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THE STALINS METHOD FOR MEASURING TRAJECTORIES FOR TAKE-OFF AND LANDING PERFORMANCE MEASUREMENTS

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Abstract

This paper describes a method of trajectory measurement for the evaluation and certification of runway performance of aircraft. It was developed by the NLR at the request of Fokker, as a replacement of the nose-camera method previously used. The primary data source is an INertial Sensing system (INS). The characteristic of the nose camera method, that (nearly) all measuring equipment is carried on board the test aircraft, is retained but the data turn-around time is much reduced.
A few results of tests with an F27 aircraft 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 afterwards. The paper also discusses the operational aspects of the application of the STALINS method and a few new developments for application in future Fokker projects.

List of symbols

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 centre line in STALINS runway axis system or runway profile	(m)
RA	radar altimeter output	(m)
t	time of day, in between brackets it indicates a time dependent parameter	(s)
tØ	start time of test run	(s)
VEW	east-west velocity output of platform	(ms^{-1})
VEW(Ø)	idem at standstill or Schuler velocity error in VEW	(ms^{-1})
VNS	north-south velocity output of platform	(ms^{-1})
VNS(Ø)	idem at standstill or Schuler velocity error in VNS	(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 expressed in STALINS runway axis system

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I. Introduction

The method was developed by the NLR at the request of Fokker as a replacement for the nose camera method (1) which was used previously.
The method makes use of the outputs of an inertial stable platform to calculate trajectories for take-off and landing evaluation and certification of aircraft performance. The code name STALINS is an acronym of the Dutch equivalent of "Take-Off and Landing with an Inertial Sensing system".

The main advantage over the camera method is quick, computerized data processing instead of time consuming film reading. It can be used on non-instrumented airfields as most of the measuring equipment is located on-board the test aircraft. Special update procedures have been developed which make the accuracy comparable to the best methods that are now in use elsewhere such as kinetheodolites and laser trackers.

Fokker specified the following design goals when the development started in the latter half of the 1970's:

a. The accuracy of the distance along the runway from standstill to the point where the aircraft reaches the obstacle height of 35 feet (for take-off) or from 50 feet height to standstill (for landing) should be within 0.1 % (1σ) of that distance.
b. The accuracy of the height above the ground over that same distance should be within 0.15 metres (1σ).
c. The measurement of distance and height should continue to a height of 300 feet (with reduced accuracy).
c. Flight tests on non-instrumented airfields all over the world should be possible; therefore any necessary ground equipment should be transportable by the test aircraft.
e. Final results should be available within 24 hours from delivery of the test data to the data processing station.

A feasibility study (2) indicated that, with suitable updates, it would be possible to meet the design goals with inertial platforms of the "2NM per hour drift category". These platforms are widely used for long range navigation of civil aircraft. The final tests were done with a Litton LTN-58 platform.

The theoretical principles of the method are described in section 2. The flight test data are recorded on tape in the aircraft. This tape is transported to the data processing station on the ground to provide the input for the STALINS software. Data processing and software aspects are the subject of section 3. A few results from a series of 200 take-off and landing runs with a Fokker F27 are presented in section 4. More detailed information on the results of these tests can be found in reference 3. Section 5 discusses the operational aspects of the STALINS method in relation to the experience gained during the F27 tests. In section 6 the present developments for application in new Fokker projects are briefly discussed.

II. Theory

General

An inertial sensing system, such as the Litton LTN-58 used for the STALINS tests, continuously calculates the velocity and the position of the aircraft with respect to the earth. These outputs are, however, not accurate enough to be used directly for the application described here. Special updates are required, which are applied in the ground computer. It was found that the velocity outputs of the LTN-58 were the most suitable outputs for further processing.

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

Horizontal velocities and positions

The platform computer produces two horizontal velocities: the North-South Velocity (VNS) and the East-West Velocity (VEW). In the STALINS software these velocities are integrated to provide distance with respect to the position of the aircraft at the beginning of the test run. The distances in NS- and EW-directions must be converted to distances along and perpendicular to the runway direction: X(t) and Y(t).

In VNS and VEW 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
- calibration errors of the accelerometers
- incorrect orientation of the platform with respect to the North direction.

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 with a period of about 84 minutes and an angular amplitude of less than 0.01 degrees. The components of the acceleration of gravity sensed by the horizontal accelerometers due to this motion, integrate to errors in the velocity outputs of the order of 0.5 m/sec. The errors are corrected by measuring the values of VNS and VEW during standstill immediately before take-off or immediately after landing. The change in these "Schuler velocity errors" during a testrun (usually less than one minute) was small (less than 0.02 m/s) as can be seen from figure 1, where the values of VNS and VEW measured at standstill during one flight are plotted against time. This effect is usually neglected in the STALINS calculations. If extreme accuracy is required the linearized rate of change of the "Schuler velocity errors" can be estimated from plots like figure 1. The true kinematic horizontal velocities can then be calculated from:

$$VNS_{true} = VNS_{measured} - VNS(\emptyset) - \frac{\Delta VNS(\emptyset)}{\Delta t}.\ (t-t_{\emptyset}) \qquad (1)$$

$$VEW_{true} = VEW_{measured} - VEW(0) - \frac{\Delta VEW(\emptyset)}{\Delta t}.\ (t-t_{0}) \qquad (2)$$

Calibration errors in the horizontal accelerometers are small. The shift in the zero point of the calibration is specified to be less than 50 micro-g, which would cause a maximum error of 0.625 m after 50 seconds 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 groundspeed. In principle the calculated runway direction is equivalent to the direction of the runway centre line. This direction is used for the transformation of the distances in NS- and EW-directions to the STALINS runway axis system of figure 2.

The origin of this system is defined as the intersection of the runway centre line and the most westerly runway threshold. As the curvature of the earth cannot be neglected in the height calculation, a Lambert I co-ordinate 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 co-ordinate system. In general the runway surface of the centre line 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

$$A_z(t) = AZ(t) - g \qquad (3)$$

The first integration executed in the LTN-58 platform, is accurate enough to calculate the vertical velocity from the digital "integral of vertical acceleration" (IVA) output of the platform

$$V_z(t) - V_z(t_{\emptyset}) = IVA(t) - IVA(t_{\emptyset}) - g(t-t_{\emptyset}) \qquad (4)$$

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

$$Z(t) - Z(t_{\emptyset}) = \int_{t_{\emptyset}}^{t} IVA(t).dt + (V_z(t_{\emptyset}) - IVA(t_{\emptyset}))(t-t_{\emptyset}) - \tfrac{1}{2}g(t-t_{\emptyset})^2 \qquad (5)$$

Direct application of this equation using a local g value obtained from outside sources does not provide the required accuracy due to several reasons:

a. The IVA output of the LTN-58 platform is not corrected for Coriolis effects.

b. In most cases the local acceleration of gravity is not known with sufficient accuracy.

c. The calibration errors of the accelerometer will have a more significant influence on the calculations in the vertical direction than in those in the horizontal directions. There are two reasons for this difference: the required accuracy in height is of the order of 10 times higher than in the horizontal distances, and the effect of accelerometer sensitivity errors is greater because the mean acceleration level is 1 g.

The Coriolis correction is applied in the STALINS software. The problems mentioned under b and c are both solved by a special update procedure.

The principle of that procedure is that during part of each test run, i.e. the ground run, the height of the platform can be obtained from independent sources. That means that equation (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. This eliminates 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 as illustrated in figure 3. 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 one minute.

The independent sources that are used for the determination of the platform height during the ground run are:

- the runway profile (see figure 2). The profile is measured by survey methods.
- the pitch angle of the aircraft as measured by the platform.
- the variation in height due to changes in the undercarriage length. These are measured using a radar altimeter. Although this instrument is not accurate enough to measure the height during the whole test run, it was found to be accurate enough to measure these small changes.

The contributions of all sources are shown in figure 4. For the ground run part of a test run the platform height can be calculated with

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

where $PROF(X_{RS}(t))$ = height of runway at the aircraft X-position in the STALINS runway axis system

$\Delta RA(t)$ = $RA(t)-RA(t_{\emptyset})$

$\Delta x, \Delta z$ = difference in x en z of the positions in the aircraft of the platform and the main wheels.

Substitution of equation (6) in equation (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 the local acceleration of gravity are incorporated and 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 co-ordinates. This is done by recording on-board the passage of a small RASP radio beacon. (Radar Altimeter based System for Positioning, 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, so that the accumulation of time dependent platform errors is somewhat reduced.

III. Data processing and software aspects

All data processing takes place on the ground. The measured digital data is recorded on tape on board of the aircraft. This tape is transported to the data processing station (DVSV) at the NLR in Amsterdam. In this station 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 millisecond. The time histories of the selected parameters are send to a database. This database is the primary data source for the STALINS software as well as the storage device for intermediate results. A block diagram is given in figure 5.

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, the ground run and the airborne fase 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 are calculated, respectively. All necessary auxiliary data such as the runway profile and the RASP position, are read from a central database where these data are permanently stored.

The program automatically processes all selected recordings of one flight. The results are written in the database, 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 has the possibility to correct data errors or to adjust erroneous results of the routine PREPARATION. 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 figure 6), 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 8 times per second on a fixed time raster. The results can be presented on a graphics terminal with hard copy unit, printed or plotted at the NLR, and/or sent to the user for further analysis of aircraft performance.

IV. Accuracy

The absolute accuracy of the STALINS method is difficult to establish, because there are no "calibration methods" which have a significantly better accuracy. In order to obtain an indication of the achieved accuracy, the results obtained during 200 test runs with an F27 at Torrejon 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 analysed. The results are described in detail in Reference 3. The main results are briefly discussed below.

The comparison with the camera method figures 7 and 8) was in general based on one picture taken during the ground run and one taken during the airborne part of each test run. The positions of a number of lamps along the runway had been measured by survey methods before the tests started. Unfortunately a different part of the runway had to be used than had been anticipated because of repairs. The positions of the measured lamps that could still 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 which represent twice the "theoretical" standard deviation of the camera results. This standard deviation mainly depends on the distance between the aircraft and the first lamps used in the calculations as shown in figure 7a: the larger standard deviations are in the middle of the graph where no close-by measured lamps were available.

The main conclusions from Reference 3 about the comparison with the camera results are:

1. The spread in the (reliable) DX values is within ± 1 metre.
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 of the order of 0.3 metre. 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 significantly increase with time. Platform errors would be expected to cause position errors which do increase with time of measurement.
6. All outliers could be traced to errors in the camera results.
7. At heights greater than 25 metres the camera results are no longer reliable.

In order to have more evidence on the accuracy of the height, a comparison with the radar altimeter was made at a height of 100 metres. The results (after a correction for the time lag of the radar altimeter) are shown in figure 9. The variation in the difference is well within ± 0.5 m, and it can be assumed that at lower heights the correspondence must be better.

The plot of all calculated g-values in figure 10 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 errors in height of several metres. The drift is obviously due to continued (temperature) stabilization within the platform during the first hour after the initial alignment on a day.

Although the absence of accurate reference methods and the uncertainties in a theoretical analysis do not allow a 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 take-off 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.

V. Operational aspects

The application of the STALINS method has two operational aspects: the runway profile must be known before the test data can be processed and 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 can in general be used until major repairs are made to the runway. The previously used nose camera method required a simular effort for measuring runway light positions.

The requirements imposed on the execution of the fligth tests are:

- To achieve the accuracy shown in this paper, the initial conditions for the integrations must be measured while the aircraft is at absolute standstill for 2 or 3 seconds. This can be a serious limitation because brake temperature may rise quickly after a landing or an accelerate-stop test. Development of sufficient accurate methods for measuring near-zero velocities would require a major effort and an extension of the instrumentation system.
- The aircraft must pass at least one RASP beacon at or near the ground.

For take-offs and rejected take-offs this is no problem. For landings is is felt by the pilots as a limitation which can affect the quality of the test run. Using several RASP beacons along the runway will solve this to a large extent.

VI. Further developments

Fokker has used this method for certification and verification tests with a modified F27 in 1982. On the basis of the results of those tests, the method will in the near future be used for the certification of the take-off and landing performance of the Fokker 50 and Fokker 100. For those tests the NLR has ordered a few slightly modified Litton LTN-76 inertial platforms which are expected to give some improvement in accuracy.

The NLR is also developing a variant of the STALINS method for use in the testing of Autoland systems. This method, which will use, in addition to the STALINS hardware, a camera to achieve the high accuracy that is required for lateral deviations from the runway centre line, will also be used for the flight testing of the new Fokker aircraft.

VII. Conclusion

A detailed analysis of the results of 200 take-off and landing tests have shown that the STALINS method meets the design goals. It has an accuracy that is comparable to the best methods of trajectory measurement that are available, a 24-hours data-processing turn around time and can be used on non-instrumented airfields. It has been chosen by Fokker as the standard method for runway performance tests.

VIII. Acknowledgement

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IX. References

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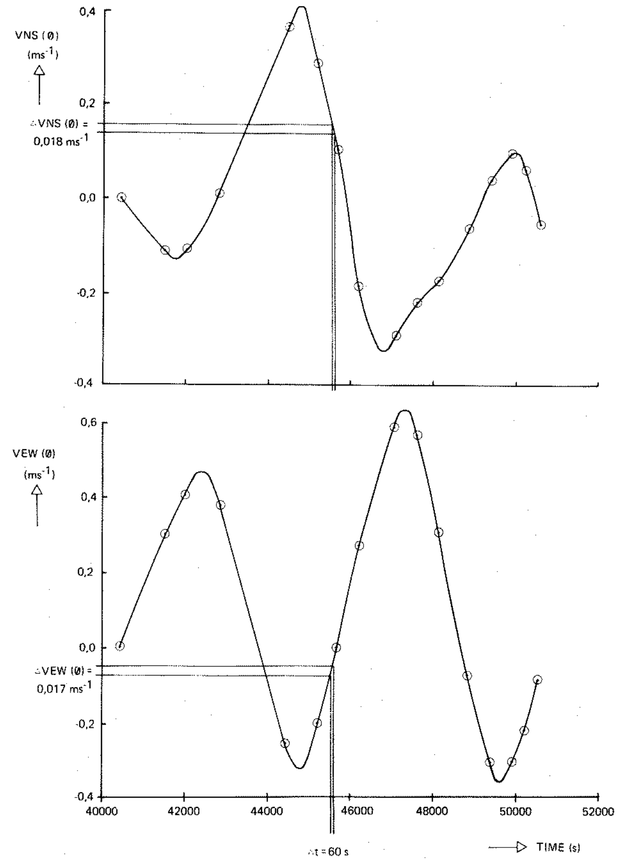

Fig. 1 The effects of the schuler motion on the horizontal velocities during one flight

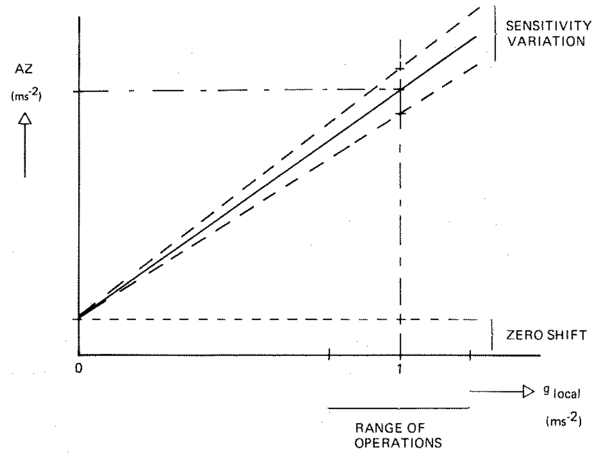

Fig. 3 The calibration of the vertical accelerometer output at the local acceleration of gravity

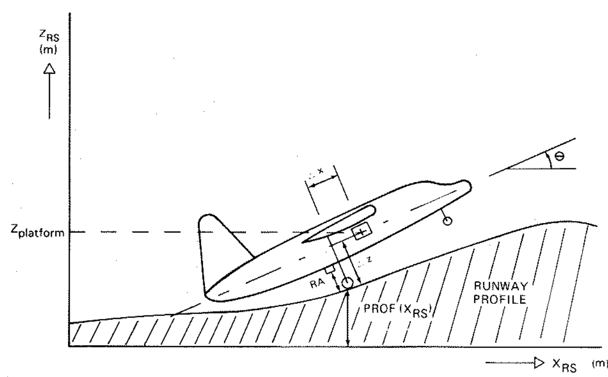

Fig. 4 Platform height Z with respect to the XY reference plane during the ground run

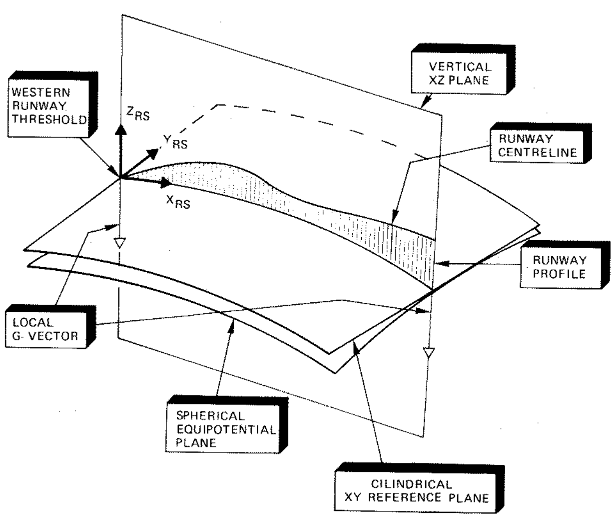

Fig. 2 The STALINS runway axis system

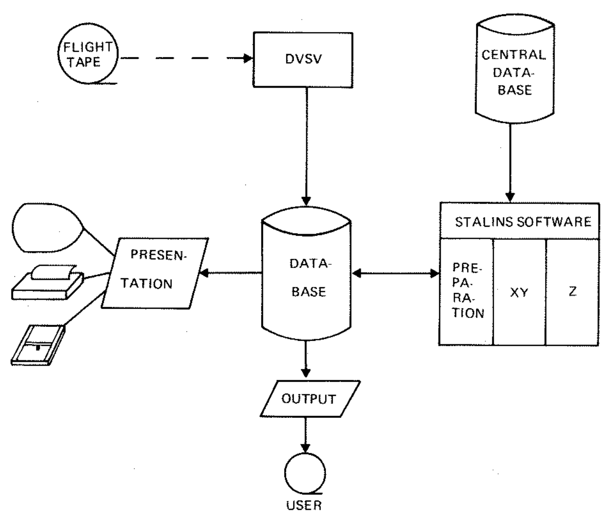

Fig. 5 STALINS data processing

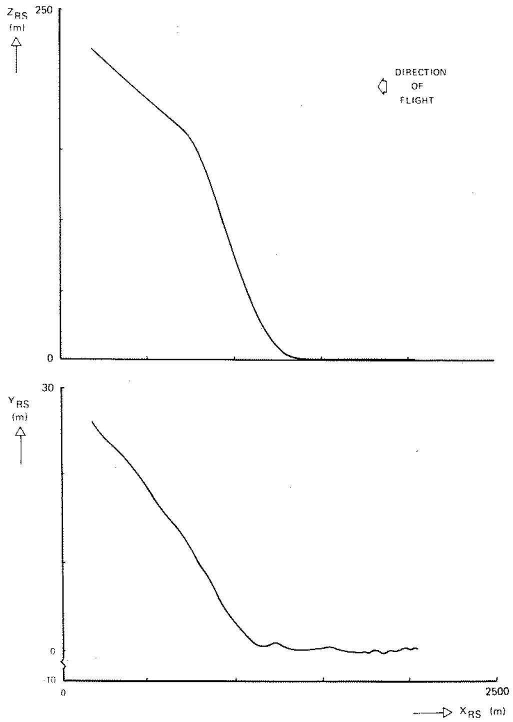

Fig. 6 Final position results of STALINS

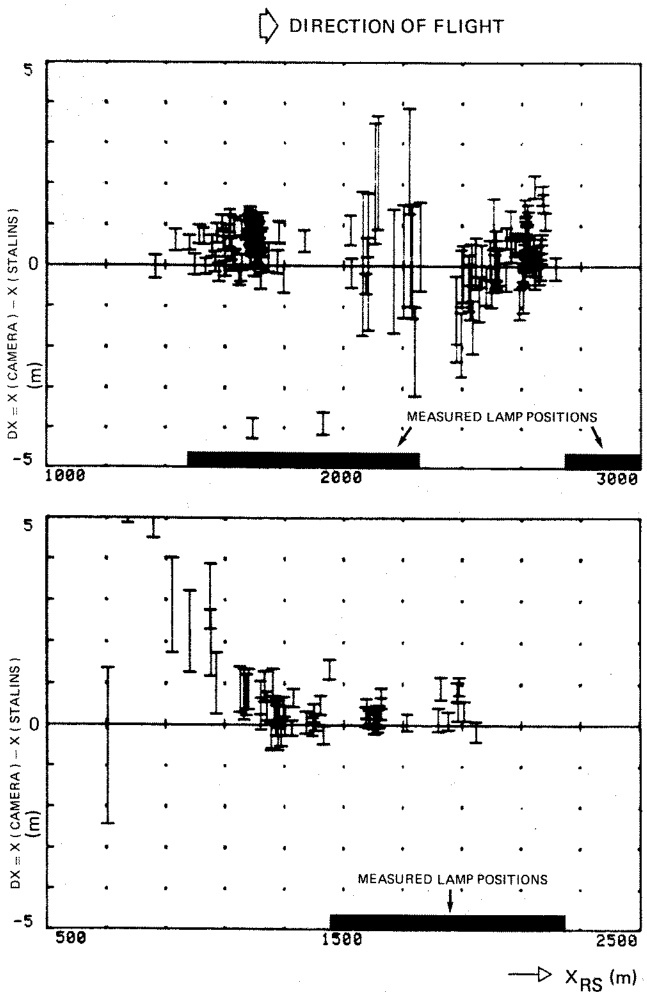

Fig. 7 Comparison of X from camera and STALINS for take-offs (top) and landings (bottom)

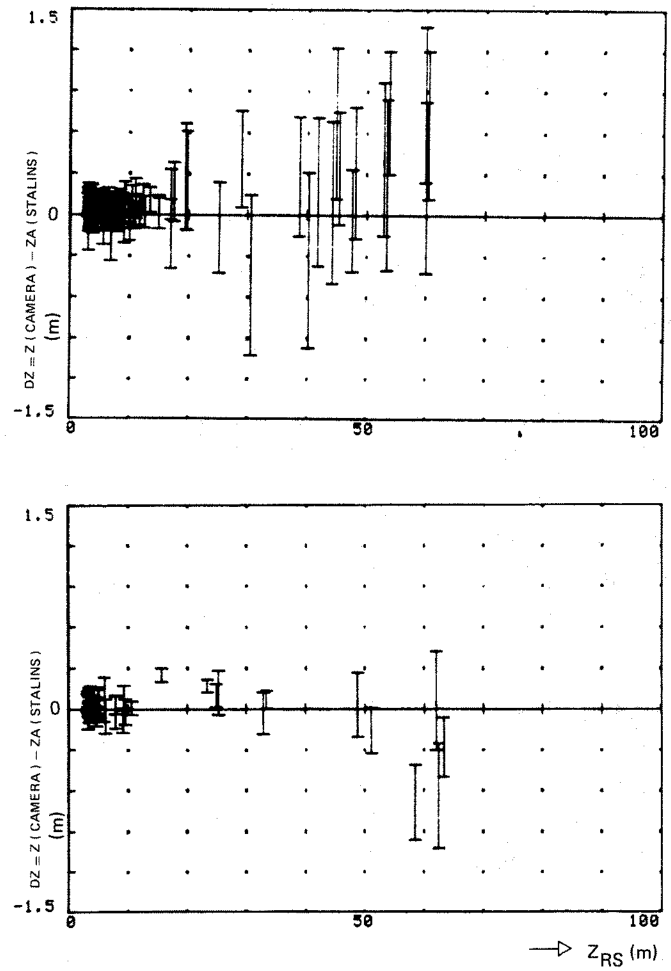

Fig. 8 Comparison of Z from camera and STALINS for take-offs (top) and landings (bottom)

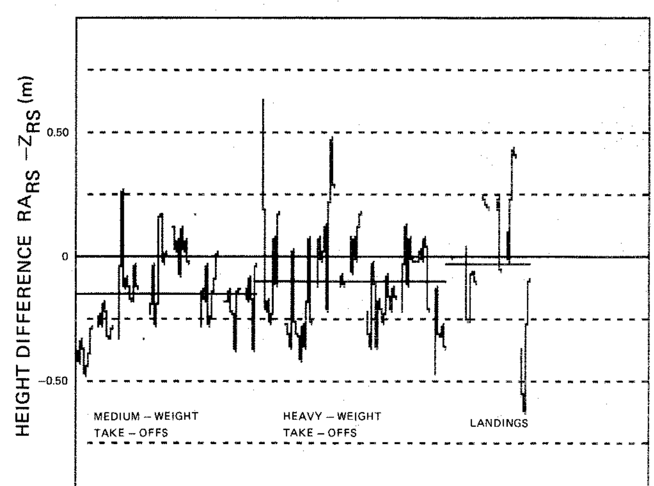

Fig. 9 Comparison of radar altitude outputs and STALINS heights at Z_{RS} = 100 m after correction for 80 milliseconds time lag is radar altimeter output

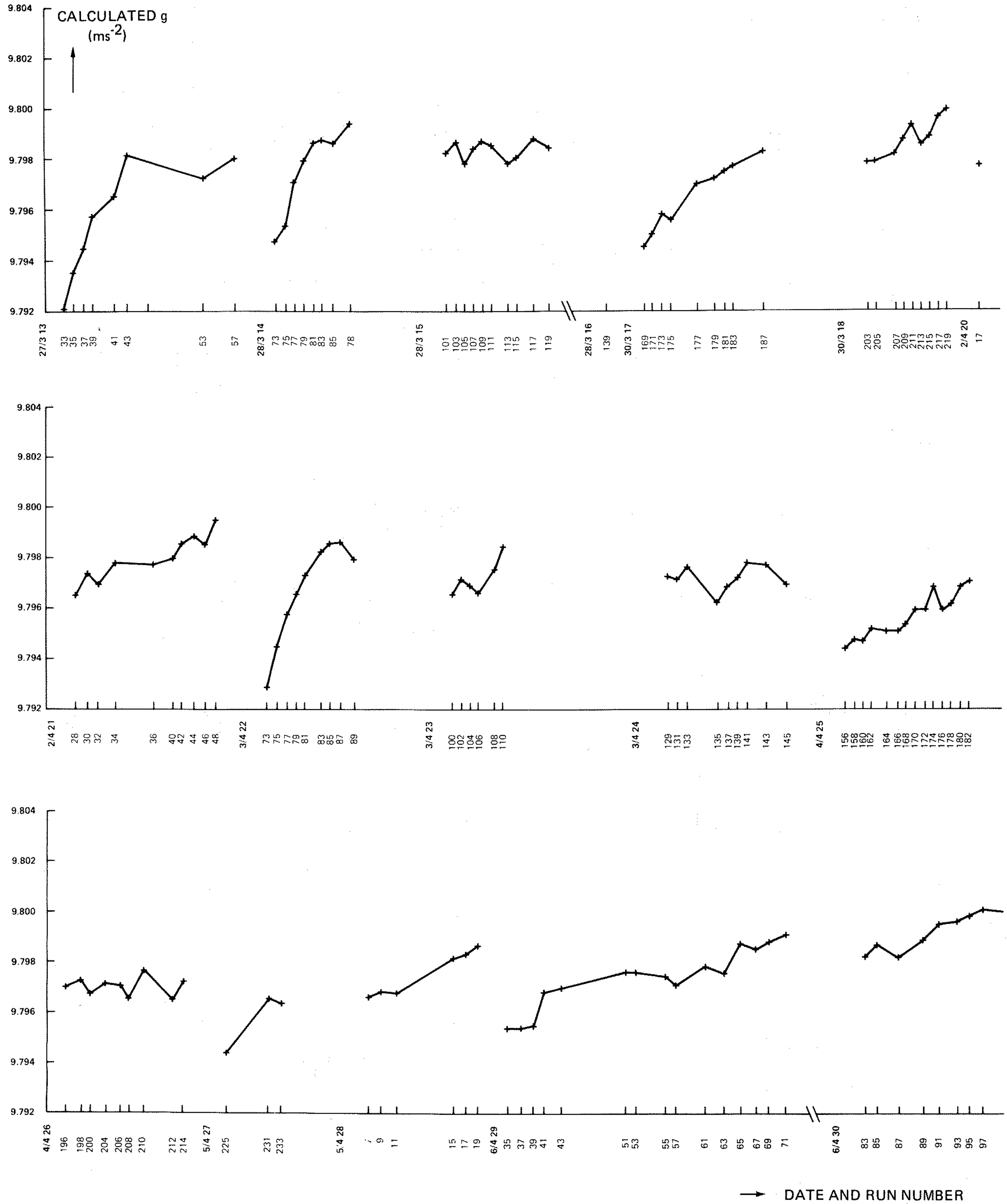

Fig. 10 Calculated g values for a number of runs on several days