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AGARD Flight Test Instrumentation Series Volume 16 on Trajectory Measurements for Take-Off and Landing Tests and Other Short-Range Applications

by

P.de Benque d'Agut, H.Riebeek and A.Pool

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TRAJECTORY MEASUREMENTS FOR TAKE-OFF AND LANDING TESTS AND OTHER SHORT-RANGE APPLICATIONS

by

P.de Benque d'Agut, H.Riebeek and A.Pool

Volume 16

of the

AGARD FLIGHT TEST INSTRUMENTATION SERIES

Edited by

A.Pool

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PREFACE

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development recognized the need for a comprehensive publication on flight test techniques and the associated instrumentation. Under the direction of the AGARD Flight Test Panel (now the Flight Mechanics Panel), a Flight Test Manual was published in the years 1954 to 1956. The Manual was divided into four volumes: I. Performance, II. Stability and Control, III. Instrumentation Catalog, and IV. Instrumentation Systems.

As a result of developments in the field of flight test instrumentation, the Flight Test Instrumentation Group of the Flight Mechanics Panel was established in 1968 to update Volume III and IV of the Flight Test Manual. Upon the advice of the Group, the Panel decided that Volume III would not be continued and that Volume IV would be replaced by a series of separately published monographs on selected subjects of flight test instrumentation: the AGARD Flight Test Instrumentation Series. The first volume of the Series gives a general introduction to the basic principles of flight test instrumentation engineering and is composed from contributions by several specialized authors. Each of the other volumes provides a more detailed treatise by a specialist on a selected instrumentation subject. Mr W.D.Mace and Mr A.Pool were willing to accept the responsibility of editing the Series, and Prof D.Bosman assisted them in editing the introductory volume. In 1975 Mr K.C.Sanderson succeeded Mr Mace as an editor.

Special thanks and appreciation are extended to Professor T.van Oosterom, NE, who chaired the Group from its inception in 1968 until 1976 and established many of the ground rules under which the Group operated, to the late Mr N.O.Matthews, UK, who chaired the Group during 1977 and 1978 and to Mr F.N.Stoliker, US, who chaired the Group from 1979 until its termination in 1981.

In 1981 the Flight Mechanics Panel decided that the Group should also supervise a new series of monographs in the field of Volumes I and II of the Flight Test Manual. The Group was therefore renamed Flight Test Techniques Group. However, this Group also continues the publication of the volumes in the Flight Test Instrumentation Series. The Group gratefully remembers the way Mr Stoliker chaired the Flight Test Techniques Group during 1981 and 1982 and marked the outlines for future publications.

It is hoped that the Flight Test Instrumentation Series will satisfy the existing need for specialized documentation in the field of flight test instrumentation and as such may promote a better understanding between the flight test engineer and the instrumentation and data processing specialists. Such understanding is essential for the efficient design and execution of flight test programs.

In the preparation of the present volume the members of the Flight Test Techniques Group listed below have taken an active part. AGARD has been most fortunate in finding these competent people willing to contribute their knowledge and time in the preparation of this volume.

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ACKNOWLEDGEMENTS

The genesis of this volume took many years and involved many persons. The first framework was set up by Mr A.Fert of the Centre d'Essais en Vol (CEV), France. A first draft in French for what are now Chapters 3 to 5 was then prepared by Mr P.de Benque d'Agut of CEV, who died in an aircraft accident shortly before his draft was ready. His wife Mme.G.de Benque d'Agut finished this draft in French.

The final English version was prepared by A.Pool of the NLR, Netherlands (editor of the AGARD Flight Test Instrumentation Series) and H.Riebeek of Fokker, Netherlands. Mr Riebeek contributed section 2.2 and advised on other sections.

The authors thank many specialists of Fokker and the NLR for contributions to many sections of this AGARDograph. They also thank the members of the AGARD Flight Test Instrumentation Group (FMP Working Group 01, later 11) for many suggestions for improvement. Mr J Buhrman, retired from the NLR and former member of the AGARD Flight Mechanics Panel, was a great help in the editing of the final text.

CONTENTS

TRAJECTORY MEASUREMENTS FOR TAKE-OFF AND LANDING TESTS AND OTHER SHORT-RANGE APPLICATIONS

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Summary

This AGARDograph presents a review of the methods that are used for short-range trajectory measurements. Chapter 2 briefly reviews the instrumentation requirements of the applications: take-off and landing performance measurement, autoland performance measurement, noise measurement and flight inspection of radio beacons. The remainder of the AGARDograph discusses the methods used for such applications, and is subdivided into optical methods (including lasers), methods using radio or radar and methods using inertial sensing systems.

1 INTRODUCTION

1.1 Scope of this volume

The purpose of this AGARDograph is to review all methods for measuring short-range aircraft trajectories and to present guidelines to flight test engineers on how to choose the method of trajectory measurement that will best suit his requirements. Section 1.2 discusses the major aspects that can affect such a choice.

When this AGARDograph was originally planned it was intended that it should cover only methods of trajectory measurement for take-off and landing performance assessment. During the preparation it became clear that many of the methods used for that one purpose are also applied in other areas of flight testing. It was then decided that trajectory measurements used in three other fields should also be covered. These fields are:

- flight testing of autoland systems
- noise measurement
- flight evaluation of radio navigation aids

Each of the four areas of flight testing mentioned above has its own specific requirements which affect the choice of the method of trajectory measurement to be used. Even within each area, the requirements may differ according to the details of the purpose of the test. To give the reader some insight into the main requirements for each application, Chapter 2 describes in general terms each of the areas of flight testing mentioned above. These sections do not give detailed treatises on all aspects of these flight test methods, but concentrate on those aspects that are directly concerned with the measurement of the trajectory. For each of the four areas of flight testing the discussion is divided into five parts:

- The objectives of the flight tests in which trajectory measurements are required
- The government requirements concerning the flight tests and the application of the results
- The execution of the flight tests
- Specific requirements regarding data processing
- Accuracy requirements for the trajectory measurements.

Section 2.2 on take-off and landing measurements goes into more detail than the other sections, because there is very little literature on that subject. The remaining sections are much shorter, as good references to other literature can be given there.

The later chapters describe the methods of trajectory measurement that are in use today. The methods are divided into three groups:

- Optical methods, including laser methods (Chapter 3)
- Radio and radar methods (Chapter 4)
- Methods using inertial sensing systems (Chapter 5).

Most of the methods are still in use at the present time. Only in Section 3.3.2 and 4.4.4 very brief descriptions are given of methods that are seldom used now, but have a strong historic interest.

In some of the methods described in Chapters 4 and 5 equipment is used that is in general operational use in aviation (ground radars, DME receivers, inertial platforms, etc). In these cases the description of the equipment has been kept very brief, and the treatment is restricted to discussions on accuracy and on special aspects such as data processing. In all methods described in Chapter 3 and in some in Chapter 4 the equipment used for the trajectory measurements is not standard aviation equipment. In those cases the description has, in principle, been set up along the following lines:

1. General principle of the method
2. Brief description of one specific version of the hardware
3. Special procedures for setting up the equipment
4. Data processing
5. Accuracy
6. Review of the different versions of the method that are in use and of the applications for which they are suitable.

If suitable references are available these are given and the treatment is relatively brief. The kinetheodolite method is discussed in some detail in Section 3.2 because it is still regarded by many as the most accurate, adaptable and reliable method and because, curiously enough, there is very little accessible literature on that subject. A few of the aspects discussed there in some detail are also of interest to some of the other methods.

1.2 Choosing a system for a particular application

Where so many different methods are available, the choice of the best method for a particular application must be a rather subtle process. In this section a few of the main aspects that determine that choice are reviewed in order to assist the reader in making an optimal choice. The sequence in which these aspects are given here is, to a certain extent, arbitrary. The aspects which carry the most weight will depend on the circumstances.

The most important aspects that affect a choice of method are:

- Accuracy. As a general rule, cost, complexity, elaborateness of data processing, etc. increase disproportionally with the required accuracy. Careful assessment of the required accuracy is, therefore, required. If high accuracy is not required, methods based on the use of generally available radio beacons may be of interest, with easily available measuring equipment and manual processing of the data. Many of the more complex high-accuracy methods (kinetheodolites, onboard cameras, laser trackers) provide accuracies of about the same order, so that other aspects must determine which method should be used.
- Availability and experience. All methods require much experience and, in some cases, complex computer software to produce optimal results. A less accurate method for which all problems and error sources are well-known through years of experience may well provide more accurate and reliable results than a new method that is in principle more accurate, but is not applied properly in all details.
- Processing time. If processing time is of interest, all methods requiring the reading of pictures (kinetheodolites, on-board cameras) have great disadvantages. The use of computers can, once the software is available and tested, greatly increase the processing speed. If decisions have to be made during the course of the tests, real-time computation will be necessary, unless the decisions can be based on the (limited) observations by special observers.

- On-board or ground measurements. If the flight tests are to be done at locations where suitable ground measuring equipment is not available, or must be executed at many different locations, then the use of measuring equipment that is installed in the aircraft (on-board cameras, inertial systems with updates that can be measured on board the aircraft) may provide the best solution. If the tests are done at an airport, portable objects (the corner reflectors in the method described in Section 5.3.4 and the special radio beacon in that of Section 5.3.2), which produce signals that can be recorded on board the aircraft, can be carried to the location of the tests in the aircraft. On the other hand, the use of ground-based equipment at specially instrumented airports with experienced operators can also have great advantages.
- Cost. Cost effectiveness is in all cases a decisive factor, as the cost of each method must be weighed against the gain achieved. Very costly equipment may be cost effective if the equipment must be used frequently or if the added accuracy is economically advantageous (see the argument at the beginning of Section 2.2.5).

2 APPLICATIONS OF SHORT-RANGE AIRCRAFT TRAJECTORY MEASUREMENTS

2.1 Introduction

In this chapter brief descriptions are given of the applications of aircraft trajectory measurements for the assessment of take-off and landing performance and for the other objectives mentioned in Chapter 1. These descriptions do not give information on all details of the execution of the the tests and of the interpretation of the results, but concentrate on the background information that is necessary for choosing the most suitable method of trajectory measurement for each application.

2.2 Take-off and landing performance measurement

2.2.1 Objectives

The objectives of take-off and landing performance measurements can be divided into several categories:

- Evaluation of the take-off and landing characteristics of new aircraft, usually as a preparation for certification measurements
- Certification, which means the determination of the performance data required for the production of the aircraft flight manual according to the rules laid down in the relevant airworthiness requirements
- Collection of data for further improvement of performance prediction models
- Collection of data for the further development of the aircraft type that is being tested.

Although the requirements for the method of trajectory measurement will be similar for all four categories for a given aircraft type, each category has a few specific requirements. In the evaluation phase quick data turn-around is more important than high accuracy. Real-time analysis is desirable, if necessary with a less accurate quick-look measuring system. In the certification phase, where a large number of take-offs and landings must be executed within a short time, reliability and consistency of the measuring equipment are of primary importance. For these first two categories the emphasis is mainly on distance and height measurements, as these are the basis for the certification. For the development of performance prediction models the aircraft speed, acceleration and attitude are often of great importance. If the information for the latter two objectives must be mainly obtained from the data collected during the certification phase, which is often the case as flight tests are very costly, then the equipment used for certification must also meet the special requirements of these two objectives.

Other important criteria for the selection of the trajectory measuring equipment may be:

- The possibility of executing flight tests on airfields other than the flight test base. This may be specifically required for the measurement of the acceleration and deceleration performance on runways with a non-standard surface such as gravel, sand or grass, runways covered with water or slush, or on runways at high altitude or in arctic or tropic regions.
- The possibility of using the system in aircraft other than the specific "prototype" aircraft. Especially when later developments of an aircraft type must be tested, for example for an increase in all-up weight, the flight tests will often have to be executed in normal production aircraft. If the measuring system can be easily installed in such aircraft, this may appreciably reduce the flight test costs in such cases and that may, in the long run, provide a reduction in the overall flight test costs.

2.2.2 Airworthiness requirements

2.2.2.1 Government regulations

All new civil aircraft types and all civil aircraft derived from an existing type by important modifications have to be certified according to the relevant national airworthiness standards before they can be registered in a country. As an example, the US airworthiness requirements for the take-off and landing performance of aircraft are part of four Federal Aviation Regulations (FARs, Refs. 1-4). In many other countries the FARs have been accepted as national standards, sometimes with small national variants.

In other countries, notably the UK (Ref. 5), the national standards have been derived independently from the FARs and show larger differences. Recently the Airworthiness Authorities Steering Committee, founded by several European countries including the UK, has approved two Joint Airworthiness Requirements (JARs, Ref. 6-7). JAR 25 is based on FAR 25, but "there are a number of areas in which variations and additions have been considered necessary" and in a few cases "national variants" are declared. For the supersonic Concorde aircraft a special standard (Ref. 8) has been agreed by the UK and France.

These civil airworthiness standards define:

- the minima to be observed and the limits to be determined in aircraft performance and handling characteristics, based on accepted safety standards
- the performance data which have to be determined and published in the Flight Manual.

The discussions in the following sections will be mainly based on FAR 25 and JAR 25. These requirements give only general rules. To assist in the interpretation of the formal rules in the FAR, guidelines have been published in Reference 9; similar guidelines for the JAR are given in a final chapter. The details about test methods and the accuracies that must be achieved are, for each certification, agreed between the certifying authority and the manufacturer.

For military aircraft no general standards like FAR and JAR exist. The tasks of military aircraft are so diverse that no general rules can be given. The requirements are specified in each individual design contract for the special missions for which the aircraft must be designed. The general flight test philosophies for military aircraft have been laid down in publications by the military certifying authorities in the different countries, e.g. in References 10 to 12.

2.2.2.2 Requirements concerning take-off and landing distances

To determine the data that must be published in the Flight Handbook, distances must be measured for each take-off and landing configuration (flap/slat position) for the following cases:

- Continuous take-off (CTO). The CTO-distance is the distance covered from standstill to a screen height of 35 feet. The CTO-distances must be determined over the full thrust/weight range with all engines operating, and also with one engine inoperative from a critical engine failure point. Trajectory data must provide the distances, ground speeds and accelerations in horizontal and vertical direction.
- Rejected take-off (RTO). The RTO-distance is the distance covered by the aircraft accelerating from standstill to a specific engine failure speed and then decelerating to standstill. The RTO performance must be measured for a range of engine failure speeds and the effect of the available deceleration aids (lift spoilers, speed brakes, automatic brake-pressure control system) must be determined. Trajectory data are used to determine distances, ground speeds and decelerations in horizontal directions.
- Landing. The landing distance is the distance covered from a height of 50 feet above the runway to standstill. The effect of the braking aids available in the aircraft on the landing distance must be determined. Trajectory data are used to determine the distances, ground speeds and decelerations in horizontal and vertical directions.

Besides these measurements under normal conditions, verification is required that the performance is still sufficient under a few specified "abused conditions":

- It must be shown that an all-engine CTO with an early and fast rotation does not result in a marked increase of the take-off distance over that established for normal conditions. An "early rotation" means an initiation of the rotation 10 kts or 7 % (whichever is less) below the scheduled rotation speed. A "marked increase" means: more than 1 percent of the scheduled distance.
- It must be shown that, if the aircraft is mistrimmed during a normal CTO, there will be no "marked increase" over the scheduled take-off distance.
- It must be shown that, when the rotation is initiated 5 kts below the scheduled rotation speed during a CTO with one engine out, the distance does not exceed the scheduled distance.

2.2.2.3 Requirements concerning speeds

Before starting the trajectory measurements for certification, the manufacturer must define the speed schedule for which the certification is requested. The take-off procedure for a given aircraft weight, centre of gravity position and configuration (flap position, slat position, external stores, etc.) is defined by three (calibrated) airspeeds (see Figure 1):

V_1 - the engine failure recognition speed - if an engine fails before this speed, the take-off must be discontinued

V_R - the rotation speed - at this speed the rotation to lift-off must be initiated, followed by a rotation procedure that results in a lift-off speed (V_{LOF}) from which V_2 will be reached at the required point.

V_2 - the take-off safety speed[4] - this speed must have been reached before the aircraft is at a screen height of 35 feet; during an all-engine take-off, the speed at that point is usually higher than V_2.

For certification it must be shown that the requirements mentioned further on in this section are met if the take-off is based on these speed values.

For landings, FAR 25 requires the definition of only one speed for each landing weight and configuration: the minimum constant approach speed V_{TH} at 50 feet height. The British standard defines a few additional constraints on the speed scheduling. In JAR 25 both methods are given and certification can be obtained on the basis of either method.

The requirements for certification make use of a number of speed values that must be measured separately:

V_S - the free-flight stalling speed

V_{MC} - the free-flight minimum control speed

V_{MCG} - the minimum control speed on the ground

V_{MU} - the minimum unstick speed - the speed at which the aircraft can lift-off and continue flight safely; this speed can be limited by the maximum ground angle ("geometry limitation").

In addition, the time interval between an engine failure and the moment the pilot has recognized and reacted to that failure must be measured. This time difference defines the difference between the engine-failure speed V_{EF} and V_1. FAR 25 also defines two additional speed values and a gradient of climb that play a part in the requirements for certification:

$V_{2_{min}}$ = the minimum take-off safety speed
= $1.2\ V_S$ or $1.1\ V_{MC}$ for two and three engined aircraft
= $1.15\ V_S$ or $1.1\ V_{MC}$ for aircraft with more than three engines

$V_{LOF_{min}}$ = the minimum lift-off speed after a maximum practicable rate of rotation $\dot{\theta}_{max}$.

γ = the gradient of climb with the undercarriage retracted, the aircraft in the take-off configuration and the critical engine inoperative. For 2-engined, 3-engined and 4-engined aircraft this gradient must not be less than 2.4 %, 2.7 % and 3 %, respectively.

The airworthiness requirements state that the speeds mentioned at the beginning of this section must be chosen so that:

scheduled $V_1 \leq V_R$
$\geq V_{EF}$

scheduled $V_2 \geq V_{2_{min}}$

= V_R + the speed increment obtained before reaching 35 feet height (for the CTO with 1 engine out and with a normal rate of rotation)

scheduled $V_R \geq V_1$
$\geq 1.05\ V_{MC}$

scheduled $V_{EF} \geq V_{MCG}$

This must result in:

$V_{LOF_{min}} \geq 1.10\ V_{MU}$ with all engines operating
$\geq 1.08\ V_{MU}$ with all engines operating if V_{MU} is "geometry limited".
$\geq 1.05\ V_{MU}$ with one engine out.

The effect of the limitations is shown in Figure 2 for one special case: take-offs with n-1 engines that are only limited by V_{MU}. The figure shows (linearised) lines for the ratios of several speeds with V_S as a function of the thrust-weight ratio. The main requirement is that V_2 should be equal to or greater than 1.2 V_S; that is shown by the (partly continuous, partly dotted) horizontal line at the top. If there are no V_{MU} limitations, the rotation speed ratio V_R/V_S required to reach V_2 at the height of 35 feet will decrease roughly linearly with the thrust-weight ratio (lower partly continuous, partly dotted straight line in the figure). The figure also shows the line for $V_{LOF_{min}}$ = 1.05 V_{MU}, which in this case is assumed to be the limiting factor. The value of V_{MU} is directly related to the angle of incidence at lift-off and may be determined by:

- stalling of the wing
- a too high drag rise which reduces the acceleration of the aircraft to zero
- a limitation of the ground pitch angle (geometric limitation).

At the point where the vertical line is drawn $V_{LOF_{min}}$ reaches the V_{MU} limitation i.e. V_R + the speed increment required to rotate at the maximum rotation rate becomes equal to 1.05 V_{MU}. For higher thrust-weight ratios a higher value of V_R must be used as shown by the continuous line. This will result in a value of V_2 at the threshold height which is higher than 1.2 V_S, as shown by the continuous line The figure also shows the lines for V_{LOF}, i.e. the lift-off speed with a normal rate of rotation. It is derived from the previously established line of V_R by adding the speed increment during normal rotation.

2.2.2.4 Extrapolation of test results

The main flight test programme will normally be executed on one test airfield and under favourable atmospheric conditions. This means that the flight test results represent a limited sample from the operational envelope to be published in the aircraft flight handbook. As a normal practice, the following flight envelope must be covered in a flight handbook:

Aircraft weight: operational empty weight to structural weight or permissible weight limited by minimum climb requirements.

Runway slope: 2 % downhill to 2 % uphill. Operational experience has shown that this slope range covers most operational conditions.

Airport altitude: sea level to up to 8000 feet. The tests must be performed at an airfield altitude between sea level and 2000 ft. Extrapolation to other altitudes is subject to the following rules:

- If proven test and data processing methods are used, for which extrapolation has previously been verified by high-altitude tests, then extrapolation is allowed from 3000 feet below to 6000 feet above the test altitude.
- If unproven test and/or data processing methods are used, extrapolation is allowed from 2000 feet below to 2000 feet above the test altitude.
- Extrapolation outside these ranges is possible if a specified conservatism is included in the extrapolation calculations or if the extrapolation is verified by additional high-altitude flight tests.

Air temperature: - 50 °C to ISA + 35 °C (ISA = International Standard Atmosphere). These limits are mainly justified by thrust specification limits for the engines. If such thrust data are not available, additional verification tests under extreme conditions are normally required.

Wind speed: 10 kts tailwind to 40 kts headwind. Experience has shown that the wind range is sufficient to cope with the operational conditions encountered. When certification for stronger tail winds is wanted, additional flight testing under these wind conditions is required.

Extrapolation of the test data to this full flight envelope must be based on analytical models which adequately describe the relevant aircraft performance and which use the actually measured data. The validity of these models must be carefully verified and must be accepted by the certifying authority. The validity of the results will depend on:

- the accuracy with which the analytical model describes the flight manoeuvre
- the statistical relevance of the test data
- the accuracy of the measured trajectory data.

Prior to the introduction of a new instrumentation system or a new analysis model for the determination of aircraft performance, a validation will usually be required. For a new method of trajectory measurement this if often done by measuring a number of flights by both the old and the new methods, and comparing the results.

2.2.3 The important phases in the flight test programme

2.2.3.1 Evaluation testing

The main aspects of take-off and landing performance flight testing in the development and evaluation phase, in which trajectory measurements play an important role, are:

- determination of the reference speeds (V_S, V_{MU}, V_{MC}, etc.) as a function of flap/slat position
- determination of the aircraft handling procedure which can be effectively reproduced under operational conditions with optimum performance in terms of distance
- determination of the certification speed schedules
- determination of the aircraft configurations to be certified.

The evaluation test programme is first set up as an outline programme and the programme details will be filled in as the evaluation progresses. The test results will, to a high degree, determine the course of action. This means that the flight test data must be available for interpretation as soon as possible. Real-time analysis is the ideal in this phase. If off-line data processing must be used, the data processing time is extremely important. Although the number of tests is less than for the certification phase, the choice of a system with a short data processing time may, in many cases, be economically justified.

The take-off distance is, for a given installed thrust-to-weight ratio, mainly determined by the rotation-to-lift-off phase and the climb-out to 35 ft height. The distance covered in these flight phases depends on the take-off handling procedure used by the pilot. Except for cases dictated by special operational requirements (when higher than normal risks are acceptable), the take-off procedure selected should be such that it can be applied easily and consistently by pilots. Careful optimization of this procedure during the evaluation flight test phase can provide considerable economic benefit to the manufacturer. As small variations in rotation speed, rate of rotation and flight attitude can have a significant effect on the distance achieved, optimization can produce better Flight Handbook performance.

When the final speed schedule for the take-off has been established, the relationship between take-off distance and take-off weight can be determined. In figure 3 the dashed line shows the optimal relationship. A procedure based on this line would, however, require an infinite number of flap settings. In practice, certainly for small aircraft, a limited number of flap settings will be used. The number of flap settings and their distribution over the available flap-angle range must be chosen for a minimum take-off penalty for the runway lengths most likely to be used. From the performance point of view a larger number of flap settings will provide the best results. There are, however, practical limitations. For each flap setting a number of take-off test runs must be performed and analysed to provide the data for certification and for the Flight Handbook. An increase in flap selection possibilities will, therefore, increase the certification period and the costs.
Figure 3 shows the effect of a limited number of flap settings on the required runway lengths versus weight. Since in most cases the best climb speed will be higher than the minimum speed for shortest take-off distance ($V_2 > V_{2min}$) a higher weight can be carried at the expense of required take-off distance. This will, partly, overcome the loss in take-off weights for a given runway length due to the limited number of chosen flap settings.

The final result of the evaluation tests is a complete take-off speed schedule for each intended flap setting. The results must be available before the certification test programme can be designed and executed. The time required for producing the evaluation test data and the associated analysis time have a large influence on the progress of the test programme and the achievable certification and delivery dates.

2.2.3.2 Certification

The evaluation period can be characterized as the development phase in which the configuration and basic handling characteristics are determined. The certification period can then be characterized as a production phase, production of a large number of test runs and analysis results.

The certification test programme, test execution, data sampling and analysis methods have to be designed to systematically produce the required data for the Flight Handbook calculations. The test programme has to provide the necessary flight tests for demonstrating that the aircraft meets the minimum performance standards as laid down in the applicable airworthiness requirements.

The number of flight tests may be quite large. As an example, for certification of a small commercial aircraft type 80 flight hours were used for take-off and landing tests. The take-off performance was determined for 3 flap configurations, the landing performance for 2 flap configurations. In the table below a break-down of a basic test programme is given in numbers of test runs performed. For more complex aircraft the number of test runs may be higher.

Flight tests:	Runs	Total
Continuous take-off (CTO) tests		
all engines operating	50	
one engine made inoperative	60	110
Abused CTO demonstration tests	27	
Take-off speed schedule determination	28	
Minimum unstick speed determination	35	90
Rejected take-off performance	95	
Ground friction and aircraft drag on the ground	15	110
Landing performance determination		70
		380

The regulations require that the data on the one-engine-out take-off in the Flight Handbook be based on a complete loss of power. This can only be simulated by interrupting the fuel flow to the engine. Such a procedure might be acceptable for a small number of test runs, but the required number of one-engine-out runs is such that the risk of damage due to thermal shock to the calibrated test engines (and consequently an engine change during the execution of the programme) is too high. To avoid engine damage, engine failure is usually simulated by closing down the throttles to idle. The run-down time of a jet engine is, however, very long. If the engine is throttled back to idle at V_1, the residual thrust during the rotation and air distance phases will influence the test results. In order to reduce this effect, a procedure is used in which the engine is closed down to idle somewhat earlier during the acceleration phase prior to rotation to lift-off.

In planning these tests, consideration must be given to the possibility of genuine loss of thrust from one of the remaining engines. The pilot must be briefed fully on the procedure that must be followed in that event. If possible, the tests should be done on a very long runway, on which the aircraft could still land if a second engine failed during the critical phase after V_1 has been passed. If this is not possible, the tests should be made with the test engine throttled to a condition such that it can be opened up rapidly in an emergency. The correction for the remaining thrust will then be more difficult.

The test programme will preferably be executed as one consecutive series. Constraints will be

- availability of a suitable airport with a low traffic density
- prolonged favourable weather conditions, i.e.:
  - . No precipitation
  - . Low wind speed. Flight tests will, normally, not be allowed if the total wind speed is greater than 8 kts, if there is a headwind greater than 7 kts or if there is a crosswind greater than 5 kts. Tail winds will generally be avoided during the flight tests

. No convection turbulence. Tests executed under conditions of high convection turbulence or when there are excessive temperature gradients close to the ground may provide trajectories that are not representative of normal aircraft performance. No testing should be done while such conditions prevail.

In general, a complete take-off and landing certification programme, as described above, can be executed within 4 weeks.

2.2.3.3 Analysis for the further development of the aircraft and for a better understanding of the basic phenomena

In the evaluation and certification tests discussed in the previous sections the main emphasis is on obtaining the certification of a particular aircraft type within a limited time. The development of both the speed schedule and the analysis model is primarily based on the basic phenomena, supplemented by the results of the flight tests for the particular aircraft. In the analysis model empirical elements are used because the effects of, for instance, ground effect on the aerodynamic forces and friction are imperfectly understood.

Due to the high pressure of work during a period of prototype testing there is little opportunity for a basic analysis of the data. The analysis will generally be concentrated on those aspects which, on the basis of previous experience, were known to be critical. The flight test results contain, however, a wealth of information which may, after further analysis, be used for more precise generalizations of the aircraft performance as a function of the basic aerodynamic parameters and for verifying the assumptions used in the previous analysis. For instance, such further analysis may provide important information for

- improvements in performance prediction methods
- studies on possible areas of improvement in the design of future versions of the aircraft tested, and for the future design of new aircraft
- a better insight in the application of wind-tunnel data to full-size aircraft
- the design of flight simulators.

The requirements for such further analysis should be taken into account when planning the flight testing of prototype aircraft. Special attention should be paid to the following aspects:

- The specification of the accuracy of the measuring system. For the trajectory measurements, for instance, a high accuracy in the acceleration measurements is more important for this analysis than for the actual certification.
- The storage of the flight test data after certification. Good accessibility and a good indexing system can considerably facilitate this future analysis.

2.2.4 Analysis of test results

This section presents a brief discussion of the analysis of take-off and landing performance measurements. It only gives a broad outline of the methods used and presents the main equations, in order to provide a basis for the discussion on the choice of the measurement systems in the next section.

The certification and the flight manual information must cover a continuous range of such variables as wind velocity, barometric pressure, temperature and runway slope. It is impossible to execute flight tests for all combinations of values of these parameters. To cover all these combinations, a mathematical model which can be verified and updated from the flight test results is essential.

The verification of the mathematical models for take-off and landing is rather complex when compared to models used in free-flight performance calculation. This is caused by the closed-loop nature of the take-off and landing manoeuvres: the variability introduced by the pilot has a larger effect on the reproducibility of the final results. Also, there are several parameters which are difficult to measure directly and for which no accurate determination from other sources is available, for example lift and drag in ground effect and rolling and braking friction. As these parameters are only important during the ground run, the model is usually broken down into two parts: the ground run phase and the air phase, which are separated by the point of lift-off for take-off and the point of touchdown for landing.

The equation of motion for the take-off ground run phase is:

$$\frac{a}{g} = \frac{F_N}{W} + \gamma_r - \lambda \qquad (2.2.1)$$

Where a = the acceleration of the aircraft
g = the acceleration of gravity
F_N = the net engine thrust
W = the aircraft total weight
γ_r = the runway slope angle (radians, positive downhill)
λ = an acceleration loss term, which can be written as

$$\lambda = \mu + (C_D - \mu C_L)\frac{q_c S}{W} \qquad (2.2.2)$$

where μ = the coefficient of rolling friction
C_D = the drag coefficient with ground effect
C_L = the lift coefficient with ground effect
q_c = impact pressure
S = wing area

In order to be able to use the model equation (2.2.1), the corresponding value of λ must be obtained as an average from the flight test results. The method by which this is done will depend on the effort that is expended on the analysis, and on the accuracy of the measured parameters. The simplest approach would be to use a single value of λ which is representative for the whole ground run. A next step is to assume that λ depends only on airspeed and to determine it as a function of that airspeed. This requires a good quality of the acceleration measurement during the ground runs. With more effort, separate values for C_D and C_L in ground effect and of μ can be derived to obtain a more accurate model.

During the air phase between lift-off and the point where the aircraft reaches 35 feet altitude, a number of conditions will change, for instance:

- the influence of ground effect on lift and drag
- the influence of undercarriage retraction
- the normal force applied by the pilot during the transition to climbout
- the variation of the wind velocity as a function of time and height.

A useful method of incorporating the test results in the model for the air phase is to calculate the effective lift-drag ratio:

$$\left(\frac{D}{L}\right)_e = \frac{F_N}{W} - \left(\frac{\bar{V}.\Delta V}{g} + h\right)\frac{1}{X_A} \qquad (2.2.3)$$

Where F_N = the net engine thrust
W = the aircraft total weight
$\bar{V}$ = the average ground speed during the air phase
ΔV = the difference between the ground speed at 35 feet and V_{LOF}
h = the height gained
X_A = the distance covered during the air phase.

As the speed increment is usually small (3 to 4 kts for take-offs with n - 1 engines) this method puts high requirements on the accuracy with which the ground speed is measured.

The pilot uses the airspeed indicator connected to the pitot-static system, and sees the ASIR (airspeed indicator reading)[1]. The analysis described above is based on experimental data mainly derived

[1] The term IAS (indicated airspeed) is, in the AGARD Multilingual Aeronautical Dictionary, reserved for the reading, corrected for instrument error.

from trajectory measurements, which are related to the ground speed V_g. The relationship between ASIR and V_g at low altitude is

$$ASIR = (V_g + V_W) \frac{pT_o}{p_oT} - \Delta V_{PEC} - \Delta V_i \qquad (2.2.4)$$

Where V_W = head wind component

$\frac{pT_o}{p_oT}$ = the relative air density

ΔV_{PEC} = the position error correction of the pitot-static system

ΔV_i = the instrument error correction of the airspeed indicator

The wind correction which is used in (2.2.4) and in those parts of the analysis where data are transformed to other meteorological conditions, is generally based on the wind speed measured at one point near the runway used, and at one height (usually about the height of the aircraft drag centre). In the calculations the wind speed along the runway is assumed to be constant and to vary only with height. According to the present certification recommendations and practice, the wind at a height h above the runway is calculated using the standard equation for the velocity profile in an undisturbed boundary layer:

$$V_W = V_{Wo} \cdot \left(\frac{h}{h_o}\right)^{1/7} \qquad (2.2.5)$$

where V_{Wo} is the measured wind speed at the height h_o where the measurement was made, and V_W is the associated wind speed at height h.

2.2.5 The choice of a trajectory measuring system

The choice of an instrumentation system for take-off and landing measurements (of which the trajectory measurements form an important part) is, in the last resort, an economic choice. If the results of the analysis are relatively inaccurate, the certifying authority will require that they will be applied with a certain conservatism, which means an economic penalty during the operation of the aircraft, making it less competitive on the market. Improved instrument accuracy and more detailed analysis will, on the other hand, be costly. For each new aircraft, therefore, the manufacturer has to decide on a compromise which will be heavily influenced by the hardware and software which are available. The accuracy that can be obtained is not only limited by that of the trajectory measuring system, but also by the accuracy of certain other aspects. In this section these aspects will be briefly reviewed, before a few examples are given of how a trajectory measuring system was chosen in particular cases.

The equations and considerations given in the previous paragraph indicate, that a number of aspects besides trajectory accuracy can influence the accuracy of the results. The more important of these are:

- The accuracy with which the net engine thrust is available. For jet engines intended for civil transport aircraft, the engine thrust as determined from tests in static and high-altitude test beds has been shown to be accurate to 2 to 4 % (Ref. 13 and 14).
- Adherence to take-off and landing procedures, e.g. rotation technique, aircraft climb-out attitude and speed schedule. Monitoring of the adherence to the speed schedule is most important. Certifying authorities usually accept variations of ± 2 kts in $V_{2_{min}}$, but these can already cause appreciable scatter in the trajectory parameters.
- The stability of the atmospheric conditions during each test. Wind speed and direction are very important in this respect. They may vary with time and distance along the runway, and the variation with height may differ from the model given by eq. (2.2.5). Some effects that can cause such variations are:
  - early-morning ground inversions
  - vertical wind speed gradients
  - influence of surroundings on wind conditions along the runway
  - temperature gradients over the runway
  - heat-induced turbulence.

To illustrate the effect of the runway surroundings, landing tests can be cited which were performed on a single runway situated in a wooded area with 10 m high trees. The wind was measured at a height of 3 metres. Comparison with previously obtained results showed that the air distances from 50 feet altitude were on the average 9 % longer and that the touchdown speed showed an average difference of 3 kts. The explanation was that the wind above the trees differed considerably from that measured at 3 metres.

In view of these inaccuracies in the other parameters it might seem that the accuracy requirements for the trajectory measurements would not be extreme. This is, to a certain extent, true for the measurement of the distance along the runway, where errors of a few metres can be tolerated. But not for the height measurement: because of the low rate of climb, an error in the measurement of the 35 feet end point of the air phase may appreciably affect the length of that air phase. For the minimum climb gradient of 2.4 % required for twin-engined aircraft, an error of 0.1 m (1/3 of a foot) in measuring the 35 feet will produce an error of about 4 metres in the air distance. For the analysis model the accuracies of the speed and the acceleration are also important. In order to exploit the full possibilities of eq.(2.2.3), the ΔV of 3 to 4 kts should be known to about the 2 to 4 % accuracy with which F_N is known. Similarly, the acceleration a in eq. (2.2.1), which may be as low as 0.1 g, should be known to 2 to 4 %. In practice the inputs to the model are averages over a number of flight tests. This somewhat reduces the accuracy requirements for random-type errors, but not those for systematic errors. It must, therefore, be concluded (as has been mentioned at the beginning of this section) that the accuracy of the trajectory measurements should be as high as possible within the flight test budget. When choosing a system, the speed and acceleration accuracies should be taken into account, as well as the distance and height accuracies.

To illustrate the relationship between claimed tracking accuracy and the scatter in final aircraft performance test results, a few results are given from a certification test programme with a civil transport aircraft. During that programme the tracking system used a camera mounted in the nose of the aircraft, using the runway lights as a reference. The following 2σ accuracies were claimed for this system:

distance	0.6 m
first derivative (speed)	1.0 m/s (average value over 1 second)
height	0.12 m
pitch	0.001 rad.

The measurements were first processed in the normal way to obtain flight handbook data, using test engine thrust performance and the average trajectories as determined from a large number of runs. Later, for analysis purposes, these flight handbook data were applied to the actual meteorological circumstances of each individual measurement run, and the ratios between the actually measured distances X_m and the calculated distances X_c were determined. It was found that the average values of X_m and X_c were the same, which was to be expected if no errors were made in the analysis. The standard deviations of $X_m - X_c$ were, however, 24 metres for the ground distance (average ground distance was 1220 m) and 18 metres for the air distance (average air distance to 35 feet height was 305 m). These differences must be due either to the fact that the pilots could not exactly follow the speed schedule, or to the fact that the data reduction model was not completely realistic. No further analysis was done, but these values give an indication of what variability can occur even in flight tests flown by experienced test pilots.

From these actual test results it was concluded that the analysis model and the analysis methods reasonably well represented the average flight performance (because the average values were equal) but that the test scatter was relatively large. This was partly due to the environmental effects discussed above, but also to the low accuracy with which the speeds and accelerations can be derived from the measured trajectory data. Smoothing improved the speed data to a certain extent, but the second derivative of such smoothed data is not very accurate. It was therefore concluded that this nose-camera method, though the distance data are reasonably accurate, did not provide sufficient accuracy in the first and second derivatives of these distance data. As described in Chapter 3 some improvement can be obtained by combining the nose-camera measurements with measurements of accelerometers in the aircraft.

The choice of a trajectory measuring system is not only determined by accuracy aspects. Other aspects that must be taken into account are:

- Data turn-around time requirements. If a short turn-around time is required, computer processing is essential. Photographic trajectory measuring systems, which require film development and measurements on individual pictures, have definite disadvantages. In that case systems with digital or analog electrical outputs that can be digitized to sufficient accuracy are preferable.

- Quick-look of tracking data. If real-time trajectory information is required for deciding what to do in the next test run, computerized systems working in real time, such as laser trackers, have important advantages.
- Measuring equipment on board or on the ground. If the tests can all be done on well-equipped airports, the latter is generally preferable. If a large part of the tests must be done on not very well equipped airfields, equipment on board the aircraft (e.g. nose-cameras, ISS system) may be preferable.
- If on-board measuring equipment must be used in many aircraft, is should be easily transferable from one aircraft to the other.

In reference 15 a manufacturer of general aviation aircraft has given his reasons for replacing the measurements with a single photo theodolite by a short-range DME-type system combined with a radio altimeter system. The conclusions are that this system is relatively inexpensive, easy to use, and has a sufficient accuracy. In comparison with the system previously used it permits data reduction by computer, which shortens the turn-around time and reduces the man-hours required.

In reference 16 a manufacturer of military and large civil jet aircraft has given a comparison of several trajectory measuring systems in the light of his requirements. In figures 4 and 5, which are copied from reference 16, summaries are given of their tracking requirements and of the main characteristics of a number of tracking systems, both in terms of performance and cost. The final choice was an automatic laser tracking system.

In reference 17, the accuracy requirements specified by a manufacturer of medium-sized commercial jet aircraft for an on-board system using an inertial sensing system (ISS) are given. In this choice the inherent accuracy of the acceleration and speed data of the ISS method also carried a certain weight.

2.3 Flight testing of automatic landing systems

2.3.1 Objective

The objective of the flight testing for the certification of autoland systems is to show that the performance calculations, made by computer simulation, provide realistic results.

2.3.2 Airworthiness requirements

FAR 25 and JAR 25 do not give detailed requirements for the testing of autoland systems. The basic requirements in these documents are those of para 1309, "Equipment, Systems and Installations". More detailed requirements have been published by the USA (Ref. 18 and 19) and the UK (Ref. 20 and 21) which are similar in principle but differ in many details. The following brief discussion will be primarily based on the US requirements. These can be summarized as follows:

1. Requirements on the standard deviations of the longitudinal and the lateral positions of the touchdown point relative to the runway threshold and the centre line.
2. A requirement that it shall be improbable (10^{-6}) that the aircraft under realistic environmental conditions will land outside a dispersion area limited longitudinally by a line at least 200 feet beyond the threshold and a line at which the pilot is in a position to see at least 4 bars (on 100 feet centers) of the 3000 foot touchdown zone lights, and laterally by lines that are 5 feet from the lateral limits of a 150 foot wide runway.
3. Requirements about the probability of a failure in the system and about the warnings to the pilot for the detection of such failures.

2.3.3 Flight test procedures

The requirements mentioned in the previous section must be verified by flight tests. It must be shown that they are met under practical meteorological conditions, including effects of head, cross and tail wind, wind shear, etc. As it will be difficult to execute flight tests in which all of these conditions

are present in the correct proportion, and as a flight test verification of the low probability specified under . would require a very large number of landings, the main emphasis in this verification is laid on a computer simulation. The flight tests are used to show that the simulation results are realistic. In the interpretation of these flight test results a simplifying assumption can be used without additional proof: the assumption that the distribution of lateral deviations of the touchdown points is Gaussian.
The FAA requirements do not specify the number of flight tests required. The number of tests and the test programme are, for each aircraft type, negotiated with the FAA. The UK CAA requirements specify that at least 100 landings must be measured.

2.3.4 Measuring accuracy requirements

The accuracy requirements are similar to those mentioned in section 2.2 for take-off and landing performance measurements with one important exception: for the performance measurements the measurement of the lateral deviation is relatively unimportant (in the requirements of Ref. 2 and 7 it is hardly mentioned), but for automatic landing system flight testing they are very important. An accuracy of 0.30 metres (2σ) is specified for the lateral displacement with respect to the runway centre line at touchdown.

2.4 Noise measurements

2.4.1 Objectives

The term "noise measurements" is used for two categories of measurements, which have different applications and accuracy requirements. These are:

- Measurements for the noise certification of aircraft, i.e. measurements of the noise produced by a particular type of aircraft
- Measurements of noise exposure on the ground in the vicinity of airports.

These two categories are discussed separately in Sections 2.4.2 and 2.4.3.

2.4.2 Noise certification of aircraft

2.4.2.1 Government regulations

International rules limiting aircraft and aircraft engine noise have been published by ICAO (Ref. 22). Where States have their own regulations, such as the USA (Ref. 23), these differ only by details.

For noise certification take-offs and landings must be made, during which sound measurements are made directly below the aircraft trajectory and at a point 450 metres to the side of that trajectory. The point below the aircraft trajectory must be located 6500 metres beyond the point of standstill for take-offs and 2000 metres before the runway threshold for landings. The sideline point must be located at the point along this sideline where the sound level is highest. The trajectory measurements must be made from the start of the take-off to well beyond the point at which the highest sound levels are measured and, for landings, from a point well before the highest sound level is recorded to standstill. Both positions and speeds must be provided at time intervals of at least 0.5 seconds. The final certification procedure is based on a nominal trajectory, and the sound measurements must be corrected for, among other variables, the deviations of the actual trajectory from that nominal trajectory and the deviations of the actual speeds from their nominal values.

2.4.2.2 Requirements for the trajectory measurements

References 22 and 23 do not specify accuracy requirements for the trajectory measurements. These must be agreed by the certifying authority during negotiations about the method of measurement proposed by the manufacturer. In practice the accuracy will have to be within a few metres in the distance along the runway centre line and a few feet in height.

For practical reasons the trajectory measuring equipment should be able to operate continuously for several hours, without breaks for resetting or recalibration. The equipment will not only be used for the actual noise certification, but often also during noise demonstration flights at various noise-sensitive airports. For these applications the ground equipment should be easily transportable and any on-board equipment should be easy to install in production aircraft.

2.4.3 Noise exposure on the ground

2.4.3.1 Government regulations

The evaluation of noise exposure on the ground is of rapidly increasing interest in matters of regional planning and noise annoyance. The method of evaluation is roughly similar everywhere: a model provides contours of areas where the noise rating is above a certain value. The details of the models and the definition of the noise rating differ, however, from State to State, as do the applications. A review of the noise ratings used in the different States is given in Ref. 24. Ref. 25 gives a brief description of the model used in the UK.

The inputs for the models are generally obtained from different sources:

a. The standard take-off and approach paths (SIDs and STARs) for the airports concerned.

b. The amount of traffic along each SID and STAR, differentiated according to time and to aircraft type. These must be obtained from actual traffic statistics.

c. Normal power settings used by the aircraft during the phases of interest; these are obtained from airline procedures.

d. Data on the noise produced by aircraft as a function of power setting; these data must be obtained from the aircraft manufacturers, but the FAA has a programme to assemble these (Ref. 26) and has published several surveys (e.g. Ref. 27).

e. Data on the spread of the aircraft trajectories about the SIDs and STARs.

Trajectory measurements are required only for d. and e. above. For measuring the noise data mentioned under d. the manufacturers will in general use the equipment with which they do the noise certification of their aircraft. The requirements for the measurements mentioned under e. are briefly discussed below.

Some States also want to detect aircraft that follow trajectories outside the permitted corridors. The requirements for those measurements are also mentioned in Section 2.4.3.2.

2.4.3.2 Requirements for the trajectory measurements

The main requirements for the trajectory measurements mentioned above are:

- the measurements must not require special equipment in the aircraft or co-operation from the pilots or ATC
- the horizontal projection of the trajectory and the height must be measured
- the individual aircraft must be identified or at least the aircraft type must be known
- automatic data processing is desirable for the measurement of the spread of trajectories and absolutely necessary for detection of offenders.

For major airports, where all aircraft are equipped with SSR transponders, surveillance radars with mode C are generally used. No accuracy figures have been quoted, but SSR with mode C is generally accepted for these purposes. For measurements which include aircraft without transponders no solution is readily available; all solutions reviewed until now require extensive human participation.

2.5 Flight testing of radio navigation aids

2.5.1 Objectives

Trajectory measurements and measurements of geographic positions also play an important role in the calibration of the radio navigation aids which are essential for the navigation of civil and military aircraft. The most important of these are: ILS (categories I, II and III), VOR, DME, TACAN and surveillance radars (primary and secondary) and, in the near future, MLS.

In general it can be said that the objectives are twofold:

- Calibrations of the beacons within the range where they are normally used. The requirements for these tests are briefly discussed below.
- Measurements of the limits where the beacon is still received. For these tests the accuracy requirements are very low and the measured values are often read from operational navigation equipment.

2.5.2 Government requirements

The system specifications for all the above-mentioned radio navigation systems (except TACAN) have been laid down by ICAO in reference 28. Test procedures have been published in reference 29. Although the procedures actually used differ from country to country, mainly because of differences in available test equipment, they are in general similar to those described in reference 29.

For DME and radars there are no requirements for periodic flight checking, though flight tests have been done for research purposes. Flight measurements of ILS, VOR and the directional part of TACAN have to be done periodically, at intervals varying from 4 months to 4 years depending on the type and quality of the navigation aid.

In the calibration and periodic checking of ILS, accurate trajectory measurements of the test aircraft are required for the determination of the position and quality of the course line defined by glide path and localiser, and for determining the sensitivity, i.e. the rate of change of the signal with the distance perpendicular to the course line. The limits on the course line are differentiated between course alignment (i.e. the position of the average course line) and course structure (i.e. the bends about the average course line). The limits are different in the horizontal and vertical directions, and for the different categories. They become narrower as the threshold is approached.

For the calibration and periodic checks of VORs, accurate flight measurements must be made of the course errors of the radials. Although the details of the procedures differ between States, the flight measurements on course alignment are usually executed during two types of orbit:

- orbits around the VOR (which are often circular but can also have other shapes) which give a 360 degree overall check on the alignment of the radials
- flights along specific radials (in the first place those used for IFR traffic) in order to make a detailed analysis of the course structure.

2.5.3 Required measuring accuracy

The trajectory measuring equipment used for ILS and VOR calibrations is usually chosen so, that its accuracy is equal to or better than 1/6 of the maximum allowable misalignment of the beacon. The allowed misalignments are angular values, and for ILS they differ with the category of the ILS. In some cases the course errors are measured as angular errors (see e.g. Section 3.5.1 below and Ref. 29, Part 2, Section 7.3). But in most cases the trajectory measurements are executed as position measurements, i.e. the required accuracy requirement varies with the distance from the beacon. In order to give some insight in the required position accuracies, a few examples will be calculated here. For VOR the allowable error in the alignment of the radial is ± 3 degrees. At 1/6 of this value, the trajectory measurement must be accurate to about 45 m at 5 km and to about 1700 m at 200 km from the beacon.

In the following tables the required lateral deviation and height accuracies are calculated for 3 important points along an ILS beam, for each of the 3 categories of ILS. The Cat. II values in parenthesis are recommended values.

Acceptable RMS errors for measurement of localizer (metres)

Distance before threshold (m)	Cat. I	Cat. II	Cat. III
0	-	2.8 (1.9)	1.5
1050	7	3.7 (2,5)	2.0
7500	27	25	24

Acceptable RMS errors for measurement of glide path (metres)

Distance before threshold (m)	Cat. I	Cat. II	Cat. III
0	no	0.5	0.5
1050		1.9	1.2
7500	requirement	12	8

3 OPTICAL METHODS OF TRAJECTORY MEASUREMENTS

3.1 Introduction

Since the earliest beginnings of aircraft trajectory measurement, photographic methods have been used whenever high accuracy was required. Until very recently no other methods could rival those methods. During the 1930s, when good cameras became available, the kinethodolite (Section 3.2) was developed to an accuracy and reliability that is still unchallenged, and it is still used all over the world. The kinetheodolite method presents, however, a number of problems:

- They require a relatively large ground crew of specialists.
- The ground equipment is sensitive and heavy, which is a problem when trajectory measurements must be made at inaccessible locations.
- Data processing begins with film development and then many pictures must be individually processed; this requires, even with modern kinetheodolites and advanced reading equipment, much manual labour.

The search for more efficient methods of trajectory measurement has gone in many directions. Other methods based on the use of ground cameras (Section 3.3) have reduced the ground crew requirements and, to some extent, the problems of data processing and of measurements on non-instrumented airfields. But they have never attained the accuracy of the kinetheodolite methods. An important development was the airborne camera (Section 3.4), which is very useful for measurements at inaccessible locations. But that method also requires lenghty data processing with much manual labour.

The new developments in the video, infra-red and laser techniques and in advanced software (e.g. image processing) have recently provided optical methods which can be regarded as replacements for the kinetheodolites (Section 3.5). There is still much development going on in this field (Section 3.5.1), but for the present the laser tracker (Section 3.5.2) seems to have the best prospects. These methods can fully replace the kinetheodolite methods in all respects, and provide the quick-look facilities and the short data processing delays which cannot be realized by the methods using photographic cameras. In general, however, these methods require expensive equipment and large computer facilities for data processing. Kinetheodolites remain in use for tests where obtaining quick results is not of the utmost importance and they play an important role in the validation of all new methods.

3.2 Kinetheodolites

3.2.1 General principles

A kinetheodolite is in principle a telescope which can be easily rotated both in azimuth and elevation to track the aircraft. In most kinetheodolites the telescope is manually directed towards the aircraft. Attached to the telescope, with its optical axis aligned parallel to that of the search telescope, is another telescope with longer focal length, through which a camera takes pictures of the aircraft. The azimuth and elevation are measured and recorded with an accurately known frequency in the range of 1 to 4 per second, in a few systems up to 30 frames per second. These azimuth and elevation values provide the first-order direction in which the aircraft was seen. A correction on this direction is obtained by measuring the position of the aircraft with respect to cross hairs on the camera pictures, which are made at exactly the same time as the azimuth and elevation recordings.

If a single kinetheodolite is used for measuring a trajectory, this is usually placed to the side of the trajectory to be measured (Figure 6). It is then assumed that the aircraft remains in the vertical plane through the runway centreline. The position of the aircraft can then be calculated from the distance D between the kinetheodolite and the runway centreline and the azimuth and elevation under which the kinetheodolite sees the aircraft. Using the co-ordinates defined in Figure 6, the position co-ordinates are:

$$X = D \tan A$$

$$Y = 0 \qquad (3.2.1)$$

$$Z = D \frac{\tan E}{\cos A} + h$$

where h = the height of the kinetheodolite above the runway level. If the aircraft deviates from the vertical plane through the centre line, the errors in X and Z are small when the aircraft is near the point C_o, but increase rapidly for a given lateral deviations when the aircraft gets further away from C_o.

For some special applications a single kinetheodolite is used which looks in the direction of flight. Then additional information on the height of the aircraft must be obtained from a pressure altimeter or a radio altimeter in the aircraft. The lateral and longitudinal positions of the aircraft can then be calculated from the measured azimuth and elevation angles and the height of the aircraft. This method has the disadvantage that the ground and on-board measurements must be synchronized. It has been used, for example, for the calibration of the radio-defined axes of an approach system for helicopters. It will generally be too inaccurate for sophisticated take-off and landing measurements.

A much higher accuracy can be obtained if two kinetheodolites are used, which aim at the same point and take pictures at the same instant. The equations for the calculation of the co-ordinates will be given for the case of Figure 7, where the kinetheodolites are placed at a distance 2B from each other on the Y-axis of the co-ordinate system and the origin is in the middle between the two kinetheodolites. Then the following equations can be given

$$X = (D-Y) \tan (180°-A_1) = (D+Y) \tan A_2$$

$$Z = \frac{X}{\sin (180°-A_1)} \tan E_1 = \frac{X}{\sin A_2} \tan E_2 \qquad (3.2.2)$$

solution of X, Y and Z gives

$$X = 2D \frac{\sin A_1 \sin A_2}{\sin (A_1-A_2)}$$

$$Y = D \frac{\sin (A_1+A_2)}{\sin (A_1-A_2)} \qquad (3.2.3)$$

$$Z = 2D \frac{\sin A_1 \tan E_2}{\sin (A_1-A_2)} = 2D \frac{\sin A_2 \tan E_1}{\sin (A_1-A_2)}$$

In these equations it is assumed that the lines defined by A_1 and E_1 and by A_2 and E_2 do intersect in space. Due to measuring errors this will in general not be the case. As there are 4 angles available to calculate 3 co-ordinates, statistical methods can be used to improve the (average) accuracy. A very simple method is to use X and Y as given in eq. (3.2.3), (they depend only on A_1 and A_2) and to replace Z by the average of the two values given

$$Z = D \frac{\sin A_1 \tan E_2 + \sin A_2 \tan E_1}{\sin (A_1-A_2)} \qquad (3.2.4)$$

A more accurate method first calculates the perpendicular between the lines defined by the pictures from the two kinetheodolites, and then determines the position of the aircraft as the most probable point on that perpendicular (Figure 8). To derive the co-ordinates of this point, let the co-ordinate of the two kinetheodolites be P_1 (X_1, Y_1, Z_1) and P_2 (X_2, Y_2, Z_2) and let the directions defined by the two kinetheodolites be expressed by their direction cosines: U_1 (Q_1, R_1, S_1) and U_2 (Q_2, R_2, S_2). Then it can be shown that

$$D_1 = M_1P_1 = \frac{P_1P_2 \cdot U_1 - (P_1P_2 \cdot U_2)(U_2 \cdot U_1)}{(U_1 \cdot U_2)^2 - 1} \qquad (3.2.5)$$

$$D_2 = M_2P_2 = \frac{(P_1P_2 \cdot U_1)\ (U_1 \cdot U_2)\ P_1P_2 \cdot U_2}{(U_1 \cdot U_2)^2 - 1}$$

The co-ordinates of point M_1 and M_2 are

$$\begin{array}{ll} A_1 = X_1 + D_1Q_1 & A_2 = X_2 + D_2Q_2 \\ B_1 = Y_1 + D_1R_1 & B_2 = Y_2 + D_2R_2 \\ C_1 = Z_1 + D_1S_1 & C_2 = Z_2 + D_2S_2 \end{array} \qquad (3.2.6)$$

Assuming that the errors in all measured angles are randomly distributed, the most probable position M of the aircraft on the line M_1M_2 is defined by

$$\frac{M\,M_1}{M\,M_2} = - \frac{(P_1M_1)^2}{(P_2M_2)^2} = - \frac{D_1^2}{D_2^2} \qquad (3.2.7)$$

The co-ordinates of the point M are then

$$X_M = \frac{D_2^2A_1 + D_1^2A_2}{D_1^2 + D_2 2}$$

$$Y_M = \frac{D_2^2B_1 + D_1^2B_2}{D_1^2 + D_2^2} \qquad (3.2.8)$$

$$Z_M = \frac{D_2^2C_1 + D_1^2C_2}{D_1^2 + D_2 2}$$

Although positions in space can be completely determined from the data of two kinetheodolites, more than two kinetheodolites are used in some applications. This is done in the following cases:

- If the test is unique and cannot be repeated, the kinetheodolites can be duplicated in order to have complete data in case of a failure of one of the kinetheodolites. In this case the command unit will also be duplicated.
- If the trajectory to be measured is too long to be covered by two kinetheodolites, additional units will be set up which can take over when the target comes near the limits of the range of the first pair. In this case all kinetheodolites will be connected to one command unit, in order to ensure correct synchronization.
- If the trajectory of the target cannot be well predicted, it may fly into areas where the accuracy of the primary kinetheodolite pair is not optimal (see below section 3.2.3). In those cases a third kinetheodolite is mounted and the data at any moment are calculated from the pair which provides the best accuracy.

3.2.2 Description of a kinetheodolite system

The Askania kinetheodolite system described in this section is probably the oldest type still in general use. More modern systems in general have electrical methods for measuring elevation and azimuth, which must be read from the film in the case of the Askania theodolites. Other facilities are present in modern kinetheodolites, such as the use of radar for early detection of an approaching target.
But the Askania system provides an accuracy similar to that of the more modern systems and is relatively easily transportable. For this reason Askania kinetheodolites are still used in many parts of the world where no instrumented test ranges are available.

A kinetheodolite system consists of two or more kinetheodolites and a command station. Figure 9 shows one Askania theodolite with its individual control unit and the command station. Each kinetheodolite consists of three main parts:

- A pedestal, which stands on three leveling screws. Using the two bubble levels mounted on the pedestal,these screws are used to bring the azimuth axis to an exactly vertical position. In the upper part of the pedestal are mounted:
  - A toothed ring for driving the rotation of the upper parts in azimuth
  - A glass disc (the azimuth scale), accurately graduated in grads (400 grads = 360 degrees) over the full 400 grads. The accuracy of the scale is ± 0.0015 grads.
  - A second azimuth scale projected in the aiming system used by the operator.
- A lower casing which can turn relative to the pedestal about a vertical axis. This contains the driving mechanisms by which the operator can move the system in azimuth and elevation and the microscopes which project the azimuth and elevation scales on the film. They provide a magnification of 35. The overall reading accuracy of the scales is ± 0.005 grads.
- An upper casing which can move relative to the lower casing about a horizontal axis. This contains:
  - The glass elevation scale, graduated from -10 to +210 grads (0 and 200 grads corresponding to horizontal positions).
  - The telescope system for use by the operators who point the system to the aircraft. There are two telescopes, one on each side. Figure 10 shows how a telescope is used.If the kinetheodolite is operated by two persons, each uses one of the telescopes and one operator moves the system only in azimuth, the other only in elevation. These telescopes have a field of view of 6 degrees and a magnification of 10.
  - The camera system, that moves with the telescopes. The 35 mm camera has interchangeable lenses. The choice of the lens depends on the average distance of the aircraft from the kinetheodolite and on the type of manoeuvres that are executed. Four focal lengths are available: 300 mm (field of view 7 degrees), 600 mm (3.3 degrees), 1000 mm (2.1 degrees) and 2000 mm (1 degree). The latter two are catadioptric mirror telescopes. The exposure time is fixed at 1/150 second. Two other systems project images on the picture: a frame number and the azimuth and elevation scales. These latter are projected in the upper corners of the frames, whereby the scales are illuminated by flashlight (10^{-4} s). The maximum frame rate of the camera is 20/second. There is an acoustic warning if the film transport fails. A typical picture is shown in Figure 11.

The total mass of one kinetheodolite is 120 kg.

The command station is connected to both kinetheodolites either by cable or by radio. A block diagram of a typical system using radio is given in Figure 12. The function of the command station is to generate commands to both cameras (thereby ensuring that both cameras take pictures with negligible time difference) and to record the time of each command and of the shutter contact in each camera. The commands sent to the camera operate the shutter, flashlight and film transport; the times at which the shutters actually operate are sent back to the command station. At the command station there is a capability for displaying the shutter contact signals. This is used to adjust the command signals for any differences in the delays in operation in the two kinetheodolites.

3.2.3 Preparation of a measurement series

On airfields where trajectory measurements are frequently made, the kinetheodolites are usually placed at fixed positions. Then the preparation will be confined to a thorough test of the equipment and making pictures of a few characteristic points in known directions. If, however, the kinetheodolites have to be set up at an unknown location or for a special type of test, the following procedure must be followed:

- A general survey of the site must be made especially concerning the possibilities of accessability, the presence of obstructions, etc. This can to a large extent be done by studying detailed maps.
- The choice of the positions of the kinetheodolites will depend on the topology and on where the the highest accuracy must be obtained. For take-off and landing measurements the highest

accuracy is usually obtained when the two kinetheodolites are placed on both sides of the trajectory, near the middle of that trajectory. If this is impossible, the best compromise must be chosen using graphs like Figure 13. This gives, for assumed angular errors of 10^{-4} radians in elevation and azimuth and for a distance between kinetheodolites of 1000 m, the magnitude of the errors in X, Y and Z of the target at zero height, similar graphs exist for other distances between kinetheodolites and heights.

- When the positions have been chosen, the co-ordinates must be measured accurately by survey. By the same method the elevation and azimuth of a number of characteristic points, as seen from the kinetheodolites, must be accurately measured. Such characteristic points can be on towers or other outstanding fixed objects, or on objects especially placed there for that purpose.
- Before each series of measurements a number of pictures are taken of each of these characteristic points and the camera shutters are synchronized exactly as described in the previous section.

Excluding the geodetic survey, which is usually made beforehand, the setting up of a pair of kinetheodolites will take about half a day.

Another important point is the choice of the reference point on the aircraft, for which the position must be measured on the picture. This point must be visible for both cameras during the complete manoeuvre. If this is taken too far from the centre of gravity of the aircraft, a correction must be applied for the attitude of the aircraft, which must then be measured also. For high-accuracy measurements a lamp is often mounted on top or below the fuselage, as near as possible to the centre of gravity of the aircraft.

3.2.4 Data processing

The goal of the data processing is to produce the azimuth and elevation values of the reference point on the aircraft from each picture. A block diagram of the data processing is given in Figure 14.

During film reading the azimuth and elevation values and the picture number are read and the position of the reference point on the aircraft relative to the cross hairs is measured. These data define the direction of the line-of-sight from the particular camera to the aircraft. They are sent to a computer, where they are combined with the data from the pictures from the other kinetheodolite(s), with the timing data recorded at the command station, and with the position co-ordinates of the kinetheodolites. The computer then calculates the trajectory.

This film reading involves much time-consuming manual labour. Much work has been done on reducing that labour. As already mentioned, in many theodolites the elevation and azimuth scales have been replaced by coded discs, the positions of which can be directly recorded at the command station. Complex film readers are available in which variable magnification of the projector and simple movement of the picture can be used to position fiducial markings on the projection table, and in which the position of the cross hairs used to measure the reference point on the aircraft picture is recorded directly when a footswitch is pressed. These (very expensive) film readers considerably reduce the time required for reading of films and eliminate several sources of errors.

3.2.5 Accuracy of the measurements

A detailed analysis of the functioning of a kinetheodolite reveals the following causes of errors in the measurement of azimuth and elevation:

a. errors due to poor construction or poor maintenance:
   - errors in the orthogonality of the axes of rotation
   - errors due to eccentricity of the azimuth and elevation scales
   - lack of parallelism between the line connecting the reticules defining the optical axis and the elevation axis
   - graduation errors on the scales
   - mechanical play

b. errors due to poor use of the available adjustment possibilities:
- errors in the adjustment of the levels
- collimation error
- error in the positioning of the elevation scale
- distortion in the objective

c. errors due to deformation of the kinetheodolite, its support or the film:
- deformations due to ageing of components
- deformations due to temperature, wind or forces exerted by the operators
- deformation of the film between the taking of the picture and its reading

d. errors due to non-rectilinear propagation of light

e. errors in the use of the kinetheodolite:
- errors in the measurement of the positions of the kinetheodolites
- levelling errors
- errors in the azimuth and elevation of the characteristic points measured during setup

f. errors in the data processing
- errors in the reading of the recticule images defining the optical axis
- errors in the reading of the reference point on the aircraft
- linearity errors in the film reader
- errors in the magnification ratio of the film reader
- use of over-simplified calculation methods.

There are, therefore, more than twenty causes for errors, some of which are systematic and others random, and a complete error analysis is very complex. It is usually sufficient to reduce the systematic errors to negligible values by adjustment and to determine the random errors from repeated measurements of the characteristic points mentioned in Section 3.2.3. This will provide an overall order of magnitude of the errors in elevation and azimuth for each kinetheodolite. Previous experience with the same kinetheodolites should also be used.

If the errors in the azimuth and elevation measurements are known, it is possible to calculate the errors in the position co-ordinates of the aircraft. In the case of measurements with one kinetheodolite this depends on the lateral deviation Y of the aircraft from its assumed path, which is not measured. If this is assumed that the error in the distance D between the kinetheodolite and the assumed trajectory (see Figure 6) is large with respect to the lateral deviations Y of the aircraft, then eq. (3.2.1) can be written as

$$X = (D+Y) \tan A$$
$$Z = (D+Y) \frac{\tan E}{\cos A} \qquad (3.2.9)$$

and the following error equations can be derived

$$\Delta X = Y \tan A + \frac{\Delta A . D}{\cos^2 A} \qquad (3.2.10)$$

$$\Delta Z = Y \frac{\tan E}{\cos A} + \Delta A . D \tan A \;.\; \frac{\tan E}{\cos A} + \frac{\Delta E . D}{\cos A \cos^2 E}$$

Calculations have been made using representative values for the parameters in these equations ($D = 500$ m, $\Delta A = \Delta E = 10^{-4}$ rad, $A < 1$ rad, $E < 0.5$ rad). These show that the coefficients of Y are of the same magnitude or larger than the values of the remaining terms in the equations if A is more than a few degrees. This means that for Y values of 1 metre or more the lateral deviation from the nominal track dominates the errors.

Much higher accuracies can be attained if 2 kinetheodolites are used. The error equations for that method can be derived by differentiation of eq. (3.2.3) and (3.2.4)

$$\frac{\Delta X}{X} = \frac{\Delta A_1 \sin^2 A_2 + \Delta A_2 \sin^2 A_1}{\sin A_1 . \sin A_2 . \sin(A_1 - A_2)}$$

$$\frac{\Delta Y}{Y} = \frac{\Delta A_2 \sin 2A_1 - \Delta A_1 \sin 2A_2}{\sin A_1 - \sin A_2} \qquad (3.2.11)$$

$$\frac{\Delta Z}{Z} = \frac{\Delta E_1}{\sin 2E_1} + \frac{\Delta E_2}{\sin 2E_2} + \frac{\sin A_2 + \sin A_1 \cos(A_1 - A_2)}{\sin A_1 \sin(A_1 - A_2)} \Delta A_1 + \frac{\sin A_1 + \sin A_2 \cos(A_1 - A_2)}{\sin A_2 \sin(A_1 - A_2)} \Delta A_2$$

Expressed in standard deviations and assuming that $\sigma(E_1) = \sigma(E_2) = \sigma(A_1) = \sigma(A_2) = \sigma(A)$ this becomes

$$\sigma\left(\frac{\Delta X}{X}\right) = \frac{\sqrt{\sin^4 A_1 + \sin^4 A_2}}{\sin A_1 \sin A_2 \sin(A_1 - A_2)} . \sigma(A)$$

$$\sigma\left(\frac{\Delta Y}{Y}\right) = \frac{\sqrt{\sin^2 2A_1 + \sin^2 2A_2}}{\sin A_1 - \sin A_2} . \sigma(A) \qquad (3.2.12)$$

$$\sigma\left(\frac{\Delta Z}{Z}\right) = \sqrt{\frac{1}{\sin^2 2E_1} + \frac{1}{\sin^2 2E_2} + \left(\frac{\sin A_1 + \sin A_2}{2 \sin A_1 \sin A_2} - 1\right) \cot an^2(A_1 - A_2) + \frac{\sin^4 A_1 + \sin^4 A_2}{\sin^2 A_1 \sin^2 A_2 \sin^2(A_1 - A_2)}} . \sigma(A)$$

The assumption that the lines of sight intersect is not realistic. The calculation can also be made without that assumption. The formulas are then more complex. The results are usually presented as in Figure 13: for one selected value of the distance 2D between the kinetheodolites, for one selected value of the RMS angular error $\sigma(A)$ and for one selected altitude Z. It should be noted that:

- these graphs are different for each altitude Z
- the errors are inversely proportional to the distance P_1P_2 between the two kinetheodolites
- the errors depend on the values of $\sigma(A)$ and $\sigma(E)$. If these are all increased by the same ratio, the errors will increase by the same ratio.

A general impression of the accuracy that can be obtained with well maintained kinetheodolites, when films are good and the film reading has been done with sufficient care, is given by the following table:

Parameters	Errors using 2 kinethoodolites		
	6000 m > X > 2000 m	2000 m > X > 1000 m	1000 m > X > 0
X	5 m	1 m	0.5 m
Y	5 m	1 m	0.5 m
Z	2 m	0.5 m	0.3 m
V_x	5 m/s	2 m/s	1 m/s
V_y	5 m/s	2 m/s	1 m/s
V_z	2 m/s	1 m/s	0.5 m/s

The accuracy of the results can be increased somewhat by smoothing. Even if smoothing is applied, accelerations calculated from them will not be very accurate. A discussion on the accuracy of a kinetheodolite system is given in Ref. 30.

3.2.6 Applications of kinetheodolites

The Askania theodolite described above is relatively easily transportable and has an accuracy which is of the same order as that of the more modern kinetheodolites. The main advantage of many of the other kinetheodolites is, that the frame number and the azimuth and elevation of the camera need not be read from the picture frame. Many theodolites are equipped with a digital frame counter and coded disks for the azimuth and elevation measurement. These outputs are recorded on tape, or directly sent to a computer which then provides the rough trajectory in real time. The film reading is then somewhat reduced and writing errors are eliminated for these parameters. Another modern feature is a coupling to a lock-follow radar, which permits earlier interception of the target. Many of the modern kinetheodolites are permanently mounted on towers on a test airfield, which limits their usage to that one instrumented airfield but reduces the work involved in setting up. At present fully automated theodolite systems are being investigated (see Section 3.5.1). They will use computers with shape-detection programmes, which can detect a marker on the aircraft and make the kinetheodolite follow the target automatically. It is not clear yet whether such kinetheodolites will be able to compete with other types of trajectory measurement, such as laser-theodolites and methods using inertial systems.

Kinetheodolites, when used with the experienced personnel that are available in many places around the world, are still regarded by many as the most reliable and accurate method for close-range trajectory measurements. Their disadvantages, mainly the amount of manual labour by experienced operators required for data processing and the long data processing delays, have led to the development of many of the other methods of trajectory measurement described in this AGARDograph. Until very recently none of these other methods could produce results with similar reliability and accuracy. Kinetheodolites play an important role as a reference method in the development of other methods.

The main disadvantages of the use of kintheodolites are:

- Very laborious and time consuming data processing
- A requirement for very good weather conditions. With optimal visibility a range of 15 km can be attained, but this is markedly reduced if the weather is not perfect.
- A relatively large number of experienced operators is required, both for operation of the theodolites and for film reading.
- In modern take-off and landing performance analysis the accuracy of the velocities and accelerations is of high interest. The kinetheodolites provide a very high position accuracy, but the velocities and accelerations must be calculated by single and double differentiation of the position data. Some of the other methods (especially those using inertial systems) provide about the same position accuracy but much higher accuracies for the velocities and accelerations.

3.3 Other methods using cameras on the ground

3.3.1 Introduction

The simplest, and probably oldest, method uses a fixed camera, which looks perpendicular to the trajectory. The focal length and distance are chosen so that the whole trajectory is within the field of view of the camera. Pictures are taken at constant time intervals. The focal length can be calibrated by using landmarks on the pictures, the directions of which relative to the camera are known. The accuracy is less than that of a kinetheodolite because of the much larger field of view that is required.

The Fairchild F-47 take-off and landing camera was a compromise between the costly kinetheodolite and the too inaccurate fixed camera. It could follow the aircraft in azimuth, but not in elevation. The turn axis is vertical and the azimuth motion is damped by a "gyroscopic head", in which a heavy disc immersed in fluid is directly attached to the camera. The camera is turned by an observer who uses a sight to direct it towards the aircraft. Each picture shows, in addition to the aircraft, readings of azimuth (to 0.05 degrees) and time (to 10 milliseconds). For azimuths within ± 30 degrees from the perpendicular to the runway centre line, an accuracy of a few metres in distance is attained and an accuracy of 3 % in the aircraft velocity.

In another method, that was extensively applied in several countries, a camera with two degrees of freedom is used, which photographs the aircraft through a wire grid before the camera. Plane, cylindrical and spherical gride are used (Figure 15). The accuracy depends critically on the precision with which the grids are constructed and positioned.

A very ingenious camera is the Fairchild Model IV A Photographic Flight Analyser take-off and landing camera. This is a fixed camera with a field of view of 90 degrees. The camera must be positioned so far from the plane of the trajectory that the part of interest of the flight is just within that angle. The ingenuity lies in the fact that up to 58 pictures of the aircraft are made on one photographic glass plate (Figure 16). Each picture is made through a narrow slit that moves directly in front of the glass plate. This slit is displaced manually by the operator, who follows the aircraft through binoculars that turn with the slit movement. The pictures are made automatically at regular angular intervals. The time of each picture is printed below it, with a sensitivity of 1 millisecond. The shutter speed is 1/1000th of a second. It is claimed that velocities can be determined to an accuracy of 0.5 m/s and accelerations to 0.3 m/s^2. The glass plates are very stable and different trajectories can be compared by putting two plates on top of each other.

3.3.2 Vertical camera

An application of the ground-based camera still in general use is the vertical-looking camera for the calibration of static pressure errors. The aircraft flies over the camera at a height of the order of 100 metres, with its wings level. The camera takes a picture when the aircraft is directly above it. The geometric height of the aircraft can then be calculated from

$$H_g = f \frac{S}{S'} \qquad (3.3.1)$$

where
S = the wing span of the aircraft
S' = the wing span on the picture
f = the focal length of the camera

The combination of focal length and the height of the aircraft must be carefully chosen to ensure that the full span will be shown on the picture. This can usually be achieved by making S' about one third of the picture dimension or less depending on the speed of the aircraft. In order to calculate the static pressure error the weight of the air column between the camera and the aircraft must be known. This can be done by measuring pressure and temperature on the ground and measuring temperature in the aircraft. If the weather is stable, no sunshine and no pressure disturbances (measurements in an open area such as an airfield), the pressure altitude error can be calculated to an accuracy of a few feet.

3.4 Methods using on-board cameras

3.4.1 Introduction

For many tests the use of ground-based cameras (or other ground-based measuring devices) poses problems. This is especially the case if tests have to be done at airfields which have no permanent instrumentation, which often occurs when tests must be made under artic or tropical conditions or at high-altitude airports. In those cases it can be of great advantage if all (or nearly all) measuring equipment is installed in the aircraft.

Until the development of methods using inertial sensors (see Chapter 5) the only methods using mainly on-board equipment were those using on-board cameras. These methods were used extensively for take-off and landing performance measurements in many countries. For this application they are now gradually being replaced by more modern methods such as laser tracking and the use of inertial platforms. The on-board camera methods are, however, receiving a new impetus from autoland testing. It is perhaps the best method to achieve the ±0.3 metres accuracy required for the determination of the touchdown point (see Section 2.3) on many different airports.

The on-board cameras usually take pictures of the landing and centre-line lights along the runway. The positions of these lamps are usually not known to the required accuracy, so that these must be measured beforehand by survey methods.

The most generally applied method uses forward-looking cameras in the nose of the aircraft. This method is described in the Section 3.4.2. An application with a side-looking camera is briefly described in Section 3.4.3.

3.4.2 Measurements using a forward-looking camera

The description given here is mainly based on the method developed in the Netherlands (Ref. 31). The methods used elsewhere (USA, France) are very similar. The runway lights are photographed and the position and attitude of the aircraft are calculated from the positions of the lamps on the picture.

The principle of the method is shown in Figure 17. The camera is usually tilted down somewhat, so that as many lamps as possible are on the picture. The accuracy of the measurement increases as lamps close to the aircraft are used. Drawings of film pictures are given in Figures 18-21. The data processing provides 6 parameters: the distances X (along the runway), Y (relative to the centre line between the lamp rows) and Z (height) and the angles θ (pitch), φ (roll), and ψ (yaw relative to the centre line). Therefore, the positions of at least 6 lamps must be measured. Usually a few more lamps are measured on the picture and the redundant information is used to check the apparent focal length and to calculate a figure of quality.

The principle of the calculation is shown in Figure 18 for a very much simplified case. In this case 4 of the 6 parameters are zero: θ, φ, ψ and Y. For the calculation of the remaining two parameters, X and Z, only two lamp positions are required. These have been chosen as lamps on each side of the runway centre line. Figure 18a shows the vertical plane through the runway centre line, Figure 18b the plane through the lamps and the camera optical centre and Figure 18c shows the picture made by the camera in the nose of the aircraft. As $\theta = 0$ (the optical axis is horizontal) the horizon is in the middle of the picture. By simple geometry it can be seen that the co-ordinates of the aircraft with respect to the lamps can be calcualted from

$$X = \Delta L \frac{f}{x_{L1} - x_{L2}}$$

$$Z = Z_L + X \frac{y_L}{f} \qquad (3.4.1)$$

where
- X = the horizontal distance between the camera and the lamps
- Z = the height of the camera above the runway reference height
- Z_L = the height of the lamp above the runway reference height
- f = the focal length of the camera
- x_{L1}, x_{L2} and y_L = the co-ordinates measured on the picture.

For the definition of the runway reference co-ordinate system see Appendix 1. It should be noted that the curvature of the Y-axis can be neglected in the calculation, because the horizontal distance to the lamps used is small (a few hundreds of metres at most).

For the general case, where all six outputs are non-zero, the equations are complex and a computer is used for the calculation. Figures 19-21 show drawings of typical pictures.

Pictures can be made on black and white film and on color (negative or reverse) film. Color film usually gives slightly better results, especially under critical light conditions. The shutter speed must be as short as possible, 1/250 second or less. At a speed of 100 kts the aircraft will move 20 centimeters during 1/250 second, so the lamps will not be sharp on the picture and the film reader must choose the centre of a small blurred speck.

Film reading is usually done on special film readers, the same as are used for kinetheodolites. They range from relatively cheap (with more manual work) to complex and expensive. The measured co-ordinates are usually directly entered into a computer, which then does the calculation.

A special problem is posed by the fact that the distance X along the runway is calculated relative to the first lamp on the picture, and that this lamp must first be identified. In practice this is not a great problem as specific lamp patterns occur near exits. During landings the first lamp of the runway can be identified. Once one lamp on one picture has been identified, the computer will calculate which lamps are seen on the basis of an approximate value of ground speed entered into the computer.

The accuracy of the method has been assessed on the basis of comparisons with ground-based cameras and accelerometers and from error calculations using data from redundant lamps. The accuracy decreases as the first lamp is further away. For a distance of about 100 m from the camera to the first lamp the following accuracies can be attained:

in X : ± 0.6 m
in Z : ± 0.12 m
in θ : ± 0.06 degrees = ± 1 milliradian

3.4.3 Side-looking camera

A problem with the nose cameras is that the accuracy depends so much on the distance to the first useable lamp. Especially during the important pitch-up period of a take-off, this first lamp can be far away. A solution for this problem is provided by the Llori camera system, which was developed in France. A similar system has been used by Lockheed.

The camera is mounted below the fuselage, with the lens looking down. A mirror system attached to the camera reflects the light from the runway boundaries into the camera (Figure 22). The two mirrors do not touch in the centre, so that a slit of 2 degrees is left free through which the camera sees the runway centre line.

The principle of the calculations is shown in Figure 22, for the case that the roll angle φ, the yaw angle ψ and the lateral displacement of the aircraft Y are zero. The pitch angle θ can then be calculated directly as half the angle between the lines on the picture through the lamp images. The height of the optical centre of the camera above the lamps is (see Figure 22):

$$Z = (00_1 + 0_10_2 + 0_20_3)\cos\theta \qquad (3.4.2)$$

00_1 is the fixed distance h between the optical centre and the point of intersection of the planes of the mirror surfaces with the optical axis. 0_10_2 can be calculated by first calculating 0A in the triangle $0A0_1$ using the sine rule, and then 0_10_2 in the triangle 0_1A0_2 using the sine rule:

$$0_10_2 = \frac{\sin(\delta-\rho)}{\sin(2\delta-\rho)} \cdot 0A_1 = \frac{\sin\rho}{\sin(2\delta-\rho)} \cdot h \qquad (3.4.3)$$

If B is the actual distance between the lamps on opposite sides of the runways, then

$$0_20_3 = \frac{0.5\,B}{\tan(2\delta-\rho)} \qquad (3.4.4)$$

Combination of these equations yields the following expression for the height

$$Z = \tfrac{1}{2}B.\frac{1 + \frac{2x_o}{f}\tan 2\delta}{\tan 2\delta - \tan\rho} + h\left(1 + \frac{\frac{2x_o}{f}}{\sin 2\delta - \frac{2x_o}{f}\cos 2\delta}\right) \qquad (3.4.5)$$

where θ = the angle between the optical axis and the vertical (= the aircraft pitch angle of the aircraft if the camera looks parallel to the aircraft Z-axis)
B = the distance between lamps on opposite fields of the runway
h = the fixed distance 00_1 in Figure 22
δ = the angle of the mirror (see Figure 22)
f = the focal length of the camera
x_o = the distance on the film indicated in Figure 23

θ can be calculated from the film picture as shown above and all other values are constants except x_o, which can be measured on the film picture.

For the calculation of X with respect to lamp 1 we first calculate the X co-ordinate of the point where the optical axis intersects the ground.

The co-ordinates for this point, in the symmetrical case considered here, is, in the notations of Figure 23:

$$X' = X_1 + \frac{y_1}{y_1 + y_2} \cdot L \tag{3.4.6}$$

The X co-ordinate of the optical centre of the lens is then

$$X = X' - Z \cos\theta = X_1 + \frac{y_1}{y_1 + y_2} \cdot L - H_L \cos\theta \tag{3.4.7}$$

where H_L = the height of the lamps above the reference surface.

In the general case, in which φ,ψ and Y are not zero, the calculation is more complex. Then the position of the runway centre line on the picture is also used. The accuracy depends very much on the precision with which the mirrors are fixed with respect to the camera. In practice, errors of the same order as those for the nose camera method are found.

3.5 Optical methods without photographic cameras

3.5.1 General introduction

Until quite recently the use of optical methods for trajectory measurement simply meant photographic recording. Recent developments in video, infra-red and laser techniques, together with the development of computer programmes which can perform automatically the tasks which the operator of the film reader has to do manually, are now completely changing the situation. At present it would seem that the laser tracker, described in Section 3.5.2 below is the most likely candidate for succeeding the kinetheodolites as the precision instruments for trajectory measurements. But so much development is going on in parallel fields that this may well change in the next few years. At this point in time it cannot be said that these methods have completely replaced the photographic methods, but they are rapidly gaining ground. It is still difficult to attain the accuracy and reliability that kinetheodolites provide when operated by experienced field operators and film readers. But this is rapidly improving and the advantages are overwhelming: simpler operation, requiring less highly qualified personnel, and automatic data processing, including real-time presentation of the processed results.

Before treating the laser theodolites in some detail in the next section, a few developments in the other fields mentioned above will be briefly reviewed. As the starting point was the photographic kinetheodolite, video methods seem an obvious candidate for its succession. A review of the state of development of video cameras is given in Ref. 32. Studies to replace the kinetheodolite by a video camera, retaining the manual operation and the manual picture reading is being investigated at the A & AEE in the UK. At the Naval Air Development Center in the USA a similar system is being investigated (Ref. 33), but there semi-automatic data processing using image processing techniques in a computer is considered. For the present it would seem that fully automated systems, using on-line shape detection processing as the basis for automatic tracking, will be difficult to realize because of the high background noise. Video can, however, have an important function as a monitoring system for automatic tracking systems. It is used in this function in the STRADA laser tracker described in the next section.

Infra-red techniques have been applied, with different stages of automation, to the tracking of aircraft for ILS calibration (see e.g. Ref. 29, Part 2, Section 7.3). In that application the detector is placed on the ground near the glide path antenna and tracks a light bulb mounted on the aircraft. This system is very useful for measuring the angular deviations from the line defined by the intersection of the glide slope and localizer planes. Another application of infra-red techniques for measuring aircraft trajectories is the method mentioned in Section 5.3.4 and described in Ref. 34 for measuring aircraft position relative to the runway threshold.

3.5.2 Trajectory measurements using lasers

3.5.2.1 General aspects

The laser trackers, development of which started in the early 1970s, provide in many respects an important advance over the earlier optical methods. Their primary advantage is that the aircraft position and velocity coordinates are immediately available. The accuracy is of the same order as that of kinetheodolites and onboard cameras, and only one unit is required which measures elevation, azimuth and distance. The principle is very like that of the lock-follow radar (see Chapter 4), but the frequency is much higher and consequently a higher accuracy can be achieved. The frequency of most present-day laser trackers is in the infra-red region and for this reason they are discussed here and not in Chapter 4.

The important advantages are, however, accompanied by a few disadvantages:

- the laser beam can be dangerous to human eyes and consequently strict precautions must be taken
- a reflector is required on the aircraft.

Laser trackers can be stationary (such as the STRADA system used in France), or transportable (in which case they are mounted in a van). In the next section the principal characteristics of the laser trackers will be highlighted in a description of the stationary STRADA system developed in France. A description of a transportable system is given in Ref. 35.

3.5.2.2 General description of the STRADA system

The general layout is given in Figure 24. The laser tracker is mounted on a tower at about 10 m above the ground at 500 m from the runway centre line. The tracker measures elevation S, azimuth G and slant range R with respect to a rectangular coordinate system fixed on the ground.

In order to reduce the laser power required and to fix a specific point on the aircraft, a "corner reflector" is mounted on the aircraft (see Section 3.5.3). Reflective tape is also used for this purpose in other applications, but then more laser power must be transmitted to obtain the same reflected power at the receiver optics.

The laser is mounted at the tower top. The laser itself is fixed, but the beam can be turned about a horizontal and a vertical axis by means of a mirror system. The laser of STRADA is of the solid-state laser. The active medium is an yttrium-aluminium garnet doped with neodynium. The laser emits pulses of 3200 Hz which are generated from a continuously burning lamp by a system of rotating mirrors. The aperture is 10 milliradians, the wave length is 1.06 μm and the peak power is 5 kW.

A general block diagram of the system is given in Figure 25. For the measurement of the angular misalignment of the tracker the image of the reflector on the aircraft is projected on a cathode-ray tube. If the reflector image is not at the centre of the tube, the servo motors are actuated and direct the laser beam to the reflector on the aircraft. The elevation and azimuth of the beam are measured by encoders, the output of which is sent to the computer. The slant range is measured by two cascade diodes. One receives a small part of the light from the transmitted beam, the other receives part of the reflected beam. The time between the pulses generated by these diodes is measured, using a 200 MHz time base. The average of 64 of these time differences is calculated and is sent to the computer 50 times per second. In the computer the direction and distance information is transformed to the runway co-ordinate system described in Appendix 1. The X, Y and Z co-ordinates of the aircraft and velocity components along those axis are plotted on-line on strip charts and recorded on magnetic tape.

The whole system is directed from the control desk. On the desk is a television screen that displays the image from a television camera that moves with the laser beam. It is focused automatically by the computer. Target acquisition is usually done manually from the desk by moving a speck on the television screen that indicates the direction of the laser beam. It is also possible to acquire the target automatically, using information from a lock-follow radar.

3.5.2.3 The reflector on the aircraft

This reflector consists of an assembly of so-called corner reflectors or retroreflectors, i.e. devices which reflect light in the direction from which it came. The principle of a corner reflector is shown in Figure 26. It consists of a reflecting internal pyramid in which the top angles of all sides are 90 degrees.

The right-hand figure shows the path of a light ray which is perpendicular to one of the edges of the pyramid: the reflected ray is parallel to the incident ray. If the incident ray is not perpendicular to an edge, it will be reflected by 3 surfaces of the pyramid, with the same result.

The corner reflectors are made of glass or quartz coated with gold. Their effectiveness depends to a high degree on the flatness of the mirror surfaces and on the exactness of the angles between them. Their production becomes more difficult with increasing size. The effectiveness is also affected by the angle of incidence of the laser beam. It is greatest when the beam is perpendicular to the front surface, as indicated by the arrows in Fig. 26. As the angle between the beam direction and the perpendicular increases, the amount of reflected light first decreases slowly, but at angles of the order of 45 degrees the rate of change becomes high.

Figure 27 shows how these problems were solved for autoland measurements with STRADA. When the aircraft is far away the beam is reflected by the 12 reflectors on the one side (each with 4 cm diameter). When the aircraft is on the runway beside STRADA, only the 4 reflectors on the other side reflect the beam. The large surface is curved to ensure a gradual changeover. The complete assembly measures 150x150x100 mm^3 and has a mass of 5 kg.

The best position of the reflector on the aircraft is as near as possible to the center of gravity. Care must be taken, however, that the line between the laser and the reflector cannot be obstructed by parts of the aircraft at any point of the trajectory. In practice a compromise solution must be found for every aircraft. For the Concorde autoland tests the reflector was placed on the nosewheel strut, for the Caravelle and the Mystère XX at the wing leading edge at the root of the wing, for the Airbus A-300 on the emergency exit door below the wing.

3.5.2.4 Operational and safety aspects

The STRADA system is highly automated and can be operated by one man, who can conduct the complete operation from the control desk. There the azimuth and elevation of the laser beam are displayed digitally and during measurements also the co-ordinates of the aircraft. All equipment can be switched on at the control desk and the system can be set in the acquisition or in the tracking mode. Switching from one to the other of these modes can also be done by the computer. The operation of the television camera can also be controlled from the control desk, as can the adjustment of the focal distance of its zoom lens.

The power in the laser beam required for the maximum range of 7 km can be dangerous for human eyes at shorter distances. Several committees all over the world have tried to determine what quantities of laser energy are acceptable for the human eye. This has resulted in safety regulations, which define, as a function of the emitted power, minimum safe distances from the laser source. For the STRADA system at full power this distance is 1100 m.

In the STRADA system the following safety measures have been taken:

- Operation at full power is only allowed in a certain part of the hemisphere in which the beam could, in principle, move. In determining this part, account has been taken of the trajectories which may have to be measured and of places where people could be. If the beam at full power moves accidentally out of this region, the laser transmission is cut automatically.
- An attenuating disc placed in the front of the transmitter automatically reduces the emitted power as the aircraft approaches. At full attenuation the safe distance is reduced to 100 m. This ensures that the crew of the aircraft is always farther away than the minimum safe distance from the laser.
- A communication, display and remote control system has been developed which keeps the air traffic controllers informed about the operation of the laser. They can stop the laser transmision immediately if the need should arise.
- Mechanical stops have been installed in the tower which make it impossible for the moving frame to move to certain zones.
- All personnel are alerted not to look towards the laser through optical devices such as telescopes.

4 TRAJECTORY MEASUREMENT USING RADIO AND RADAR METHODS

4.1 Introduction

Electromagnetic waves at frequencies well below those of light are extensively used for radio beacons for civil and military navigation applications all over the world, and for radars. On-board transmitters, receivers and transponders are readily available and if the accuracy and range are sufficient for specific flight test purposes, they provide a very cheap way of trajectory measurement. In many cases, however, the accuracy of the ground beacons and/or the airborne equiment are not sufficient for flight test purposes. They have been designed to meet the accuracy requirements for normal aircraft navigation and their general use makes it necessary to produce very reliable equipment as cheaply as is consistent with those requirements. The principles of these methods often allow the achievement of much higher accuracies if more advanced design principles are used. In this chapter we will briefly review the systems that are available for normal navigation and then discuss in some more detail a few further developments which allow higher accuracies.

The frequencies of the measuring systems described in this chapter range from about 10 KHz (30 km wavelength) for OMEGA to about 30 GHz (1 cm wavelength) for some radars. The electromagnetic waves in this range have a number of properties which can be used in different ways for the measurement of the position and velocity of a target. The most important of these are:

- The speed of electromagnetic waves in vacuum is a physical constant. The effect of the atmosphere on this speed is small and in many cases corrections can be applied for that effect
- The time in which a wave travels from one antenna to another is affected by the frequency of the signal: up to about 3 MHz the path by which the waves travel is bent along the surface of the earth, in the range between 3 and 30 MHz they are reflected by ionospheric layers and at frequencies above about 30 MHz they only travel in straight paths.
- The waves can be transmitted omnidirectionally or in narrow beams, depending on the type of antenna used and on the frequency.
- The waves are reflected by objects such as aircraft. Then a small portion of the transmitted energy can be received back at the position of the transmitting antenna. Spurious reflections, e.g. from objects on the ground or from ionospheric layers can, however, affect the measurement.
- The frequency of an electromagnetic signal reflected by an object that moves with respect to the transmitting/receiving antenna is shifted by an amount proportional to the relative velocity between the object and the antenna (Doppler effect).

Section 4.2 briefly reviews the techniques by which these properties are used to measure aircraft position and speed. These techniques are mainly based on two measurement principles:

- The measurement of distance, making use of the extreme constancy of the velocity of electromagnetic waves,
- The measurement of the direction from which the (reflected) wave is received (often called the line of sight), making use of narrow-beam transmitters and determining at the receiver the direction from which the highest (or in some cases the lowest) power is received.

A single measurement of one of these two types cannot establish the position of an aircraft. To establish an unambiguous position by distance measurement only, distances of the aircraft from at least three different points must be measured. Two line-of-sight measurements (each usually expressed by azimuth and elevation angle) from different points also establish an unambiguous position. The third possibility is to combine one distance measurement with one measurement of the line of sight from the same point. These measurement principles are not unique to radio and radar measurements. An example of a measurement of the line of sight is the kinetheodolite discussed in Section 3.2 (two kinetheodolites are required to establish an aircraft position) and an example of a combination of the measurement of one distance and one line of sight is the laser theodolite described in Section 3.5.2.

In Section 4.2 a few of the general principles of the measuring techniques will be described, subdivided in techniques using distance measurement only (4.2.1) and techniques using distance and line of sight (4.2.2). Section 4.3 very briefly characterizes the methods that are generally available for normal navigation and tracking, with an indication of the accuracies that can be achieved. Section 4.4 describes in some more detail a few more accurate methods based on distance measurement only, and Section 4.5 describes the use of radars for trajectory measurement.

4.2 General principles

4.2.1 Methods based on distance measurement only

Because the speed of propagation of electromagnetic waves is almost constant, the measurement of the distance between a transmitter and a receiver is in essence a measurement of the time during which the signal travels. In order to measure the distance with an accuracy of 1 metre, the time must be measured with an accuracy of 3 nanoseconds. That means that the transmitter and the receiver must be of good quality, but also that they must be synchronized to better than these 3 nanoseconds. Such synchronization can only be achieved if the transmitter and the receiver are synchronized to a common time base. That is relatively easy when the transmitter and receiver are at the same location, as is the case with radars. If they are not at the same location, the receiver may be synchronized to the transmitter via cables or a radio connection, or both can be synchronized to an independent reference frequency. In these cases corrections have to be applied for the delays in the cables or in the radio transmission, which requires that the relative positions are known to a precision that is better than the required accuracy. For periods of a few hours synchronization can be achieved by using atomic clocks as the time base of both the transmitter and the receiver, and synchronizing these before the start of the test. If atomic clocks must be used over periods of more than a few hours, they must again be synchronized to a master atomic clock, as is done in NAVSTAR GPS (Section 4.4.5).

If the transmitter and the receiver are co-located, part of the transmitted signal must be "reflected" to the receiver. This can be an actual reflection as in the case of radars or an artificial reflection by a transponder, i.e. a device which retransmits the signal it receives (in some cases at a different frequency). For transponders the delay between the reception of the signal and its retransmission must be known with the required accuracy. Transponders in the aircraft are also used for "secondary" radars on the ground, in order to increase the signal strength of the "reflected" signals.

The measurement systems based on the direct comparison of transmitted and "reflected" signals are called circular systems, as the measured distances define (circular) spheres. Examples of circular systems are DME and the distance measuring part of radars. In hyperbolic navigation systems the receiver in the aircraft measures the differences in the distance from the aircraft to pairs of transmitters on the ground. These ground transmitters are all accurately synchronized with each other. The points of equal signal are on hyperboloids defined by the positions of the transmitters. Examples of hyperbolic systems are LORAN, OMEGA and Decca.

From the point of view of trajectory measurement the systems which only use circular of hyperbolic inputs have one important disadvantage: the measurement of height is very inaccurate when the height of the aircraft above the plane through the ground antennas is less than about 10 to 15 % of the distances from the antennas to the aircraft. For systems used for long-range navigation, such as OMEGA, this is no problem as aircraft navigation is based on pressure altitude and not on the geometric altitude which the system could provide. For many flight test applications, specifically take-off and landing tests, it is a serious disadvantage. For the MAPS system described in Section 4.4.3, which is specifically designed for short-range flight test applications, a complex Kalman filter programme based on inputs from both pressure and radio altimeters has been developed to improve the height accuracy at lower altitudes.

In many circular systems the Doppler shift is measured in addition to the distance in order to obtain accurate values for the velocity component along the line of position.

4.2.2 Methods also using direction measurement

Besides the radio methods based on the measurement of the distance of the aircraft from several points on the earth described above, trajectory measurements using radio or radar can also be based wholly or in part on the measurement of direction. The following measuring principles are of interest:

- The antenna can be rotated about 1 or 2 axes. In a search fase it is turned by external means (by hand or by a preprogrammed search movement) until it points in the direction from which the strongest signal is received. This principle is used in lock-follow radars (Section 5.4.3), where the antenna can rotate about two axes, one vertical and the other horizontal. Once the target has been found, the system can be locked on that target and gives its azimuth and elevation continuously. The same principle, but now with an antenna with one degree of freedom on board the aircraft, is used in the ADF (Aircraft Direction

Finding) navigation system, where the azimuth of NDBs (Non-Directional Beacons) with respect to the longitudinal axis of the aircraft is displayed in the cockpit. In modern ADF systems the antenna is not actually turned, but the signals from two mutually perpendicular antennas direct the pointer of an indicator.

- The antenna rotates at a constant speed about a vertical axis. The antenna beam is shaped as a thin vertical sheet and only azimuth is measured by establishing the antenna angle at which a strong signal is received, with respect to a reference direction (often the North direction). This principle is used in the surveillance radars described in Section 4.5.2.
- A somewhat similar method is used in the VOR (VHF Omni Range), only there the information from the signals generated on the ground is measured in the aircraft. The ground beacon transmits a cardioid pattern which rotates at 30 rps (generating a 30 Hz sine wave in the aircraft receiver) and an omni-directional 30 Hz signal which has a known phase angle when the rotating pattern points in the (magnetic) North direction, both modulated on the same carrier frequency. The phase angle between the two 30 Hz sine waves is measured on board the aircraft and provides the direction in which the aircraft is seen from the ground beacon. In the direction part of TACAN a similar method is used at a higher frequency.

In most applications (e.g. in radars and in the VOR/DME measurements that are generally used in aircraft navigation) the direction measurement is combined with a distance measurement from the same location to provide a position measurement. In principle, methods using several direction measurements from different locations can also be used (e.g. 2 VORs), but those methods are seldom used.

4.2.3 Principles of technical design

A discussion of the technical design of these electronic measuring systems is beyond the scope of this AGARDograph. The reader is referred to handbooks such as Refs. 36 to 40. In this section only a few of the main design considerations will be briefly mentioned:

- The importance of the frequency has already been mentioned in Section 4.1. A world-wide navigation system based on only a few ground stations, such as OMEGA, uses very low frequencies to benefit from the propagation property that these waves follow the curvature of the earth. On the other hand, radars use very high frequencies at which ionospheric reflections are negligeable. In order to reduce interference between different types of applications of electromagnetic waves, special frequency bands have been allocated by international agreement for each application.
- In most cases the basic or carrier frequency is modulated by signals of lower frequencies. Many modulation techniques are used, the most common are amplitude modulation, pulse modulation and frequency modulation. Such modulations hardly affect the propagation characteristics of the signal and can in many ways increase the information content of the signal. Important applications of modulation techniques are the possibility to transmit additional information (the identification of the transmitter or transponder or the inclusion of more complex messages such as in surveillance radars with Mode C or Mode S) and the elimination of ambiguity in distance measurements.
- Techniques are used to eliminate spurious signals such as reflections and interference from other sources. A very effective technique is the tracking technique. The receiver calculates, on the basis of earlier returns, when the next pulse can be expected to appear. The receiver is only sensitive to returns during a very small time "window" around the expected time and will reject all other incoming signals. Radars have "moving target indication" (MTI) which only accepts signals from targets that move with a velocity higher than a certain minimum, thereby rejecting all reflections from stationary objects on the ground.

4.3 Generally available radio and radar trajectory measuring methods

As stated previously, a number of radio and radar methods of trajectory measurement are available in large parts of the world and can be used at low cost if they are available and sufficiently accurate. They are in daily use for aircraft navigation, air traffic control and military applications. They are, in general, not very accurate as they have been designed for day-to-day use to specifications which stress reliability and low cost. For most of the civil equipment ICAO has laid down the specifications in Ref. 41.

More detailed descriptions of many of the systems can be found in Refs. 36, 37 and 38. It should be stressed here that many of those systems are, in general, considerably more accurate than is required by the specifications when used with high-quality measuring equipment. An example is the multiple-DME system described in Section 4.4.2.

These systems will be briefly reviewed here, with the emphasis on availability and achievable accuracy. They can be divided into the following general categories:

- long-range navigation systems (OMEGA, LORAN C)
- medium-range navigation systems (VOR, DME, TACAN, Decca)
- landing aids (ILS, MLS)
- surveillance radars
- lock-follow radars
- satellite navigation systems (NAVSTAR GPS)

LORAN C is a hyperbolic system with a range of about 1500 km. It is available along the Atlantic and Pacific coasts of the USA and in a few other areas in the North-West of the Atlantic and in the Pacific and is mainly used for coastal shipping. Its accuracy of the order of 100 m to 2 km, depending on the position of the aircraft relative to the ground antennas. LORAN A, which was specially designed for navigation of aircraft over large oceanic areas in the 1940s, has been discontinued in 1978 and its function has been taken over by OMEGA. LORAN C provides no height information.

OMEGA is a VLF hyperbolic navigation system that has virtually world-wide coverage. It is based on 8 ground stations which each send out four frequencies in the range between 10.2 and 13.6 kHz. If a receiver is tuned to 3 or more stations, frequencies from the different stations can be chosen for optimal signal quality and for optimum reduction of position ambiguity; in many receivers this frequency selection is automatic. The position accuracy is a few km under good reception conditions, but errors up to 10 km can occur under adverse ionospheric or sun-spot conditions. No height information is supplied.

VOR (VHF Omnidirectional Range) and DME (Distance Measuring Equipment) are the most common navigation aids in continental areas. VOR provides on-board information about the radial to the ground beacon. Its specification requires that the error is less than 3 degrees, but the accuracy is often much better, especially for Doppler VOR (DVOR) beacons. DME provides on-board information on the distance to the beacon, which is usually co-located with a VOR beacon. Its specified accuracy is 0.5 NM of 3 % of the distance measured (whichever is greater) but its actual accuracy with good on-board equipment generally is of the order of 200 metres.

TACAN (TACtical Air Navigation) is a military system which is similar to a combination of VOR and DME. The "DME part" is compatible with civil DME, the "VOR part" uses a higher frequency than civil VOR.

Decca is a medium-range hyperbolic system with an accuracy of about 200 metres. It is only available in parts of Western Europe.

ILS (Instrumented Landing System) defines an optimal landing trajectory by the intersection of two radio-defined flat planes: one vertical (localizer) and one at about 3 degrees to the earth's surface (glide path). The accuracy with which the line is defined is high, but the accuracy with which deviations from that line are given is very low. It is, therefore, not very useful for position measurement. MLS (Microwave Landing System), which is destined to replace ILS during the next two decades, will be much more useful in that respect. It is designed to a specification which requires an accuracy of 0.1 degree in azimuth and 0.01 degree in elevation, and a distance accuracy of about 1 % of the measured distance, all measured with respect to the antenna system on the ground near the runway threshold.

No satellite navigation systems are at present in operational use for normal navigation or flight testing. That is likely to change when the NAVSTAR GPS system, for which a few satellites are already in orbit and which is expected to be fully operational by 1989, becomes available. In Section 4.4.5 below this system is briefly described.

Two types of radar are generally available: surveillance radars used for (civil) air traffic control and lock-follow radars, mostly used for military purposes. They are described in some detail in Section 4.5.

4.4 Accurate systems based on distance measurement only

4.4.1 Introduction

The systems mentioned in Section 4.3 have been designed as aids for the normal navigation of aircraft. They will in many cases not be accurate enough for the types of testing discussed in this AGARDograph. But a few systems have been developed especially for flight testing which use the same technical principles and have a substantially higher accuracy. The multi-DME systems (Section 4.4.2) use the operational DME ground system and commercially available high-quality receivers, but provide high-accuracy position information by using several DME inputs and computer processing. Section 4.4.3 describes a system that provides a very high accuracy at much shorter range and is used for flight test purposes in the USA. In Section 4.4.4 the use of radio altimeters for measuring the height of an aircraft over runways during take-off and landing tests is described, whereby accuracies are attained which are much higher than those claimed by the manufacturers. In Section 4.4.5 some information is given about the expected use of the NAVSTAR GPS system for flight test purposes.

4.4.2 Multi-DME systems

The traditional navigation in continental areas is based on the use of VOR combined with DME. In that combination the DME is considerably more accurate than the VOR. Position measurements based on two (or more) DME measurements are, therefore, more accurate than those based on DME and VOR. Many Inertial Navigation Systems (INS) used as a primary navigation aid in modern aircraft have an update system for the INS which continuously uses two DME inputs. In the INS computer memory a list of DME position co-ordinates and frequencies is stored and the computer selects the two DME stations that are most favourably located and uses those for updating. A few low-cost navigation systems use the same method of position measurement but without the INS.

Analysis has shown that a large part of the DME errors is due to errors in the published co-ordinates of DME (and especially TACAN) beacons and to (reasonably constant) delays in the ground transponders (Refs. 42, 43). These systematic errors can be detected from an analysis of measurements during which more than two DMEs are used and corrected during the final analysis. The first system in which this was applied is the French SAVVAN system for the calibration of VORs (described in Ref. 44). The NLR has developed a similar system. It uses an INS and up to 32 DME inputs, which are scanned successively at 2-second intervals. During the final analysis the systematic errors of the DME stations are detected by statistical methods and corrected, and the trajectory is calculated. Ref. 43 describes the results of tests with that system. The report concludes that, depending on the number of DMEs that are received (i.e. altitude), the positions of the aircraft can be measured with accuracies of 20 to 50 metres.

4.4.3 Microwave Airplane Position System (MAPS)

An example of a very accurate short-range (10 km) radio position measuring system is the MAPS system developed at the request of Boeing (Refs. 45 and 46). The system can handle up to 19 ground transponders. The on-board equipment includes an airborne computer which provides real-time data. The data are also recorded on board for final data processing in a ground computer.

Each battery-powered transponder only replies after having received its unique identification code. The transponder retransmits the signal received from the aircraft with a shift in the carrier frequency. Power consumption of the ground transponders is low so that they can be left unattended for several days.

The on-board transmitter/receiver can sample 40 transponders per second. Its signal first gives the identification code of the transponder to be interrogated and then the measuring signal which consists of 4 harmonically related frequencies modulated on one carrier frequency. From each transponder return the slant range is calculated from the phase shifts of the signal frequencies and the range rate from the Doppler shift in the carrier frequency. When the responses of all transponders have been received, the computer calculates the aircraft position, velocity and direction of motion. The computer contains a Kalman filter which takes into account the time differences between the successive replies, the positions of the transponders relative to the flight path and atmospheric refraction. The software has four modes of operation:

1. The initialization mode, which includes startup, loading the data base into the computer memory from a floppy disk and, if necessary, inserting changes to the data base,
2. The preflight mode, which allows ground testing before the flight,
3. The flight operation mode, in which the Kalman filter supplies 3 components of the position and velocity vectors every 25 milliseconds. The automatic initialization of the Kalman filter can start at any moment and ensures full accuracy within a few seconds,
4. The ground tracking mode for measurements at low elevations, at which the height information supplied by the system is inaccurate. In the original design this mode was intended for tracking vehicles on the ground. Height and vertical velocity were then assumed to be zero, and only X, Y and the horizontal velocity components were calculated. In a later extension (Ref. 46) the Kalman filter was extended to use pressure altitude and/or radio altitude as additional inputs. This extension takes over from the flight operation mode when the aircraft height is less than 50 metres.

The MAPS system was originally designed mainly for use in noise measurements at heights above 50 metres. In that region the accuracy has been shown to have standard deviations of less than 0.3 metres in X, Y and Z, and standard deviations of less than 0.5 m/s in the velocity components. At heights of less than 50 metres the accuracy of the height measurement decreases sharply. In the extended MAPS system the height information is so much improved (somewhat depending on the shape of the trajectory) that the system can now also be used for autoland tests.

4.4.4 Radio altimeters

Radio altimeters play an important part in modern autoland systems and in many flight test trajectory systems such as MAPS (Section 4.4.3) and STALINS (Section 5.3.2). Many of the modern radio altimeters are manufactured to the ARINC 707 specification, which requires a range of 0 to 500 or 1000 feet, an accuracy of 0.3 metres or 2 % of the measured height (whichever is greater), a sensitivity of 2.5 cm and a time constant of less than 0.1 second. The frequencies at which the ARINC 707 radio altimeters operate are in the 4.2 to 4.4 GHz band, some mainly military radio altimeters operate at higher frequencies.

The principle of a radio altimeter is that a radio signal is sent out by the aircraft and that the earth reflection of that signal, as received in the aircraft, is compared with the transmitted signal. The result of the measurement is, in principle, only determined by the shortest distance to the reflecting surface. When a radio altimeter is used to measure height above the earth, the following errors may occur:

- If a steep incline is present near the course of the aircraft the instrument may indicate the slant range to that surface.
- The measured value may vary with the type of surface from which the signal is reflected. Measurements at the same true height over quiet water, grass or concrete may differ by a metre or more.
- In theory the radio altimeter should, at not too large angles of pitch and roll, be independent of these angles. In practice this is not completely true. Even when flying over a flat surface, the effect of an angle of pitch or roll of 15 degrees may cause an error of up to 3 % in the measured height. If very precise measurements must be made at high attitude angles, it may be useful to mount the antenna in such a way in the aircraft that it looks down vertically in the middle of the range of angles that is of interest.
- A time constant of 0.1 seconds can still cause appreciable errors when the aircraft is climbing or descending. At a climb speed of 10 m/s, which can well occur during take-off measurements, the error would be 1 metre. When this effect is important, it can be corrected during data processing.

If due account of all these error sources is taken, the errors of radio altimeters can be reduced far below the accuracy specified in the manufacturer's specification. In Ref. 47 it is shown that the difference between the height calculated by the STALINS system (Section 5.3.2) differed from the radio altitude measured over a runway by less than about 25 cm at 100 metres height if all corrections were applied. Although both measurements may have had systematic errors, it seems unlikely that they would, by chance, have been that accurately equal.

4.4.5 NAVSTAR GPS

Around 1989 the NAVSTAR Global Positioning System, that will provide around the world accurate position and velocity information (Ref. 48), will be operational. The system will consist of 18 satellites (+ 3 operational spares) in 12-hour orbits and a ground control system consisting of a master control station, five monitor stations and 4 ground antennas. The satellites are equipped with very accurate atomic clocks. The master control station continuously checks, on the basis of information from the monitor stations, the deviations of the satellites from their nominal orbit and the deviation of the atomic clock in each satellite from the master clock on the ground. That information is transmitted to the satellites every 8 hours as digital messages that are incorporated in the signals transmitted by the satellites.

Each satellite transmits two signals, L1 at 1575.42 MHz and L2 at 1227.6 MHz. Superimposed on each carrier is a coded message unique to each satellite and controlled by its atomic clock. The codes are of two types: the C/A code, which can be easily acquired but gives relatively low-accuracy position information and the above-mentioned message, and the P code, which can only be acquired if the C/A mode is received and gives high-accuracy position information. The C/A code is only transmitted on L1, the P code on both frequencies. When the system will be operational, a special signal (Y code) will be superimposed on the P code, which will make it accessible only to (military) authorized users. The C/A code will be accessible to everyone who has a suitable receiver.

The principle of NAVSTAR is as follows: a GPS receiver on the ground or in an aircraft compares the code received from a satellite with its own clock (which is of less than atomic quality) and can then calculate its apparent distance from the satellite, taking into account the information contained in the message. This distance is called the "pseudo range" because it still contains errors due to the inaccuracy of the clock in the receiver. Using the pseudo ranges from four satellites, the computer in the receiver can calculate its position in an earth-centered co-ordinate system and the error of its own clock using the following equations:

$$R_i = (X_i-X)^2 + (Y_i-Y)2 + (Z_i-Z)^2 + C.\ t_{A_i} + C\ .\ t_u \qquad (4.1)$$

where:

- R_i = the measured pseudo range to the i-th satellite
- X_i, Y_i, Z_i = the coordinates of the i-th satellite in an earth-centered coordinate system
- X, Y, Z = the (unknown) coordinates of the receiver in the same coordinate system
- t_{A_i} = the propagation delay of the signal due to ionospheric effects
- t_u = the (unknown) clock off-set of the receiver clock from the reference GPS time
- C = speed of light

The time delays due to ionospheric effects can be calculated if the P code is used. If only the C/A code is available, an approximate correction can be calculated by using a mathematical model of ionospheric effects or by using the differential method mentioned below.

For this differential method a ground station must be within radio range of the aircraft, to which the NAVSTAR information received in the aircraft is retransmitted by radio. The station also directly receives the signals from the same satellites. From these latter signals it can calculate the position errors (mainly due to ionospheric effects) in its own position by comparing them with its known position. As the aircraft will be relatively close to the ground station, the same or slightly adapted corrections can be applied to the aircraft data received by radio. This method has the additional advantage that the aircraft positions are accurately known on the ground, where they can be used for flight safety measures.

At present experimental ground stations are available and five experimental satellites are in orbit. By 1989 the system should be fully operational. User equipment with different degrees of sophistication is now under development for "authorized" and for "non-authorized" users. It is expected that, when the system is completely operational, 95 % of the calculated horizontal positions will be within 18 metres and of the heights within 32 metres with receivers using the P code. For receivers only using the C/A code these numbers will be 100 metres and 174 metres. Differential measurements are expected to improve these numbers appreciably, but no quantitative information is available yet. Further improvement of the accuracy will be possible in all cases if the successive position and velocity data are smoothed.
A review of possible applications in flight testing is given in Ref. 49.

4.5 Radars

4.5.1 General principles

In this section only ground-based radars are considered. On-board radars with terrain-following software are used for trajectory measurements in military applications, but these methods are classified and are not used for flight test purposes.

The measuring principles used in radars have been briefly mentioned in Sections 4.2.1 and 4.2.2. Two types of radar are used for trajectory measurements:

- Surveillance radars, which are in general use for military and civil air traffic purposes. The antenna rotates with a constant angular speed (usually 6 rpm) about a vertical axis. As the height information that can be obtained from a radar is not of interest for air traffic control (pressure altitude is used in aircraft navigation), the antenna pattern is a vertical sheet (elevation from about 0 to 45 degrees) with a thickness of about 1 degree. These radars provide slant range and azimuth. When used for trajectory measurements, these data must be supplemented by height data from another source, e.g. a radio altimeter or a pressure altimeter. The main characteristics of surveillance radars are discussed in Section 4.5.2.
- Lock-follow radars transmit a pencil beam with a width of about 1 degree. A target must be found by moving the antenna in a search mode until the target is detected. Then it is switched to the lock-follow mode, in which it automatically keeps the beam directed towards the target. The radar provides slant range, azimuth and elevation of the target. Lock-follow radars are mainly designed for military purposes. Their main characteristics are discussed in Section 4.5.3.

Before going into the descriptions it seems useful to define a few notions that are common to all radars. That is done in the remaining paragraphs of this section.

Primary radars transmit pulse or sinusoidally modulated signals in a narrow beam. The receiver, that is colocated with the transmitter and uses the same antenna, detects any part of that signal which is reflected back. The direction from which the strongest reflected signal is obtained is the direction to the target. The distance is calculated from the time difference between the transmittion of the pulse and the reception of the reflection of the same pulse or, in the case of a continuous-wave sinusoidal signal, from the phase angle of the transmitted and received waves.

The reflected signal received by a primary radar is weak, especially if the aircraft is far away. In secondary radar systems a transponder is available on the aircraft; when the transponder receives a signal transmitted by a radar, i.e. when a transmitter beam touches its antenna, it retransmits that signal at a different frequency and with a known time delay. The signals received back by the radar are then much stronger.

Primary radars, especially at low elevation angles, receive reflections from all kinds of stationary objects. To distinguish the reflection of an aircraft in this clutter, Moving Target Indicator (MTI) techniques have been developed (see e.g. Ref. 39 for the details). These techniques compare the reflections with those measured during previous revolutions of the radar and reject all those that have not changed position. This technique is very powerful, but can give problems in cases where, for instance, the trajectory of a stationary or nearly stationary helicopter must be measured.

4.5.2 Surveillance radars

Surveillance radars rotate about a vertical axis and only provide azimuth and slant range information. Their range usually is of the order of 90 km (terminal-area radars) or 350 to 400 km (radars for en-route surveillance). They usually combine a primary and a secondary radar on a single shaft. Transponders for the secondary radar must be on board of all aircraft that want to fly in busy terminal areas, or above 12000 feet (about 4000 m) in areas where radar air traffic control is conducted. Until recently all transponders that were touched by the radar beam immediately replied; if two aircraft were close together, the replies could overlap and become unintelligeable to the radar processor. In radars now coming into use (Mode S) this is eliminated because the radar sends out a discrete address to which only the transponder with that address responds. In the return signals from the transponders messages can be incorporated. In most cases only an identification number and the pressure altitude of the aircraft are in this message (Mode C). Messages in Mode S can be more complex.

The data from most surveillance radars are processed in digital computers, where the successive positions of the same aircraft are correlated and pass through a simple filter (plot filter). It is usually relatively easy to extract these track data from the computer. This technique has been extensively used in studies about the track keeping accuracy of aircraft in flight executed under the aegis of ICAO (see e.g. Ref. 50 and the references mentioned therein).

The accuracy of surveillance radars is usually in the order of several hundreds of metres. Studies have shown that a large part of the errors is due to systematic errors in the slant-range measurement and in the North reference direction, and to errors made by the very simple on-line plot filters when the aircraft changes its heading. In Ref. 51 measurements of a terminal area radar are reported. It is shown there that an accuracy of better than 100 metres could be obtained if the systematic errors were corrected and the data were passed through a good off-line filter.

4.5.3 Lock-follow radars

Lock-follow radars (often also called pencil-beam radars) provide azimuth, elevation and slant range of the aircraft relative to the radar. The circular beam has -3 dB at 1 degree or less from its nominal direction. Lock-follow radars consist of two separate systems, often with different antennas: a search system and a tracking system. In the search mode the radar scans a relatively large part of the sky. When it has found its target it switches to the tracking mode, in which servo systems make the beam follow the target.

The systematic errors mentioned in the discussion of surveillance radars are also present in lock-follow radars but can be more easily corrected. Before a measurement run the radar can be pointed to several towers or transponders on the ground. If the geographical positions of the radar and the towers and transponders are accurately known, the systematic errors can be determined. Accurate corrections can then be applied to the azimuth and slant range. The calibration of the elevation angle presents more difficulties: points with accurately known positions at high elevation angles usually are not available. Other sources of error during the measurement are:

- The effect of wind on the antenna, which may be significant in strong winds. It is, in practice, impossible to correct for this error.
- Atmospheric refraction, which depends on the temperature gradients in the atmosphere and on its water content. If radio-sonde data are available, corrections can be calculated which, at the short ranges mainly of interest here, are reasonably accurate.
- Ionospheric reflections, which at short ranges and relatively low heights are usually negligible. At longer ranges their effect may be minimized by using the "window" technique: the next position of the aircraft is predicted on the basis of previous measured positions and only reflections which are received during a small window around the time at which the reflection from that predicted position should come back are used in the calculation.

Even if the required measuring accuracy is so high that a radar cannot be used as the primary trajectory measuring instrument, it can have a useful function in combination with modern precision short-range measuring systems. It is then used to track the aircraft while it is beyond the measuring range of the primary measuring device and can aid that device in locking on to the aircraft as soon as it comes within its range. This can appreciably extend the practical range of the short-range system. Examples of such radar aiding have been mentioned earlier in this paper for laser theodolites (Section 3.5.2) and for the MAPS system (Section 4.4.3).

Most lock-follow radars fall in one of two classes: short-range radars with ranges of 20 to 40 km and designed for directing anti-aircraft guns, and long-range radars primarily designed for early interception of aircraft and missiles. Both can be used for measuring short-range trajectories. An example from each class is briefly discussed below.

A short-range radar that has been used for short-range trajectory measurements is the Flycatcher radar (Ref. 52). It was primarily designed as a fire-control radar against low-flying aircraft under all weather conditions. The system is easily transportable and has a range of 20 km. In the search mode a separate antenna can display the plan positions of several aircraft on a scope. The aircraft to be tracked can be selected using a joystick which moves a symbol on the scope. The tracking mode uses two frequencies, 9 MHz and 34 MHz. Both frequencies are transmitted by the monopulse technique via the same antenna, using different types of reflector grid. In the receiver the signal with the best signal-to-noise ratio is selected for further processing, with a preference for the higher frequency which provides the best accuracy. A TV camera with zoom lens (30 to 300 mm) is mounted on the antenna. Digital MTI is provided in the computer, which can detect targets flying at very low speeds (helicopters) up to Mach 3. The errors of the radar when tracking a small object are about 5 m in slant range and an angular error of about 0.3 milliradian (1 minute of arc, or 5 m at a range of 20 km). As only primary radar is available, the errors may be larger when a large aircraft is tracked, because then the point of reflection may wander across the surface of the aircraft.

A typical long-range radar is the Bearn used by the CEV in France. It is a pulse-type secondary radar with a peak power of 800 kW, in which the carrier frequency can be adjusted between 5450 and 5825 MHz in order to obtain optimal performance from individual transponders. The beam width (-3 dB) is 0.9 degrees, the pulse frequency is 585 Hz and the pulse width is 1.7 microseconds. This gives the radar a range without ambiguity from 1 to 256 km. The actual range is much farther than that, but then there is an ambiguity of multiples of 256 km. The maximum angular speeds of the radar are 1 rad/s in elevation and 0.5 rad/s in azimuth. The maximum angular acceleration is 2 rad/s^2. The accuracy is similar to that of the Flycatcher: standard deviations of 7 m in distance and 0.3 milliradian in the angles.

5. TRAJECTORY MEASUREMENTS USING INERTIAL SYSTEMS

5.1 Introduction

The term "Inertial Sensing System" (ISS) is used here for an instrument incorporating gyroscopes and accelerometers, that measures aircraft position with respect to the earth, i.e. which includes Schuler tuning. These instruments are widely used in military and civil aircraft for long-range navigation.

The use of inertial sensing systems for the measurement of short-range trajectories has appealed to flight test engineers ever since these systems came into use for long-range navigation. These instruments produce exactly what is required: aircraft positions, velocities and accelerations in horizontal and vertical directions and all three attitude angles. For the trajectory measurements there is, in principle, no requirement for ground personnel because all the equipment is mounted inside the aircraft. For aircraft where an inertial system is available for operational use, its application for trajectory measurements during tests is even more attractive.

It has, however, taken a considerable effort to develop flight test methods in which these advantages could be used economically and with sufficient accuracy. The best inertial systems that are commercially available at a reasonable cost have been designed for long-range navigation, and are of the "2 NM per hour" drift category (if no external updating is used). The velocities and positions which these systems provide as direct outputs are not sufficiently accurate for the types of measurement discussed in this AGARDograph. More accurate systems are made, but they are extremely expensive and their availability is limited by military restrictions. Methods have now been developed by which the errors of inertial systems of the "2 NM per hour" category can be corrected to such a degree that they are fully applicable for short-range trajectory measurements. These methods and the applications based on them are the subject of this chapter.

There are, in principle, two types of inertial sensing systems that can be considered for use in these tests: stable platforms and strap-down inertial systems. In stable platforms the gyros and accelerometers are mounted on a platform which is maintained horizontal by the system itself, in strap-down systems they are mounted to the aircraft construction. Although the general operation of these two systems, and their basic equations, are very similar, there are a few practical differences:

- Of the systems that are at present commercially available, the platforms seem to provide slightly more accurate velocities and positions. That may be partly due to the fact that the environment in which the gyros and accelerometers must operate is more severe in a strap-down system, because they are subject to higher angular displacements, angular velocities and linear and angular accelerations. But another important reason is that most of the strap-down systems have been specifically designed for use with continuous DME-DME updating (so that some drift can be tolerated), while most of the present-day platforms have been designed for use during long periods without updating.
- Most commercial platforms have synchro outputs for pitch and roll angles, which have an accuracy of about 0.1 degree. Pitch and roll rates must be calculated by differentiation of those outputs, which are usually provided at relatively low frequencies (order of 6 samples/second). Most strap-down systems use rate gyros for the angular measurements. The accuracy of the pitch and roll measurements, and especially of the angular rates from strap-down systems is, therefore, usually considerably higher than those from platforms.
- Strap-down systems are expected to become considerably less costly than platforms of similar performance in the future. At present the price differences are small.

In most short-range trajectory measurement applications platforms are used. That may be partly due to their better position accuracy, but it must also be realised that most of these methods of measurement were developed at a time when strap-down systems were not yet available. For applications where the accuracy of the angular and angular rate measurements is critical, as in the method described in Section 5.3.5, strap-down systems are used.

In recent years many flight test methods have been developed in which trajectory measurements using ISS play a main part. A number of these are briefly described in Section 5.3. They include applications in take-off and landing performance measurement (Sections 5.3.1 and 5.3.2), flight testing of radio navigation aids (Sections 5.3.3 and 5.3.4) and measurement of aircraft performance and stability in non-stationary flight (Section 5.3.5).

Before these applications are described, Section 5.2 will give a brief review of the essential characteristics of inertial systems for those tests and of the methods of "updating" that are used to exploit these to the high accuracies that can be achieved.

5.2 Principles

5.2.1 ISS error characteristics

It is not the purpose of this section to give a detailed description of inertial sensing systems. There is an extensive literature on that subject, from which Ref. 53 is mentioned here because it treats the subject from the point of view of flight testing. This section will concentrate on those aspects of platform operation and platform errors that are of primary importance for the methods of short-range trajectory measurements discussed later in this chapter.

During the pre-flight alignment procedure of an inertial platform the accelerometers are accurately aligned along and perpendicular to the direction of the local vertical, the North direction is determined by the platform computer from the effect that the rotation of the earth has on this process, and the geographic position of the aircraft is manually entered into the computer. At the end of the alignment period the platform outputs will be correct with high precision, providing accurate starting conditions for the measurements. From that moment the platform will, in principle, remain aligned parallel to the local horizontal at every point of its trajectory and the North direction will be available in the platform computer.

The platform outputs used for trajectory measurements are the geographic position, the horizontal velocities in the North and East directions, the integral of vertical acceleration, the aircraft pitch, roll and heading angles and, if available as outputs, the accelerations along three mutually perpendicular axes (one of which the local vertical). These outputs will with time develop errors, which are caused by the accumulated effects of drift in accelerometers and gyros, errors in the entered position co-ordinates of the point where the platform was aligned, rounding errors in the platform computer, errors in the earth model used, etc. The error equations of an ISS are complex, with a large number of parameters that vary in a complex way during flight (see, for instance, Ref. 53). In general terms, however, it is possible to summarize the characteristics that are of primary importance for short-range trajectory measurements as follows:

- The ISS outputs accurately reproduce small disturbances in the aircraft trajectory. The dynamic response of the system is high enough to follow all motions of the aircraft.
- Most errors vary about sinusoidally with time with a period of about 84 minutes (the Schuler period), a few at even lower frequencies. This means that, even though the errors themselves may be large, their rate-of-change is very low.

All methods for the measurement of short-range trajectories which use inertial sensing systems are designed to exploit these characteristics as well as possible. They use "updates" from other sources to correct the errors at a few points during each test and can then use the platform outputs with very much simplified error equations. For tests with a duration of the order of 1 minute or less, it may even be assumed that the ISS errors remain constant for the duration of the test run. Then one update per test run will suffice. For tests of longer duration (but still short with respect to the Schuler period), more than one update per test run is used, in combination with simplified and linearized error equations for the ISS. The accuracy of the trajectories obtained from these method then depends on the short-term accuracy of the platform outputs and the accuracy of the updates. These aspects will be discussed in some detail in the next two sections.

5.2.2 Short-term accuracy of ISS outputs

As stated earlier, most of the methods described here use inertial stable platforms of the "2 NM per hour drift" category, which have been designed for long-range navigation of aircraft. In practice, the overall drift rates of these platforms will be somewhat lower than the 2 NM per hour in their specification. The drift rate can often be lowered somewhat more if selected accelerometers and gyros are mounted in the platform. The short-term accuracy and stability of the platform outputs is then mainly determined by the accuracies of the accelerometers and angular measurements, and by the accuracy of the calculations in the platform computer.

In inertial platforms of that category very accurate accelerometers are used. The zero offset stays within about 5×10^{-4} m/s² and the average slope of the calibration curve is correct to within 10^{-4}. For the test durations of a few minutes considered here, the stability will often be better (Ref. 47). An important characteristic for tests in which the platform is subject to heavy vibrations (such as for instance take-off and landing tests) is the linearity of the acceleration output. Nonlinearity will cause rectification of vibration accelerations, which causes an offset in the low-frequency response of the accelerometer.

The Schuler tuning trips to keep the platform aligned perpendicular to the local vertical. In practice the platform will oscillate about sinusoidally about this position with an amplitude of the order of 0.005 degrees with the Schuler period of 84 minutes. Due to this extremely small angle the effect of these oscillations on the vertical acceleration and its integrals is negligible. This is not true for the horizontal channels. The importance of this will be illustrated by an example. If the amplitude of the Schuler motion of the platform is 0.0035 degrees, the amplitude of the error in the horizontal acceleration caused by the component of gravity will be about 0.0006 m/s², in the horizontal velocity 0.5 m/s and in the horizontal position about 400 m. This is due to the long duration of the Schuler period. It will, therefore, be clear that updating is absolutely essential, even if no extreme accuracies are required.

The accuracy of the pitch and roll outputs of the platform are, in principle, only limited by the (very small) uncertainty on the horizontality of the platform (order of 0.005 degrees). In commercially available platforms the accuracy is limited by the fact that the platform angles are usually measured by synchros or resolvers with an accuracy of about 0.1 degree. In the application described in Section 5.3.5, where a higher accuracy was required, this was the reason for using a strap-down inertial system, together with a dedicated data processing in a ground computer. This allows a better exploitation of the full potential accuracy in that case.

The North direction known to the platform computer will, in general, drift slowly with time. During the first few hours after alignment the error will generally stay within 0.1 degree, which is sufficient for most short-range trajectory measurement applications. For take-off and landing measurements, where often many runs are made during one "test flight", it may be useful to realign the platform about every two hours.

The accuracy of the calculations in the platform computer also plays a role in many test applications. In principle, all data processing can be done in a separate flight test computer, either off-line or in real time, either on the ground or in the aircraft. Such data processing should then use as its inputs the measured accelerations and the measured pitch, roll and heading angles. With an ISS a different approach is often taken. The accelerations must be sampled at a rather high rate, in order to avoid errors (including aliasing of vibrations in the aircraft) and digital acceleration outputs of that type are usually not provided in commercially available platforms. It has, therefore, advantages to use the integrations in the platform computer to obtain velocity or position outputs, which are available and for which the sampling rates of the platform outputs usually are sufficient for further use in the trajectory calculation.
In practice, the velocity outputs of the platform are often used, as the normal position outputs are often rounded and will not provide sufficient accuracy.

The accuracy of the horizontal channels of a platform is sufficient for use in short-range trajectory measurements if suitable updates are used to correct for the Schuler errors. To achieve sufficient accuracy in the vertical channel can cause more problems. There are three reasons for that:

- For some types of measurements, such as take-off and landing measurements, the accuracy in the vertical direction must be significantly higher than that in the horizontal directions (see Section 5.3.2). Then the absolute accuracy of the accelerometer is approached and small effects like temperature changes can significantly affect the accuracy.
- The horizontal accelerations that must be measured are close to zero and the small uncertainty in the slope of the calibration curve then has little effect on the accuracy. The vertical acceleration varies around 1 g and a deviation from the nominal slope of 10^{-4} there causes an error of 10^{-3} m/s², which after double integration over 60 seconds produces an error of 1.8 metres. Such errors must be determined by very accurate update methods.

- For purposes of normal navigation, for which most of the platforms have been designed, the accuracy of the vertical channel is of less interest. For reasons of economy the vertical accelerometer and its integration circuit are often manufactured to a somewhat lower quality than those of the horizontal channels. Often no Coriolis correction is applied in the vertical channel, which must then be applied during processing.

A curious example of problems that can occur in a vertical channel can be given here as a warning: In a platform that had been in general use for long-range navigation for many years, rounding errors of considerable magnitude occurred in the vertical channel when the vertical acceleration differed from 1 g. This had never been detected until the platform was evaluated for application in short-range trajectory measurements.

In summary it can be said that the (partial) use of the calculations in the platform usually has important advantages, but that some care should be taken, especially as regards the vertical channel.

5.2.3 Update procedures

Update techniques have been applied ever since inertial systems came into use for long-range navigation. Re-alignment of a platform during short stops on the ground has always been a standard procedure to maintain the best accuracy. Manual updating in flight, using visual cues or radio beacon information, can ensure a good accuracy to the end of very long flights. Automatic in-flight updating has more recently become a standard feature for long-range navigation. For flights over continental areas the double-DME or VOR/DME updating is a standard feature in modern navigation (see e.g. Ref.54) and flight management systems and global systems using inputs from NAVSTAR GPS are in an advanced stage of development.

These techniques do not attain the accuracies that are required for precise short-range trajectory measurements. For those applications a variety of special updating techniques has been developed, some of which are described in some detail in Section 5.3. The choice of the best technique depends on 3 criteria:

- The accuracy that is required
- The duration of the test run
- The type of update that can be most easily obtained.

When assessing the effect of the duration of the test on the accuracy, it must be realized that some types of error (e.g. errors in the calibration of the accelerometer) have a quadratic effect on the calculated distances. For tests of very short duration (order of 1 minute) the use of a single update per test run for each parameter is often sufficient (see e.g. Section 5.3.1). For tests with a duration of several minutes (i.e. still short with respect to the Schuler period), more than one update per test run is generally necessary (Section 5.3.3).

The type of update is generally chosen such that it can be obtained without too much effort. For take-off and landing tests the periods of standstill before a take-off or after a landing can be conveniently used for updating. The update information is then obtained from the measured velocities and/or accelerations during standstill. If the nature of the test does not allow one or more periods of standstill per test run, then other sources for updating must be found. Sections 5.3.3 to 5.3.5 show how this was done in specific cases.

If a single update in each of the co-ordinate directions is used per test run, their introduction into the data processing must be based on the assumption that the error remains constant for the duration of the test run. If two updates per test run are obtained, as in the method of Ref. 34 described in Section 5.3.4, then the obvious assumption to use is that the error in the updated parameter varies linearly with time for the duration of the test run. Other assumptions are possible: if it is expected that a constant error in the acceleration caused the difference between the calculated position and the update, then a quadratic change of a distance error with time must be assumed.

If more than one or two updates per test run are available, as in the methods described in Sections 5.3.3 and 5.3.5, more complex statistical processes of trajectory reconstruction may be used to obtain optimal results. In those methods the (linearized) error equations of the platform and the update information are incorporated in the trajectory reconstruction algorithm. There is an extensive literature on such methods, of which Ref. 55 is a good example. In practice, the methods of reconstruction can be divided into two groups: batch methods and recursive methods. In the batch methods all data are simultaneously used to reconstruct the trajectory in an off-line computer processing. The recursive processes, of which the Kalman filter is the best-known example, use each data point in sequence to improve and extend the trajectory estimate that was based on all previous data points. They are, in principle, real-time methods, but the first trajectory estimate can be further improved by an off-line reversed processing run (fixed-interval Kalman filter/smoother). The Kalman filter technique is used in most of the applications reviewed for this AGARDograph. A good discussion of these techniques is given in Ref. 56. Ref. 57 compares the results of processing the same data by a batch method and a Kalman filter method; it is shown that the results themselves and the computer times required are very similar.

5.3 Examples of trajectory measurements using ISS

5.3.1 Take-off and landing tests with F-16

Reference 58 describes how an inertial platform was used for the flight testing of the F-16 aircraft. The Delco Caroussel ISS, that is used in many civil and military aircraft as the primary navigation system, was slightly modified for application in flight testing. The main modification was that the vertical acceleration could be obtained as an output parameter. The report on its use in take-off and landing performance measurements will be briefly summarized here.

The updating was done once for each test run: during standstill before each take-off and after each landing. Updates were obtained for the horizontal velocities and positions, and for the 1 g value of the vertical acceleration. These provided the integration constants for the trajectory calculation, in which computations by the platform computer were used where available.

Reference 58 does not give values for the accuracy that was achieved. It is stated, however, that "every comparison that has been made between these results and phototheodolite data have shown virtually identical results".

5.3.2 The STALINS method for take-off and landing trajectory measurement

This method (Ref. 17 and 47) was developed by the NLR in response to a request for a method for the measurement of take-off and landing trajectories which should replace the nose camera method used at that time. The new method should meet the following requirements:

- It should be applicable on non-instrumented airfields,
- It should meet the requirements for the certification of civil transport aircraft. The main requirements were quantified as follows:
  - The standard deviation of the error in the measured distance along the runway from standstill to the point where the aircraft reaches 11 metres height (take-off) or from 15 metres height to standstill (landing) should be within 0.1 % of that distance,
  - The standard deviation of the height error over those same distances should be within 0.15 metres,
  - The measurement of distance and height should continue until the aircraft reaches a height of 100 metres (with reduced accuracy),
- Final results should be available within 24 hours from delivery of the flight tapes to the data processing station.
- It should be as far as possible independent of weather conditions (especially light rain).

When preliminary tests had shown the feasibility of ISS measurements for this purpose, an evaluation was made using a platform that had been in service for many years for long-range navigation, the Litton LTN-58. The platform does not provide accurate acceleration outputs, so the calculations are based on the velocity outputs. It was found that the horizontal distances can be calculated with sufficient accuracy using the velocity updates at standstill: that velocity value is subtracted from the velocities measured during the test run and these are then integrated. For the short duration of the test run (less than one minute) the rate of change of the Schuler motion can be neglected, though the computer program allows a (relatively time-consuming) correction if required.

Preliminary tests of the height measurement showed that using only the period of standstill to establish the vertical update cannot provide the required accuracy. The main reason is that the period of standstill after a landing is restricted for operational reasons to 3 seconds. During that brief period it is impossible to measure the rate of change of the "integral of vertical acceleration" with the high accuracy required. A rather elaborate, but effective, method was developed to solve this problem. The period for establishing the vertical update is not restricted to standstill only, but also includes the ground run. During that period the actual height of the platform is calculated from the height profile of the runway (previously established by survey methods), with corrections for the pitch angle of the aircraft (measured by the platform) and the change in the length of the undercarriage (measured by an accurate radio altimeter). This actual height is compared with the double integral of the vertical acceleration in a second-order least-squares process. The coefficients of the second-order correction equation are then also used as the update during the remainder of the test run.

In order to determine the correct value of the runway height from the measured profile, the measured horizontal distance along the runway (which is in the first instance integrated from the point of standstill) must be transformed to the runway co-ordinates in which the runway height profile has been measured. That is done using a small radio beacon that is placed beside the runway at a point of which the runway co-ordinates are known. A receiver in the aircraft produces a marker in the on-board recording at the moment the aircraft passes that beacon.

Data processing of the magnetic tapes recorded on board is done in a ground computer and is fully automated. The computer determines the points of standstill, the duration of the ground run and the time the radio beacon was passed, and from these calculates the trajectory and the components of the velocity and acceleration in three directions.

In a series of over 200 take-offs and landings this method has been compared with other methods, mainly the nose camera method. The results (Ref. 47) show that the above-mentioned requirements are met. The method, now with a slightly modified Litton LTN-76 platform, will be used in the near future for the certification of new aircraft in the Netherlands.

5.3.3 The DFVLR methods of trajectory measurement

The German research institute DFVLR has developed several methods for measuring somewhat longer trajectories (duration of several minutes) using updated ISS data. The first version was used for the flight evaluation of the MLS version developed in Germany (Ref. 53, Section 8.3). The updates were obtained from measurements with kinetheodolites and, at greater distances, from a tracking radar. For the height measurements pressure altitude was also used as an update. Data processing was done in a ground computer using a Kalman filter which contained a simplified version of the platform equations of motion. The overall accuracy was about the same as that which could have been achieved with kinetheodolites alone, but the inclusion of a platform in the system had a number of important advantages:

- The kinetheodolite data were processed at 8-second intervals, instead of the one or two pictures per second that would otherwise have to be processed. This meant a very significant reduction in the data processing time,
- Small disturbances in the aircraft trajectory, that were important in the analysis for which the trajectory measurements were made, were shown more precisely,
- The trajectory beyond the range of the kinetheodolites, which was of interest, though with lower accuracy requirements, could be reconstructed more accurately.

A further development of that system is described in Ref. 59. The Kalman filter now receives data from a platform, a laser tracker and a precision radar. Data processing is fully automated. Using up/down telemetry and computers with periferals both in the aircraft and on the ground, on-line displays of the trajectory data are possible both in the aircraft and on the ground. Final (off-line) processing in a ground computer will improve the accuracy of the results.

5.3.4 Flight inspection of ILS and VOR

During a flight inspection of an ILS or VOR the aircraft flies certain prescribed trajectories. The signals received from the beacons are compared with the aircraft position. If the signals are outside specified limits, the beacon electronics on the ground must be readjusted and then the flight procedure must be repeated. Real-time processing of the data is, therefore, essential for reducing the time during which the aircraft must remain available.

Until recently the flight calibrations were mainly based on the use of optical tracking methods. The flight procedures and the methods of measurement are described in Ref. 29. The methods were cumbersone and prone to errors. The new inertial technology and the recent possibilities of on-board computing have made much more efficient methods possible. These methods not only provide more timely and accurate real-time results, but the inertial system, when coupled to the autopilot of the flight inspection aircraft, also allows more accurate flying of the prescribed trajectories. Two such modern methods will be briefly discussed here: one which is already in use with the FAA for some years (Ref. 60) and one which became operational in the Netherlands in 1983.

The calibration of VORs in both methods is very similar to the SAVVAN method described in Ref. 44, but an inertial sensing system is included in the on-board system. The updates are obtained from several DME stations in the neighbourhood of the VOR that is calibrated. In both newer methods data processing is done in real time, using an on-board computer. Ref. 43 gives an analysis of the accuracy that is obtained by the Netherlands method of VOR calibration. For calibrating ILS both methods use the same principle: the aircraft trajectory is obtained from the ISS, corrected by updates at both thresholds of the runway for which the ILS must be calibrated. In the FAA method (Ref. 60) the moment at which the aircraft passes the threshold and its lateral deviation from the ideal flight path are observed visually and the height is measured by a radio altimeter. After each test run the visually obtained parameters are entered into the on-board computer, which then immediately presents the results of that test run. The method, which is already in use with the FAA for several years, is said to give great satisfaction. No accuracy figures have been published.

The method used in the Netherlands is similar in principle, but is further automated. At each threshold of the runway, for which the ILS must be calibrated, two corner reflectors (see Fig. 26) are placed, one on each side of the runway. The light from two rows of infra-red sources mounted on the aircraft is reflected by the corner reflectors. At the moment the aircraft passes a threshold, the reflected infra-red light is thrown on an array of photocells mounted on the aircraft. The positions of the corner reflectors on the ground are entered into the on-board computer before the flight starts. From the outputs of the individual photocells the computer can then calculate the height of the aircraft and its deviation from the ideal line at the moment it passed the threshold. That information is then used to update the platform position measurements, which are then compared with the received ILS signals. The computer presents the results of each test run immediately after the aircraft has passed the second threshold. The data are also recorded for detailed analysis on the ground. A description of an early version of this system is described in Ref. 34. In Ref. 61 the results of extensive tests are given.

Similar systems are being designed in other countries. Ref. 62 describes a French approach.

5.3.5 Performance and stability measurement in non-stationary flight

In the previous examples mentioned in this chapter the updates were used to obtain a more accurate trajectory with respect to the earth. In the method described in Ref. 63 and 64 the update procedure is used to calculate the best trajectory with respect to the air surrounding the aircraft during flight. The object of the method is to determine the complete lift-drag polar curve of an aircraft in one particular configuration from a single test run of 2 to 3 minutes. The manoeuvre starts by flying the aircraft horizontally at the minimum practicable airspeed and then selecting the desired power setting. The aircraft accelerates at a constant rate of 0.5 to 1 m/s^2 through its complete speed range; the acceleration is kept constant by the pilot by controlling the pitch angle. The aircraft is then decelerated back to low speed and horizontal flight.

The performance calculations are made for the closely controlled accelerated part of the manoeuvre only. The accelerations measured by the (strap-down) ISS are proportional to the forces acting on the aircraft along the 3 body axes. The aerodynamic forces acting along the body axes are then calculated by subtracting the engine thrust components, using the information supplied by the manufacturer (these tests are usually executed with specially calibrated engines). The lift and drag values must then be calculated by transforming the aerodynamic forces to the air-flow axis system, using the incidence and slip angles. As the values of these angles that can be obtained by normal methods, such as vanes, are too inaccurate, a method based on trajectory measurement is used.

The principle of this method, which is called the flight-path reconstruction method, is that the trajectory as calculated from the ISS is updated using accurate height and airspeed measurements corrected for lag in the tubing and for position error. A Kalman filter/smoother algorithm is used to obtain the trajectory with respect to the surrounding air by an optimal combination of inertial and pressure inputs. The incidence and slip angles can then be determined as the differences between the attitude angles and the flight path angles, and these are used for calculating lift and drag.

As the instrumentation used for these tests must have a large dynamic range and a high sampling rate, the flight-path reconstruction method can also be used to calculate stability and control derivatives from aircraft responses to specially designed control inputs. For further details see Ref. 63 and 64.

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APPENDIX 1

THE RUNWAY CO-ORDINATE SYSTEM

The height of an aircraft is defined as the (vertical) distance of the aircraft to a (curved) plane, in general mean sea level. The climb performance of an aircraft is related to the rate of increase of potential energy with respect to an equipotential plane of gravity. For the short distances involved in take-off and landing measurements, these two planes can be assumed to coincide. Therefore, the co-ordinate system used in the calculations should have an XZ plane which is vertical through the centre line of the runway, and the XY plane should be a curved plane that is horizontal at every point, i.e. it should follow the curvature of the earth.

For this reason, the runway co-ordinate system for take-off and landing performance calculations should be defined as shown in figure 31. The X-axis is curved and follows the runway centre line, the Z distance is measured along the local vertical at every point. The Y-axis should, in principle, be curved also. As the Y distances during take-off and landing measurements are generally small, the Y-axis can for convenience be defined as a straight line without introducing significant errors. The origin of this Lambert I co-ordinate system is usually chosen as the point of intersection of the runway centre line with one of the runway thresholds.

Figure 32 illustrates (not to scale) the importance of using the correct co-ordinate system. There, in addition to the Lambert I X-axis, are shown two possible straight X-axes: one which is horizontal at the origin of the co-ordinate system (system 1) and one which passes through both thresholds of a 3000 m runway (system 2). The differences in height are shown in figure 33. It will be seen that they are quite large with respect to the accuracies that must be achieved. In the horizontal plane the differences are negligible.

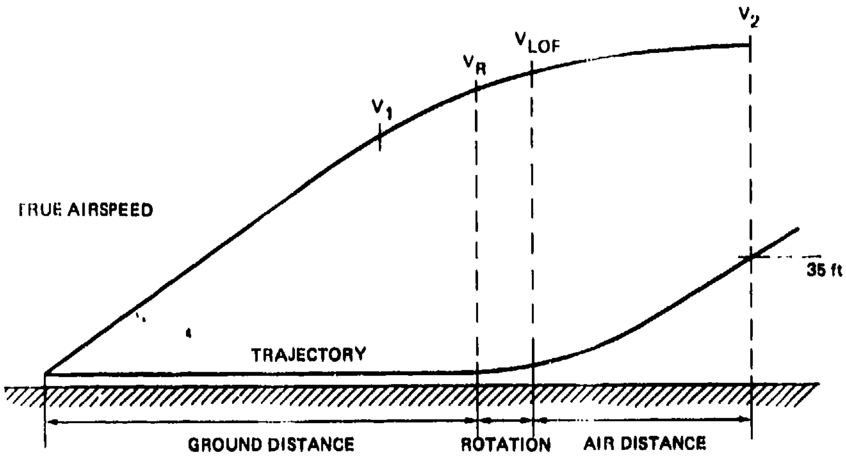


Fig. 1 The speed and trajectory schedule for a take-off

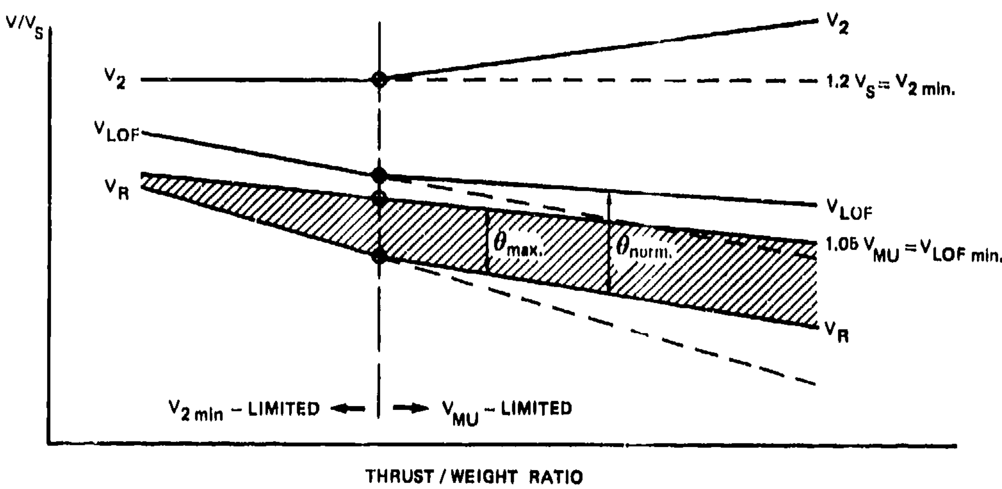


Fig. 2 Relations between several speed values for a take-off schedule

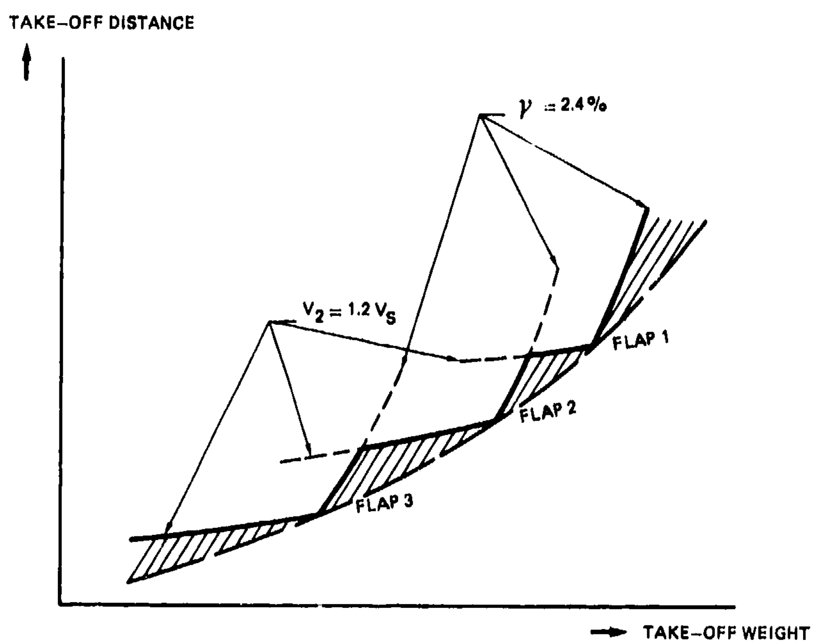


Fig. 3 Limitations of the take-off distance if only 3 flap settings are available

DEMONSTRATION AND CERTIFICATION TEST	PERFORMANCE REQUIREMENTS					DATA TURN-AROUND TIME	DC-10 TEST SITE
	RANGE (FT)	TIME-OF-DAY	SAMPLING RATE (S/SEC)	ACCURACY			
				POSITION (FT)	VELOCITY (FT/SEC)		
Take-off performance							
Take-off acceleration	10,000	early morning	5	±2	±0.5	overnight	EAFB, YUMA and Colorado Springs
Continuous take-of	10,000	early morning	5	±2	±0.5	overnight	EAFB, YUMA and Colorado Springs
Rejected take-off	10,000	early morning	5	±2	±0.5	overnight	EAFB and YUMA
Landing performance air distance	10,000	early morning	5	±2	±0.5	overnight	EAFB and YUMA
Ground distance	10,000	early morning	5	±2	±0.5	overnight	EAFB and YUMA
Thrust reverser effectiveness	10,000	early morning	5	±1	±0.2	overnight	EAFB and YUMA
Minimum unstick speed - Vmu	10,000	early morning	10	-	±0.5	overnight	EAFB and YUMA
Flyover noise	30,000	day and night	2	±5	±2	12-24 hrs	YUMA and San Diego
Radio altimeter (height)	10,000	daylight	10	±1	-	overnight	YUMA Accuracy
Area nav. accuracy verification	80,000	day or night	10	±50	-	overnight	YUMA
Cat. III landing performance	10,000	daylight	5	±1 (offcenter)	-	overnight	YUMA,PMD,SMF OAK,SCK,LS
ILS beam definition	80,000	day or night	20	±5	-	1-2 days	YUMA
Flare profile	10,000	day or night	20	±2	-	1-2 days	YUMA
Wind shear during autoland	20,000	daylight	10	-	±1	1-2 days	YUMA

Fig. 4 Tracking requirements for commercial aircraft flight development (copied from Ref. 16)

SYSTEM	PERFORMANCE PARAMETERS					MOBILITY	RELIABILITY	COST CONSIDERATIONS			
	VISIBILITY REQUIRED	SAMPLING RATE (S/SEC)	TRACKING RANGE (NM)	PRECISION				OPERATIONAL MAN-LOADING	DATA PROCESSING MAN-LOADING	DATA TURN-AROUND DAYS	APPROXIMATE INVESTMENT
				HORIZONTAL POSITION (FT)	FLIGHT VELOCITY* (FT/SEC)						
On-board camera (ground reference required)	Daylight and clear (night using runway lights)	6	1–2	3–4	1–2	Mounted on ACFT	Good	1	3	1–2	$ 10,000
Ground cine-theodolite (min 3 sites)	Daylight and clear	4	15–20	1–15	0.5–5	Permanent installation	Excellent	7	Test range task	10–30	Test range equipment
Take-off and landing photo theodolite (2 sites)	Daylight and clear	4	3–6	2–10	1–4	Permanent installation	Excellent	2	4	2–10	Test range equipment
Mobile photo theodolite (1 site) (asumes ACFT on runway center)	Daylight and clear	10	2–3	5–30	2–4	1–2 day preparation	Good	1	3	1–3	$ 30,000
Douglas laser tracker (retro reflector A800 on ACFT)	Day or night (limited visibility)	100	10–15	1–3	0.5–1	Mobile 1–2 day preparation	Average pre-flt verification necessary	2	1	minutes	$300,000

* Numerical smoothed velocity data.

Fig. 5 Comparison of tracking systems for commercial aircraft flight development (copied from Ref. 16)

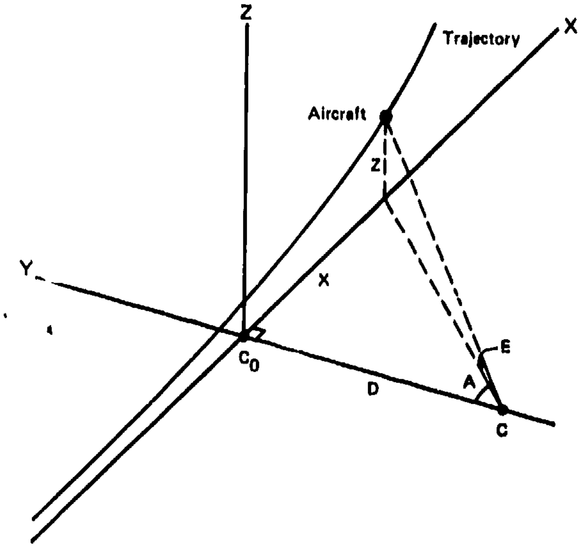


Fig. 6 Measurement of a take-off trajectory using a single kinetheodolite

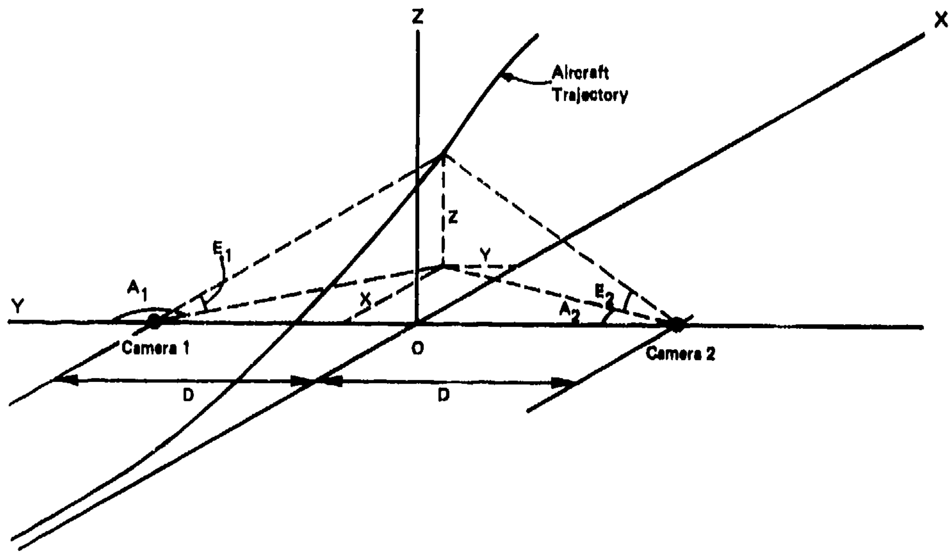


Fig. 7 Measurement of an aircraft trajectory using two kinetheodolites

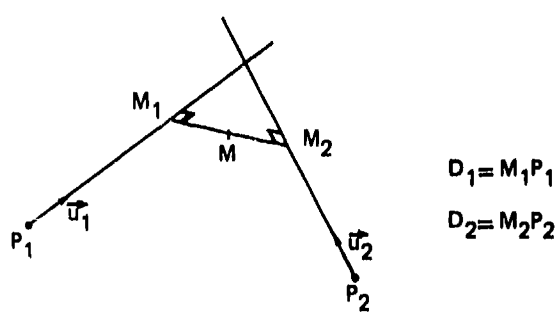


Fig. 8 Definition of parameter in Eq. 3.2.5

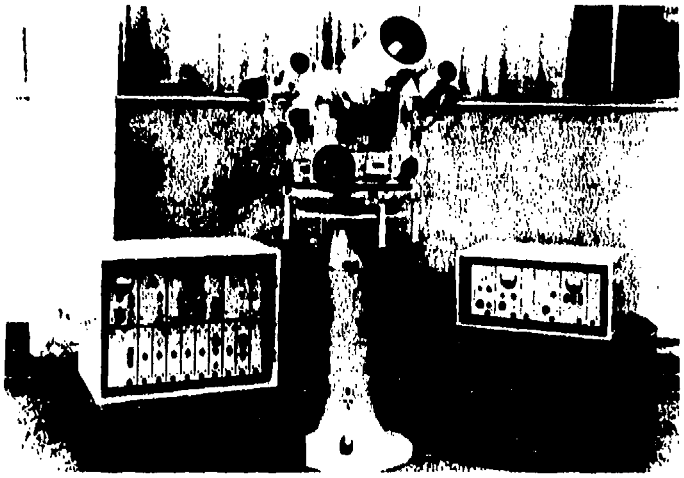


Fig. 9 An Askania kinetheodolite with (right) its control unit and (left) the command station

Fig. 10 The use of a telescope of an Askania kinetheodolite

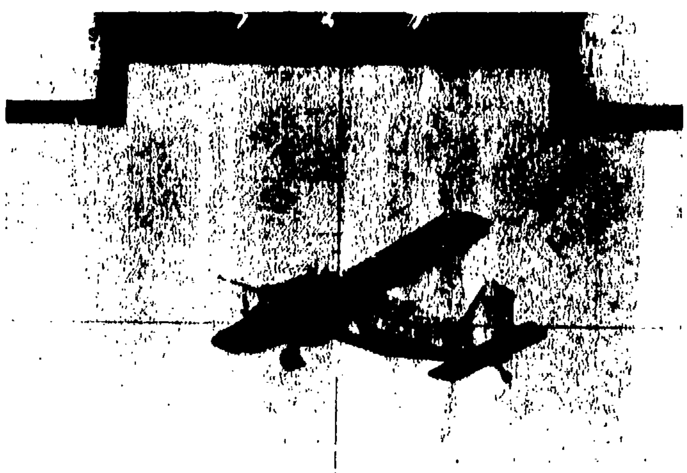


Fig. 11 Picture of an Askania kinetheodolite; it is picture number 747, the left scale indicates an azimuth of 38.79 grads, the right scale an elevation of 23.63 grads

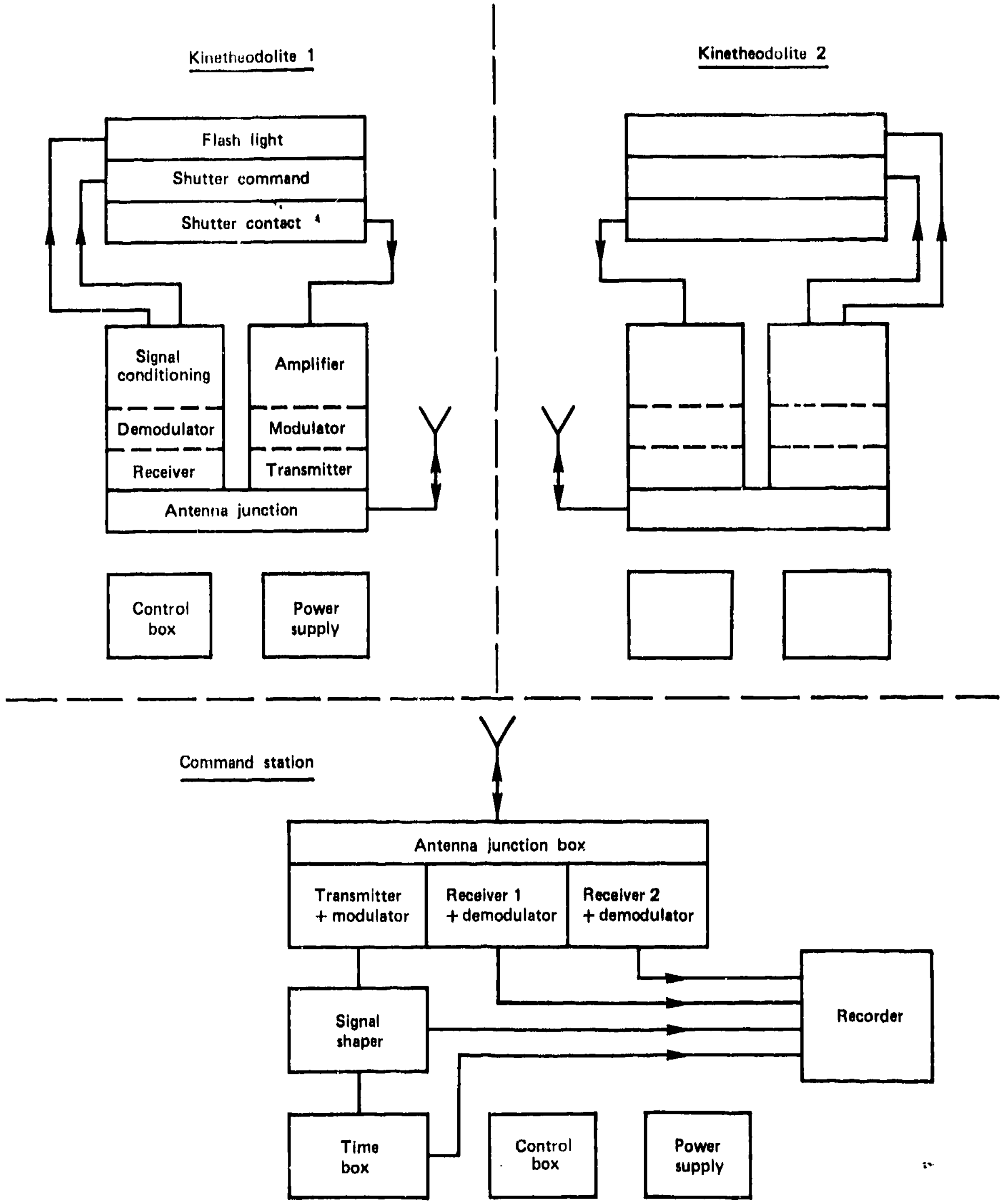
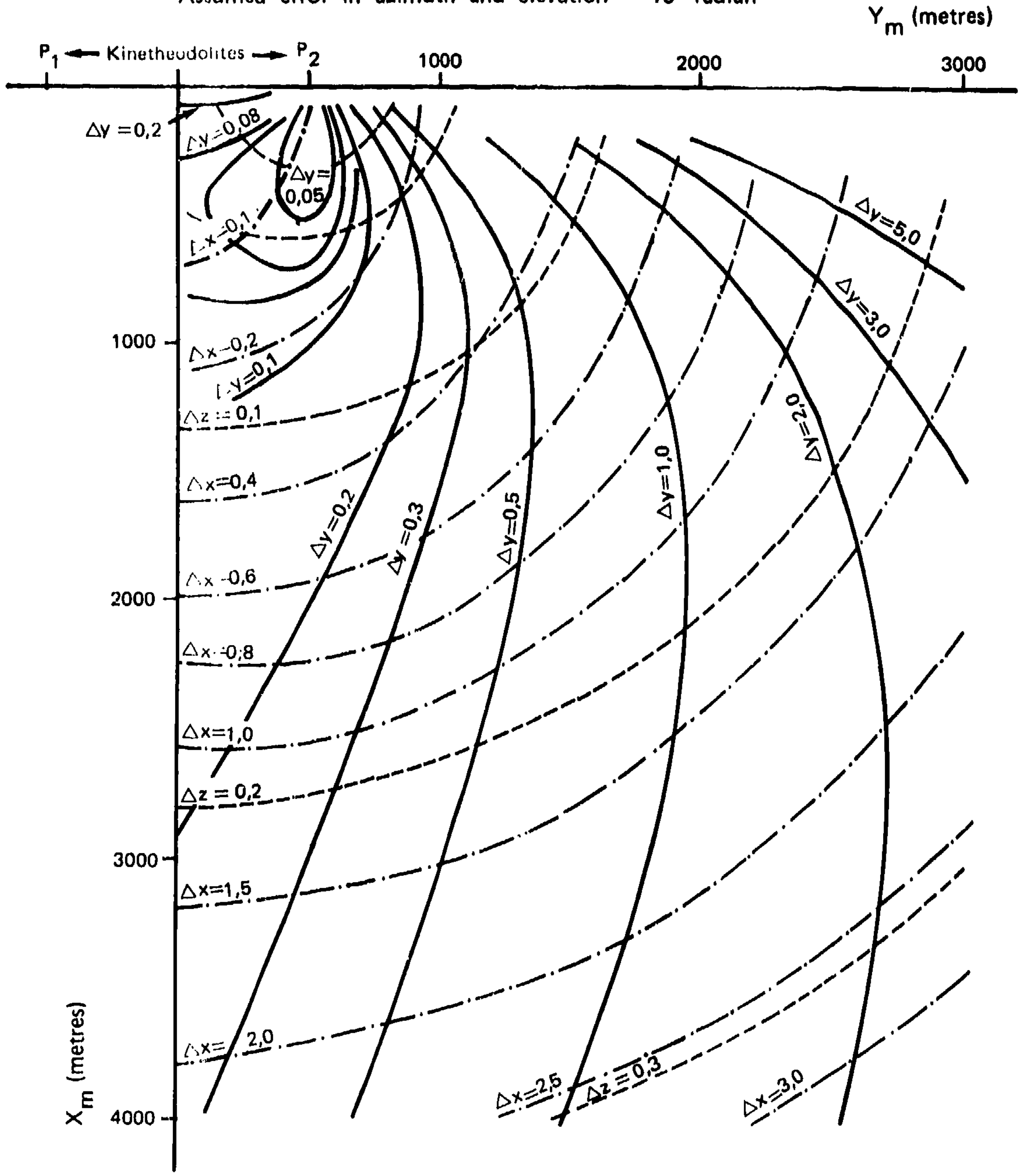


Fig. 12 Block diagram of a setup with two kinetheodolites connected to the command station by radio

Distance between kinetheodolites	1000 m
Height of target above kinetheodolites	0 m
Assumed error in azimuth and elevation	10^{-4} radian



—·—·Lines of constant error Δx in the direction of the x–axis

——— Lines of constant error Δy in the direction of the y–axis

– – – –Lines of constant error in height Δz

Fig. 13 Typical graph showing kinetheodolite errors for fixed values of the distance between the kinetheodolites (1000 m), height of the target (0 m) and assumed angular errors (10^{-4} radian)

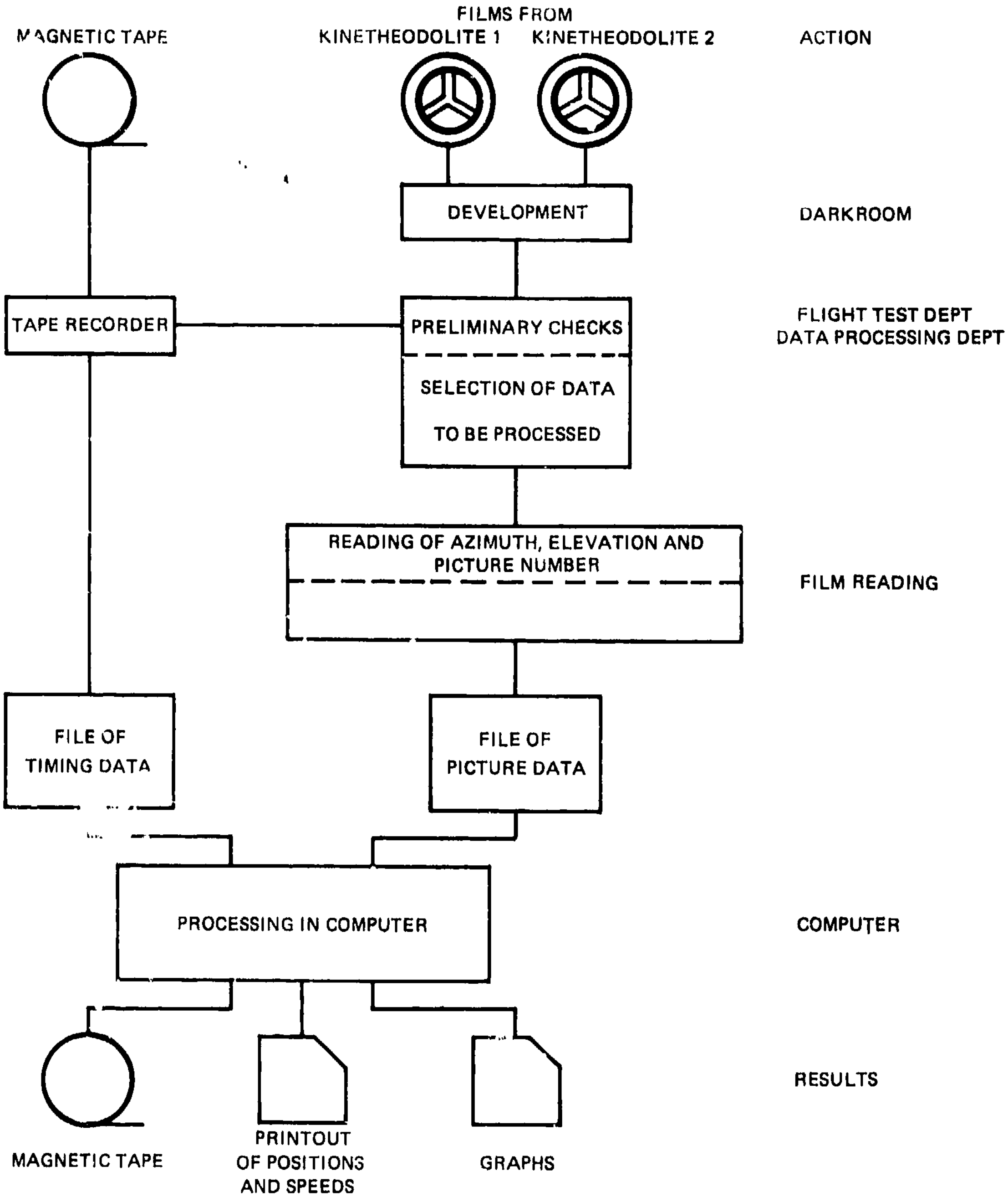


Fig. 14 Block diagram of kinetheodolite processing

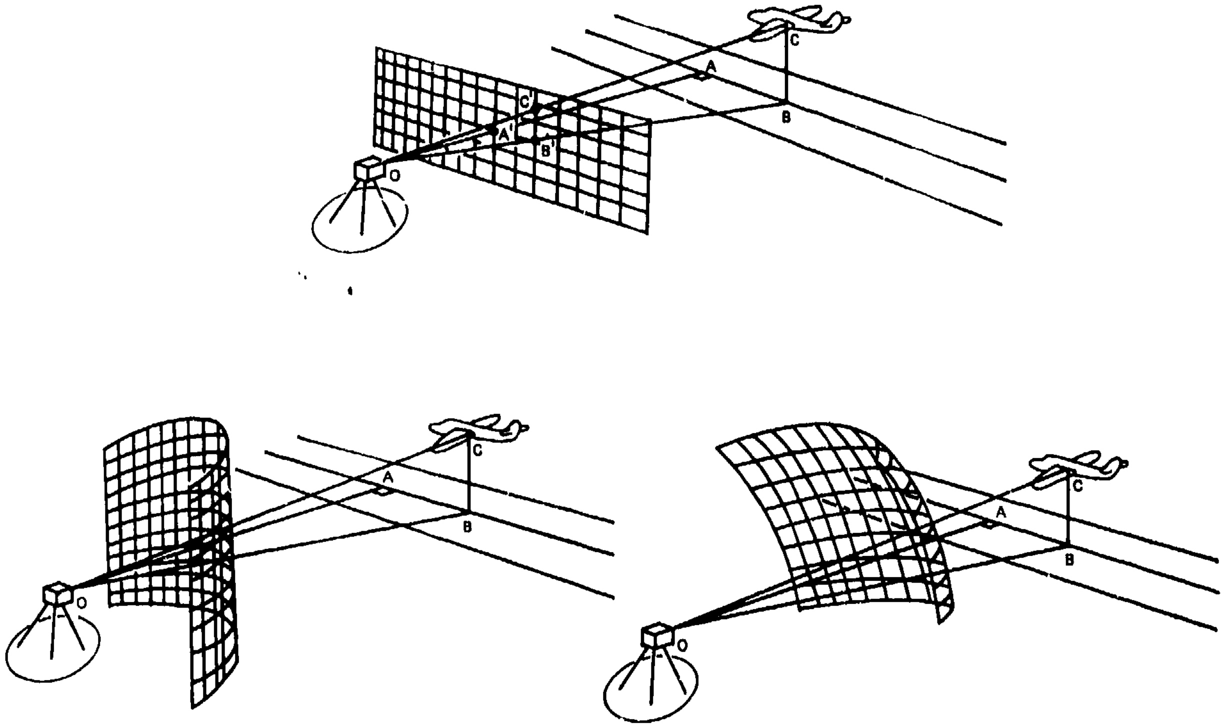


Fig. 15 Cameras photographing through a plane, a cylindrical and spherical grid

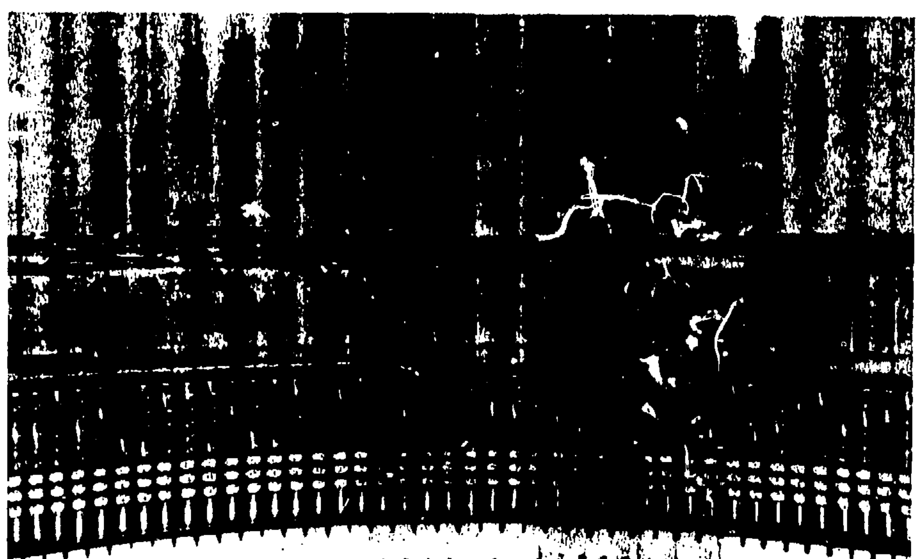


Fig. 16 Example of a picture of the Fairchild FDF A-044 camera

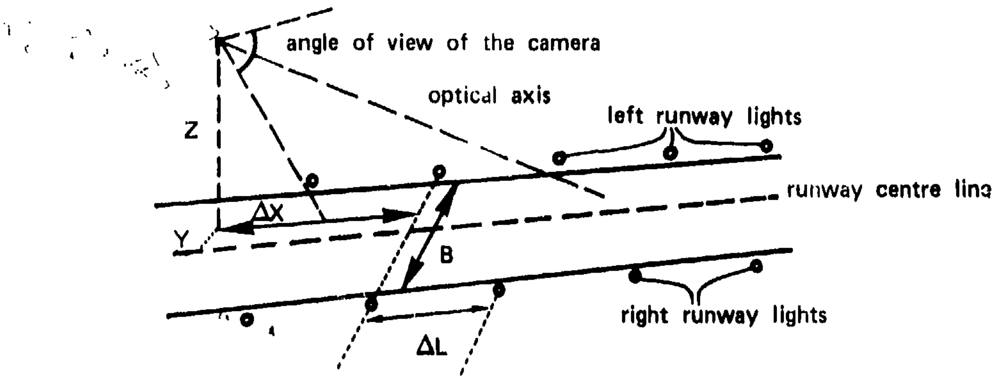


Fig. 17 Principle of the nose camera method

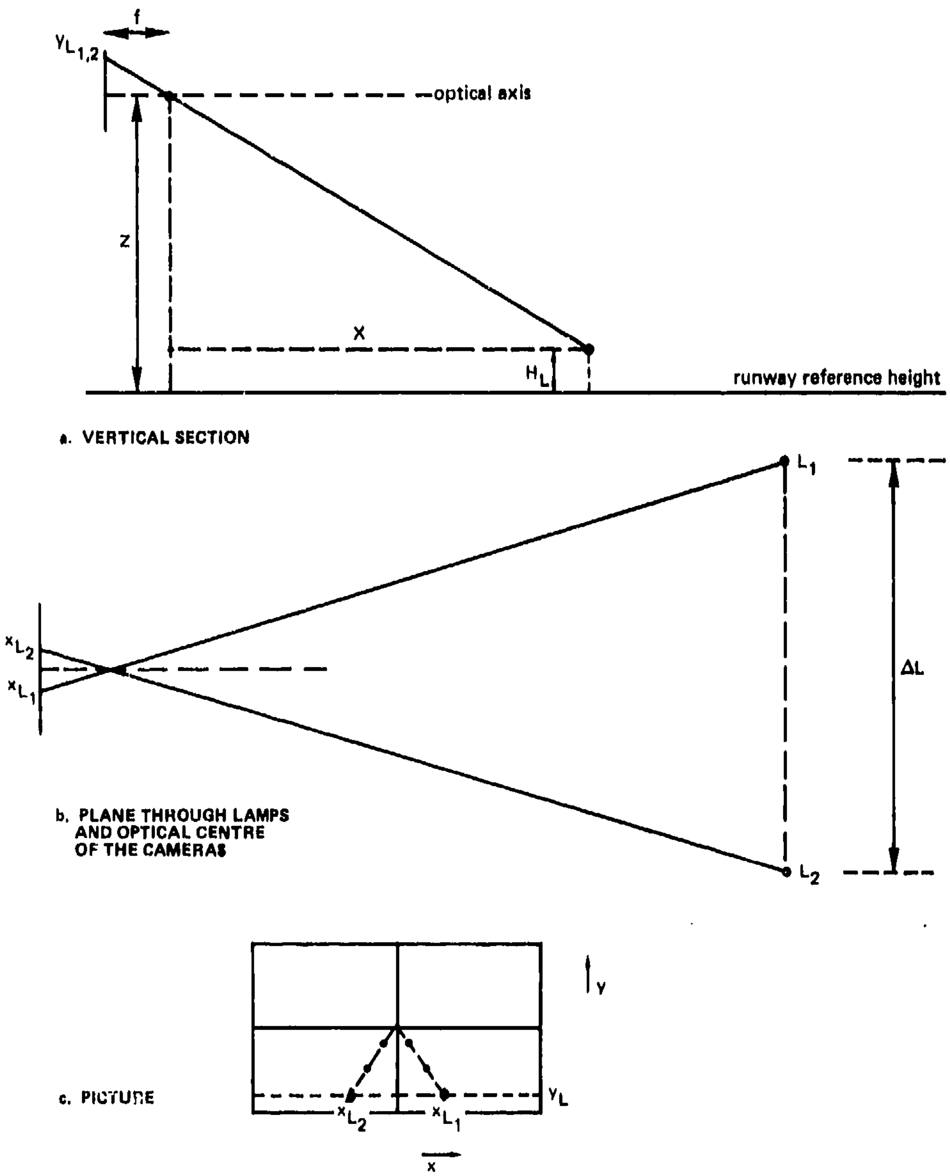


Fig. 18 Optical schematics and film picture of a nose camera if θ, φ, ψ and Y are zero

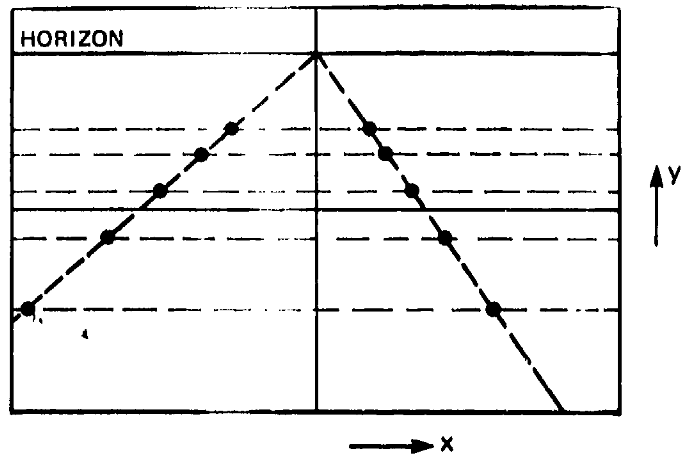


Fig. 19 Nose camera picture for the case that φ and ψ are zero, Y is non-zero

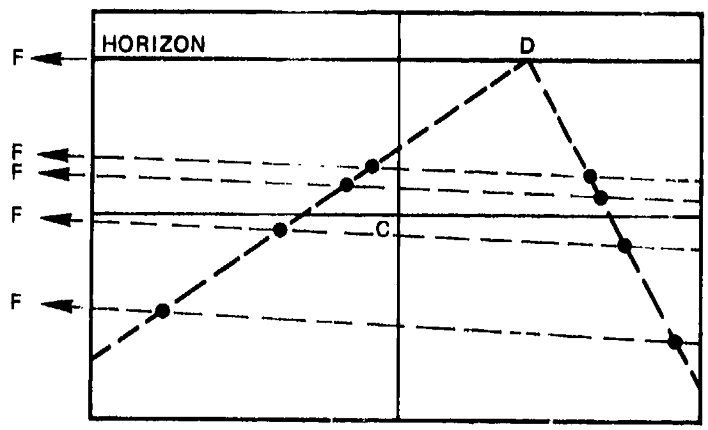


Fig. 20 Nose camera picture for the case that φ = 0 and ψ = 10 degrees

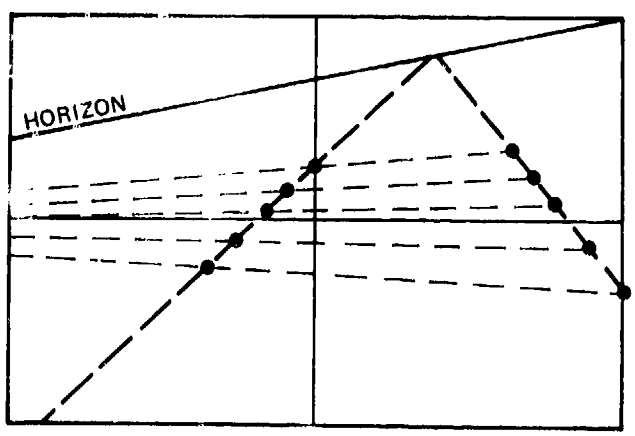


Fig. 21 Nose camera picture for the case that both φ and ψ are 10 degrees

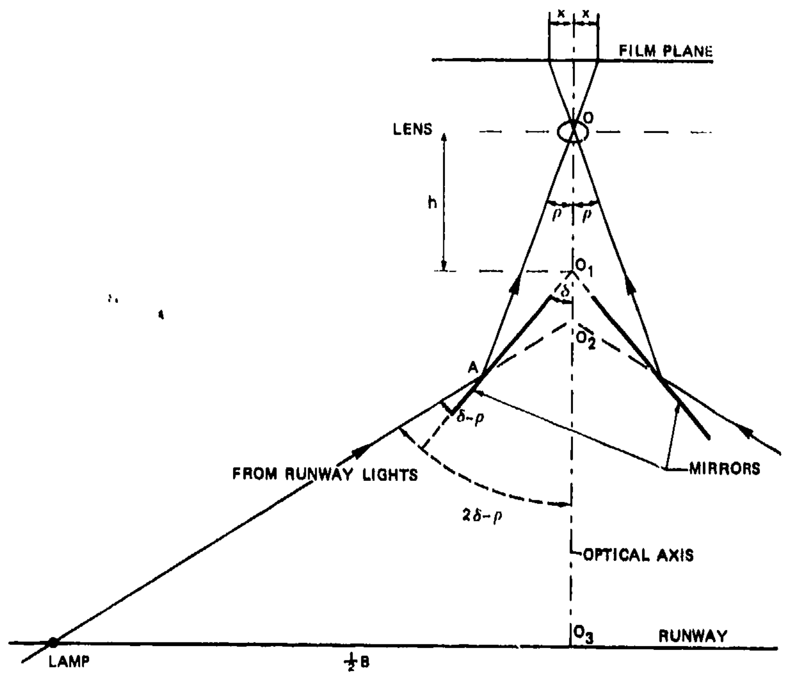


Fig. 22 Principle of the side-looking on-board camera

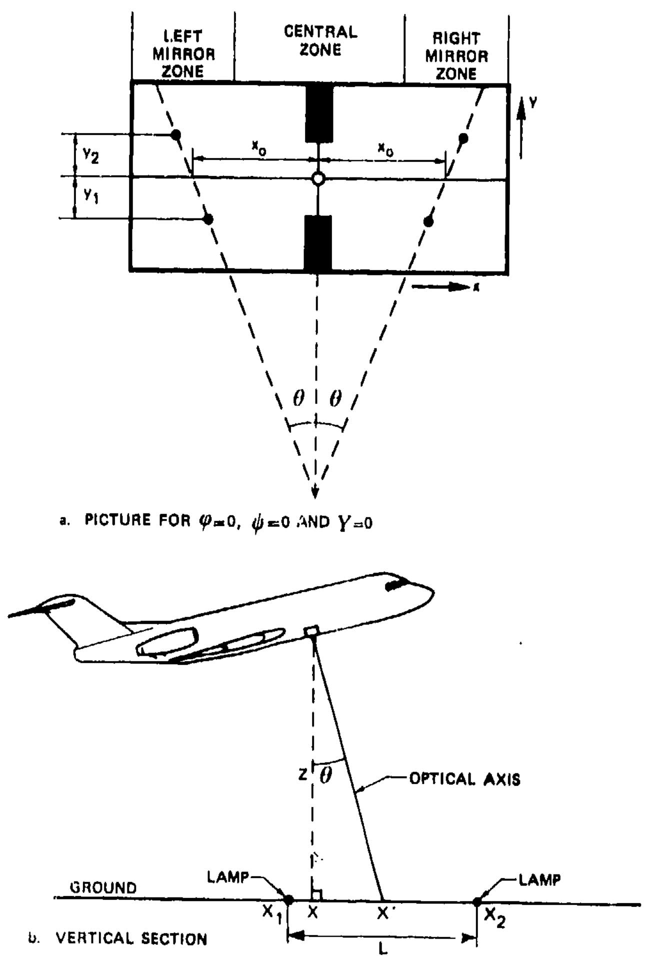


Fig. 23 Picture and simplified calculation for the side-looking on-board camera

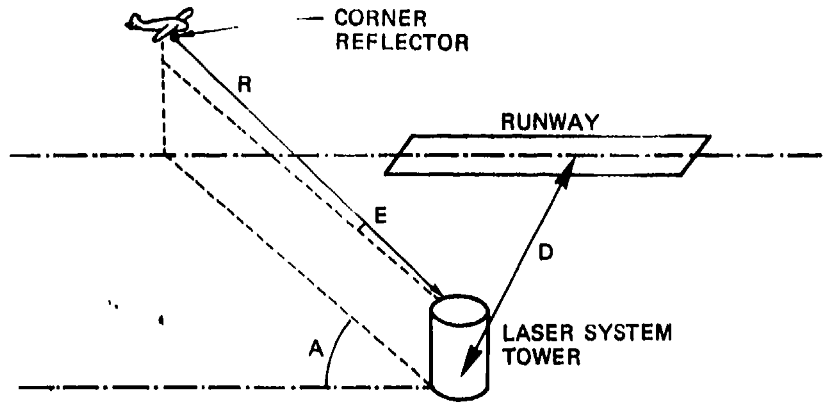


Fig. 24 Basic setup of a trajectory measurement system using a laser

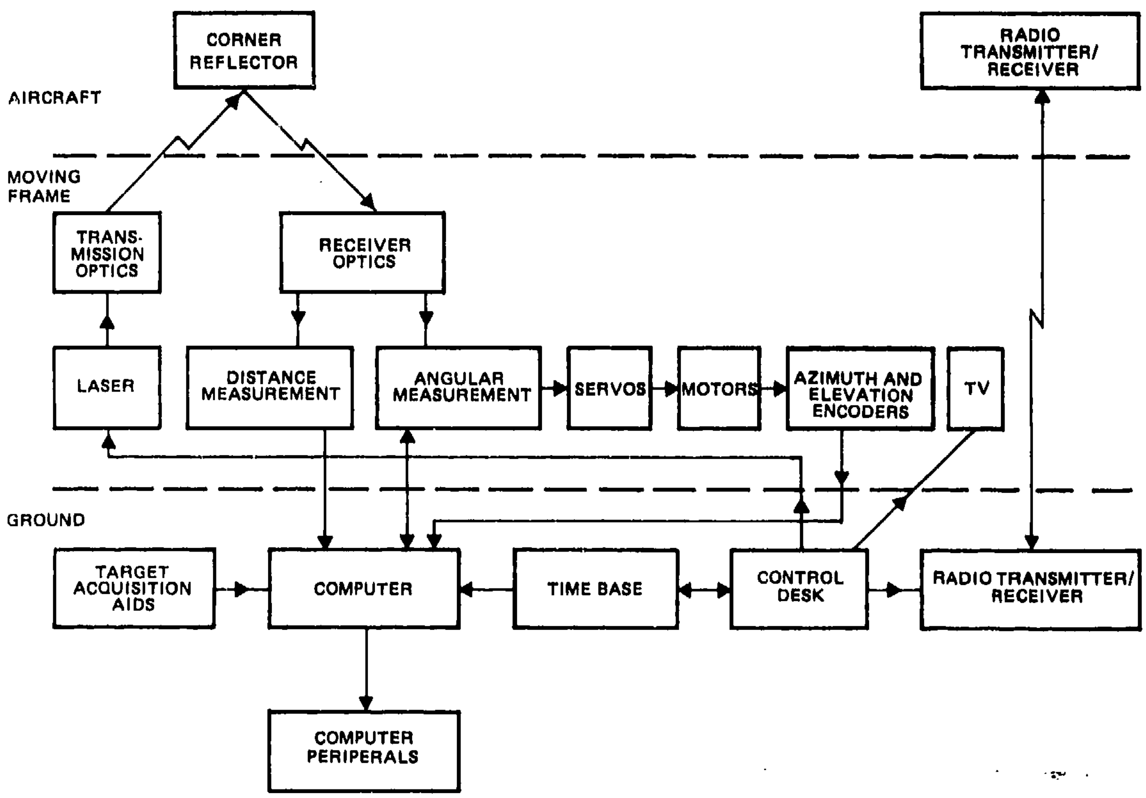


Fig. 25 Block diagram of a trajectory measuring system using a laser

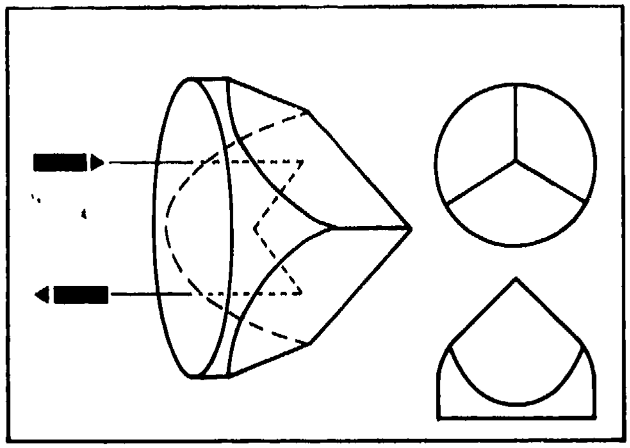


Fig. 26 Principle of a corner reflector

Fig. 27 A block of corner reflectors as used for the STRADA laser tracker

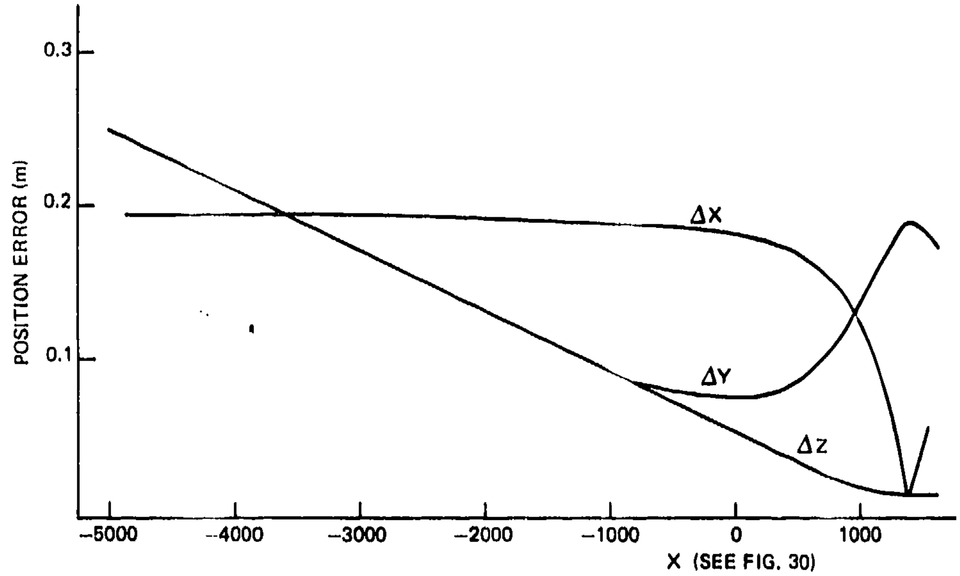


Fig. 28 Typical position errors of a laser tracker

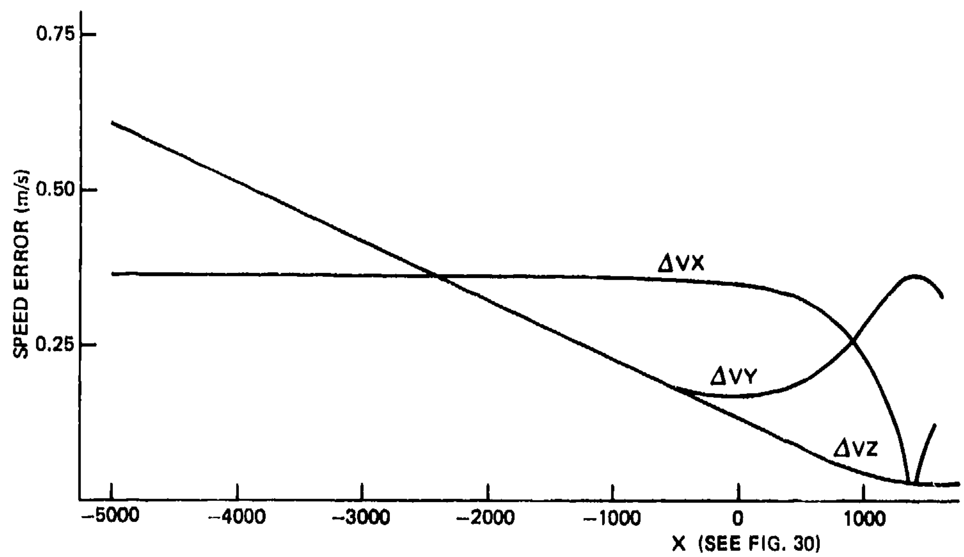


Fig. 29 Typical overall speed errors of a laser tracker

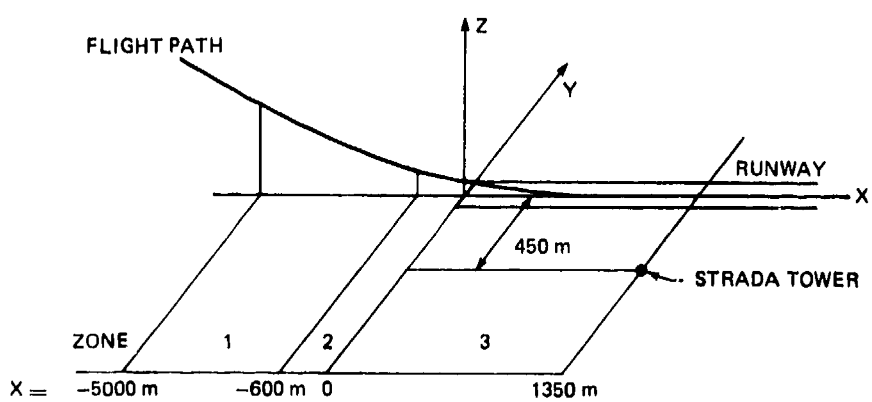


Fig. 30 Definition of axes and zones for trajectory measurements with laser

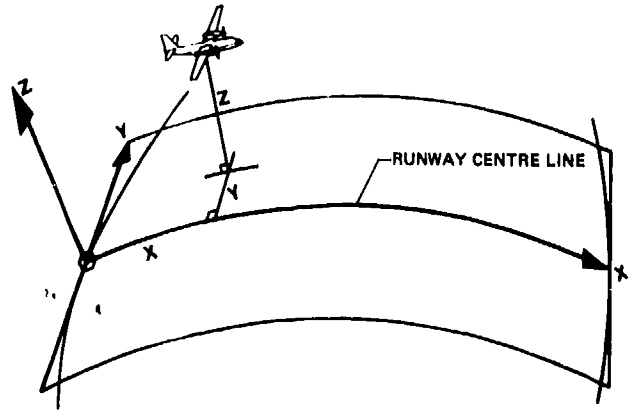


Fig. 31 The Lambert I co-ordinate system for take-off and landing measurements

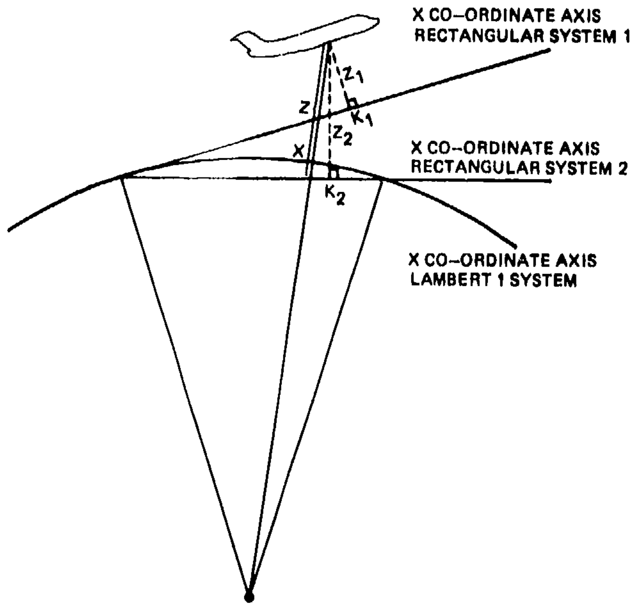


Fig. 32 The X and Z co-ordinates of the three co-ordinate systems discussed in the Appendix

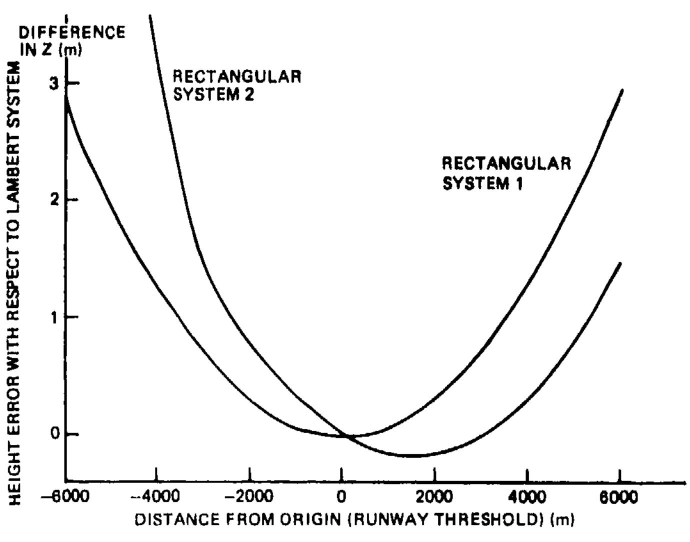


Fig. 33 Errors in aircraft height for the two rectangular co-ordinate systems

Annex 1

AGARD FLIGHT TEST INSTRUMENTATION AND FLIGHT TEST TECHNIQUES SERIES

1. Volumes in the AGARD Flight Test Instrumentation Series, AGARDograph 160

Volume Number	*Title*	*Publication Date*
1.	Basic Principles of Flight Test Instrumentation Engineering by A.Pool and D.Bosman	1974
2.	In-Flight Temperature Measurements by F.Trenkle and M.Reinhardt	1973
3.	The Measurement of Fuel Flow by J.T.France	1972
4.	The Measurement of Engine Rotation Speed by M.Vedrunes	1973
5.	Magnetic Recording of Flight Test Data by G.E.Bennett	1974
6.	Open and Closed Loop Accelerometers by I.McLaren	1974
7.	Strain Gauge Measurements on Aircraft by E.Kottkamp, H.Wilhelm and D.Kohl	1976
8.	Linear and Angular Position Measurement of Aircraft Components by J.C.van der Linden and H.A.Mensink	1977
9.	Aeroleastic Flight Test Techniques and Instrumentation by J.W.G.van Nunen and G.Piazzoli	1979
10.	Helicopter Flight Test Instrumentation by K.R.Ferrell	1980
11.	Pressure and Flow Measurement by W.Wuest	1980
12.	Aircraft Flight Test Data Processing — A Review of the State of the Art by L.J.Smith and N.O.Matthews	1980
13.	Practical Aspects of Instrumentation System Installation by R.W.Borek	1981
14.	The Analysis of Random Data by D.A.Williams	1981
15.	Gyroscopic Instruments and their Application to Flight Testing by B.Stieler and H.Winter	1982
16.	Trajectory Measurements for Take-off and Landing Test and Other Short-Range Applications by P.de Benque d'Agut, H.Riebeek and A.Pool	1984

At the time of publication of the present volume the following volumes were in preparation:

Flight Test Instrumentation Analog Signal Conditioning
by D.W.Veatch

Microprocessor Applications in Airborne Flight Test Instrumentation
by M.Prickett

2. Volumes in the AGARD Flight Test Techniques Series

	Title	*Publication Date*
AG 237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes will be published as a sequence of Volume Numbers of AGARDograph 300.

Volume Number	*Title*	*Publication Date*
1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A.Lawford and K.R.Nippress	1983
2.	Identification of Dynamic Systems by R.E.Maine and K.W.Iliff	1984

At the time of publication of the present volume the following volumes were in preparation:

Identification of Dynamic Systems. Applications to Aircraft
Part 1: The Output Error Approach
by R.E.Maine and K.W.Iliff

Identification of Dynamic Systems. Applications to Aircraft
Part 2: Nonlinear Model Analysis and Manoeuvre Design
by J.A.Mulder and J.H.Breeman

Flight Testing of Digital Navigation and Flight Control Systems
by F.J.Abbink and H.A.Timmers

Determination of Antenna Pattern and Radar Reflection Characteristics of Aircraft
by H.Bothe and D.Macdonald

Stores Separation Flight Testing
by R.J.Arnold and C.S.Epstein

Techniques and Devices Applied in Developmental Airdrop Testing
by H.J.Hunter

Aircraft Noise Measurement and Analysis Techniques
by H.H.Heller

Air-to-Air Radar Flight Testing
by R.E.Scott

Use of Airborne Scientific Computers in Flight Test Techniques
by R.Langlade

Flight Testing under Extreme Environmental Conditions
by C.L.Hendrickson

Annex 2

AVAILABLE FLIGHT TEST HANDBOOKS

This annex is presented to make readers aware of handbooks that are available on a variety of flight test subjects not necessarily related to the contents of this volume.

Requests for A&AEE documents should be addressed to the Technical Information Library, St Mary Cray. Requests for US documents should be addressed to the DOD Document Centre (or in one case, the Library of Congress).

Number	*Author*	*Title*	*Date*
NATC-TM76-ISA	Simpson, W.R.	Development of a Time-Variant Figure-of-Merit for Use in Analysis of Air Combat Maneuvering Engagements	1976
NATC-TM76-3SA	Simpson, W.R.	The Development of Primary Equations for the Use of On-Board Accelerometers in Determining Aircraft Performance	1977
NATC-TM77-IRW	Woomer, C. Carico, D.	A Program for Increased Flight Fidelity in Helicopter Simulation	1977
NATC-TM77-2SA	Simpson, W.R. Oberle, R.A.	The Numerical Analysis of Air Combat Engagements Dominated by Maneuvering Performance	1977
NATC-TM77-1SY	Gregoire, H.G.	Analysis of Flight Clothing Effects on Aircrew Station Geometry	1977
NATC-TM78-2RW	Woomer, G.W. Williams, R.L.	Environmental Requirements for Simulated Helicopter/ VTOL Operations from Small Ships and Carriers	1978
NATC-TM78-1RW	Yeend, R. Carico, D.	A Program for Determining Flight Simulator Field-of-View Requirements	1978
NATC-TM79-3SA	Chapin, P.W.	A Comprehensive Approach to In-Flight Thrust Determination	1980
NATC-TM79-3SY	Schiflett, S.G. Loikith, G.J.	Voice Stress Analysis as a Measure of Operator Workload	1980
NWC-TM-3485	Rogers, R.M.	Six-Degree-of-Freedom Store Program	1978
WSAMC-AMCP 706-204	–	Engineering Design Handbook, Helicopter Performance Testing	1974
NASA-CR-3406	Bennett, R.L. and Pearsons, K.S.	Handbook on Aircraft Noise Metrics	1981
..	–	Pilot's Handbook for Critical and Exploratory Flight Testing. (Sponsored by AIAA & SETP - Library of Congress Card No.76-189165)	1972
	..	A&AEE Performance Division Handbook of Test Methods for Assessing the Flying Qualities and Performance of Military Aircraft. Vol.1 Airplanes	1979
A&AEE Note 2111	Appleford, J.K.	Performance Division: Clearance Philosophies for Fixed Wing Aircraft	1978

Number	Author	Title	Date
A&AEE Note 2113 (Issue 2)	Norris, E.J.	Test Methods and Flight Safety Procedures for Aircraft Trials Which May Lead to Departures from Controlled Flight	1980
AFFTC-TD-75-3	Mahlum, R.	Flight Measurements of Aircraft Antenna Patterns	1973
AFFTC-TIH-76-1	Reeser, K. Brinkley, C. and Plews, L.	Inertial Navigation Systems Testing Handbook	1976
AFFTC-TIH-79-1		USAF Test Pilot School (USAFTPS) Flight Test Handbook. Performance: Theory and Flight Techniques	1979
AFFTC-TIH-79-2		USAFTPS Flight Test Handbook. Flying Qualities: Theory (Vol.1) and Flight Test Techniques (Vol.2)	1979
AFFTC-TIM-81-1	Rawlings, K., III	A Method of Estimating Upwash Angle at Noseboom-Mounted Vanes	1981
AFFTC-TIH-81-1	Plews, L. and Mandt, G.	Aircraft Brake Systems Testing Handbook	1981
AFFTC-TIH-81-5	DeAnda, A.G.	AFFTC Standard Airspeed Calibration Procedures	1981
AFFTC-TIH-81-6	Lush, K.	Fuel Subsystems Flight Test Handbook	1981
AFEWC-DR 1-81		Radar Cross Section Handbook	1981
NATC-TM71-1SA226	Hewett, M.D. Galloway, R.T.	On Improving the Flight Fidelity of Operational Flight/ Weapon System Trainers	1975
NATC-TM-TPS76-1	Bowes, W.C. Miller, R.V.	Inertially Derived Flying Qualities and Performance Parameters	1976
NASA Ref. Publ. 1008	Fisher, F.A. Plumer, J.A.	Lightning Protection of Aircraft	1977
NASA Ref. Publ. 1046	Gracey, W.	Measurement of Aircraft Speed and Altitude	1980
NASA Ref. Publ. 1075	Kalil, F.	Magnetic Tape Recording for the Eighties (Sponsored by: Tape Head Interface Committee)	1982

The following handbooks are written in French and are edited by the French Test Pilot School (EPNER Ecole du Personnel Navigant d'Essais et de Réception ISTRES – FRANCE), to which requests should be addressed.

Number EPNER Reference	*Author*	*Title*	*Price (1983) French Francs*	*Notes*
2	G.Leblanc	L'analyse dimensionnelle	20	Réédition 1977
7	EPNER	Manuel d'exploitation des enregistrements d'Essais en vol	60	6ème Edition 1970
8	M.Durand	La mécanique du vol de l'hélicoptère	155	1ère Edition 1981
12	C.Laburthe	Mécanique du vol de l'avion appliquée aux essais en vol	160	Réédition en cours
15	A.Hisler	La prise en main d'un avion nouveau	50	1ère Edition 1964

Number EPNER Reference	Author	Title	Price (1983) French Francs	Notes
16	Candau	Programme d'essais pour l'évaluation d'un hélicoptère et d'un pilote automatique d'hélicoptère	20	2ème Edition 1970
22	Cattaneo	Cours de métrologie	45	Réédition 1982
24	G.Fraysse F.Cousson	Pratique des essais en vol (en 3 Tomes)	T 1 = 160 T 2 = 160 T 3 = 120	1ère Edition 1973
25	EPNER	Pratique des essais en vol hélicoptère (en 2 Tomes)	T 1 = 150 T 2 = 150	Edition 1981
26	J.C. Wanner	Bang sonique	60	
31	Tarnowski	Inertie-verticale-sécurité	50	1ère Edition 1981
32	B.Pennacchioni	Aéroélasticité – le flottement des avions	40	1ère Edition 1980
33	C.Lelaie	Les vrilles et leurs essais	110	Edition 1981
37	S.Allenic	Electricité à bord des aéronefs	100	Edition 1978
53	J.C.Wanner	Le moteur d'avion (en 2 Tomes) T 1 Le réacteur .... T 2 Le turbopropulseur	 85 85	Réédition 1982
55	De Cennival	Installation des turbomoteurs sur hélicoptères	60	2ème Edition 1980
63	Gremont	Aperçu sur les pneumatiques et leurs propriétés	25	3ème Edition 1972
77	Gremont	L'atterrissage et le problème du freinage	40	2ème Edition 1978
82	Auffret	Manuel de médecine aéronautique	55	Edition 1979
85	Monnier	Conditions de calcul des structures d'avions	25	1ère Edition 1964
88	Richard	Technologie hélicoptère	95	Réédition 1971

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7. Presented at			
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14. Abstract

This AGARDograph presents a review of the methods that are used for short-range trajectory measurements. Chapter 2 briefly reviews the instrumentation requirements of the applications: take-off and landing performance measurement, autoland performance measurement, noise measurement and flight inspection of radio beacons. The remainder of the AGARDograph discusses the methods used for such applications, and is subdivided into optical methods (including lasers), methods using radio or radar and methods using inertial sensing.

This AGARDograph has been sponsored by the Flight Mechanics Panel of AGARD.

AGARDograph No.160 — Volume 16
Advisory Report for Aerospace Research and Development, NATO
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