STALINS Method for Takeoff and Landing Trajectory Measurements

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A method of trajectory measurement for the evaluation and certification of runway performance of aircraft is described. This method was developed as a replacement of the nose-camera method used previously. The primary data source is an inertial sensing system. The characteristic of the nose-camera method, that all measuring equipment is carried onboard the test aircraft, is almost retained but the data turnaround time is reduced substantially. Results of tests with a small civil airliner are presented to show that the accuracy is at least of the same order as that obtained by other methods. Data processing on the ground is fully automated, but anomalies in the flight-test data can be corrected interactively afterward. Also discussed are the operational aspects of the application of the switch equivalent of "takeoff and landing with an inertial sensing system" or STALINS method.

Nomenclature

AZ	= vertical acceleration output of platform, ms^{-2}
A_z	= kinematic vertical acceleration, ms^{-2}
DX,DZ	= difference between camera and STALINS results, m
g	= local acceleration of gravity, ms^{-2}
IVA	= integrated vertical acceleration output of platform, ms^{-1}
PROF	= height of runway centerline in STALINS runway axis system or runway profile, m
RA	= radar altimeter output, m
t	= time of day, s
(t)	= time-dependent parameter
t_0	= start time of test run, s
VEW, VNS	= east-west and north-south velocity outputs of platform, respectively; ms^{-1}
VEW(0), VNS(0)	= idem at standstill or Schuler velocity error in VEW and VNS, respectively; ms^{-1}
V_z	= kinematic vertical velocity, ms^{-1}
X,Y,Z	= position of platform, m
x,z	= position of an "instrument" in the aircraft, m
Δ	= difference between two parameters
θ	= angle of pitch, deg
σ	= standard deviation

Subscript

RS	= parameter in STALINS runway axis system

Introduction

THE measurement of trajectories for the certification of takeoff and landing performance of aircraft has always been a challenge for instrumentation engineers. A review of the methods used in the past few decades is given in Ref. 1. The accuracy requirements are so high they cannot be attained by the electromagnetic methods of trajectory measurement [e.g., radar, very high-frequency omni-directional range (VOR), distance measuring equipment (DME), etc.] widely used in aviation. Until recently this accuracy could be attained only by optical methods, i.e., by taking pictures on film of the aircraft (usually with kinetheodolites) and determining the aircraft position by doing measurements on each picture after development of the film. These film methods did achieve the required accuracy but the processing was very time-consuming and could be automated only to a limited degree.

In the Netherlands and a few other locations around the world a variant on this method was used: the camera was mounted in the nose of the aircraft and pictures were taken of the landing lights along the runway. Here also each individual picture had to be measured in order to determine successive aircraft positions.[2] This method had one important advantage over those using ground cameras: all measuring equipment was onboard the aircraft and, therefore, flight tests could be done on airports that were not equipped with kinetheodolites. A disadvantage was that the positions of the individual lamps had to be measured by survey methods. However, this could be done well before the execution of the flight tests and, the lamp coordinates, once measured, could be used for many years.

Recent developments in technology have finally made possible methods that can process the trajectory data automatically, without the time-consuming reading of films manually. At the present time, the most popular method uses laser theodolites, with on-line provision of the trajectory and velocity values by a computer. However, there are a few disadvantages to this system. The equipment is rather bulky and important safety measures must be taken to ensure that the laser beam does not harm living creatures in the surrounding area. Therefore, in principle, this system is suitable only for use in permanent installations, although a van-mounted laser tracker is currently available. In the Netherlands, an attempt was made to develop a method that incorporated computer processing, while retaining the important aspect that the measurements were independent of ground equipment that must be available at the airport. This resulted in the STALINS method (the Dutch eqivalent of "Takeoff and landing with an INS system") described herein, in which the trajectory measurement is based on data from an INertial Sensing (INS) system mounted in the aircraft.

The specification to which the system was developed was based on the certification requirements of civil transport aircraft. It asked for trajectory data over the height range of 0-300 ft, with a specified high accuracy over a critical part of

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that range (for takeoffs from standstill until the aircraft reaches a height of 35 ft, for landings from a height of 50 ft to standstill), and for a delivery time of the final results within 24 h after delivery of the flight tapes at the data-processing station. In the critical part of the trajectory the distance from standstill should be measured with a standard deviation of 0.1% of the distance covered in that critical part and the height with a standard deviation of 0.5 ft.

A feasibility study executed in the 1970s indicated that suitable updates could be obtained to attain these accuracies with an inertial platform of the "2 NM/h drift category."[3] These platforms are widely used for long-range navigation of civil aircraft. All later tests were done with a type of platform used by a Dutch airline company that could be maintained in the Netherlands.

First, a discussion of the theoretical basis of the method is presented. Then a few data-processing and software aspects are mentioned briefly. The flight-test data are recorded on magnetic tape onboard the aircraft. The tape is then transported to the NLR data-processing station on the ground and is preprocessed to a format that can be processed by the STALINS software in the main computer of the NLR. Next, a few statistical results are shown from a test series of 200 takeoffs and landings of a prototype developed from a small civil airliner. More detailed information on the results of these tests can be found in Ref. 4. Last, a few operational experiences during this first actual application of the STALINS method are discussed. On the basis of those flight tests, it was decided that the STALINS method will become a standard method for measurements of aircraft takeoff and landing performance in the Netherlands.

Theory

General

An INS system continuously calculates the velocity and position of the aircraft with respect to the Earth. However, these outputs are not accurate enough to be used directly for the application described herein. Special updates are required, which are applied in the ground computer. It was found that the velocity outputs of the INS used for the STALINS tests were the most suitable outputs for further processing.

The platform remains very accurately horizontal. The Schuler amplitude remained below 0.01 deg during the tests. Therefore, the calculations of the horizontal and vertical motions can be regarded as independent. The calculations in the horizontal plane and the vertical direction are, therefore, made separately.

Horizontal Velocities and Positions

The platform computer produces two horizontal velocities: north-south (N-S) and east-west (E-W). In the STALINS' software these velocities are integrated to provide distance with respect to the aircraft's position at the beginning of the test run. The distances in the N-S and E-W directions must be converted to distances along and perpendicular to the runway direction: $X(t)$ and $Y(t)$.

In the N-S and E-W velocities errors occur due to the Schuler motion of the platform, which adds components of the acceleration of gravity to the "horizontal" accelerations sensed by the platform. Also the calibration errors of the accelerometers and an incorrect orientation of the platform with respect to the north direction contribute to the velocity errors.

The Schuler tuning tries to keep the platform aligned parallel to the local horizontal as the aircraft flies around the Earth. In practice, the platform will oscillate about the horizontal position within a period of about 84 min and an angular amplitude of less than 0.01 deg. The components of gravity acceleration, sensed by the horizontal accelerometers due to this motion, integrate to errors in the velocity outputs on the order of 0.5 m/s. The errors are corrected by measuring the values of the N-S and E-W velocity outputs of the platform, VNS and VEW, respectively, during standstill immediately before takeoff or immediately after landing. The change in these "Schuler velocity errors" during a test run (usually less than 1 min) was small (less than 0.02 m/s), as can be seen from Fig. 1, where the values of VNS and VEW measured at standstill during one flight are plotted against time. This effect is usually neglected in STALINS' calculations. If extreme accuracy is required the linearized rate of change of the Schuler velocity errors can be estimated from plots such as Fig. 1. The true kinematic horizontal velocities can then be calculated from

$$VNS_{true} = VNS_{meas} - VNS(0) - \frac{\Delta VNS(0)}{\Delta t}(t - t_0) \quad (1)$$

$$VEW_{true} = VEW_{meas} - VEW(0) - \frac{\Delta VEW(0)}{\Delta t}(t - t_0) \quad (2)$$

Calibration errors in the horizontal accelerometers are small. The shift in the zero point of the calibration is specified to be less than $50\mu g$, which would cause a maximum error of 0.625 m after 50 s of measurement. Changes in the sensitivity of the accelerometer do not significantly affect the horizontal measurements because the accelerations remain small (usually less than 1.5 ms^{-2}).

The error in the platform orientation is eliminated by using a calculated runway direction instead of the nominal runway direction. The calculated runway direction is based upon a weighted first-order least-squares fit of the distance covered during the ground run. The weighting factor takes into account the changes in ground speed. In principle, the calculated runway direction is equivalent to the direction of the runway centerline. This direction is used for the transformation of the distances in the N-S and E-W directions to STALINS' runway axis system of Fig. 2.

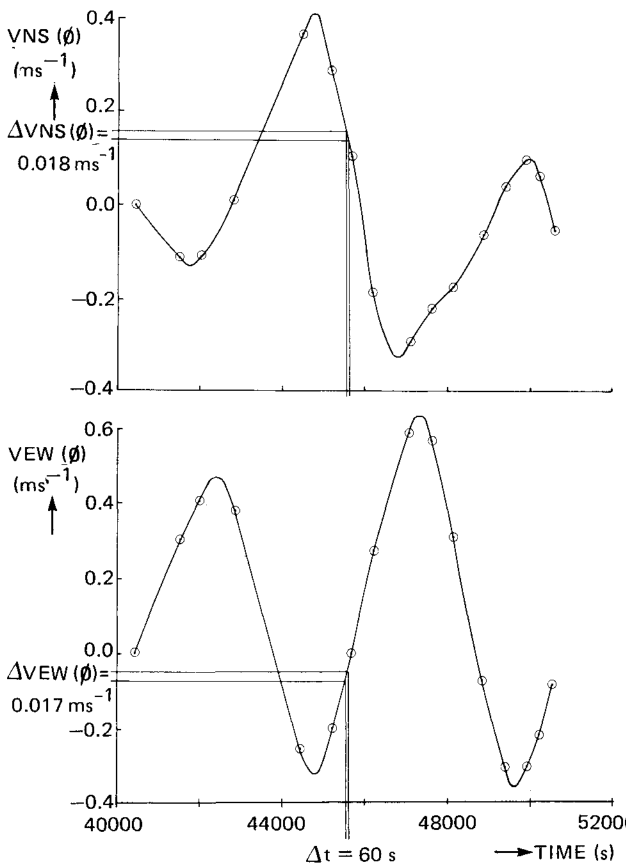

Fig. 1 Effects of the Schuler motion on the horizontal velocities during one flight.

The origin of this system is defined as the intersection of the runway centerline and the most westerly runway threshold. As the Earth's curvature cannot be neglected in the height calculation, a Lambert I coordinate system is used. The curved X_{RS} axis lies in the equipotential plane of the gravity field through the origin and points in the runway direction, the Z_{RS} axis points upward along the local g vector, and the (straight) Y_{RS} axis follows the rules of a right-hand coordinate system. In general, the runway surface of the centerline will not coincide with the equipotential plane. The difference, called runway profile, is used in the calculation of $Z(t)$.

Vertical Velocity and Height

The kinematic vertical acceleration can be written as

$$A_z(t) = AZ(t) - g \tag{3}$$

The first integration executed in the inertial platform is accurate enough to calculate the vertical velocity from the digital integral of vertical acceleration (IVA) output of the platform

$$V_z(t) - V_z(t_0) = \text{IVA}(t) - \text{IVA}(t_0) - g(t - t_0) \tag{4}$$

After a second integration, the height of the platform is given by

$$Z(t) - Z(t_0) = \int_{t_0}^{t} \text{IVA}(t)\text{d}t \quad + [V_z(t_0) - \text{IVA}(t_0)](t - t_0) - \tfrac{1}{2}g(t - t_0)^2 \tag{5}$$

Direct application of this equation using the local g value obtained from outside sources would not provide the required measuring accuracy, even if a sufficiently accurate g value should be known for the runway location (which often will not be the case). A minor problem is that in many platforms no Coriolis correction is applied to the IVA, which can be solved by including the correction in the STALINS software. However, there is a more fundamental problem: The longer-term stability of the vertical accelerometer in generally available platforms varies more than can be allowed for the accuracy requirements given above (it must be kept in mind that the required accuracy of the vertical accelerometer is about a factor of 10 higher than that required of the horizontal accelerometer). It was found that the short-term stability (over a few minutes) did meet the requirements and a special procedure was developed that depends only on that short-term stability by extracting accelerometer long-term calibration errors.

The principle of that procedure is that during part of each test run, i.e., the ground run, the platform height can be obtained from independent sources. That means Eq. (5) can be used to calibrate the zero point of the kinematic vertical velocity, averaged over the ground run. This value is then used during the airborne part of the test run, eliminating both the uncertainty about the local g values and the drift in the zero shift and sensitivity of the accelerometer at the 1-g point. The variation in vertical acceleration around the local g value still causes errors due to the changes in sensitivity, but these are negligible over the small range of operations. Tests showed that the accelerometer drift remains sufficiently constant during a test run of about 1 min.

The independent sources used for the determination of the platform height during the ground run are the runway profile (see Fig. 2), the aircraft pitch angle, and the height variation due to changes in the undercarriage length. Of these the runway profile is measured by survey methods, the pitch angle by the platform itself, and the undercarriage length changes can be derived from the radar altimeter measurements. Although this last instrument is not accurate enough to measure the height during the complete test run, it was found to be accurate enough to measure these small changes.

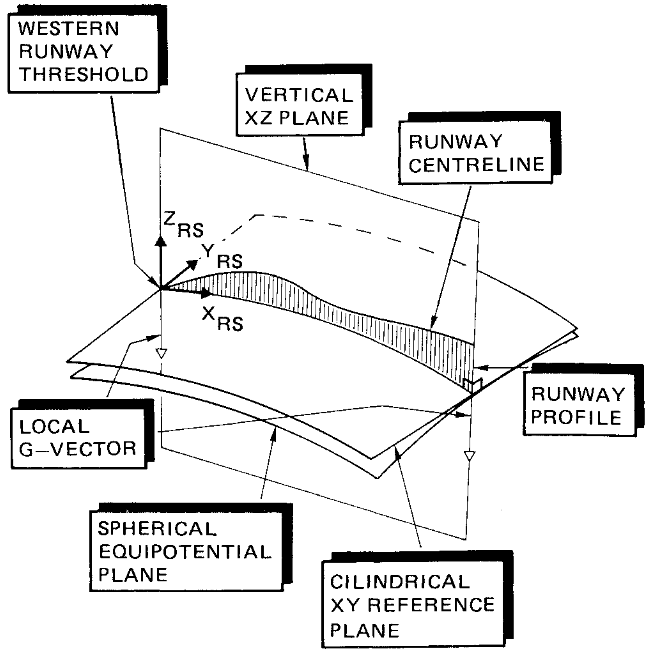

Fig. 2 The STALINS runway axis system.

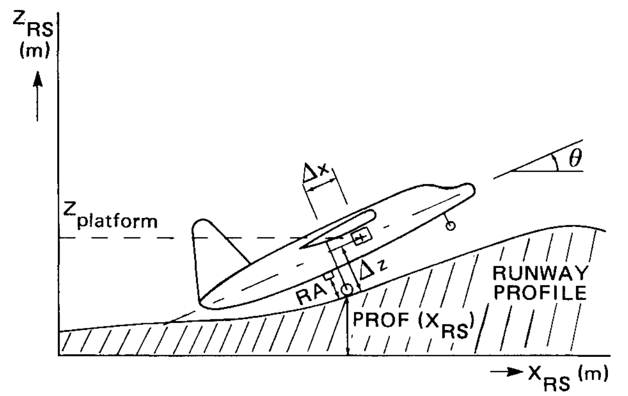

Fig. 3 Platform height Z with respect to the XY reference plane during the ground run.

The contribution of all sources is shown in Fig. 3. For the ground run part of a test run the platform height can be calculated with

$$Z(t) = \text{PROF}[X_{RS}(t)] + \Delta\text{RA}(t) + \Delta x \sin\theta(t) + \Delta z \cos\theta(t) \tag{6}$$

Substitution of Eq. (6) into Eq. (5) will give the basic equation for a least-squares fit procedure. This procedure calculates a "calculated g value" in which the accelerometer drift and local gravity acceleration are incorporated which is then used in the height calculation for the airborne part of the test run. To determine the time history of X_{RS}, the X position of the aircraft (calculated by the procedure described earlier with respect to the beginning of the test run) must be related to the runway coordinates. This is done by onboard recording of the passage of a small RASP (radar altimeter-based system for positioning) radio beacon (also developed by NLR) which is placed at a known point along the runway.

It should be noted that this procedure has another advantage. Because the height of the aircraft is accurately known during the ground run, the actual calculation of the height only starts at the beginning of the airborne part of the test run, therefore, the accumulation of time-dependent platform errors is reduced somewhat.

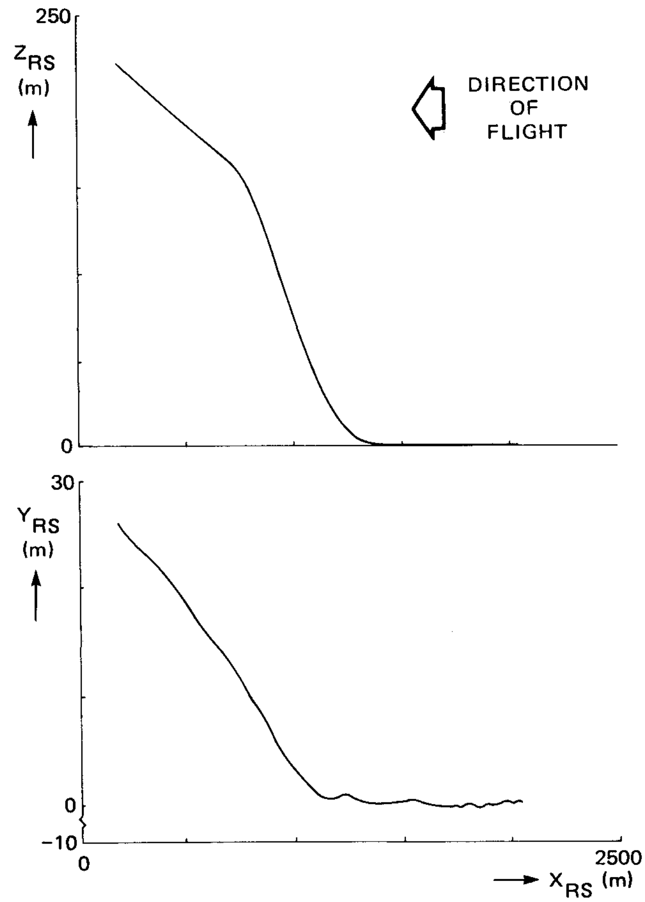

Fig. 4 Final position results of STALINS.

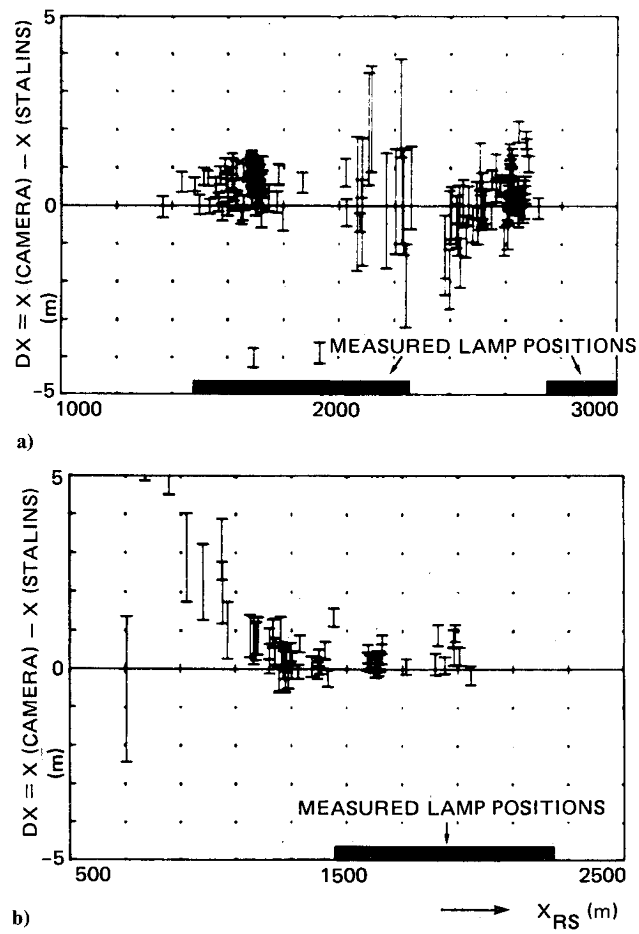

Fig. 5 Comparison of X from camera and STALINS for a) takeoffs and b) landings.

Data-Processing and Software Aspects

All data processing takes place on the ground. The measured digital data are recorded on tape onboard the aircraft. The tape is then transported to the data-processing station at the NLR in Amsterdam, where the runs selected for processing are converted to computer-compatible format. The recorded transducer outputs are transformed to engineering units and each sample is tagged with the exact time of measurement with an accuracy of about 1 ms. The time histories of the selected parameters are sent to a data base. This data base is the primary data source for the STALINS software as well as the storage device for intermediate results.

The STALINS software can be divided into three parts: PREPARATION, XY and Z calculation. The main function of PREPARATION is the selection of the significant part of a recording, which is divided into the period of standstill, ground run, and the airborne phase of the test run. Also the Schuler velocity error during standstill and the moment of RASP passage are detected. In XY and Z the horizontal and vertical trajectories, respectively, are calculated. All necessary auxiliary data, such as the runway profile and the RASP position, are read from a central data base where these data are permanently stored.

The program automatically processes all selected recordings of one flight. The results are written in the data base, which can be consulted in interactive mode by a STALINS operator. The operator checks the results for anomalies and uses a few characteristic parameters for a more detailed check. The time history of X is checked using second and third RASP beacons at known positions along the runway. For checking the Z time history the calculated g value from the fit process and the difference between Z and the radar altimeter output is used. The operator can correct data errors or adjust erroneous results of the PREPARATION routine. The STALINS program can then be rerun completely or in part with the updated data.

The final results are the components of the aircraft position, velocity and acceleration in the STALINS runway axis system (see Fig. 4), pitch and roll angle, and true heading. All parameters are transformed to a predefined reference point in the aircraft. The standard sample rate of the output parameters is eight times per second on a fixed time raster. The results can be presented on a graphics terminal with hard copy unit, printed or plotted, and/or sent to the user for further analysis of aircraft performance.

Accuracy

The absolute accuracy of the STALINS method is difficult to establish because there are no "calibration methods" that have a significantly better accuracy. In order to obtain an indication of the accuracy achieved, the results obtained during 200 test runs with an F27 at Torrejon, Spain, were compared with the results of other available methods (nose camera, radar altimeter), and a few characteristic parameters from the calculations (e.g., the calculated g value) were analyzed. The results are described in detail in Ref. 4.; the main results are briefly discussed below.

The comparison with the camera method (Figs. 5 and 6) was in general based on one picture taken during the ground run and one taken during the airborne part of each test run. The position of a number of lamps along the runway had been measured by survey methods before the tests started. Unfortunately, because of repairs, a different part of the runway had to be used than had been anticipated. The positions of the measured lamps that still could be used are indicated in the figures, but were not always optimal. To take this into account, the differences between camera and STALINS results (DX and DZ) are shown as vertical lines that represent twice the "theoretical" standard deviation of the camera results.

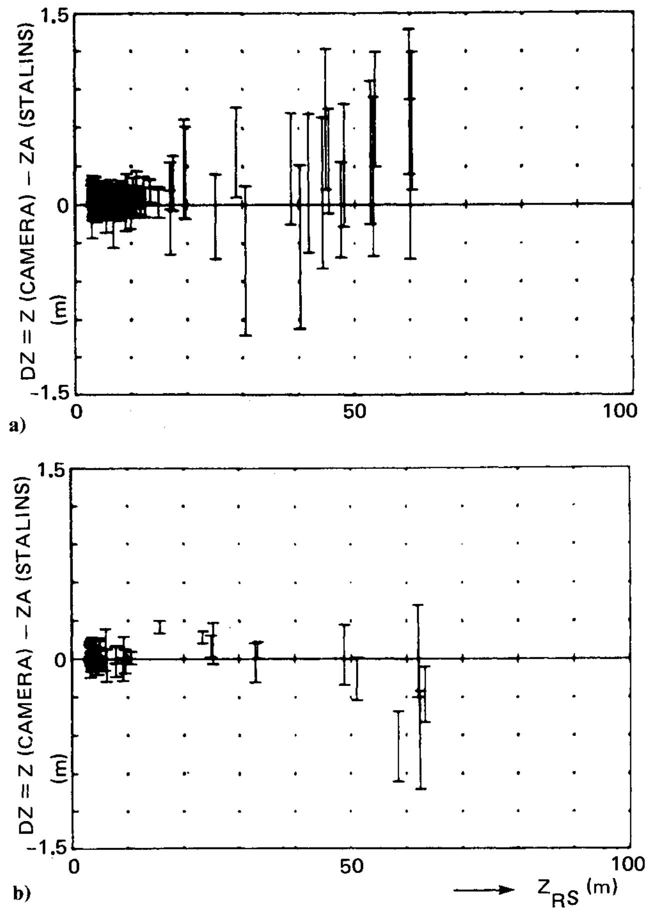

Fig. 6 Comparison of Z from camera and STALINS for a) takeoffs and b) landings.

This standard deviation depends mainly on the distance between the aircraft and the first lamps used in the calculations as shown in Fig. 5a: The larger standard deviations are in the middle of the graph where no measured lamps were available in the vicinity.

The main conclusions from Ref. 4 regarding the comparison with the camera results are:

1) The spread in the (reliable) DX values is within ± 1 m.

2) The average of the DX values is slightly positive (0.3-0.6 m). This effect is probably due to a timing error in the RASP receiver, which did not function optimally.

3) The spread in DZ is on the order of 0.3 m. It is thought that the accuracy of the camera results is of the same order.

4) No significant difference is found between positions on the ground and in the air.

5) The average values of DX and DZ do not increase significantly with time. Platform errors would be expected to cause position errors that do increase with time of measurement.

6) All outliers could be traced to errors in the camera results.

7) At heights greater than 25 m the camera results are no longer reliable.

In order to have more evidence on the accuracy of the height, a comparison was made with the radar altimeter at a height of 100 m. The results (after a correction for the time lag of the radar altimeter) are shown in Fig. 7. The variation in the difference is well within ± 0.5 m, and it can be assumed that the correspondence must be better at lower heights.

The plot of some calculated g values in Fig. 8 clearly shows the importance of the fit process. The values vary between 9.792 and 9.802 ms^{-2}, i.e., by 0.01 ms^{-2}. An error of that magnitude would have produced height errors of several meters. The drift is obviously due to continued (temperature) stabilization within the platform during the first hour after the initial alignment on a day.

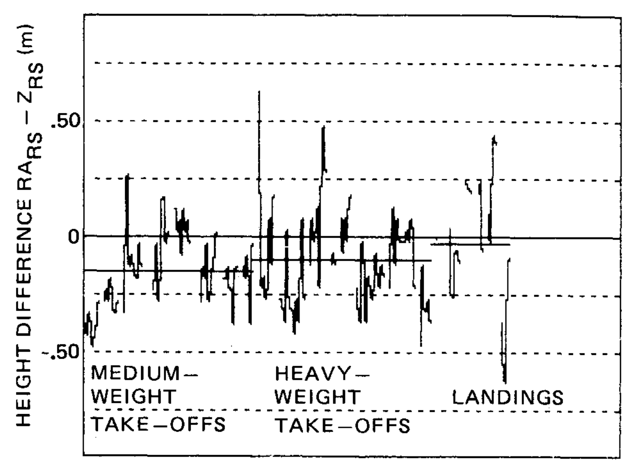

Fig. 7 Comparison of radar altitude and STALINS' height at $Z_{RS} = 100$ m after correction for an 80-ms time lag in radar altimeter output.

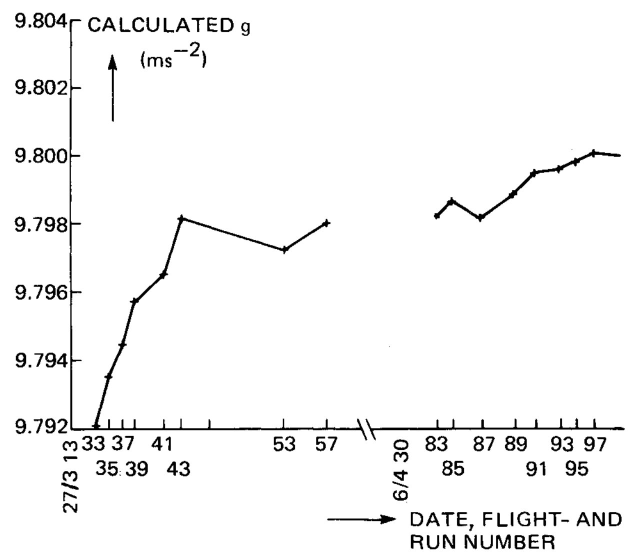

Fig. 8 Calculated g values for a number of runs on several days.

Although the absence of accurate reference methods and the uncertainties in a theoretical analysis do not allow classical proof of the accuracies achieved, the results presented above contain strong indications that the design goals are met. One accuracy aspect should still be mentioned. The calculated velocities and accelerations (which become more and more important in takeoff and landing analysis) are much more accurate than those obtained from methods where they have to be calculated by single and double differentiation from measured position data of the same accuracy.

Operational Aspects

The application of the STALINS method has two operational aspects: 1) The runway profile must be known before the test data can be processed, and 2) the method presents a few requirements to the actual execution of the tests.

For each runway used, the runway profile and predefined RASP positions must be measured using survey methods. This will take several days, especially on operational runways with much traffic. Once such a survey has been made, the results generally can be used until major repairs are made to the runway. The previously used nose-camera method required a similar effort for measuring runway light positions.

The requirements imposed on the execution of the flight test are twofold. First, the initial conditions for the integrations must be measured while the aircraft is at an absolute standstill for 2-3 s to achieve the accuracy shown herein. This can be a serious limitation because brake temperature may rise quickly after a landing test. Development of sufficient accurate methods for measuring near-zero velocities would require a major effort and an extension of the instrumentation system. Second, the aircraft must pass at least one RASP beacon at or near the ground. For takeoffs and rejected takeoffs this is no problem. For landings, the pilots feel it is a limitation that can affect the quality of the test run. Using several RASP beacons along the runway will solve this problem to a large extent.

Conclusion

A detailed analysis of the results of 200 takeoff and landing tests has shown that the STALINS method meets the design goals. It has an accuracy comparable to the test methods of trajectory measurements that are available, a 24-h data-processing turnaround time, and can be used on noninstrumented airfields and in all weather environments. STALINS has been chosen by Fokker as the standard method for runway performance tests.

Acknowledgments

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References

[1] de Benque d'Agut, P., Riebeek, H., and Pool, A., "Trajectory Measurements for Take-Off and Landing Tests and Other Short-Range Applications," AGARD-AG-160, AGARD Flight Test Instrumentation Series Vol. 16, 1985.

[2] Vleghert, J. P. K., "Determination of Take-Off and Landing Data with an Airborne Forward-Looking Camera Combined with Accelerometers," NLR Rept. V1933, 1965.

[3] Breeman, J., "Start- en landingsprestaties met het LN-3 traagheidsnavigatie-systeem," NLR TR 75027 U, 1975. (In Dutch.)

[4] Kranenburg, C. G., Pool, A., and Willekens, A. J. L., "Operational Application of the STALINS Method for Measuring Take-Off and Landing Trajectories," NLR TR 83010 L, 1983.