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Development of a position reference system for flight tests based on GPS

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ABSTRACT

At the National Aerospace Laboratory of the Netherlands (NLR) a Postition Reference System for in-flight accurate position measurements based on GPS has been developed and validated. The system uses Differential GPS positions to correct the aircraft trajectory as delivered by an Inertial Reference System. Depending on the application, a medium accuracy (± 5 m), an enhanced accuracy (± 0.6 m) or a high accuracy (± 0.15 m) update mode can be selected.
The medium- and enhanced accuracy modes are available in both real-time and after the flight, the high accuracy mode is only available after the flight.
In the paper the requirements for the Position Reference System will be given. The system hardware and software will be described.
Until now the system has been used during a number of flight test programmes with Fokker prototype aircraft. A two month period of one of these programmes was selected, flight test data from this period were processed in each of the above mentioned update modes. The results will be shown and discussed.

Abstract

At the National Aerospace Laboratory of the Netherlands (NLR) a Position Reference System for in-flight accurate position measurements based on GPS has been developed and validated. The system uses Differential GPS positions to correct the aircraft trajectory as delivered by an Inertial Reference System. Depending on the application, a medium accuracy (± 5 m), an enhanced accuracy (± 0.6 m) or a high accuracy (± 0.15 m) update mode can be selected.

The medium- and enhanced accuracy modes are available in both real-time and after the flight, the high accuracy mode is only available after the flight.

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1 Introduction

At the National Aerospace Laboratory of the Netherlands (NLR) a Position Reference System (PRS) for in-flight accurate position measurement has been developed and validated. The development of the system has been carried out under a contract awarded by the Netherlands Agency for Aerospace Programmes and in cooperation with Fokker Aircraft B.V.

The system is based on Differential GPS (DGPS) positions which are used to correct ('update') the aircraft trajectory as delivered by an Inertial Reference System (IRS). Depending on the application, one of the following update modes can be selected:

1. Medium accuracy (± 5 m) is a real time mode based on the use of (raw) coderange DGPS. Besides producing the reference position, this mode delivers guidance information to the pilot, enabling him to follow a pre-determined track defined by a series of waypoints. Without uplink for transmitting the differential correction the real time system degrades to the stand alone GPS accuracy (100 metres position accuracy).
2. Enhanced accuracy (± 0.6 m) is a postprocessing mode using carrier smoothed coderange DGPS. Moreover, the enhanced accuracy position is used in the real-time medium accuracy mode to validate the corrected aircraft trajectory.
3. High accuracy (± 0.15 m) is a postprocessing mode based on interferometric GPS, applicable within a local area only.

Until now, PRS has been used for the following applications:

- Evaluation of the system during the certification/evaluation of an automatic landing system.
- Familiarization with the system during runway performance measurements.
- Operational use of the system for guidance and position reference during fly-over-noise measurements.

From the last application, six flights in the period March/April 1996 were processed in all three update modes.

In the next chapter the operational requirements for PRS are given. Chapter 3 describes the hardware and software of the update modes. In chapter 4 the results from the above mentioned flights are presented and discussed. Chapter 5 gives some shortcomings of PRS and discusses possible solutions. Finally, conclusions are drawn.

2 System requirements

To determine the accuracy requirements and the environment where PRS has to operate, the future ’users’ of the system (at that time the design engineers at Fokker Aircraft) were interviewed.

The resulting requirements can be grouped into three accuracy classes (2σ, 3D):

- For evaluation and certification of an automatic landing system and to determine the take-off and landing performance of a transport category aircraft, a highly accurate (± 0.15 m) position reference is required.
- For applications like fly-over-noise measurements and remote sensing the system should deliver a (medium accurate) position reference of ± 5 m. It should optionally provide real-time guidance to the pilot and/or aircraft.
- For certification of enroute navigation systems a low accuracy position reference system of ± 100 m suffices.

The high- and the medium accuracy reference are required in an area with a distance no more than 10 km from the runway, and a maximum height of 500 m and 1000 m respectively. Furthermore, dynamics are restricted to typical transport category aircraft values: speed 150 m/s, acceleration 2 g’s, roll attitude 60 deg, pitch attitude 25 deg, roll- and pitch rate 20 deg/s and yaw rate 10 deg/s.

Besides from the real-time requirement for guidance, there is a general requirement to provide the reference trajectory to the design engineers as soon as possible after the flight. Ultimately the ideal solution is to provide the validated trajectory for all accuracy classes in real-time. Although the current PRS delivers high accuracy data in postprocessing only, the PRS design allows a transition to real-time with minor effort. It will be shown in chapter 4 that the currently insufficient availability and reliability of the real-time high accuracy position solution prevents this transition. Recent tests with current state-of-art hardware indicate, that a reliable real-time implementation of the high accuracy mode becomes feasible.

3 System description

The following GPS based positioning techniques have been developed:

1. Stand alone GPS having an accuracy of 100 m. This technique suits the low accuracy requirements.
2. Differential coderange GPS having an accuracy of 5 m. This technique meets the medium accuracy requirement.
3. Enhanced differential coderange GPS applying code smoothing meets the accuracy requirement during take-off and landing for e.g. commuter type aircraft.
4. Differential carrier range GPS with decimeter accuracy. This technique meets the high accuracy requirements.

The above techniques suffer however from some shortcomings.

For real-time guidance an update rate of at least 20 times per second is required, while the highest update rate found in any suitable GPS receiver is 4 per second. Moreover, the position solution time lag is at least 0.2 seconds and usually more, while a lag of some tens of milliseconds is allowed.

Also, the integrity of a reference system based on GPS alone is insufficient for flight test purposes.

To overcome these drawbacks the GPS position solution is integrated with IRS data. The properties of an IRS: an update rate of 50 Hz, a very low noise trajectory, and a low short term position drift, combine ideally with the properties of GPS: a high position accuracy and no long term drift. As a consequence the high quality dynamic position measurements by the IRS are used for position prediction by fitting these trajectory data through the accurate positions obtained from GPS a few (fractions of) seconds before.

3.1 Hardware description

Figure 1 shows the hardware layout of the system.

The Turbo Rogue SNR-8000 receiver has been selected for the aircraft. To achieve high accuracy results, code-and carrier range measurements of both GPS frequencies (L1 and L2) are used.

The IRS is a Honeywell HG1050 ring laser gyro system.

The airborne computer is a VME based system with a Motorola 68040 microprocessor. It receives its data:

- from the airborne GPS receiver,
- via a telemetry uplink from the ground based GPS receiver, and
- from the IRS.

The computer processes the data into an integrated position solution. It sends the position solution in the form of flight path deviation signals to a display in the cockpit to provide real-time guidance to the pilot. The raw data as well as the solution are stored on magnetic tape for post flight processing and analysis.

The ground reference station is also equiped with a Turbo Rogue receiver. Code- and carrier ranges are uplinked to the aircraft. They are also stored at the ground on magnetic tape to allow post flight processing.

Post flight processing and analysis is partly carried out on a mainframe Cyber 962 computer, partly on a Silicon Graphics Challenge computer with UNIX IRIX 5.2 operating system. Transition of all processing and analysis to the Challenge is under way.

3.2 Software description

Figure 2 gives a general layout of the software modules inside the on board real-time PRS computer. Figure 3 shows the postprocessing modules implemented in the flight test data processing station. In the following a short description of each module is given. A more detailed description can be found in Ref. 1.

3.2.1 Real-time software modules

Differential C/A code module

The module receives data from the airborne GPS receiver and the ground based GPS receiver. The module computes the position once per second using C/A coderanges and satellite position information. No filtering in time is carried out, neither on the raw data, nor on the calculated positions.

Enhanced differential GPS

This module computes the position using carrier smoothed pseudoranges. This technique is based on the fact that the change in coderange within the successive measurement moments equals the change in carrier range. Since the carrier range is far less noisy than the coderange it can be used to smooth the coderange.

The ’enhanced’ position solution is used by the integration module to check for anomalies in the integrated position.

GPS/IRS integration module, real-time

The basic principle of the real-time GPS/IRS integration is to use the (D)GPS position to obtain estimates of the (slowly varying) errors of the IRS using a Kalman filter. These errors are subsequently applied as corrections to the raw IRS output, effectively calibrating the IRS.

The result is a trajectory with a high update rate (the basic IRS rate of 50 Hz), a small latency (very little processing time is needed to apply a correction to the raw IRS data) and low measurement noise.

The position solution is tested for a number of criteria before it is declared valid.

Guidance module

The guidance module compares the integrated position with a pre-determined aircraft trajectory defined by a series of waypoints. The deviations are sent to the cockpit in a standard Instrument Landing System format, enabling the pilot (or the autoland system) to follow the flight path.

3.2.2 Postprocessing software modules

The high accuracy update mode uses double differenced carrier range observations on L1. Although the accuracy of the (double differenced) carrier ranges is extremely high - in the order of a few cm's - they are subject to an error of an integer number of wavelengths. The determination of this carrier range ambiguity is required for a succesful high accuracy position calculation.

The ambiguities have a fixed value as long as the carrier tracking loops inside the receivers don't loose lock on the satellites. Unfortunately, in the airborne environment this loss of lock occurs often and results in so-called cycle slips.

Cycle slip module

The Turbo Edit postprocessing algorithm (ref. 2) checks the raw carrier ranges for the occurence of cycle slips and corrects them. The corrected carrier ranges are input to the other modules optionally.

Enhanced differential module

The postprocessing enhanced differential module is to a large extent identical to the real-time module. However, additional backward smoothing is applied, further improving the accuracy.

Widelane module

In the postprocessing system two different methods to determine the carrier range ambiguities have been implemented, each with its advantages and disadvantages.

The widelane module calculates at each measurement the ambiguity numbers using linear combinations of code- and carrier ranges of both L1 and L2, and subsequently averages the values in time. With high quality measurement data these averages converge to integers, and the required L1 ambiguity values can be calculated (Ref. 3). In order to extend the time domain of the solution, also backward averaging of these widelane combinations is applied.

The advantage of this method lies in its simplicity: only the measured ranges are required. Its disadvantage's are: often a long (several minutes, sometimes tens of minutes) observation interval is required.

On-The-Fly module

The second method is based on Remondi's kinematic 'On-The-Fly' (OTF) algorithm (ref. 4). This method uses all available information such as the (corrected) ranges, the satellite positions,

the reference receiver position and the enhanced accuracy aircraft position. The latter position is used as the origin of the ambiguity search volume. The estimated error of this position determines the search volume, and thus controls the possible number of ambiguity candidates. The OTF module is run and restarted frequently throughout the flight, generating a large number of results in the form of sets of ambiguity numbers. These sets will be checked for consistency in the validation module.
The OTF algorithm with its error model is far more complicated than the widelane method, and needs much more processing time, which may be a disadvantage for real-time implementation.

Validation module
In this module all computed integer ambiguity numbers of the Wide-Lane module as well as of the OTF module are thoroughly checked. Unfortunately, no fixed criteria could be identified to automatically validate the ambiguity numbers. Thus an operator is given the choice to proceed with either the widelane ambiguity numbers, the OTF ambiguity numbers (which in the ideal case would be identical), or enter alternative numbers (e.g. based on a previous solution). After withdrawal of all inconsistent and possible unreliable results, the validated ambiguity numbers are sent to the high accuracy differential carrier range module.

Differential carrier range module
The double differenced carrier ranges are first corrected for the (differential) tropospheric delay using a model based on meteorological observations at the reference station. Using the previously determined ambiguity numbers and the (corrected) L1 carrier ranges, the calculation of the high accuracy update is straight forward (Ref. 5). All satellites in view (at least 5) are used in this calculation. A check is made on the residuals: values greater than 3 cm indicate a possible incorrect ambiguity determination. The operator may decide to step back to the validation module and start the differential carrier range module using a different set of ambiguity numbers.

GPS/IRS integration module, postprocessing
In the postprocessing mode a straightforward least-squares filter is used to fit the IRS trajectory through the high accuracy GPS updates.

4 Results

4.1 Testcase

The results presented are based on flight test data gathered during the runway performance tests of the Fokker 60 in Granada, Spain, conducted in the spring of 1996. The tests were performed on the single runway available at the airport. The direction of this runway is nearly East-West. Data of six flights were selected for analysis.

4.2 Data analysis and discussion

The data presented in the next section are either the result of in-flight, real-time processing, or processing on the ground (see chapter 3.2.2).
Four types of analysis have been carried out:

1. The availability of the real-time medium accuracy solution.
2. The accuracy of the real-time medium accuracy update.
3. The accuracy of the postprocessing enhanced update.
4. The accuracy of the postprocessing high accuracy update.

The results are given in the next sections.

4.2.1 Availability

The data of the 6 flights with the Fokker 60 prototype were analyzed on the availability of the real-time medium accuracy position solution. In this analysis the availability of the whole system is considered, including the DGPS update, the telemetry link, the IRS and the integration module.

Each test flight consists of a number of measurement segments, usually on or close to the runway and lasting a few minutes. The measurement segments are connected by transit segments. The availability of the real-time system during the measurement segments appeared to be 100 %, where the average availability during a whole flight was 94 % (at least four satellites in view). The difference is mainly due to momentarily loss of the telemetry link in the transit segments when the aircraft banked with the uplink antenna away from the ground reference station.

4.2.2 Medium accuracy results

Figure 4 shows the results of the medium accuracy DGPS solution for one flight (flight nr 105). In this figure only the flight segments close to or on the runway are presented. The data are plotted as a function of the distance along the runway (direction West-East).

The lower plot shows a top view on the runway. From this plot (and from the following top view plots) it is clear, that the aircraft always taxied within a few meters from the centerline. It thus stayed in the area where the height differences resulting from the cross curvature of the runway are still low. Therefore it is assumed that the GPS antenna height above the runway always had the same value within a few cm's.

The antenna height in earth fixed coordinates is shown in the upper plot (obviously the runway has an upward slope towards the East direction). The concentration of data at a height of 4 m between the positions 150 m and 400 m are not measured on the runway but at another location of the airfield.

Figure 5 shows the combined results of the medium accuracy DGPS solution for all six flights (including flight 105 of figure 4).

To show the spread in height in more detail a small part of the runway from 800 to 1000 m has been blown up in figure 6. In this figure again the combined results are shown of the six selected flights. This figure indicates that the accuracy of the DGPS method in vertical direction is better than the required value of 5 m.

In order to get a better insight into its accuracy, the medium accuracy DGPS solution has been compared to the high accuracy solution, wherever available. Figure 7 shows the errors in the North, East and altitude directions as function of the time index, combined over the six selected flights. The calculated accuracy (2σ) of the enhanced DGPS solution appeared to be ± 1.2 m in North, ± 1.0 m in East and ± 2.2 m in vertical direction. From this figure it is also clear that the horizontal components have a better accuracy than the vertical component, a fact that follows from the geometry of the visible satellites.

4.2.3 Enhanced postprocessing results

Figure 8 shows the results of the enhanced DGPS postprocessing for one flight (flight nr 105). Again in this figure only the flight segments close to or on the runway are presented. The relative height is shown in the top plot. The horizontal spread in the trajectories is shown in the bottom plot.

Figure 9 shows the combined results of the enhanced DGPS postprocessing for all six selected flights.

To show the spread in height in more detail a small part of the runway from 800 to 1000 m has been blown up in figure 10. In this figure again the combined results are shown of the six selected flights. This figure indicates that the accuracy of the enhanced DGPS method in vertical direction is in the order of 0.5 m.

In order to get a better insight into its accuracy, the enhanced solution has been compared to the high accuracy solution, wherever available. Figure 11 shows the errors in the North, East and altitude directions as function of the time index, combined over the six selected flights. The calculated accuracy (2σ) of the enhanced DGPS solution appeared to be ± 0.35 m in North, ± 0.3 m and ± 0.6 m in vertical direction.

4.2.4 High accuracy postprocessing results

Only the results which passed the automatic validation are shown in this section.

Figure 12 shows the results of the high accuracy differential carrier range postprocessing for one flight (flight nr 105). The relative height is shown in the top plot. The horizontal spread in the trajectories is shown in the bottom plot. Figure 13 shows the combined results of the differential carrier range processing for the six selected flights.

To show the spread in height in more detail a small part of the runway has been blown up in figure 14. In this figure the combined data are shown of the six selected flights. This figure indicates that the accuracy of the differential carrier range method is better than ± 0.15 m in vertical direction. Note that the spread in height is partly due to the high accuracy mode error, partly to the variation in the undercarriage extension, and partly due to the remaining cross runway height differences.

Comparing fig. 5 and 9 with fig. 13 it is apparent that the number of high accuracy trajectories plotted is about 50 % of the number of (enhanced) DGPS trajectories. This is due to the fact that all (enhanced) DGPS results were found to be correct while only a portion of the differential carrier range results (50 %) passed the automatic validation procedure.

It was experienced that a thorough analysis of the available data sets and especially of the integer ambiguity fixes by an experienced operator allowed all data sets to be processed in the high accuracy mode. This is, however, time consuming and as a consequence too costly.

5 Developments

As mentioned in chapter 3 and proven in chapter 4, automatic ambiguity determination succeeds in a limited number of cases only. There may be a number of reasons:

1. It is assumed that in forming double differences the atmospheric delay cancels sufficiently. In the high accuracy environment (10 km from the reference station, and up to 500 m height difference) this may not be the case.
2. The GPS receivers produce data which are not of sufficient quality (noise).
3. The selected ambiguity determination algorithms perform suboptimal.

The following possible solutions are or will be under investigation.

1a. Alternative tropospheric delay models are evaluated for their suitability within the PRS environment.

1b. Modelling of the ionospheric delay is absent in the current software. Preliminary investigation showed, that the double differenced ionospheric delay causes a negligible error in the double differenced carrier ranges within the PRS environment. A more in depth investigation will prove if this assumption is incorrect.

2. Flight tests in November 1996 with state-of-the-art dual frequency receivers indicated, that multipath and receiver noise on the L2 pseudorange and carrier range are significantly less than these figures for the Turbo Rogue (designed about 5 years ago). This may improve the ambiguity determination process.
3. Another OTF processing method is the so-called LAMBDA (Least-squares AMBiguity Decorrelation Adjustment, Refs 6 and 7) method providing the integer least-squares estimate for the ambiguities very efficiently. In cooperation with the Delft University of Technology the applicability to flight testing of this method is being investigated as an alternative to the currently implemented methods.

It is the author’s firm belief, that the above mentioned improvements will result in a significant improvement in the ambiguity determination process.

Once this stage has been reached, a real-time implementation of the high accuracy update method becomes feasible.

6 Conclusions

A GPS/inertial based Position Reference System (PRS) has been described. The system has been validated and used during a large number of flights with Fokker prototype aircraft.
Results of the system in operation were shown and discussed.
The results show that the system meets the position accuracy requirements.
The accuracy of the medium accuracy DGPS method is better than ± 2.2 m and the accuracy of the enhanced DGPS method is better than ± 0.6 m, both in three directions. The accuracy of the differential carrier range method is better than ± 0.15 m in vertical direction.
The availability of the medium- and enhanced accuracy modes turned out to be 100 % during the measurement segments and 94 % over the whole flight.
The availability and reliability of the high accuracy solution is only sufficient in the post processing mode with extensive involvement of an experienced operator. This is however time consuming and costly. Some reasons for the failure of automatic (post) processing in the high accuracy mode were given, possible solutions are under investigation.

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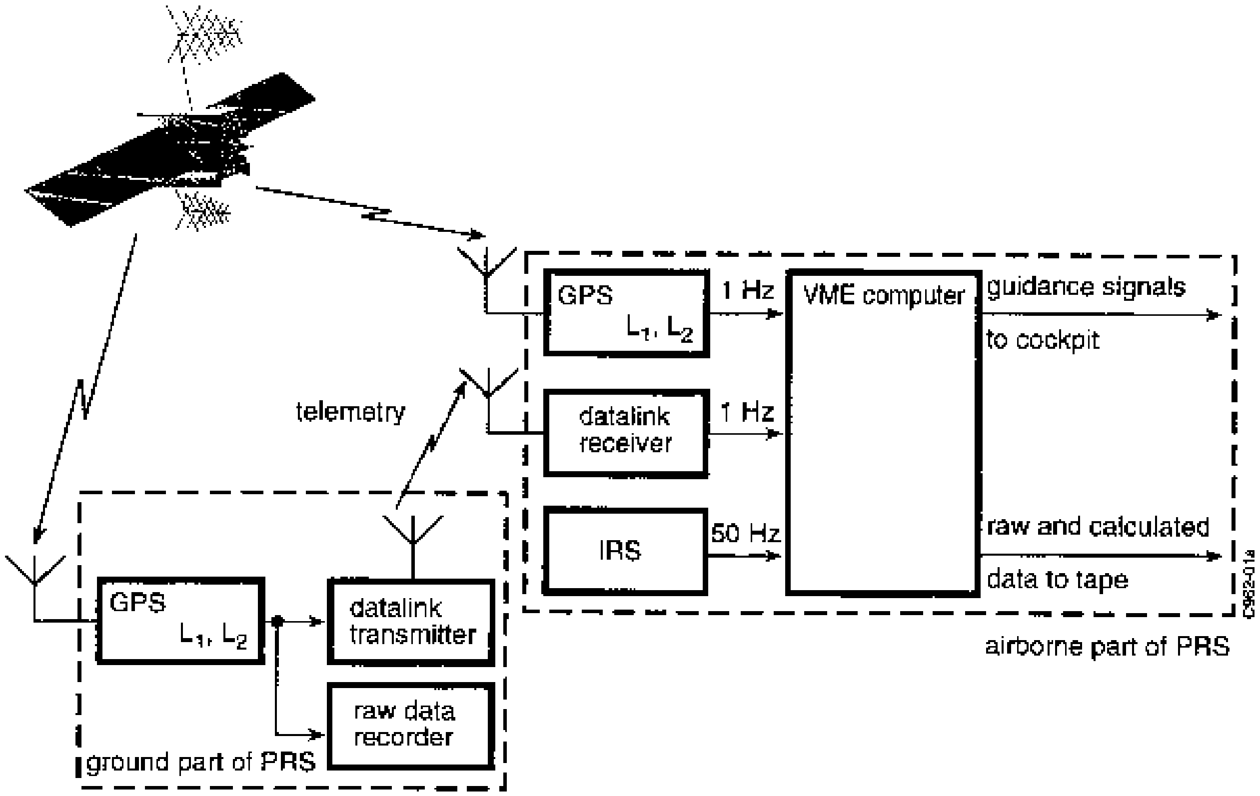

Fig. 1 Hardware lay out

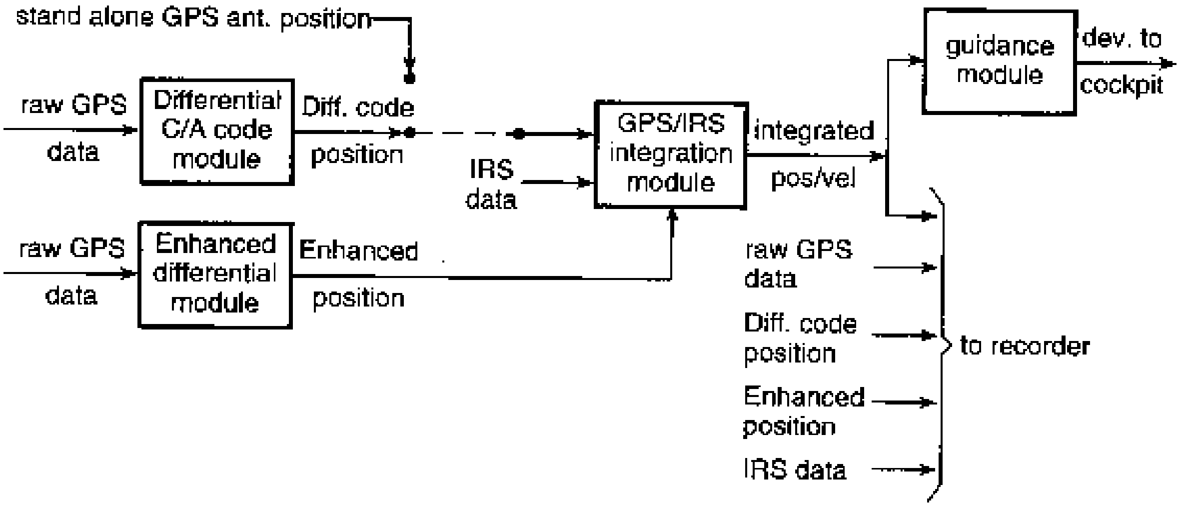

Fig. 2 On-board real-time software modules

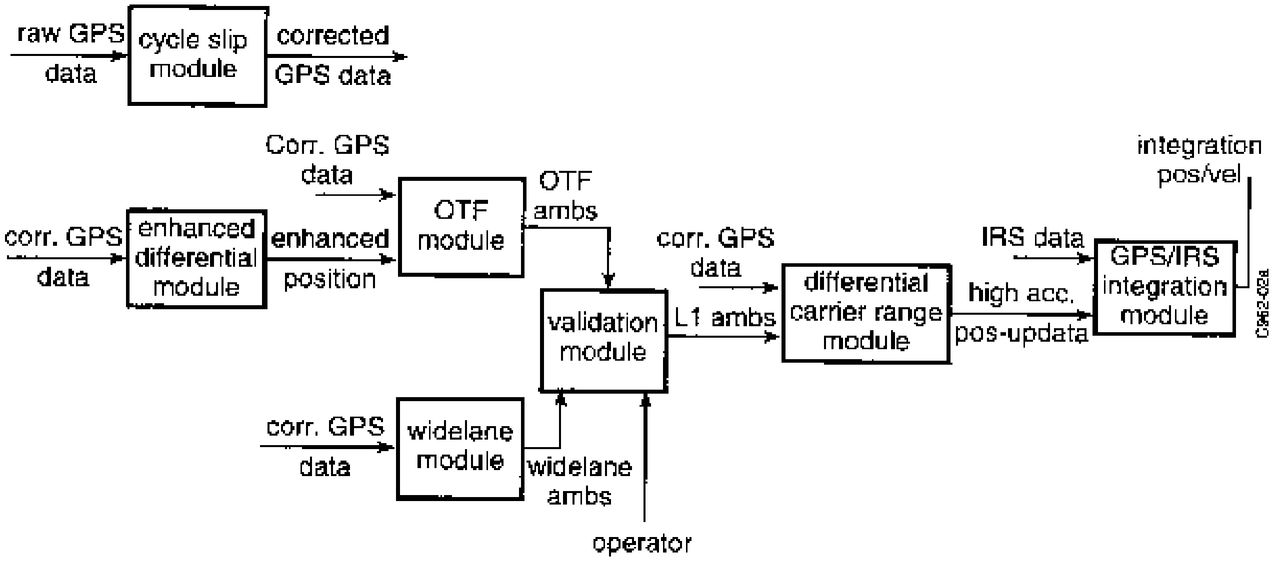

Fig. 3 Postprocessing software modules

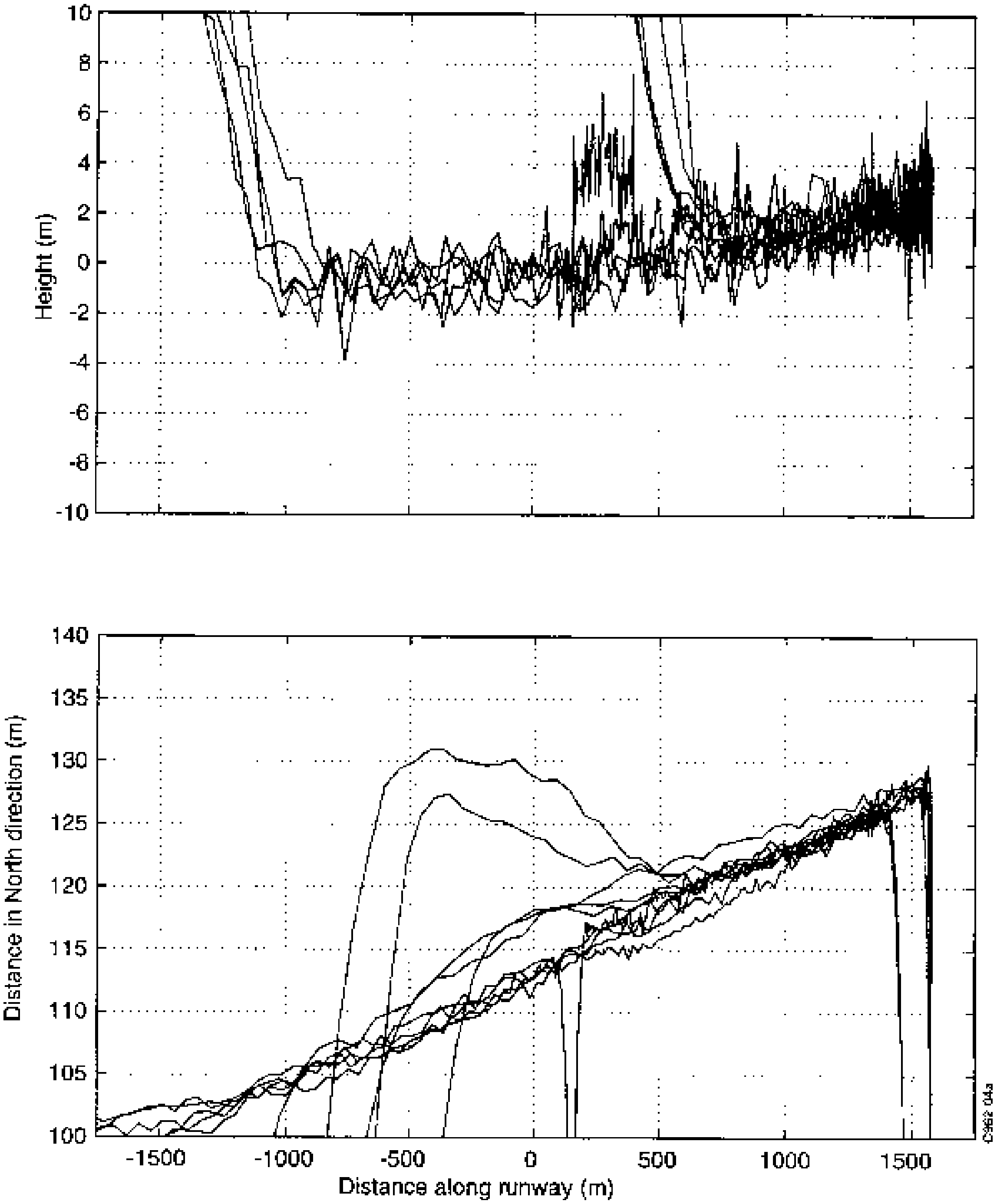

Fig. 4 Medium accuracy DGPS results close and on the Granada runway for flight 105

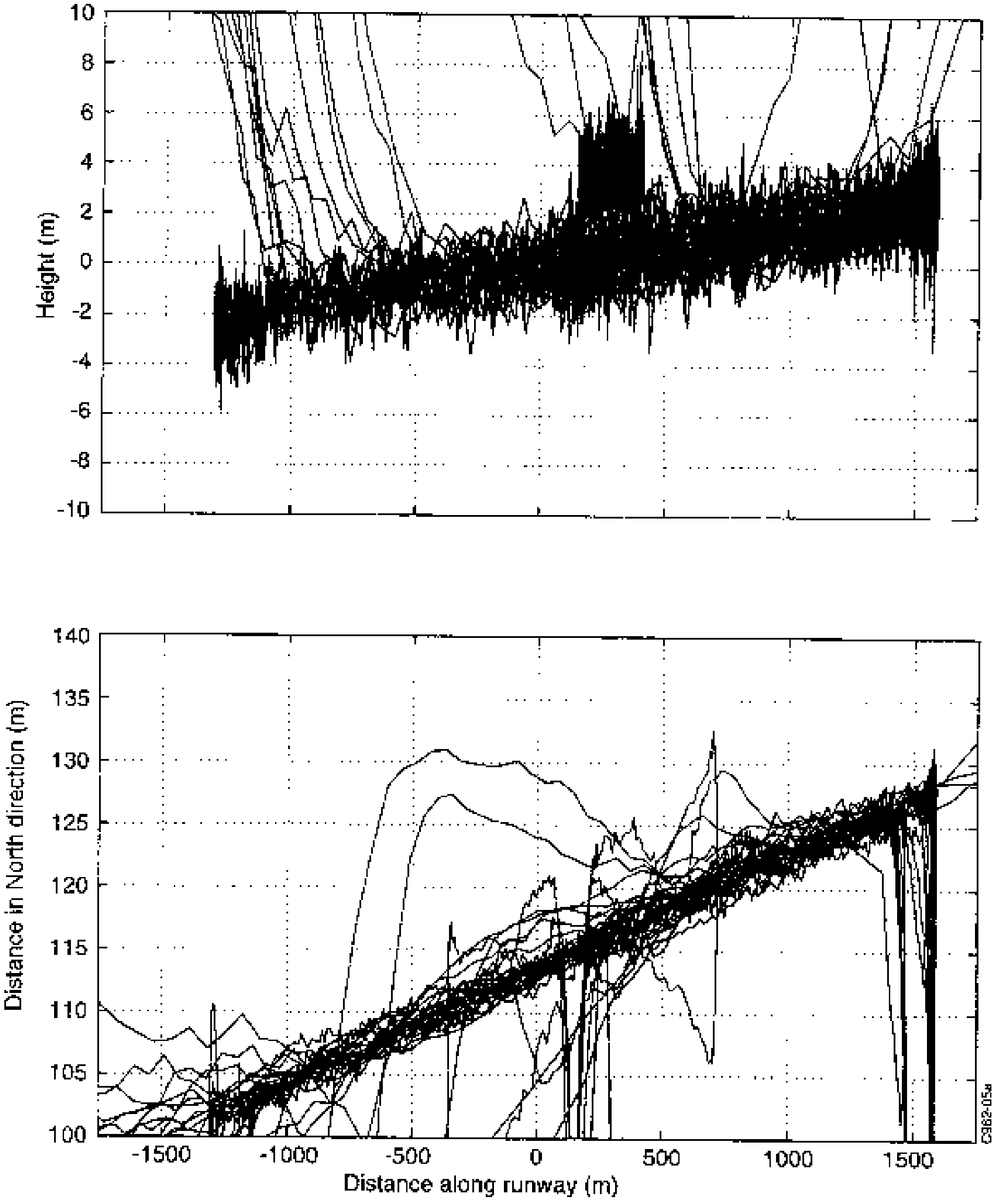

Fig. 5 Medium accuracy DGPS results of six combined flights on the Granada runway

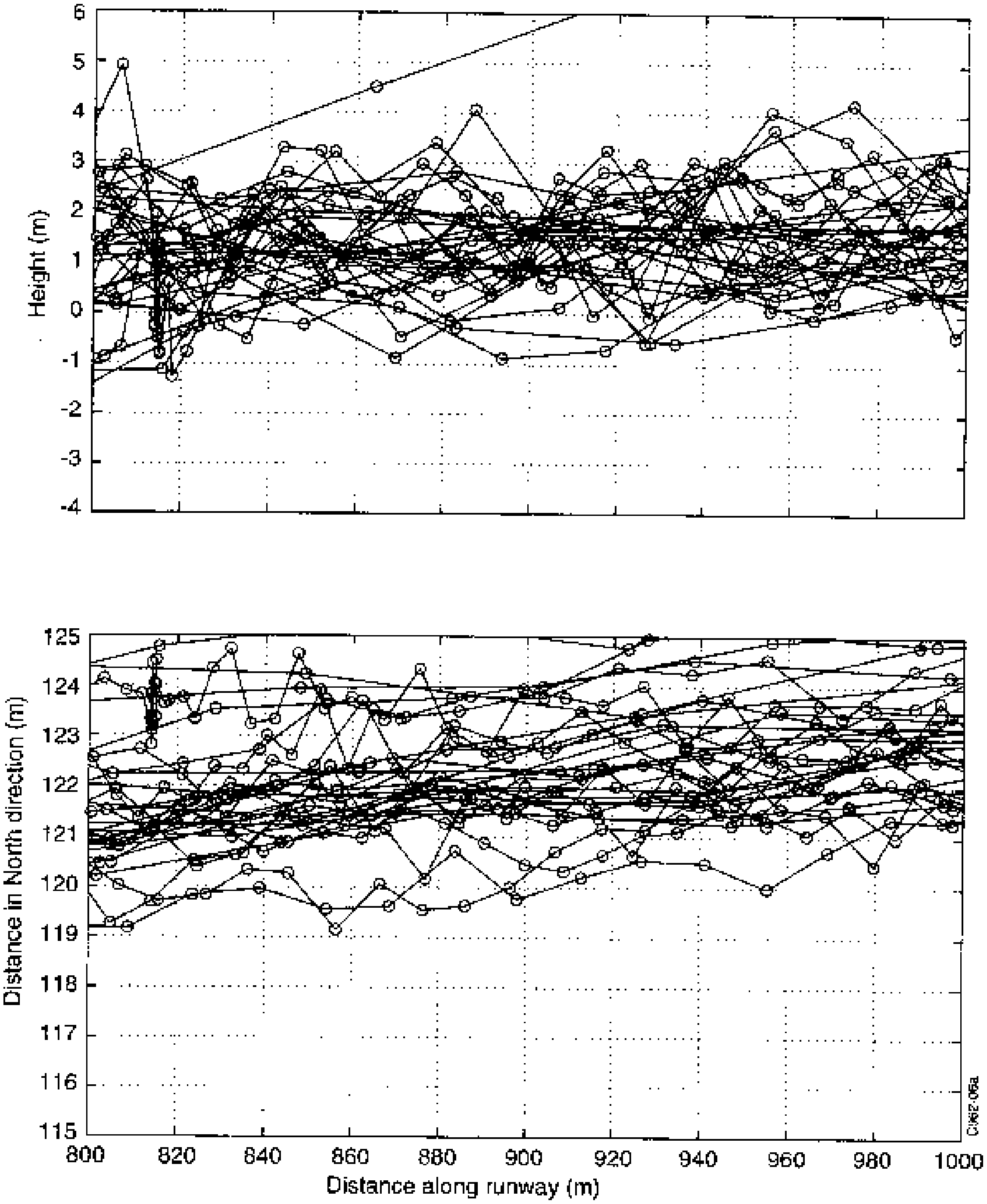

Fig. 6 Medium accuracy DGPS results of six combined flights on a part of the Granada runway

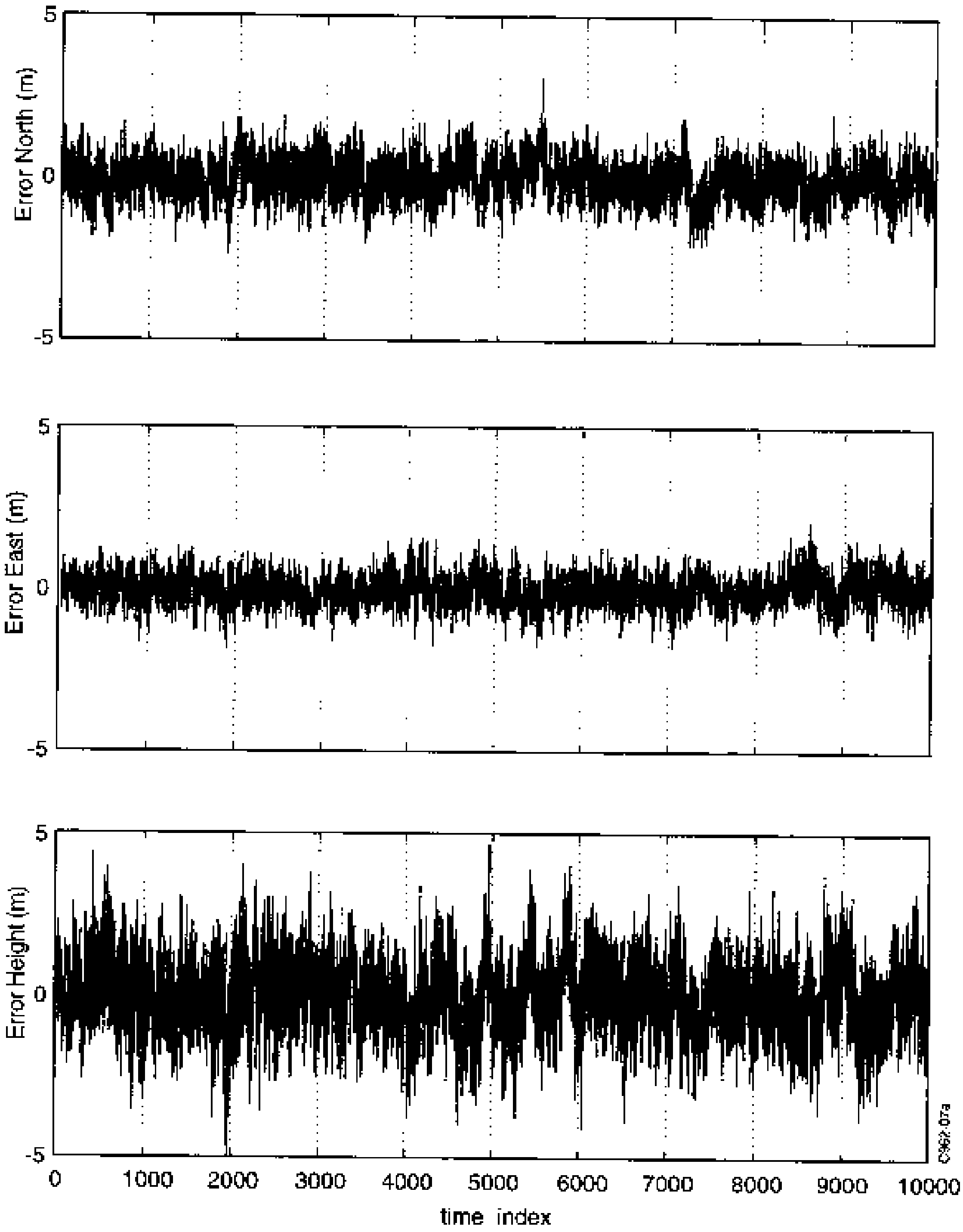

Fig. 7 Errors in three directions of the DGPS method plotted as function of the time index over the six combined flights

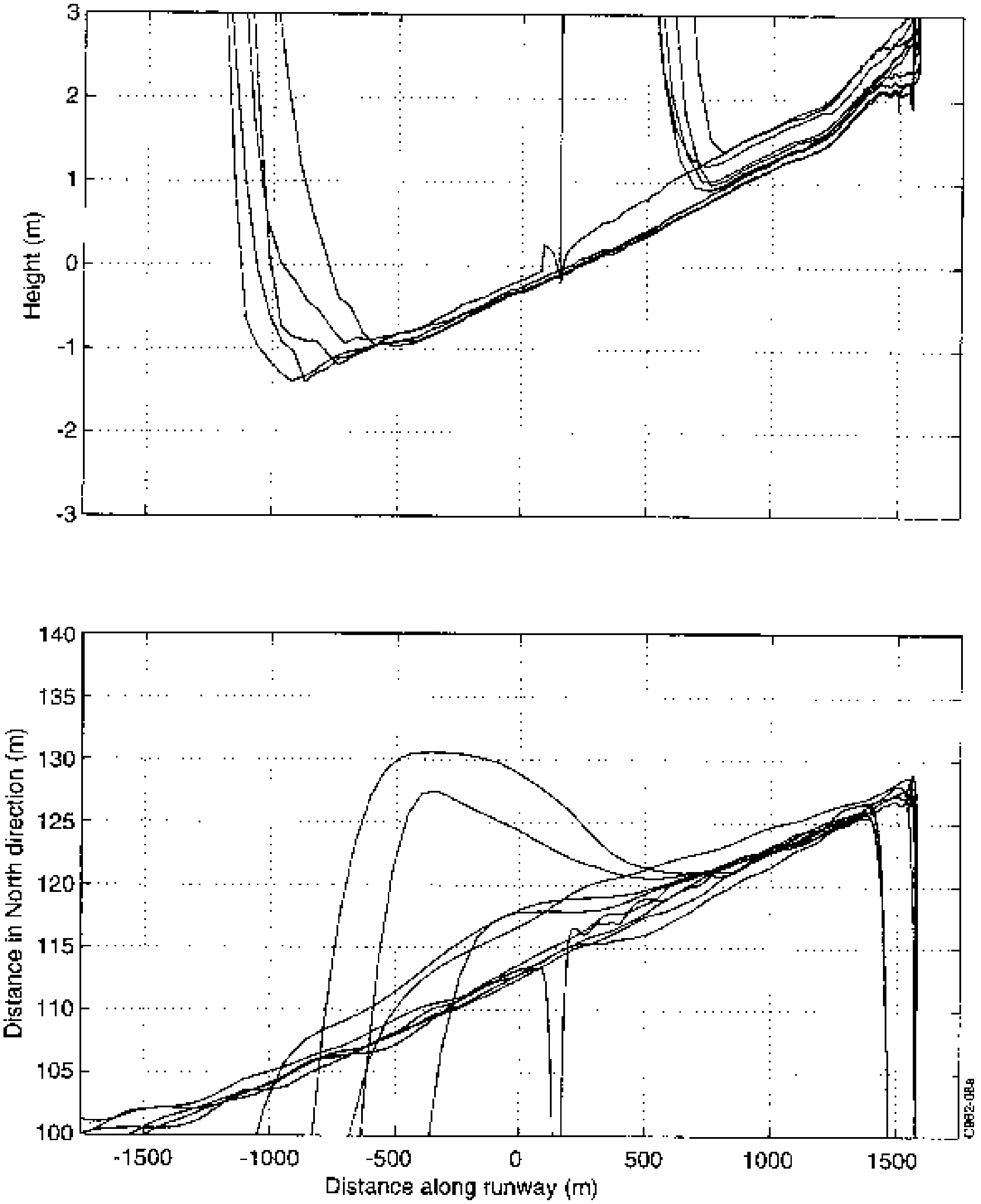

Fig. 8 Enhanced DGPS results close and on the Granada runway for flight 105

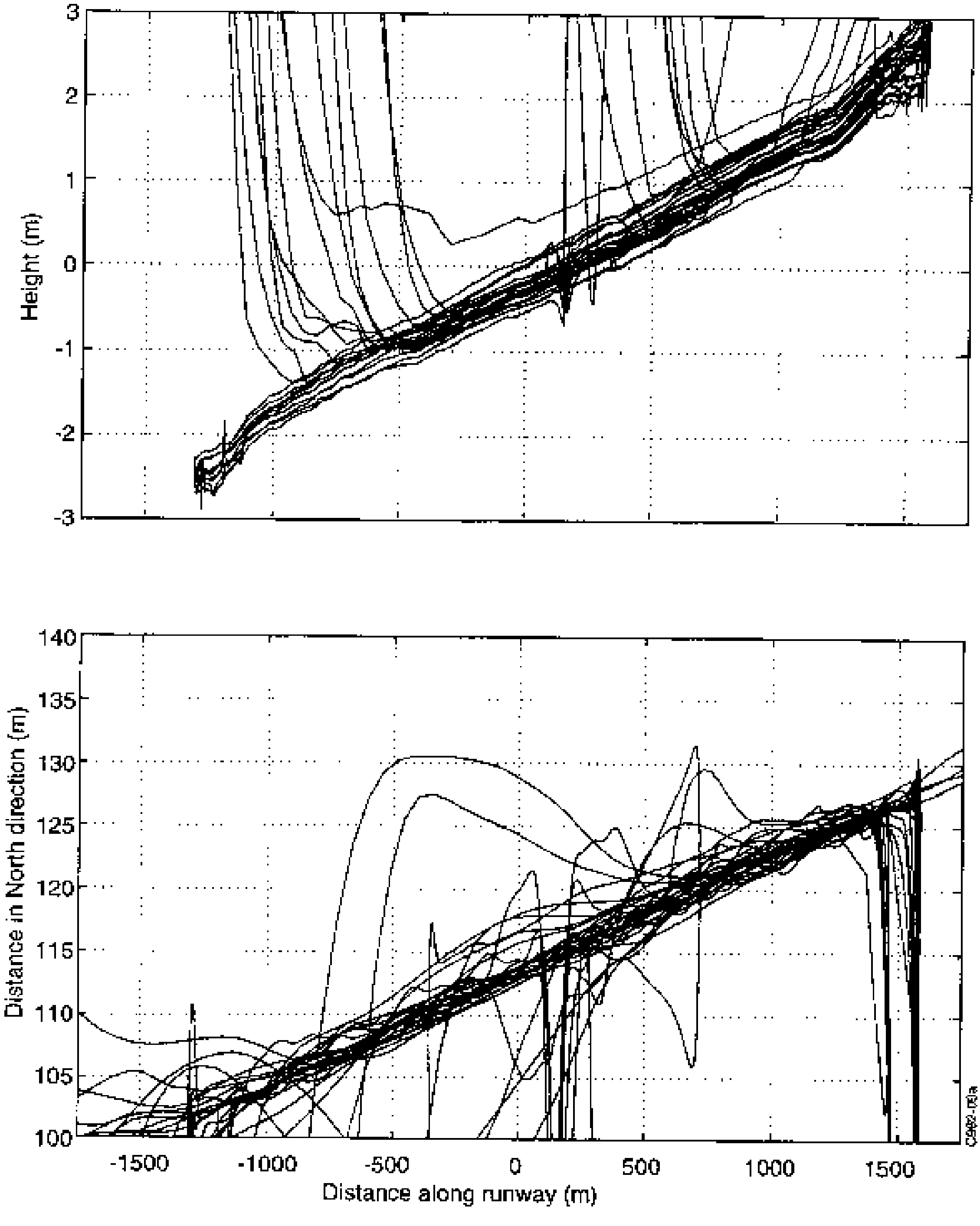

Fig. 9 Enhanced DGPS results of six combined flights on the Granada runway

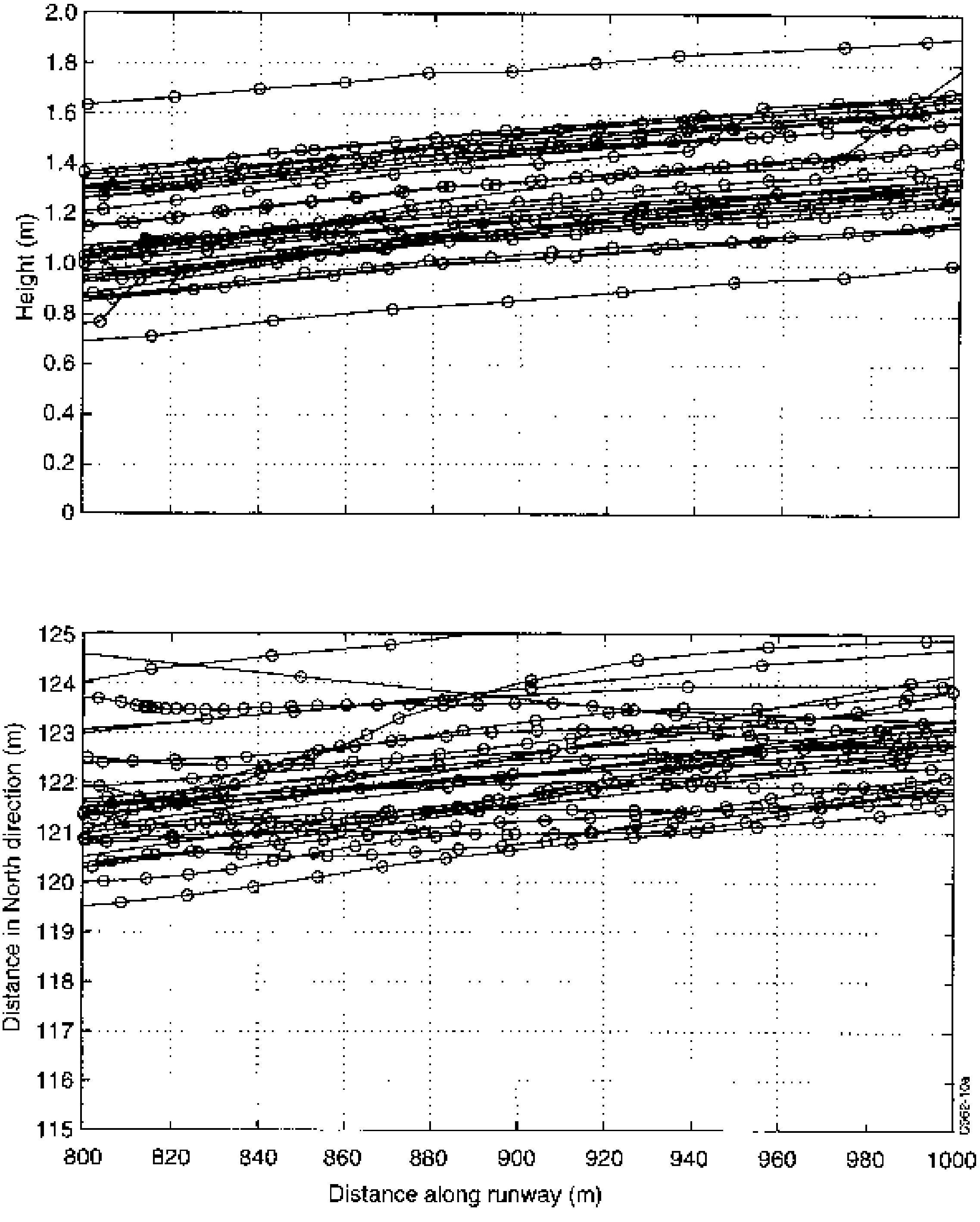

Fig. 10 Enhanced DGPS results of six combined flights on a part of the Granada runway

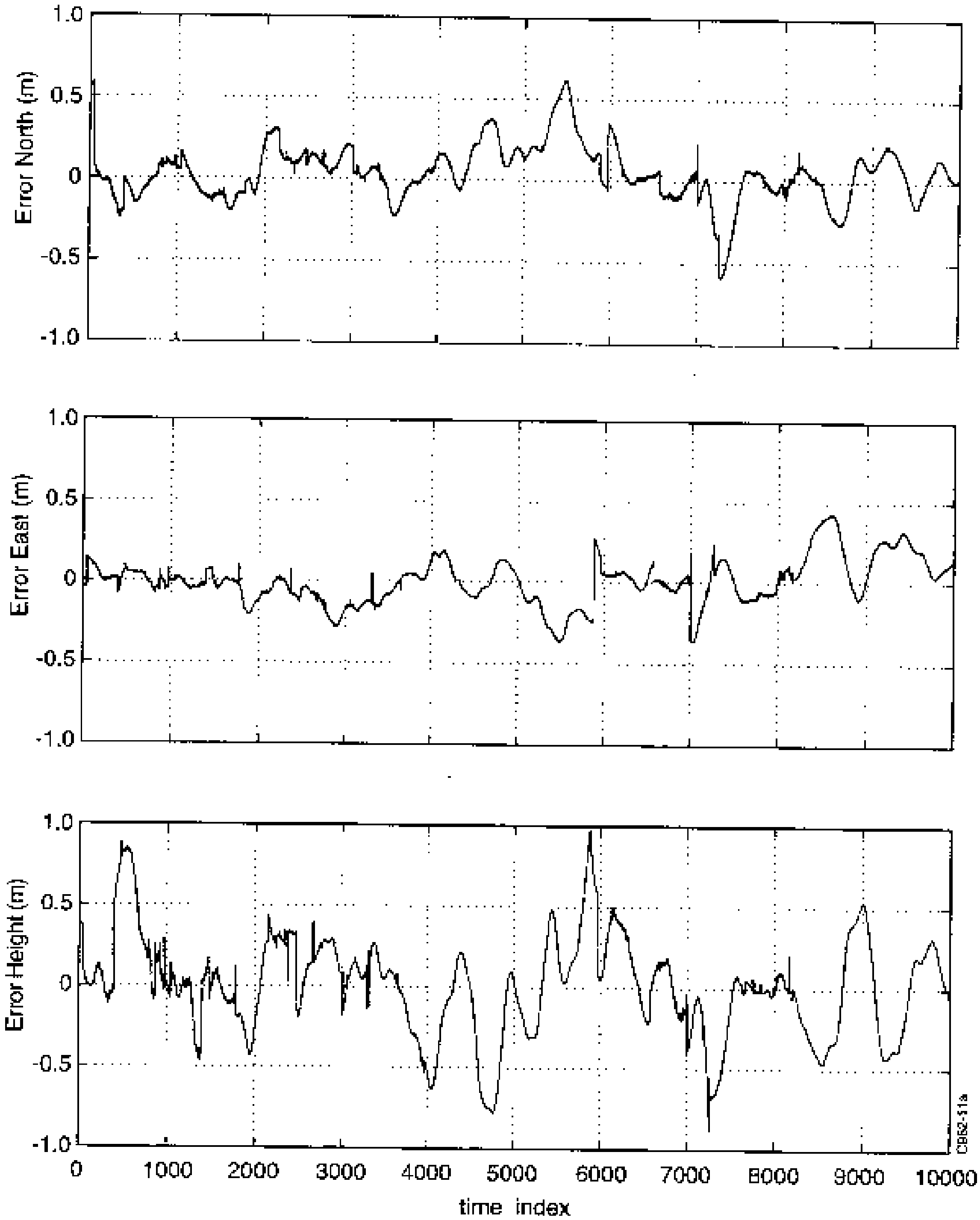

Fig. 11 Errors in three directions of the enhanced DGPS method plotted as function of the time index over the six combined flights

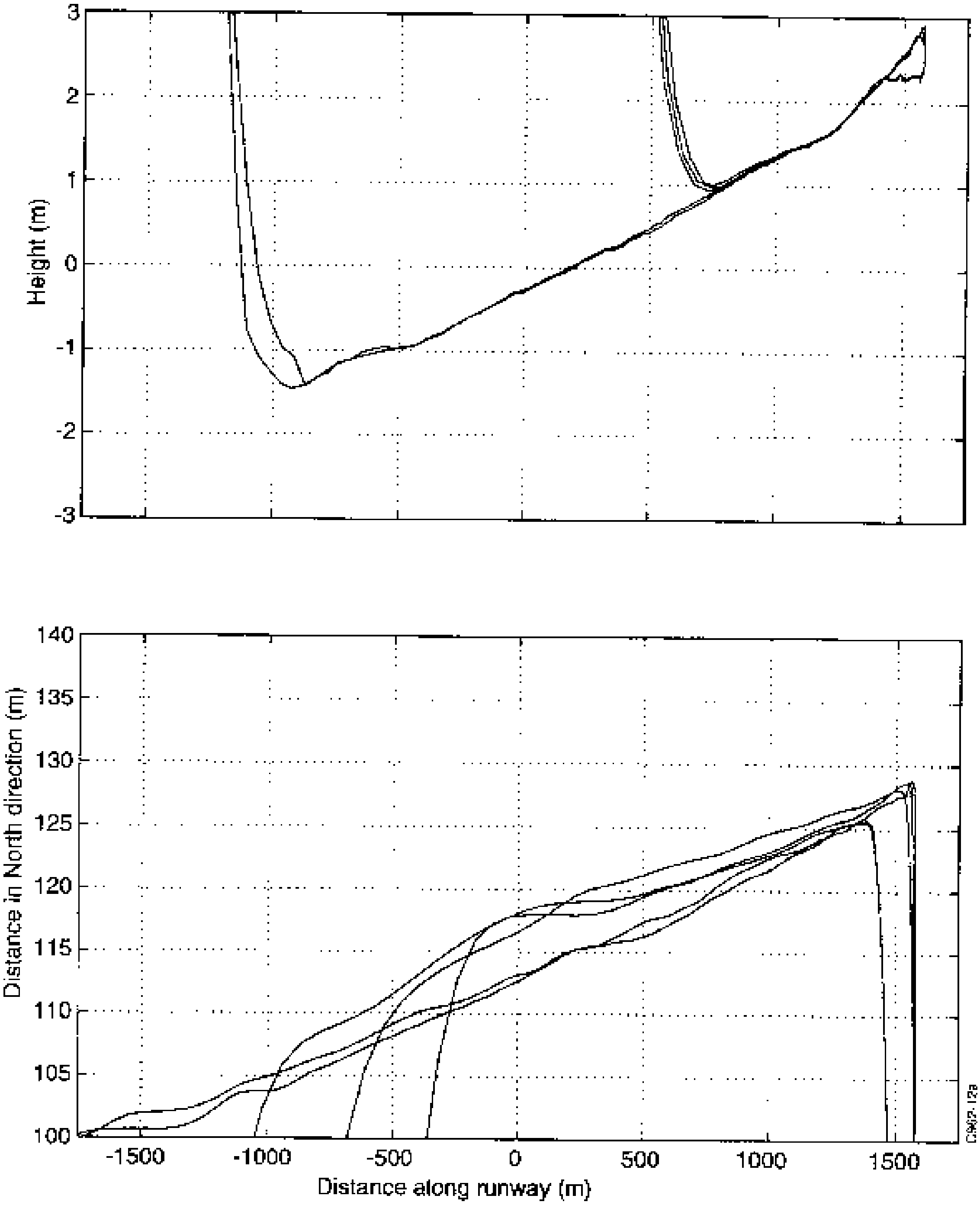

Fig. 12 Differential carrier range high accuracy results close and on the Granada runway for flight 105

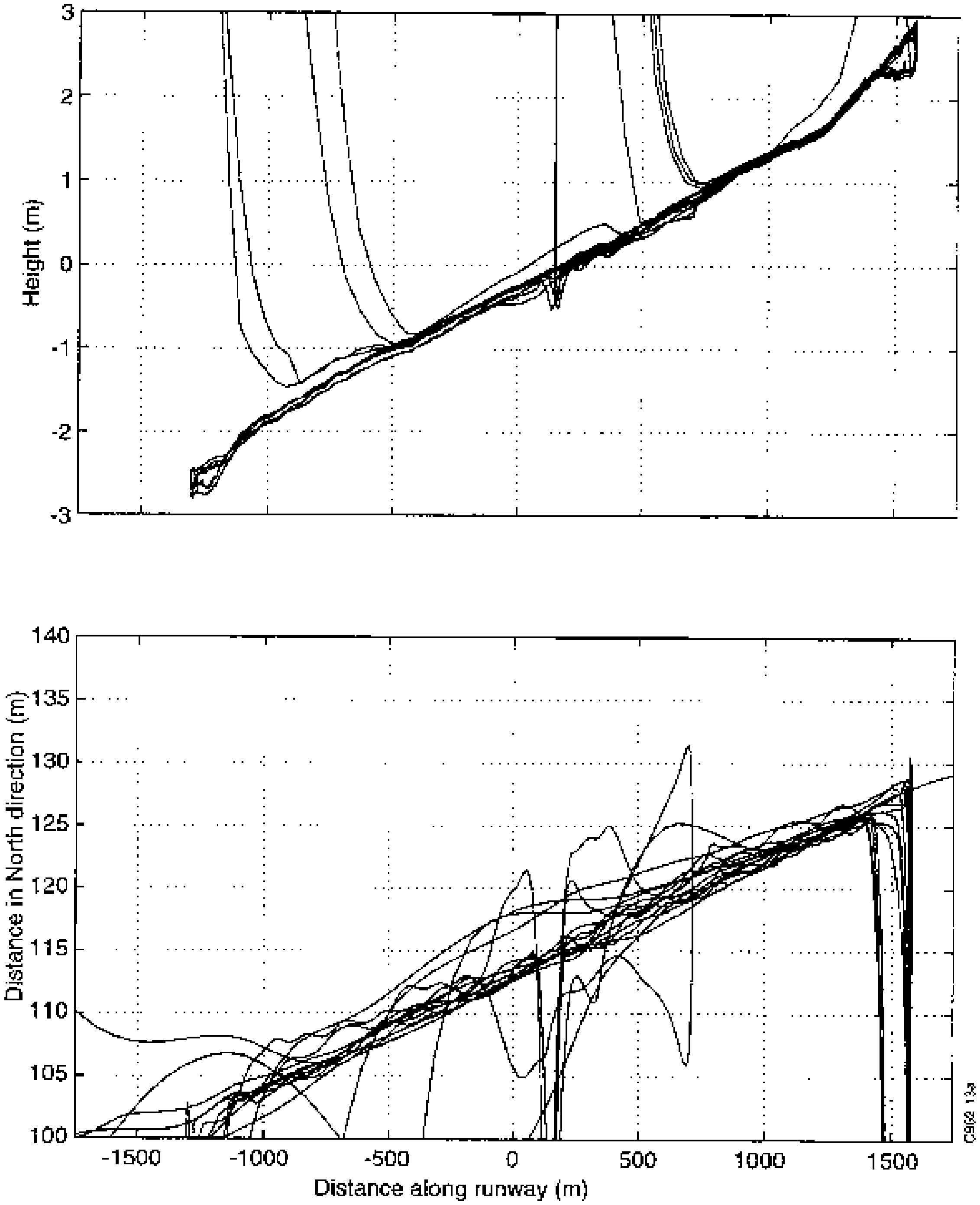

Fig. 13 Differential carrier range results of six combined flights on the Granada runway

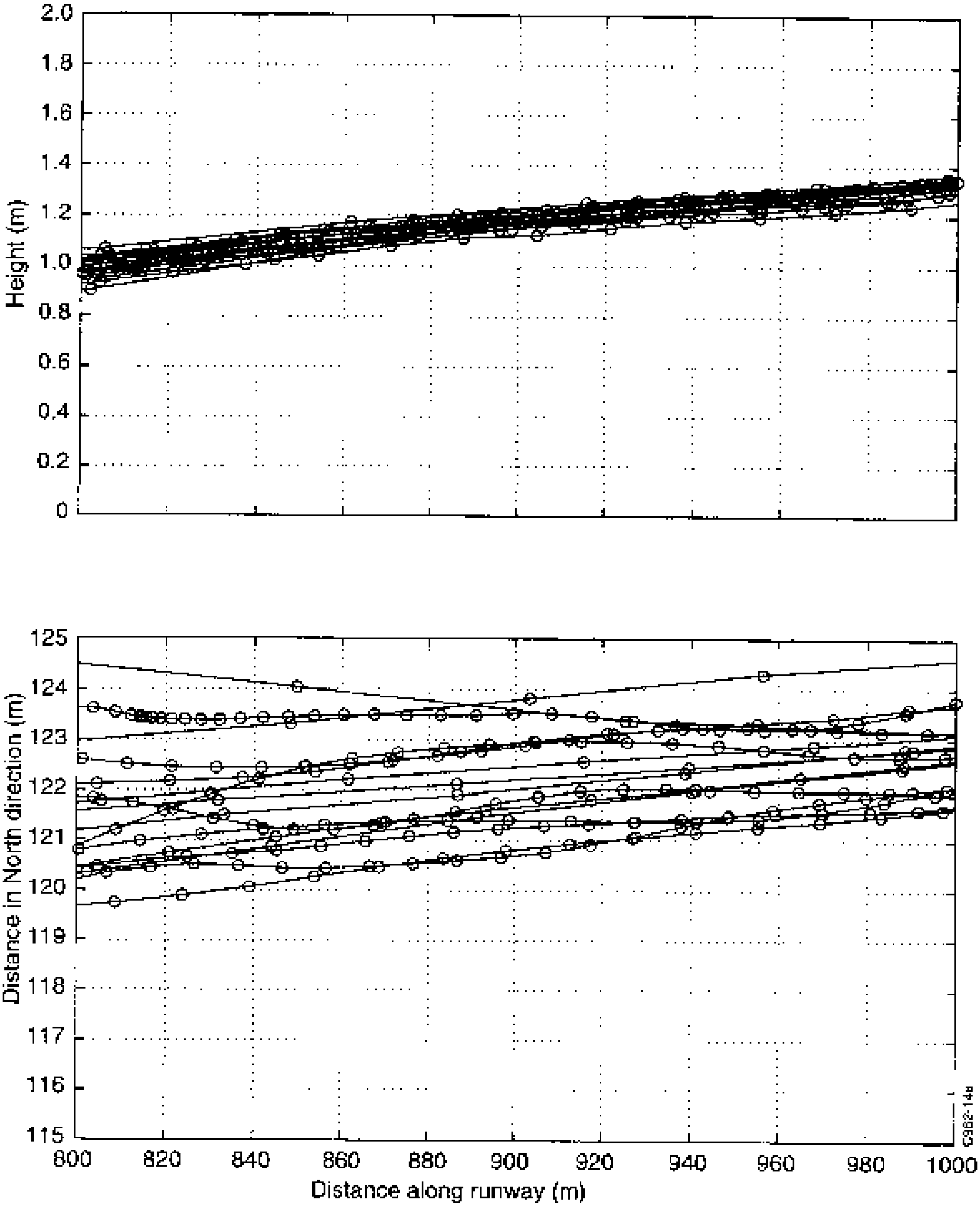

Fig. 14 Differential carrier range results of six combined flights on a part of the Granada runway