan(Vva / Ve)$$

NOTE: A Consistent set of units must be used in this equation.

The symbol for this quantity is ßvv.

The value of this quantity is reported in degrees and radians.

AIRCRAFT GEOMETRIC GLIDE SLOPE ANGLE - ßhw - This angle is determined by utilizing the Distance From The Runway Threshold To Touchdown (Xw) and Height Of Main Wheels At The Runway Threshold (Hw). These values are substituted into the equation:

$$\beta hw = \arctan(Hw/Xw))$$

NOTE: A Consistent set of units must be used in this equation.

The symbol for this quantity is ßhw.

LANDING WEIGHT - W - The landing weight reported in the survey is determined from aircraft basic weight, estimated fuel state and estimated useful load on aircraft final approach.

The Symbol for this quantity is W.

The value of this quantity is reported in pounds.

AIRCRAFT YAW ANGLE - YAW td - The Yaw Angle is the angle between the aircraft center line and the aircraft flight path at the point of first main wheel touchdown. Positive yaw angle is defined to be that orientation where a clockwise rotation of the yaw vector causes the vector to coincide with the aircraft center line using a minimum angular rotation. Yaw angle is determined from image data.

The Symbol for this quantity is YAWtd.

The value of this quantity is reported in Degrees and Radians.

AIRCRAFT FLIGHT PATH ANGLE - F.P.A. - The Flight Path Angle is the angle between the aircraft flight path and the runway center line at the point of touchdown. This measurement is determined from image data. Positive Flight Path Angle is defined to be that orientation where a clockwise rotation of the flight path vector causes the vector to coincide with the runway center line using a minimum angular rotation.

The Symbol for this quantity is F.P.A..

The value of this quantity is reported in Degrees and Radians.

HEIGHT OF MAIN WHEELS OVER THE RUNWAY THRESHOLD - Hw - The average height of the aircraft main landing gear wheels as it flies over the runway threshold is determined from the image data.

The symbol for this quantity is Hw.

The value of this quantity is reported in feet.

APPENDIX B

AIRCRAFT DIMENSIONAL INPUT REQUIREMENTS FOR LANDING LOADS SURVEYS

LANDING GEAR:

- SPAN
- TRACK
- TIRE POSITION
- POSITION OF LANDING GEAR WHEELS WITH THE STRUT FULLY EXTENDED AND THE AIRCRAFT IN FLIGHT (THIS INFORMATION REQUIRED TO DETERMINE AIRCRAFT PITCH ATTITUDE FROM MEASURED WHEEL POSITIONS).

WING:

- OVERALL SPAN (MEASURED PERPENDICULAR TO FUSELAGE CENTER LINE).
- SPAN TO OUTBOARD EDGE OF OUTBOARD FLAP.
- SPAN TO OUTBOARD EDGE OF AILERONS (PARTICULARLY IF DROOPED IN APPROACH CONFIGURATION).
- LOCATION OF 1/4 CHORD POINT ALONG FUSELAGE CENTER LINE.

FUSELAGE:

-LENGTH OVERALL

EMPENNAGE:

-HEIGHT OF VERTICAL TAIL FROM FUSELAGE CENTER LINE.
-HEIGHT OF HORIZONTAL TAIL ABOVE/BELOW FUSELAGE CENTER LINE.
-SPAN OF HORIZONTAL TAIL.
-DISTANCE OF 1/4 CHORD POINT OF HORIZONTAL TAIL FROM WING 1/4 CHORD POINT MEASURED ALONG FUSELAGE CENTER LINE.
-DISTANCE OF CENTERLINE OF VERTICAL TAIL FROM WING 1/4 CHORD POINT MEASURED ALONG FUSELAGE CENTER LINE.

MISCELLANEOUS:

-CURVE OF EQUATION DEFINING RECOMMENDED (AND MINIMUM) APPROACH SPEED AS A FUNCTION OF LANDING WEIGHT.

-FOR AIRCRAFT WITH ENGINE MOUNTED ON WING PYLONS, THE LOCATION OF THE GEOMETRIC CENTER OF EACH ENGINE INLET MEASURED FROM THE FUSELAGE CENTER LINE AND THE WING 1/4 CHORD POINT AT THE FUSELAGE CENTER LINE

APPENDIX C

LIST OF SYMBOLS

SYMBOL USED FOR LANDING PARAMETERS

V_V	Aircraft Sink Speed
V_{Va}	Average Aircraft Sink Speed
V_{VS}	Sink Speed of the Starboard Main Wheel
V_{VP}	Sink Speed of the Port Main Wheel
V_{VN}	Sink Speed of the Nose Landing Gear
K_{le}	Wing Lift Factor
Ve	Engaging Speed
Vp'af	Approach Speed
Øp	Pitch Angle
Ør	Roll Angle
$\dot{Ø}p$	Aircraft Pitch Rate
$\dot{Ø}r$	Aircraft Roll Rate
Y	Aircraft Off Center Line Distance
Xw	Distance from Runway Threshold to First Main Wheel Touchdown
ßvv	Aircraft Instantaneous Glide Slope Angle
ßhw	Aircraft Geometric Glide Slope Angle
W	Landing Weight
YAW	Aircraft Yaw Angle
F.P.A.	Aircraft Flight Path Angle
Hw	Height of Main Wheels Over the Runway Threshold

LIST OF SUBSCRIPTS

R - indicates data reported at the "runway threshold "

P - Port

S - Starboard

N - Nose Wheel

a - Average

r - Roll

p - Pitch

td - Data reported at aircraft touchdown

SYMBOLS USED IN GEOMETRIC CONSTRUCTIONS:

A - The distance from the camera to the aircraft touchdown point measured along the camera lens center line

A'- The distance from the camera to the aircraft touchdown point measured along the camera line of sight

B - The distance between the center of the aircraft's main landing gear to the nose wheel measured parallel to the fuselage center line

C - The distance from the port landing gear to the camera nodal point at the time of touchdown. Measured parallel to the camera lens center line

D - Distance between the center of the aircraft main landing gear and the camera lens center line measured perpendicular to the lens center line

DX1 - Distance between the aircraft port wing tip and the camera lens center line measured perpendicular to the lens center line

DX2 - Distance between the aircraft starboard wing tip and the camera lens center line measured perpendicular to the lens center line

DX4 - Distance between the center of the aircraft nose landing gear and the camera lens center line measured perpendicular to the lens center line

d1 - Distance between the center of the aircraft main landing gear and the camera lens nodal point measured parallel to the lens center line

d2 - Distance between the center of the aircraft nose landing gear and the camera lens nodal point measured parallel to the lens center line

d3 - Distance between the center of the aircraft port main landing gear and the camera lens nodal point measured parallel to the lens center line

d4 - Distance between the center of the aircraft starboard main landing gear and the camera lens nodal point measured parallel to the lens center line

F - Camera lens focal length.

G - The distance from the camera (lens nodal point) to the runway threshold, measured parallel to the runway center line

J - The point of intersection of the camera lens center line with the runway center line

K - The point of intersection of the aircraft fuselage center line with the camera lens center line

L - The point of intersection of the aircraft fuselage center line with the runway center line

M - The point of intersection of the aircraft fuselage center line with the plane which is parallel with the image plane and contains the center point between the aircraft main landing gear

N - The point established by intersection of the plane parallel to the image sensor and containing the center point between the aircraft main landing gear and also with the camera lens center line.

R - The distance from the camera lens nodal point to the center of the port main landing gear wheel measured perpendicular to the runway center line

S - Known aircraft dimension used in a scale factor calculation

S/2 - The distance from the wing tip to the aircraft fuselage center line.

SF - Scale factor for a particular image.

SF1 - Scale factor calculated for the port wing tip (or other feature used as a reference dimension)

SF2 - Scale factor calculated for the starboard wing tip (or other feature used as a reference dimension)

SF4 - Scale factor for the nose landing gear

T - Horizontal distance from the port landing gear wheel to the lens nodal point measured along the lens line of sight.

X1 - Horizontal distance measured on the image plane from image of the port wing tip (or other selected image feature) to the center of the image at the lens axis.

X2 - Horizontal distance measured on the image plane from the image of the starboard wing tip (or other selected image feature) to the center of the image at the lens axis.

X3 - Horizontal distance measured on the image plane from the image of the center of the port landing gear wheel to the center of the image at the lens axis

X4 - Horizontal distance measured on the image plane from the image of the center of the nose landing gear to the center of the image at the lens axis

Yp - The vertical height of the port main landing gear wheel above the reference plane

Ys - The vertical height of the starboard main landing gear wheel above the reference plane

$\alpha 1$ - The angle between the lens center line and the line of sight to the port wing tip (or other selected image feature).

$\alpha 2$ - The angle between the lens center line and the line of sight to the starboard wing tip (or other selected image feature).

β - The angle between the camera lens center line and the aircraft fuselage center line

$\Gamma 1$ - Angle established by the camera line of sight to the port wing tip with the plane parallel to the image plane and containing the center of the aircraft landing gear.

$\Gamma 2$ - Angle established by the camera line of sight to the starboard wing tip with the plane parallel to the image plane and containing the center of the aircraft landing gear.

δ - The angle between the runway center line and the plane parallel to the image plane and containing the center of the aircraft main landing gear

ε - The angle between the camera lens center line and the camera line of sight to the port main landing gear wheel

Θ - The angle between the camera lens center line and the runway center line.

η - The perpendicular distance from the camera lens nodal point to the runway Center Line

Σ - The angle defined by the intersection of the plane parallel to the image plane and containing the center of the main landing gear with the line connecting the forward edges of the aircraft's wing tips

Φ - Angle between the runway center line and the center line of the aircraft's fuselage.

Ω - The angle defined as the cosecant of the scale factor S/2 and its projection in the plane parallel to the image plane.

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