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KINEMATIC POSITIONING WITH CARRIER PHASES AND "ON THE WAY" AMBIGUITY SOLUTION

by

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Abstract

A method is described how to use dual frequency P-Code- and carrier phases to solve ambiguities with the "extra wide laning" technique in the kinematic mode. The ambiguities are solved within a few minutes "on the way", that means without the necessity to start on a known position. This makes the method also applicable for moving platforms in remote areas. Once the ambiguities are solved the full carrier phase accuracy can be exploited, thus a few centimeters in relative positions are achievable.

Two examples with real data are presented and analyzed:

- 3-D ships attitude control was investigated by use of three TI4100 equipments on the German research vessel "Meteor".
- relative kinematic positioning was performed to control the camera positions in a photogrammetric airplane with 2 TI4100 operated in the high dynamic mode.

Finally some aspects are discussed how the method may be used with dual frequency C/A-Code receivers.

1. Kinematic Positioning with Carrier Phases

Kinematic positioning with carrier phases implies the solution of ambiguities in order to exploit the full accuracy potential of the carrier phase measurements. Most applications use a method which was first described by REMONDI 1985. Two receivers start in a static mode on two stations A and B in order to determine a precisely known starting vector and to solve the initial ambiguities. The second receiver is then moved to other stations where it is stopped for a very short time. In order to shorten the initial starting period, antenna exchange techniques between A and B have been proposed and successfully used (antenna swapping). One essential aspect is, that phase loss (cycle slips) should be avoided during the moving periods. Otherwise a return to already known points may be necessary, if cycle slips cannot be recovered. This makes the method restricted to use on land within rather short distances; on a starting airplane, for instance, or a remote vessel in heavy sea, cycle slips are nearly unavoidable.

An universal solution for kinematic positioning with carrier phases requires the solution of ambiguities by using the kinematic data only, without a static starting procedure. We call this "on the way" ambiguity solution. It can be used in post-processing and in real-time modes and does not require any return to a known point when cycle slips occur.

In the following a method is described how to use dual frequency P-Code and carrier phases to solve ambiguities "on the way". The efficiency of the method is demonstrated with real data from a ship and an airplane experiment. Three TI4100 receivers have been installed during a cruise of the German research vessel METEOR in the East-Atlantic in January 1988. These allow to investigate 3-D ships attitude control. Relative kinematic positioning was performed under controlled conditions on a photogrammetric airplane in August 1988.

2. The "On the Way" Ambiguity Solution with Dual-Frequency P-Code Receivers

From dual frequency phase measurements several linear combinations can be computed which have certain characteristics. Similar linear combinations can also be formed from dual frequency P-code observations.

A short desciption of the important signals follows, a detailed discussion can be found in WÜBBENA 1989. The wide lane is computed from the difference between the L1 and L2 carrier phases. The wavelength of this signal is approximately 86.2 cm. The narrow lane is obtained from the sum of the L1 and L2 carrier phases, its wavelength is approximately 10.7 cm. The difference between narrow and wide lane propagation times depends only on the ionospheric propagation delay and on signal delays due to satellite and receiver hardware. I.e. the difference is independent on the receiver to satellite geometry. Under normal circumstances the hardware delays show only small variations in time, so they can be described by simple models. The difference between the narrow and wide lane propagation times is called the ionospheric signal.

The wide lane transmission epoch is identical with the transmission epoch of a linear combination of the L1 and L2 P-code phases. This linear combination corresponds approximately to the mean of the code phases. Thus the noise in the code phases is approximately reduced by a factor of 1.4 in this signal. The wide lane ambiguity can be determined through a direct comparison with the transmission epoch of the code phase combination. Systematic differences depend only on satellite and receiver hardware delays. Strong multipath effects may also lead to systematic errors. As with the ionospheric signal the difference between the P-code and wide lane is independent on geometry, i.e. both signals can be used for kinematic applications.

The ambiguities in the wide and narrow lane are not independent. If one of the ambiguities is even, the other has to be even and if one is odd the other has to be odd, since both are linear combinations of the L1 and L2 ambiguities. This condition leads to the fact that the effective wavelength of one of the signals increases by the factor of 2 if the ambiguity of the other signal is resolved.

The wide lane wavelength is approximately 8 times the narrow lane wavelength. From this follows that if the wide lane ambiguity is known with an accuracy of +/- 3 cycles the ionospheric signal can be treated as a signal with the narrow lane wavelength and an integer ambiguity. If this ambiguity can be fixed the effective wavelength of the wide lane increases by the factor of 2 due to the even-odd condition. I.e. the wide lane ambiguity has to be resolved for an effective wavelength of 1.72 meters. This technique is called "extra wide laning".

If the distance between two observing receivers is small (some kilometers) the ambiguity of the ionospheric signal can easily be fixed through the assumption that the single difference ionospheric delay vanishes. This condition is fulfilled for the experiments described in this paper.

The "On the Way" ambiguity solution procedure is the following. First the wide lane ambiguity is approximately estimated from the comparison with the linear combination of the P-code phases. As long as cycle slips do not occur an accumulation in time is possible and reduces the estimation error. The ionospheric signal is accumulated over the same interval and its ambiguity is estimated and fixed to an integer if a certain accuracy level is reached. This normally allows the fixing of the extra wide lane ambiguity. In this case all ambiguities are recovered and the narrow lane, which has the lowest measurement noise, is used for positioning.

The processing of the data sets presented here was done with the GEONAP GPS adjustment system.

3. Ship's Attitude Control on the Research Vessel METEOR

3.1 METEOR Cruise 6/4

Between December 28, 1987 and January 12, 1988, the German Research Vessel METEOR operated in the Romanche Fracture Zone of the Middle Atlantic Ridge in order to test the performance of the new multibeam swath system HYDROSWEEP. Main purpose of the GPS operation was to supply precise positions for the ocean bottom surveying. The availability of in total 3 TI4100 receivers on board the vessel gave the opportunity of further investigations into the use of GPS for azimuth determination and attitude control. One antenna was installed on the foremast (GIH) and two on the outrigger ends of the main mast (AWI,IFE)(Fig.1). The receiver data were recorded continuously on magnetic tape and floppy disc. The following examples refer to a rather short sample of the complete data set.

3.2 Verification of the Model

The ambiguity estimation with the METEOR data set could nearly be done in realtime. The behaviour of the ionospheric signal and the code signal is shown in figure 2. The upper plot shows a typical single difference ionospheric signal, where a constant bias due to receiver delays is removed. The units on the ordinate are cycles of the ionospheric signal wavelength, i.e. 1 cycle = 10.7 cm. First it can be noted that the receiver delays are obviously constant over the whole period. The noise is about 0.15 cycles which correspond to approximately 1.5 cm. The error reaches the +/- 0.5 cycle level only at two points. This means that the correct ambiguity of the signal can be obtained in realtime except for this two points.

Once the ambiguity of the ionospheric signal is fixed, the extra wide laning technique can be applied to determine the wide lane ambiguity. The lower part of the plot shows the offset of the code from the wide lane signal. Again a constant receiver delay bias is removed. The noise in this plot is about 0.7 cycles of the wide lane wavelength. The correct wide lane ambiguity is found if the error in the signal is smaller than 1 cycle. There are some peaks where this level is exceeded, however an integration over a few seconds yields the correct ambiguity.

3.3 Distances between Antennas

The distances between antenna installations, computed from GPS carrier phase data, must be invariant. They can therefore be used as a reliable check of the method. Figure 3 shows the results from the GEONAP solutions for the antennas. It can be seen that the noise level of the narrow lane solution is about 1 cm. It is furtheron proved that the cycle slips can be recovered already after a few seconds. Thus the efficiency of the model could be verified through the METEOR data. Figure 3 demonstrates in addition that a PDOP-peak has a considerable effect on the solution. For large PDOP's no good 3-D solution can be found, which is selfevident for navigation applications.

3.4 Attitude Control

Through the simultaneous measurements of 3 receivers onboard the vessel it was possible to determine pitch, roll and azimuth motions of the vehicle. Figure 4 shows the distance between the IFE and AWI antenna and the pitch and roll behaviour with 3 seconds resolution over a time span of approximately 35 minutes. The periods are clearly recognizable and can be analyzed. The amplitudes reach +/-4° for roll and +/-1° for pitch. The angular resolution corresponds to the baseline length and refers to 1.00 mrad for roll (1 cm over 9 m) and 0.25 mrad for pitch (1 cm over 40 m).

The azimuth determination corresponds to the pitch resolution and reaches accordingly +/-0.01° this is much more accurate than conventional gyro navigation. It should be emphasized that the high accurate azimuth control makes highly reliable stream determination possible.

3.5 Conclusions

With GPS phase measurements it is possible to monitor the time dependent behaviour of a ship with extremely high resolution. This holds for attitude control and also for ship's heading. It should also be possible to monitor deformations on tankers and other large vessels in heavy sea with 1 cm level of accuracy.

4.0 Relative Kinematic Positioning of a Photogrammetric Airplane

4.1 Project, Objectives

The use of GPS for photogrammetric control within an airplane has been widely discussed. When 3-D coordinates of the projection centre of the photogrammetric camera are known with sufficient accuracy, a strengthening of the bundle block adjustment can be achieved and the required number of ground points can be reduced. In order to provide suitable data for scientific research to this respect, a dedicated experiment was realized in August 1988. One TI-antenna was mounted on top of a photogrammetric airplane with the receiver inside the cabin, and a second TI4100 equipment was operated on a ground control point.

The flight path, as determined from the GPS solution, is demonstrated in figure 5. Five strips with in total 69 photogrammetric pictures were used in the bundle block adjustment (see Fig. 6). The coordinates of the camera projection centers, comming from the photogrammetric solution provide a very reliable 3 D control for the GPS results. The project was carried out in cooperation with the "Institut für Photogrammetrie und Ingenieurvermessung" (IPI) University of Hannover. The bundle block adjustment was realized with program package BLUE of IPI by M.Sc. Keren Li.

4.2 Technical Realization and Problems

The relation between the antenna phase center and the photogrammetric camera center could be determined within a reference frame fixed to the airplane. The eccentricities in height are about 1.30 m and in position about 0.5 m. Problems arise however because the orientation of the airplane during the flight was not measured. Consequently rough orientation values had to be estimated and were applied for the eccentricity calculation. Remaining systematic errors are estimated to be in the level of a few decimeters (see Fig. 6), because a 10° change in orientation leads already to a 40 cm change in eccentricity. Figure 11 shows the GPS determined height profile of the airplane for the five strips. From this it may be seen that the orientation changes rapidly.

The epoch of shutter operation was determined with a photodiode and related to GPS time via a UTC time signal receiver. Time information is necessery in order to relate GPS measurement epochs (every 1.2 seconds) with the image sequence (approximately 4.5 seconds) via an adequate interpolation technique. This synchronisation procedure yields a considerable error source. For the operational use it is proposed to trigger the camera operation through the GPS measurement epoch, i.e. for all 3 seconds . In addition, the camera should be fixed to the airplane body during operation . The orientation of the airplane in space can be determined then from aerotriangulation with sufficient accuracy, in order to solve the eccentricity problem .

4.3 Ambiguity Solution

The ambiguity resolution for this experiment was more difficult because the measurement noise was relatively high compared to the attitude control data set. The reason for this is probably the selected high dynamic operation mode of the receiver. Figure 7 shows the single difference ionospheric signals for two satellites. A constant bias is removed in both plots. Relatively high variations can be observed, which are common to both satellites. This means that the receiver delay terms are not constant. The double difference ionospheric signal is shown in figure 8. There are remaining systematic errors with long term variations. This may be a multipath effect. The noise is approximately 0.5 cylces or 5 cm respectively. A realtime ambiguity estimation was impossible in this case, however the integration over the complete period leads to maximum errors in the estimated ambiguities of 0.15 cycles.

Figure 9 shows a plot of the single difference code-carrier error in the wide lane. The noise was about 0.7 cycles which corresponds to the values obtained from the ship data. The estimation of the correct ambiguity in the wide lane was again possible with maximum errors in the order of 0.2 cycles.

4.4 Comparison of GPS and Photogrammetric Results

After solution of ambiguities, the positions were estimated with the ambiguity-free pseudoranges through a 12-state Kalmanfilter. The filter was necessary in order to solve the interpolation problem. However the dynamical model was given a high degree of freedom in order to exploit the high accuracy potential of the measurements. The camera positions and velocities could be estimated from the state vector for all image epochs. These values were used in order to determine the ground velocity of the airplane and to support the eccentricity calculations. It should be emphasized that all those steps are subject to errors which can be avoided, when a body-fixed camera is used in synchronous mode to GPS measurements.

The coordinates of the photogrammetric fiducial points on the ground were transformed to WGS84. The bundle-block adjustment was carried out in a local system, tied to the GPS reference control point. Thus datum problems could be avoided. A comparison of GPS and photogrammetric coordinates is given in Figure 10 for all 5 strips. It is evident that the errors in the components are of the order of 10-40 cm and contain systematic effects. The residual vectors in position and height are also shown in Figure 6. With respect to GPS results it could be proved that all ambiguities are solved correctly, because a wrong ambiguity would cause discrepancies of more than 40 cm, since all ambiguities are related to the wide lane (see 4.3). It follows from the correct narrow lane solution that the pure GPS accuracy is in the order of a few centimeters. The discrepancies certainly result from remaining errors in the bundle-block adjustment and in the eccentricity problems.

4.5 Conclusions

The experiment proves that ambiguity solutions "on the way" are also reliably possible in a photogrammetric airplane and that with relative measurements to a ground control point an accuracy of a few cm is achievable. GPS can thus be used as an important tool in photogrammetry. It is however essential to eliminate the 4-dimensional eccentricity problem through use of an airplane-fixed camera and by exposure times related to GPS measurement epochs.

5. Prospects

The described methods are only applicable when the ambiguities are solved "on the way". This is possible with P-code receivers like the TI4100 without major problems because of the rather low code measurement noise. For most available C/A-Code receivers the noise level is too high so that the code/carrier combinations are not applicable. Two possible solution concepts seem to be successful alternatives for the near future.

(1) New hardware developments include receivers with extremely low code measurement noise in the few cm-level. A 2-frequency receiver with low C/A-code noise should be applicable because the 40-cm wide lane ambiguity can be solved with a 5-cm C/A-code noise level in nearly real time.

(2) It is possible to introduce additional conditions like known inter-antenna distances. With the forthcoming availability of eight or more simultaneously visible satellites and adequate multi-channel receivers, an ambiguity search function approach will lead to rather rapid ambiguity solutions.

As a consequence, the authors believe that the proposed technique will be universally applicable for future kinematic use of GPS.

6. Acknowledgements

The METEOR experiment was carried out jointly with the Alfred Wegener Institut fuer Polar- und Meeresforschung (AWI), Bremerhaven. Leader of cruise 6/4 was Dr. H.W. Schenke. The photogrammetric experiment was carried out jointly with the Institut für Ingenieurvermessung und Photogrammetrie (IPI) University of Hannover (Dir.Prof.Dr.Konecny). The photogrammetric computations were carried out by M.Sc. Keren Li. The photo flight was made possible by Hansa-Luftbild, Münster. The observations were carried

out by staff and students of the participating organisations. The support of all individuals and institutions to this research work is thankfully acknowledged.

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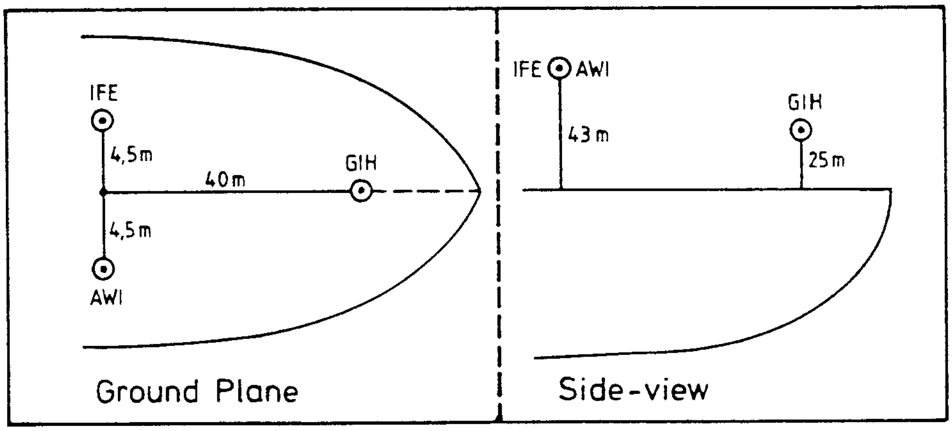

Figure 1: Antenna Mounting on the METEOR

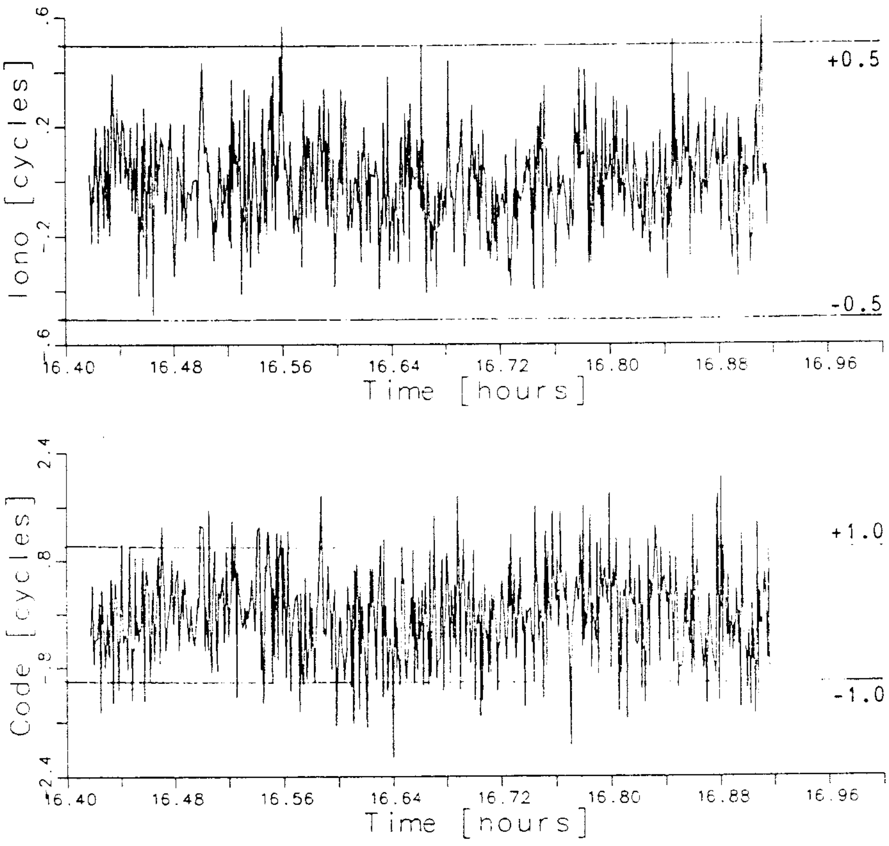

Figure 2: Single Differences of Ionospheric and Code Signals

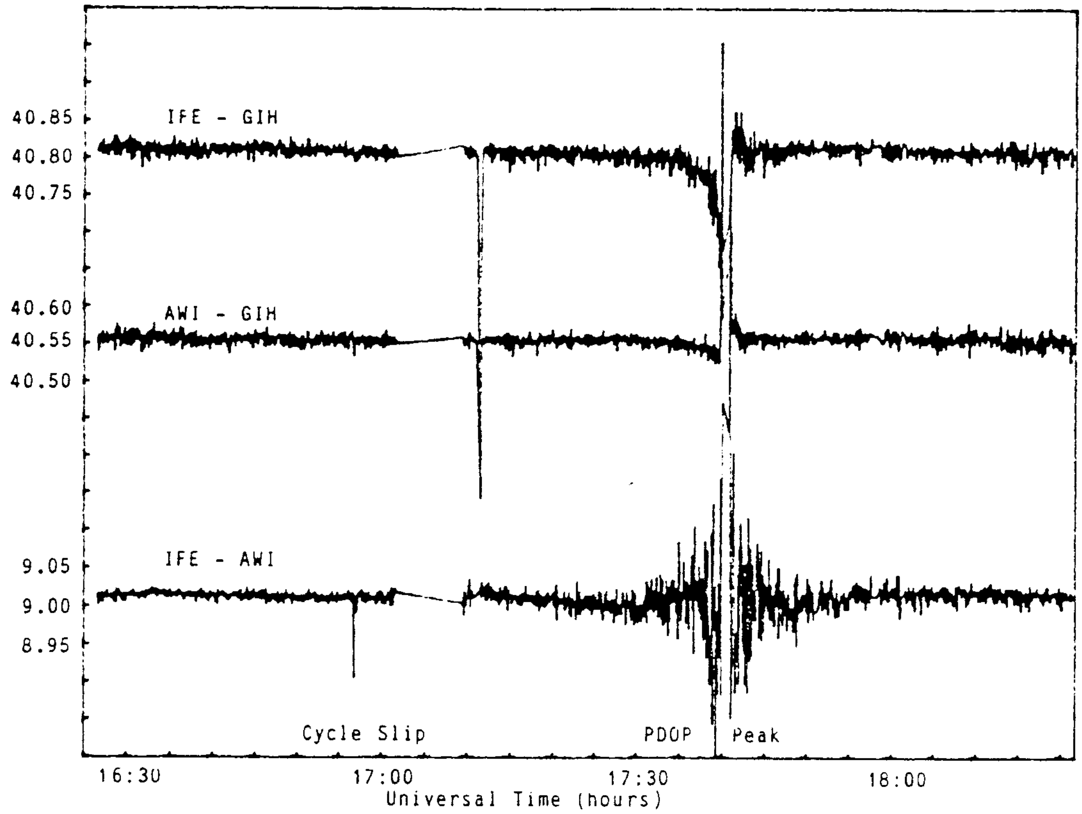

Figure 3: Computed Inter-Antenna Distances vs Time

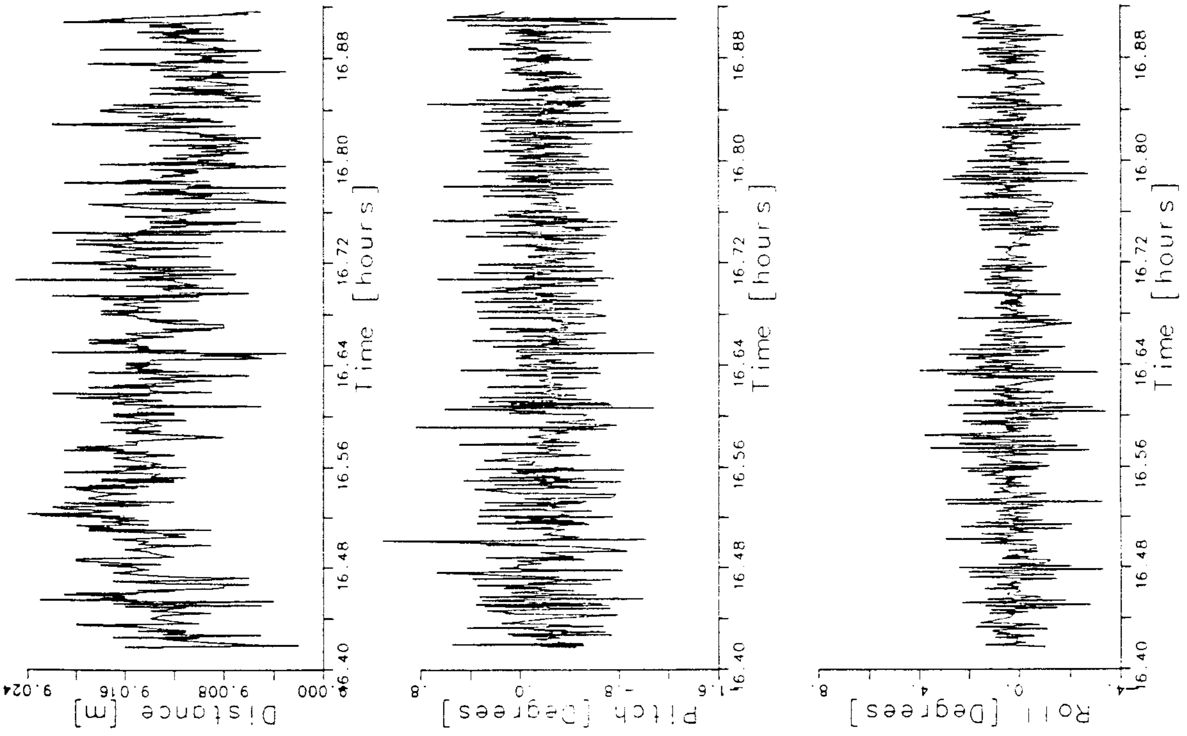

Figure 4: IFE-AWI Inter-Antenna Distance, Pitch and Roll Angles

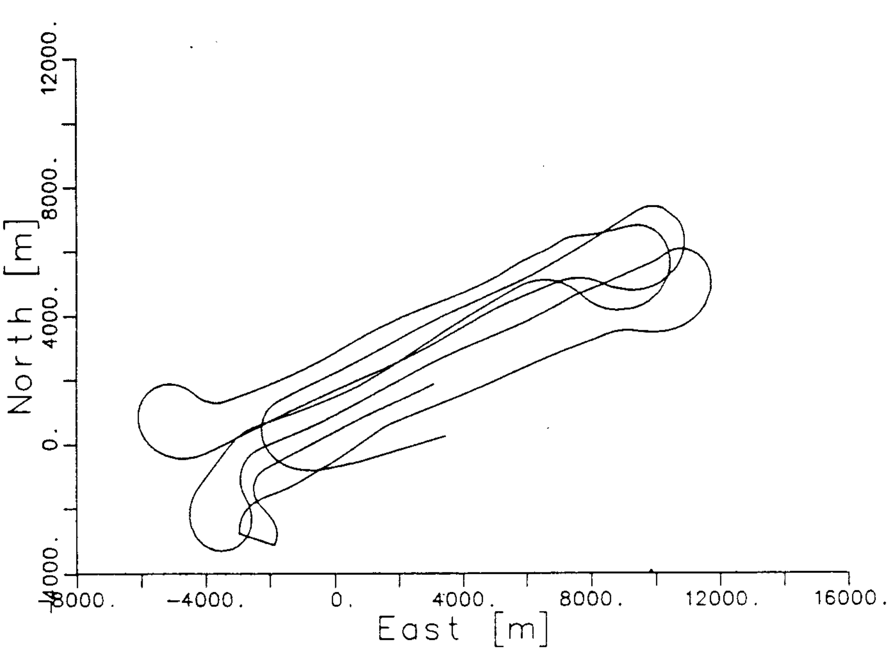

Figure 5: Ground Path of the Photgrammetric Airplane

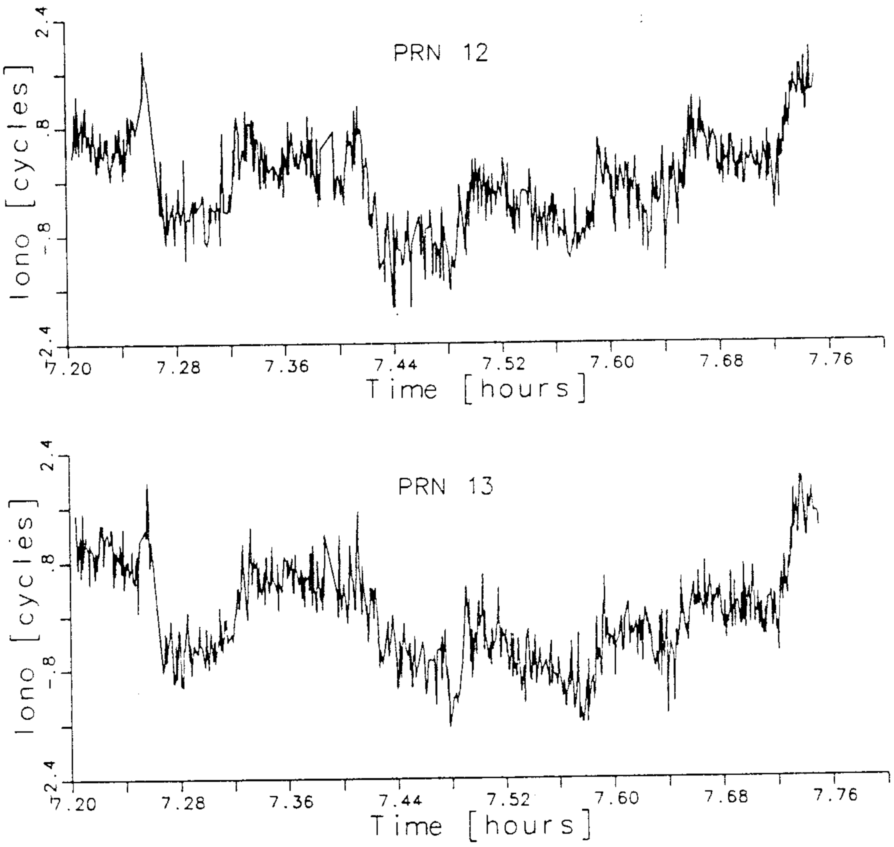

Figure 7: Single Difference Ionospheric Signals

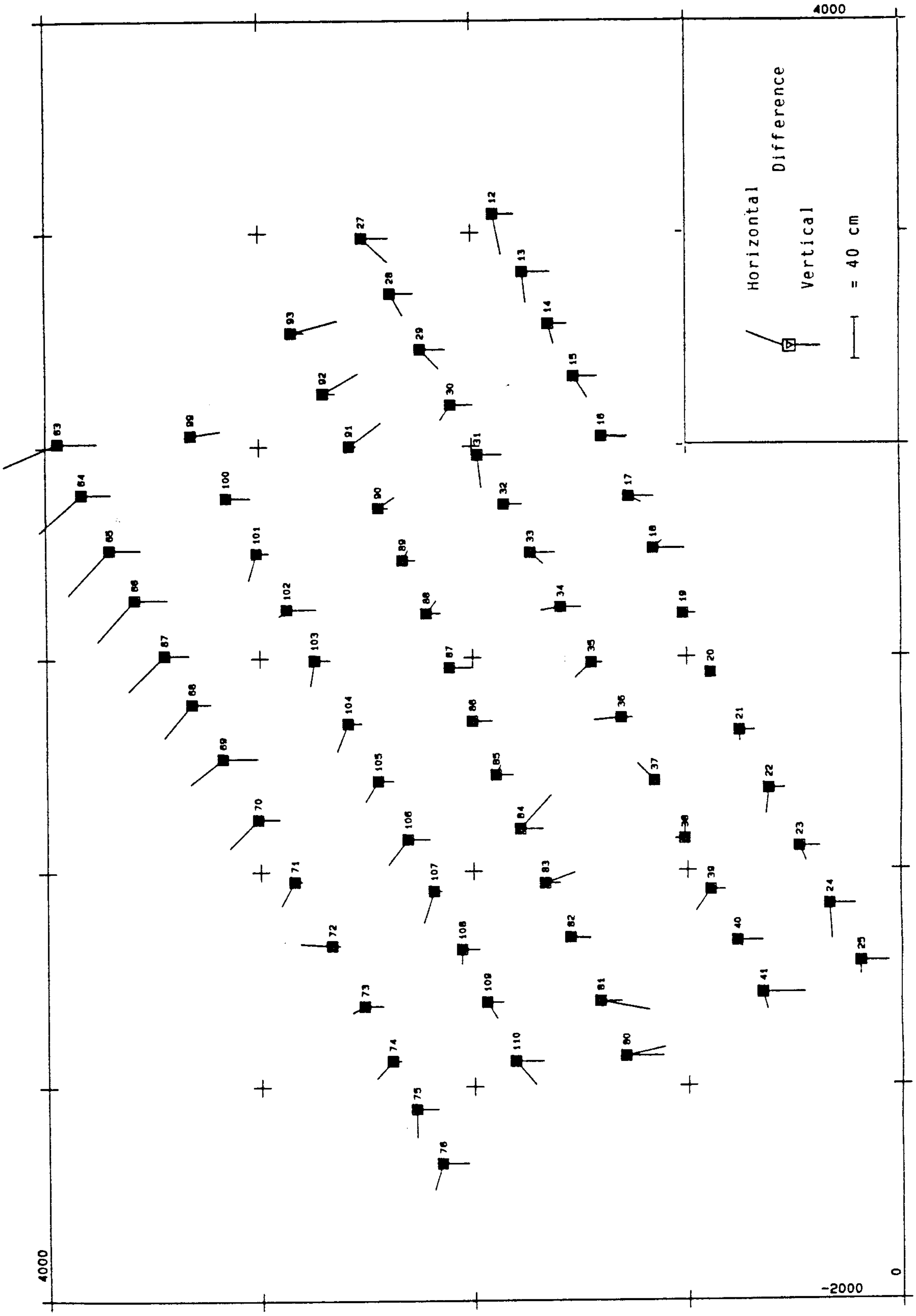

Figure 6: Photogrammetric Strips and Difference Vectors between GPS and Aerotriangulation Coordinates

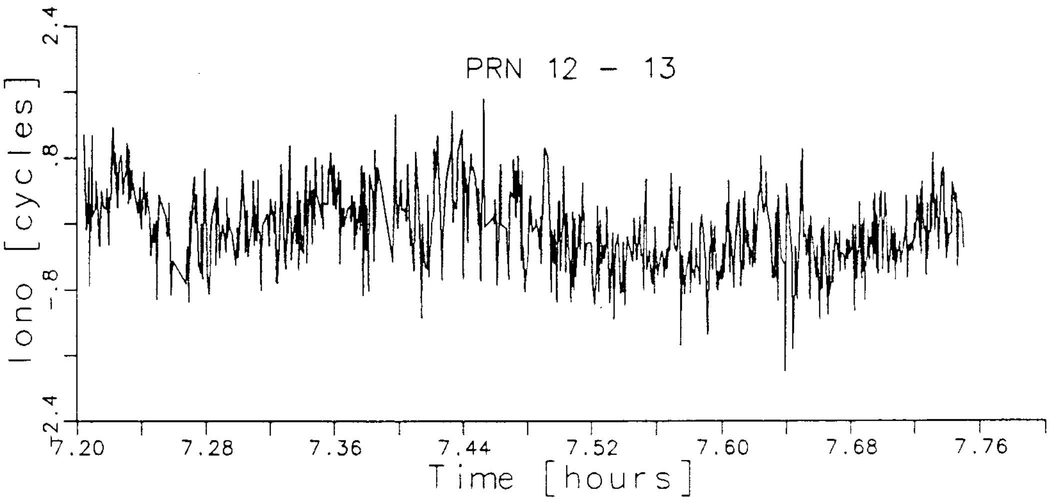

Figure 8: Double Difference Ionospheric Signal

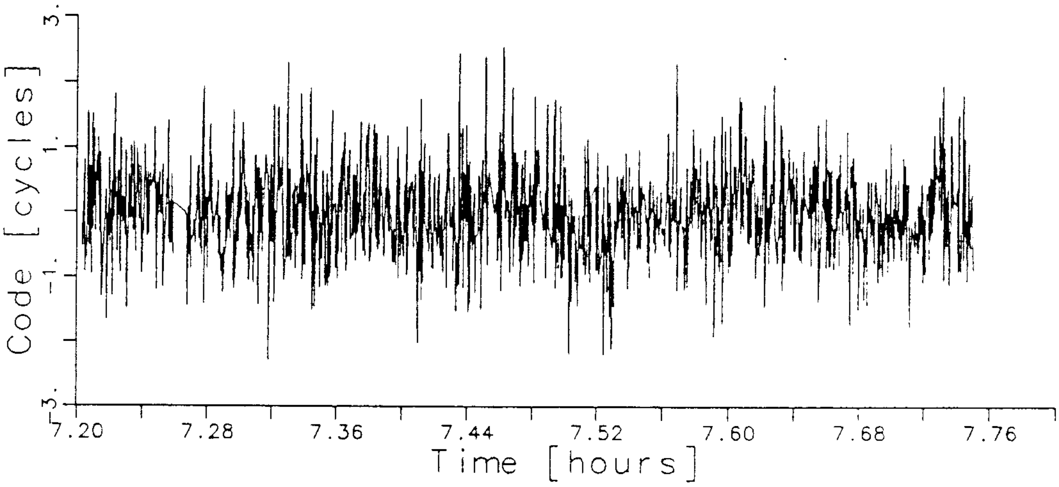

Figure 9: Single Difference Code Signal

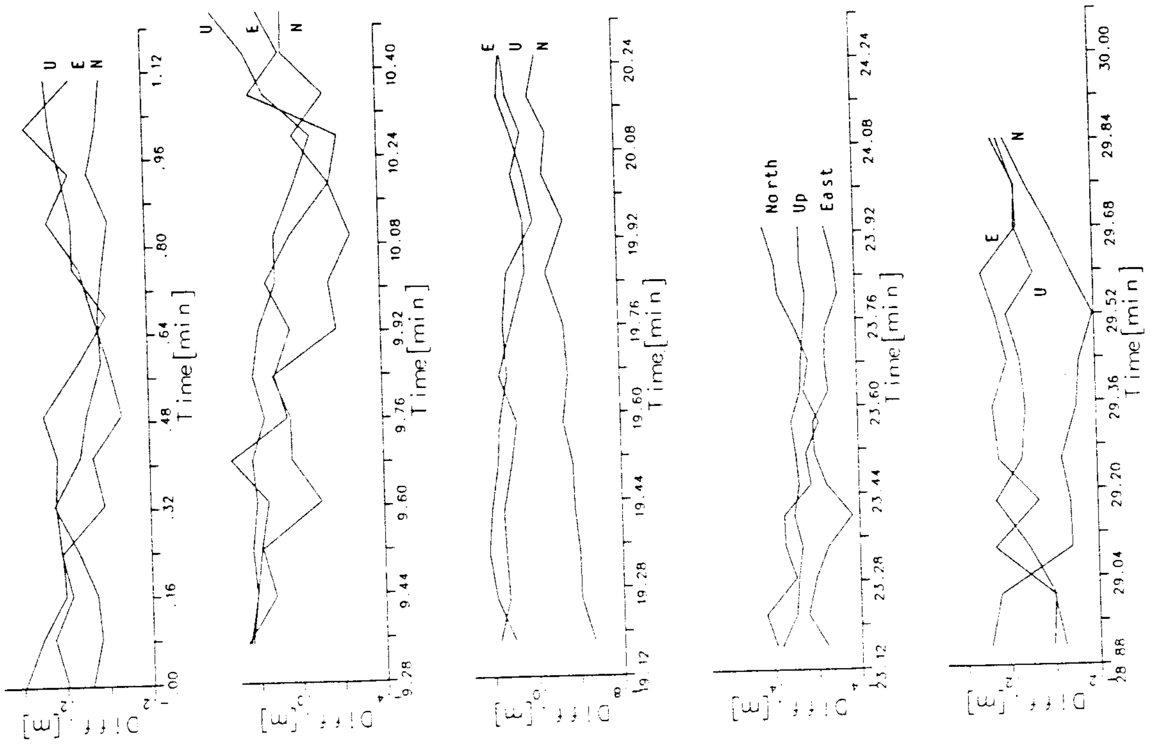

Figure 10: Comparison of Phtogrammetric and GPS Coordinates of the Projection Centers.

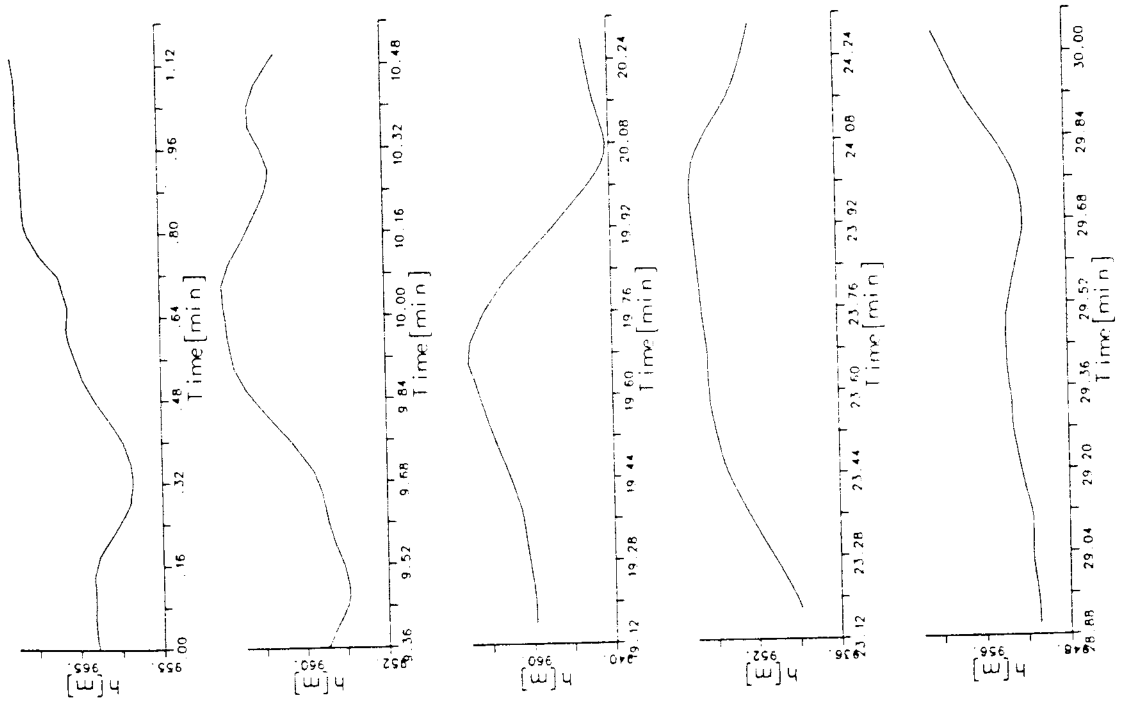

Figure 11: GPS Height Profile along Photogrammetric Strips