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PRECISE KINEMATIC GPS/INS POSITIONING: A DISCUSSION ON THE APPLICATIONS IN AEROPHOTOGRAMMETRY

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1. INTRODUCTION

Aerotriangulation without or at least with drastically minimized ground control is no more a fictitious idea. *It is quite obvious nowadays, that kinematic satellite observations to the Global Positioning System (GPS) can determine the relative threedimensional camera position in space at the time of the exposure of the photo with an accuracy of 2 ... 5 cm.* In appendix A recent results of corresponding experiments of the University FAF Munich are shown which prove this statement. However, this is not only a solely investigation on that topic; various authors have reported similar results from recent test flights, see, e.g., Refs. 5, 7, 14, 20. The developed GPS analysis software is already so sophisticated that even a large number of cycle slips in the data can be detected and removed (Refs. 4, 5, 17, 18, 19).

Thus, the work in the next years will be characterized by the transfer of the experiences mainly derived at research institutions into an airborne photogrammetric camera positioning system capable to meet the requirements for daily production work. What is left for research – so far the geodetic part is concerned – is the question of GPS attitude recovery, the role of inertial navigation systems as well as some other minor things like the calibration scenario of GPS antenna and photogrammetric camera in the aircraft, and the development of real-time solutions.

Therefore this paper discusses the requirements for routinely photogrammetric applications as well as possible implications in the near future. The contribution is mainly based on experiences of the author and his group coming from flight experiments within a research project of the German Research Foundation (Deutsche Forschungsgemeinschaft) in the last two years.

2. PHOTOGRAMMETRIC APPLICATIONS

2.1 Camera position accuracy and type of kinematic GPS positioning

As outlined in appendix B kinematic GPS positioning provides different analysis techniques depending on the type of anticipated accuracy level: *differential pseudorange, phase-smoothed pseudorange* and *phase reduction.* As a consequence, hard- and software can be different, and the right choice may lead to a substantial saving in costs and (computer) analysis efforts. Tab. 1 gives an overview as function of photoscale. The required accuracy of camera positions is based on investigations of ACKERMANN, 1986 (Ref. 1, 13). Since the vertical component of GPS-derived coordinates is always worse than the horizontal, on the other side the photogrammetric applications require the highest accuracy there, only those numbers are put in Tab. 1

Table 1: Camera Position Accuracy Requirements and Type of Kinematic GPS Positioning Technique.

Map scale	Photo Scale	Required Camera Position Accuracy (σ_z)	Kinematic GPS Positioning Technique
1 : 100 000	1 : 100 000	16.0 m	Differential pseudorange
1 : 50 000	1 : 70 000	8.0 m	Differential pseudorange
1 : 25 000	1 : 50 000	4.0 m	Differential pseudorange
1 : 10 000	1 : 30 000	0.7 m	Phase–smoothed pseudorange
1 : 5 000	1 : 15 000	0.35 m	Phase reduction
1 : 1 000	1 : 8 000	0.15 m	Phase reduction
Coordinate determination	1 : 4 000	0.15 m	Phase reduction

Assuming that the GPS observation recovery interval is 1 sec (corresponding to approx. 50 m at an aircraft velocity of 180 km/h) the requirements of photogrammetry for the creation of maps with scale 1 : 25 000 to 1 : 100 000 can be fully satisfied using a low cost *navigation* GPS receiver with only pseudorange observation capability. Work for maps of scale 1 : 10 000 can be done using the phase-smoothed pseudorange analysis method. Although it requires a *geodetic* receiver, the software is very simple, and a removal of cycle slips is not required. In addition, possible loss of satellite signal over a certain time can be more easily compensated. For all other work of map-scale 1 : 5000 and larger, kinematic GPS phase reduction software with automatic cycle slip removal capability has to be used.

2.2 GPS Attitude information

Threedimensional orientation requires at least three independent antennas to define a geometric plane. Four non-coplanar antennas could be used to define two planes and provide redundancy. Orientation solutions of the planes containing the antennas are related to the photogrammetric aircraft and a geometric link has to be established from the antennas to the camera whose orientation is desired. The preferred method of operation is to get L_1 and L_2 frequency phase observations from four and more satellites continously. In low dynamic cases – this might be assumed for a smooth photogrammetric flight – one multiplex receiver could replace the otherwise needed three four-(and more-)channel receivers. The multiplex receiver would measure the carrier signal phase from the satellites on each antenna sequentially dwelling for approx. 40 msec on each antenna.

Although research work for the recovery of GPS attitude information started very early, see, e.g., EVANS et al. (1981), Ref. 12, up till now no such GPS receiver system is commercially available. From simulations and research experiences in the last years (Refs. 11, 22) an *accuracy of 1′ over short baselines* of the order of 10 m can be expected. There is no doubt that corresponding hard- and software will be advertised in the next year. To what extent an attitude information of that accuracy level can be used in photogrammetry cannot be judged by the author.

2.3 The role of inertial navigation systems (INS)

INS of mechanical type were tested in geodesy a decade ago. Due to its limited potential for positioning (0.2 ... 0.4 m) and the high price (over a million DM) there was no break-through to practical surveying. With the development of low-cost ring laser gyros (RLG) the production of so-called strapdown ring laser gyro INS started, which are small in size, reasonable in price and more reliable. However, the accuracy (1 ... 2 m, see Ref. 24) is not as good as the mechanical platform INS. Thus, the idea to integrate GPS and INS to a hybrid instrument became obvious since both instruments complete each other with respect to their performance. For the basic concept see, for example, Ref. 10. In a combination GPS/INS the inertial navigation system contributes the following advantages:

(1) High-frequency interpolation (50 ... 200 Hz) between GPS updates (~ 1 Hz),
(2) Overbridging loss of lock of GPS signals for short times (depending on the desired accuracy level up to a few minutes),
(3) Cycle-slip recovery,
(4) Attitude information.

Ad (1): Recent experiments in photogrammetry had to interpolate *numerically* the 3d-camera-position at the exposure time between the GPS update (0.6 sec or 1 sec). It is surprising that even with simple linear methods high accuracies in the 5 cm level could be achieved. Thus, it is questioned whether photogrammetry needs an INS for that tool. More experiences have to be gained before a definite answer can be given.

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Ad (2): It is obvious, that an INS has to be updated by GPS in a Kalman filter in order to control and damp the drift of INS. During a loss of lock of GPS signals the INS acts as a free system. For example, the present available strapdown INS of highest accuracy (HONEYWELL LASERNAV2, LITTON LTN-90/92) show a drift of approx. 50 cm per minute. Thus, if camera positions are required during that time the accuracy is degraded (Fig. 1). However, in most cases photogrammetry could accept that, and such a flight has not to be repeated.

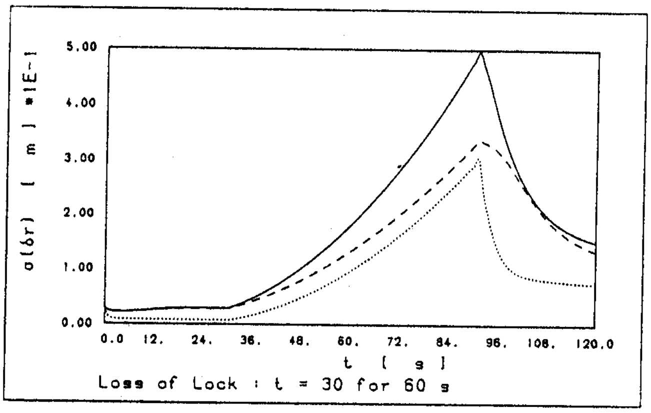

Fig. 1. 1σ-Position Error of a Precise RLG INS if Complete Loss of Lock Occurs Between 30 ≤ t ≤ 90 sec.

Ad (3): In Appendix B possible methods for cycle slip removal were already presented. A reliable RLG INS would considerably help to fix data sets, especially when a longer loss of lock appeared. The new generation of GPS receivers, however, will have a resolution in pseudoranges of a few centimeters, so that the phase integer ambiguities might be determined from pseudorange measurements. In addition, on-line fixing is planned for the future generation of GPS receivers.

Ad (4): As mentioned before, the accuracy of GPS attitude information is probably limited to 1′ and restricted to low-dynamics environment. RLG INS are able to provide 0.′1 relative attitude information between the photogrammetric images with an even higher potential still there (Ref. 16).

The Institute of Astronomical and Physical Geodesy and the Institute of Photogrammetry and Cartography of the University FAF Munich, as well as the inertial group of Surveying Engineering at the University of Calgary have carried out first GPS/INS integrated flight experiments for photogrammetry in cooperation with the Rheinbraun Mining Company, Cologne, in last September. Results will be presented in Ref. 6.

2.4 Photogrammetric flight navigation

Photogrammetric flight navigation can be done with the same GPS receiver used for the camera determination. Hereby, pseudorange observations are only needed which yield a real-time absolute position of 30 ... 50 m. Most of the receivers calculate an internal position solution (approx. every 6 sec) which can be put directly on a screen for the pilot. In case that an interval of approx. 6 sec (approx. 300 m for an aircraft velocity of 180 km/h) is not sufficient more frequent position solutions can be easily computed by a small on-board computer in real-time. For convenience, the whole flight path planning should be prepared in digital form, so that their geometry (eventually tegether with a specific digital map) can be seen on the screen as well as the actual flight path. The so-controlled accurate flight paths might meet the requirements of the photogrammetrist and costumer exactly, and a saving in work and/or photos which have to be processed can be minimized.

2.5 Datum problem

Since the threedimensional GPS camera position is determined in the geocentric ellipsoidal reference system WGS84, a transformation has to be carried out between that system, the reference system underlying the photogrammetric block adjustment, and the local or national coordinate system to which the ground stations refer. WGS84 can only be realized from the satellite observations with an accuracy of 10 ... 20 m relative, unless the ground station is collocated to a station (for example, laser station) where precise geocentric coordinates ($\sigma \leq 5$ cm) are available. However, this is, in general, not necessary for photogrammetric applications due to the following transformation to the ground-based system anyway. The second GPS receiver observing generally on the ground, together with two other in WGS84 determined control points on the ground presents a unique transformation scheme between WGS84 and the ground-based as well as the block adjustment reference system.

2.6 Ground receiver for differential corrections

The high accuracy of GPS can only be achieved relatively using a second receiver in order to eliminate the error sources by differential measurements. In recent photogrammetric papers one can find statements of type " ... *A second receiver on the ground would imply operational difficulties and cost increasing but would not really bring improvement in accuracy.*" (Ref. 7). The question, consequently, has to be answered whether photogrammetric applications could gather all necessary information using just one receiver in the aircraft.

Let us consider the observation equation for GPS carrier phases $\psi_m^j(t_i)$

$$\psi_m^j(t_i) = \delta_m t_i\, f\,(1 - \dot{\rho}_m^j(t_i)/c) - (f/c)\,\rho_m^j(t_i) - f\,\delta_s^j t_i + N_m^j + \Delta\psi_{ion}(t_i) - \Delta\psi_{trp}(t_i) + \Delta\psi_{rel}(t_i) + \varepsilon_m^j(t_i) \qquad (2\text{–}1)$$

where

$\psi_m^j(t_i)$ ... carrier phase observable of receiver m to satellite j at time t_i,
$\delta_m t_i$ ... receiver clock error at epoch t_i,
f ... frequency,
ρ_m^j ... range between receiver m and satellite j,
c ... velocity of light,
$\delta_s^j t_i$ ... satellite clock error at epoch t_i,
N_m^j ... integer ambiguity,
$\Delta\psi_{ion}$ ... ionospheric correction,
$\Delta\psi_{trp}$ ... tropospheric correction,
$\Delta\psi_{rel}$ ... periodic relativistic effect,
ε_m^j ... observation noise.

Through differencing between receivers and/or satellites and/or considering the second frequency L_2 the following errors are eliminated. In detail,

Satellite clock error $\delta_s^j t_i$:	Elimination by differencing between *receivers*,
Receiver clock error $\delta_m t_i$:	Elimination by differencing between *satellites*,
Ionospheric effect $\Delta\psi_{ion}$:	Elimination by *second frequency* L_2,
Tropospheric effect $\Delta\psi_{trp}$:	Elimination by (zenith-dependent) parameter *models*,
Periodic relativistic effect $\Delta\psi_{rel}$:	Can be neglected, elimination through $\delta_s^j t_i$.

Let us assume now, that only one GPS receiver is available (on board of the photogrammetric aircraft). The receiver clock error can be eliminated using four or more satellites. Ionospheric effects are removed by the L_2 frequency. If it is a single frequency receiver a *linear trend* of the effect can only be considered *so far control points at the beginning and end of the flight path are available, for example, from photogrammetrically-determined camera positions which would require ground control at least at the edges of a block.* This is also true with respect to satellite clock errors and the tropospheric effect. The remaining non-linear errors of the different effects are graphically shown in Figs. 2, 3, 4 for representative examples. We can further assume that the satellite clocks of the BLOCK II GPS satellites are superior over the present ones with respect to accuracy, so that that influence might be less than 1 cycle (< 20 cm). *The crucial point, however, is the question how to determine the integer ambiguity* N_m^j. Even in case that the future generation

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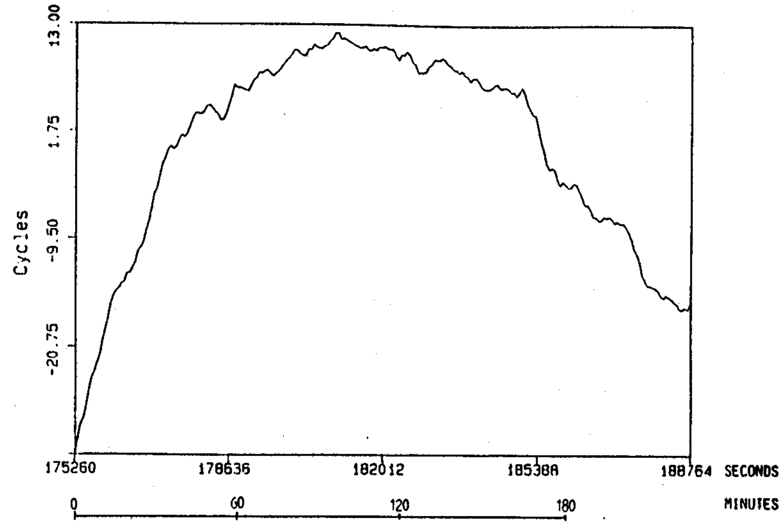

Fig. 2. Nonlinear Effect of Satellite Clock Error (GPS BLOCK I) for a Representative Example.

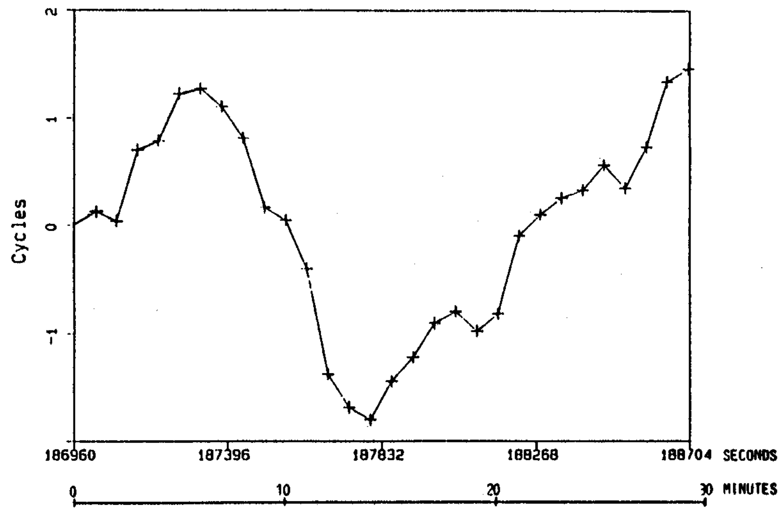

Fig. 3. Nonlinear Effect of Satellite Clock Error (GPS BLOCK I) for a Representative Example.

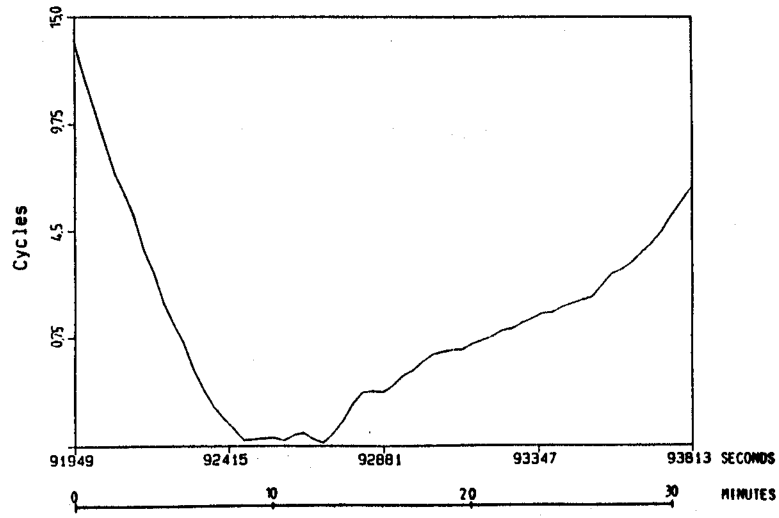

Fig. 4. Nonlinear Ionospheric Effect for a Representative Example.

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of GPS receivers will be able to observe pseudoranges with a noise smaller than the half wavelength of the carrier phases (< 10 cm), the different errors as mentioned before are mixed and will not allow to determine N_m^j with an accuracy of 1 cycle without a second receiver. In addition, multipath effects are present, so that the estimated accuracy might be not better than 2 ... 3 cycles.

Thus, as a result of this discussion, we may conclude that a second GPS receiver is essential for high-precision photogrammetric work of map scale 1 : 5000 and larger (camera position accuracy < 0.8 m). For all other aerophotogrammetric work (1 : 10 000 and smaller) the application of the (differential) pseudorange or the phase-smoothed pseudorange method with just one receiver (on board of the aircraft) may yield reasonable relative vector information between camera positions so far known camera positions at the beginning and end of the strips are available for interpolation and removal of the linear effects.

2.7 Satellite geometry and satellite availability

At present, there are only the test satellites of BLOCK I and the first satellite of the BLOCK II in orbit, so that the observation window is limited to approx. four hours per day with a shift of 4 min in time per day. In addition, satellite geometry can be unfavourable. These restrictions will vanish when all 21 + 3 GPS satellites are in orbit. According to the present plan this should be the case by 1993.

3. REQUIREMENTS FOR AN OPERATIONAL PHOTOGRAMMETRIC AIRBORNE CAMERA POSITIONING SYSTEM FOR ROUTINE WORK

Based on the experiences gathered from research *it is already now possible to build up a photogrammetric airborne camera positioning system for daily production work.* This does not include attitude determination. As mentioned in 2.3 research is still needed with that respect.

In the following the components of such a system are discussed. In particular, their requirements are outlined.

GPS receiver. Since the kinematic positioning technique is used, it is recommended to have GPS receivers (C/A code, Standard Positioning Service SPS) with eight or more channels. In addition, L_2 frequency capability would significantly contribute to the reliability of the system and recovery of cycle slips (not so much to the accuracy for these specific applications, since baselines between ground and airborne receivers are, in general, less than 20 km, and an accuracy of 15 cm is according to Tab. 1 sufficient). For photogrammetric work of scale 1 : 25 000 and smaller a pseudorange GPS receiver without phase recovery can be used (see Tab. 1). However, in each case the observation time interval should be as small as possible (≤ 1 sec) in order to obtain small interpolation distances between the time of exposure of the camera and the neighbouring, by GPS directly determined points of the flight path. In order to ensure synchronisation with the photogrammetric camera the GPS receiver should have an input where the time of the exposure (the impulse coming from the camera) is mapped on the GPS time scale. Such "photogrammetric options" are already advertised from some manufacturers. Also small light antennas which can be used on top of the aircraft are in many cases part of standard GPS receiver equipment nowadays. For the synchronization of GPS receiver and camera the one-pulse-per-second (1 pps output) impulse can also be used to some extent (see the discussion of the camera later). For the photogrammetric flight navigation the GPS receiver should be connected with a monitor for the pilot (via an on-board computer and a corresponding interface) so that the real-time GPS position solution is graphically shown on the screen together with the planned flight paths (digitally input capability!). Based on the discussion in 2.6 it is recommended to have a second receiver on the ground.

Photogrammetric camera. The camera has to be equipped with the capability of sending an electronic impulse when the shutter is open for exposure (accuracy ≤ 1 msec). No special device (external time scale, oscillator) is needed between camera and GPS receiver so far the receiver is able to accept input impulses which are mapped on the GPS time frame. Interpolation between GPS updates could be avoided if it would be possible to determine the time between sending (one of the) 1 pps-impulse from the GPS receiver and the opening of the shutter and exposure, respectively. This is a constant for a given lens and a given exposure time. Whether it can be determined in laboratory with the required accuracy of 1 msec is doubtful according to our knowledge. Here a contribution (change of shutter system?) of the photogrammetric manufacturers would be appreciated. If this possibility would exist, then a special electronic device had to fade out 1 pps-impulses and to leave only the one needed to trigger the camera. In this case the intervals between exposure times have to be a multiple of full seconds. By changing, however, slightly the velocity of the aircraft in the planning of the photogrammetric flight, this could be easily accepted.

Software. The needed integrated post-processing software should include: kinematic GPS reduction (including automatic cycle slip fixing), static GPS reduction (baseline determination on the ground for datum transformation, for example), interpolation of projection centers between GPS updates, transformation algorithms between WGS84 and the ground-based coordinates as well as threedimensional GPS baseline vector adjustment. The software needed in real-time during the flight consists of the navigation facilities (including graphics and photogrammetric flight planning) as described before. The present available firm software for GPS can only partially fulfill the requirements listed here.

Offset determination between camera and GPS antenna. Up till now all experiments have used a fixed position of the camera with respect to the aircraft body. For routine applications, however, the drift of the camera has to be changed during the flight due to changing environmental conditions. This requires the development of a procedure for automatic recording of the drift during the flight.

Geoid height information. In precise photogrammetric applications (3d-coordinate determination, orthometric heights) knowledge of the geoid heights is needed for the transformation between WGS84 and the ground-based coordinate system, as well as for the determination of orthometric heights in (hilly or mountaineous) areas with a changing geoid. It seems, that for this purpose digital models can be used which are already available in most regions.

Other requirements with respect to the photogrammetric treatment of the GPS position information are discussed, e.g., in Ref. 9. About the requirements of an INS cannot be stated anything definite.

4. POSSIBLE IMPLICATIONS ON GPS/INS POSITIONING IN NEAR FUTURE

4.1 Selective availability (S/A) and Anti-Spoofing (A-S) on GPS

Since the Global Positioning System (GPS) is primarily a military navigation system, two functions are implemented on the GPS satellites of Block II which might influence the civilian users. To *spoof* a GPS receiver is to create a false satellite signal that looks to the receiver like the real satellite signal (correct Doppler shift, transmission delay of the codes, etc.). This causes the receiver to lock onto the false signal instead of the real one. The information in the false signal is then made more and more erroneous and the GPS receiver is led astray. The spoofing threat, however, is virtually eliminated by the encryption of the P-code (changing into the so-called Y-code). The C/A-code has no A-S capability and is therefore more susceptible to this type of jamming. *Selected Availability (S/A)* will reflect (from time to time) current U.S. DoD (Department of Defense) SPS (Standard Positioning Service) accuracy for peacetime conditions. This means a reduced time accuracy and degraded accuracy of ephemerides in the navigation message. Military (and authorized) users will get the necessary memory and cryptographic functions to handle S/A and A-S. An auxiliary output chip for each hardware receiver channel provides the P-code to the Y-code transformation. The effects of the functions S/A and A-S on absolute position accuracy are summarized in Tab. 2. It is expected, however, that *differential position techniques will absorb* *most of the degradation.* In addition, for the post-processing the correct orbit information with time information when the different functions reflected GPS observations will be released within 2 weeks. Thus, photogrammetry does not rely on real-time processing; only the flight navigation accuracy might be sometimes degraded from about 30 m to twice or three times the value.

Table 2: Effects of Selective Availability (S/A) and Anti-Spoofing (A–S) on GPS Position Accuracy.

FUNCTION		CODE		NAVIGATION MESSAGE	POSITION ACCURACY		
S/A	A–S	P–(Y–)Code	C/A Code		* * *	P–Code	C/A Code
off	off			Full accuracy	16 m (P–Code)	16 m	30 m
off	on	Encrypted (Y–Code)		Full accuracy	16 m (Y–Code)	–	30 m
on	off			Degraded	16 m (P–Code)	72 m	76 m
on	on	Encrypted (Y–Code)		Degraded	16 m (Y–Code)	–	76 m

* * * Military (and authorized) user equipped with memory and cryptographic functions

4.2 GLONASS

The U.S.S.R. established a global positioning system called GLONASS which is quite similar to the U.S. GPS. It was announced that it will serve as the official *civilian* navigation system of the USSR (Ref. 3, 8). GPS as well as GLONASS will reach their final state 1992/93. Meanwhile American and Soviet aviation experts have agreed on investigations on interoperability between GPS and GLONASS which would provide the user redundancy and more integrity of the systems (Ref. 2). Also in West Germany plans are on the way to develop a hybrid GPS/GLONASS receiver. This means, that for geodesy, navigation, and photogrammetry new ways will be opened in the next years, which will emphasize even more the airborne camera positioning system capability by satellites.

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4.3 Future developments

Future developments at the University FAF Munich will concentrate on a real-time airborne camera positioning determination and a 3d-GPS-attitude observation system. Whereas the first can be reached without greater difficulties if telemetry and a high-speed on-board computer with appropriate software are available, the users rely with respect to GPS attitude recovery on the developments of the industry. However, it seems that appropriate GPS receivers will be available in the next three years.

APPENDIX A:
EXAMPLE FOR HIGH-PRECISION KINEMATIC AIRBORNE CAMERA POSITIONING

Here one example out of many photogrammetric test flights is presented to demonstrate the high accuracy of kinematic GPS positioning. In August 1988 a joint project between the Institute of Astronomical and Physical Geodesy and the Institute of Photogrammetry and Cartography of the University FAF Munich, as well as the University of Calgary and the mining company Rheinbraun, Cologne, was carried out over the open-cast mining area "Hambach". By several test flights in 900 m altitude over mean sea level using GPS receivers TI4100 and TRIMBLE 4000SX, the photogrammetric camera ZEISS RMK 15/23, and the inertial navigation system LITTON LTN-90, photogrammetric images in the scale of 1 : 5400 were taken. Detailed results are presented in Ref. 4, in particular also with respect to the use of the INS. Here just one example is taken out from Aug. 26, 1988 (Fig. 5). The differences between the photogrammetrically derived and GPS-determined projection centers of the camera are outlined in Tab. 3. The

Table 3: Differences in WGS84 Between Photogrammetrically-Derived and GPS-Determined Positions of Camera Projection Centers.

IMAGE	DIFFERENCES			STANDARD ERRORS BLOCK ADJUSTMENT		
	DX [cm]	DY [cm]	DZ [cm]	σ_x [cm]	σ_y [cm]	σ_z [cm]
7	− 3.9	1.5	0.7	4.4	8.0	7.6
8	3.2	− 2.8	− 5.9	4.9	4.8	7.0
9	2.0	2.8	5.5	5.3	4.7	6.5
11	0.8	− 2.1	− 2.9	3.1	3.1	7.0
14	− 2.9	0.7	5.4	3.0	3.1	8.0
16	− 1.0	− 2.2	2.9	3.7	3.7	8.7
17	1.9	2.1	− 6.7	4.5	4.4	9.1
30	3.6	6.8	− 4.5	5.3	5.0	8.0
32	− 4.9	5.2	0.5	4.6	4.3	7.4
34	5.3	6.4	− 0.6	3.8	3.1	7.4
36	0.6	− 17.1	7.6	3.9	3.2	7.4
39	− 1.4	− 7.6	− 0.8	3.4	2.7	7.4
42	− 7.8	− 4.3	− 2.6	3.0	2.6	7.4
45	0.3	− 0.2	1.4	3.0	3.1	7.5
48	4.3	10.7	− 1.1	3.0	3.7	7.6
mean RMS	± 3.6	± 6.5	± 3.9	± 3.9	± 4.0	± 7.6

results demonstrate accuracies of GPS kinematic airborne camera positioning in the range of 4 ... 6 cm. The mean RMS differences between L_1 and L_2 are ± 4.6 cm in x, ± 7.0 cm in y, and ± 5.9 cm in z. Looking also on the precision of camera projection centers determined by photogrammetric block adjustment (mean RMS $\sigma_x = \pm 3.9$, $\sigma_y = \pm 4.0$, $\sigma_z = \pm 7.6$) it is very hard to judge which positions are more accurate. It seems that the differences between photogrammetrically derived and GPS determined camera position are within the noise of both computations.

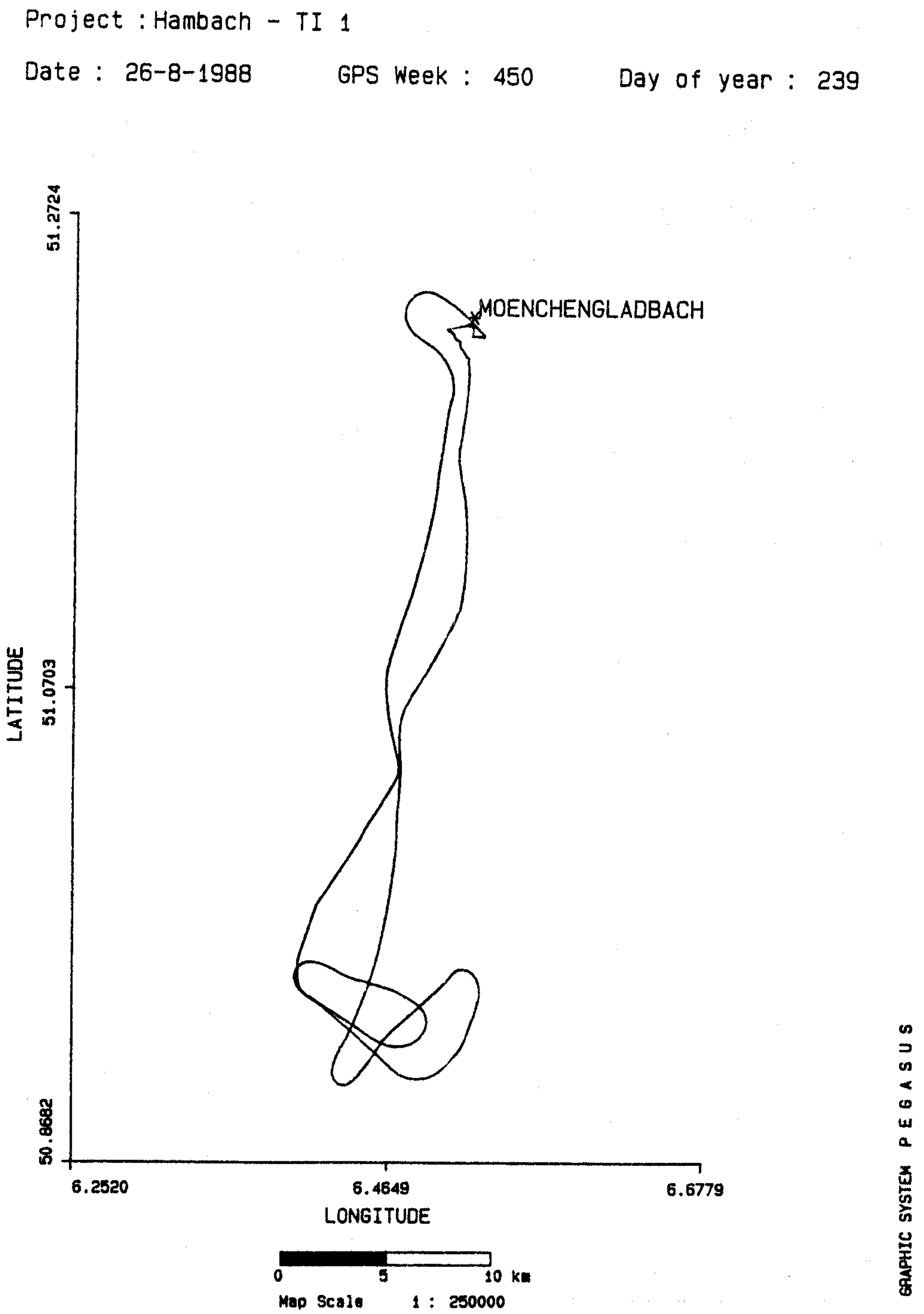

Fig. 5. Path of Photogrammetric Aircraft.

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APPENDIX B:
GPS DIFFERENTIAL HIGH-PRECISION NAVIGATION AND KINEMATIC SURVEYING: A SURVEY OF METHODS INCLUDING CYCLE-SLIP FIXING

There may be only one difference between high-precision navigation and kinematic surveying. In the latter, a real-time solution is in most cases not necessary. However, growing needs of the customer and new geodetic applications may also change this picture in the future.

Depending on the level of accuracy required, three main concepts can be used. These are discussed below.

Differential Position Corrections

The principle is simple. Differences between known and GPS-determined position or related parameters of a permanently tracking receiver at a base station are transmitted to the nearby moving receiver, where they are used to improve the (navigation) algorithm. The observables are *pseudo−ranges*. Accuracies of the moving receiver are in the range of 5 to 15 m for the Standard Positioning Service (SPS) and 3 to 5 m for the Precise Positioning Service (PPS).
The transmitted differences can be of the following form:

(i) *Errors in ellipsoidal coordinates* (φ,λ,h) *between known and GPS-determined position* – The disadvantage of this approach is that both receivers, stationary and moving, have to track the same satellites.

(ii) *Delta−range corrections* – Errors in pseudo-ranges to all visible satellites are determined and transmitted. The advantage is that the moving receiver can track different satellites since it obtains delta-range corrections to all satellites (depending only on the number of available channels of the static receiver).

(iii) *Pseudolite corrections* – A *pseudolite* is merely a simulated GPS satellite on the ground. The corresponding instrument receives GPS signals and computes pseudo-range and range rate corrections, which are transmitted at 50 bps on L-band frequency. This transmitted signal is GPS-like. The local user equipment can obtain additional pseudo-range measurements.
This concept has several advantages: the baseline to the pseudolite is very precise; the moving receivers do not need a particular hardware component to receive the corrections, as in approach (i) and (ii), and no additional channel for communication is necessary.
On the contrary, the stationary working receiver has to fulfill functions similar to those of a satellite, and thus needs appropriate hardware. In addition, visibility between the moving and stationary receivers is required.
To our knowledge, this concept has until now not been realized.

Phase–smoothed pseudo–ranges (carrier smoothed code)

With the differential position correction concept, described above, only pseudo-ranges are used as observations. In contrast, this concept requires receivers capable of observing carrier phases as well. A smoothed pseudo-range at epoch t_i is a linear combination of a pseudo-range at t_i with weight w_1 and the smoothed pseudo-range at t_{i-1} calculated for epoch t_i, using the phase difference over $(t_i - t_{i-1})$ with weight w_2. The weight scheme looks like this:

Start of observation: $(w_1 + w_2 = 1)$	$w_1 = 1.00$	$w_2 = 0.00$
	. . .	. . .
After approx. 100 measurements	$w_1 = 0.01$	$w_2 = 0.99$

If a cycle slip occurs in the phase observations, the weights are reset to

$$w_1 = 1.00 \qquad w_2 = 0.00 \ .$$

Cycle slips have to be detected, but not corrected. Several modifications in the algorithm above are possible, such as wide laning. The accuracy of the method is on the order of 1 to 3 m for SPS and 0.5 to 1 m for PPS. Whereas differential position correction is seldom applied in geodesy and surveying because of its low accuracy, many experiences with phase-smoothed pseudo-ranges, especially for marine applications, are reported in the geodetic literature.

Phase differencing

As in the stationary application of GPS in surveying and geodesy, the high accuracy potential of GPS in the centimeter (or even millimeter) range can be realized only when using carrier phases. Here also the term *kinematic surveying* may have its origin. REMONDI (Ref. 21) first showed that the kinematic case can in principle use the same algorithms as those used in stationary baseline determination.

Consider a double difference $\phi_{ij}^{12}(t)$ between two satellites and two stations:

$$\phi_{ij}^{12} = -\frac{f}{c}\,(\rho_i^1 - \rho_i^2 - \rho_j^1 + \rho_j^2) + N_{ij}^{12} \tag{1}$$

where

$$\phi_{ij}^{12} = \phi_i^1 - \phi_i^2 - \phi_j^2 + \phi_j^2 \qquad (2)$$

and

ϕ_i^k is the phase observable from station i to satellite k ,
ρ_i^k is the distance from station i to satellite k ,
f is the carrier frequency,
c is the speed of light, and
N_{ij}^{12} is the integer double difference bias.

Once N_{ij}^{12} is known, ϕ_{ij}^{12} is only a difference of ranges, allowing precise determination of position. Thus, the task is to solve for the initial double difference integer unknown N_{ij}^{12} at lock on during the solution.

N_{ij}^{12} can be determined by one of the following means:

(i) Starting from two stations with known coordinates.
(ii) Observing an initial baseline in stationary mode for 10 to 30 minutes.
(iii) Exchanging the antennas between two stations at the beginning of the survey ("antenna swap"). The apparent movement of the antennas yields twice the initial baseline vector.

In addition to the double-difference approach, the use of single differences in corresponding algorithms is also possible. As long as the clock errors are modelled epoch-wise as white noise, this is identical to the double-difference approach. However, stochastic clock error modelling can be used to improve the solution. The initial integer unknown N_{ij}^{12} remains the same.

In principle, differences between the moving receiver and the stationary one are determined. From each difference, a position solution can be achieved independently of all the other observations. Therefore, this approach is also entitled as the "no dynamics" model. A model such as the Kalman filter taking into account all measurements along the trajectory is doubtless superior to the "no dynamics" approach. In addition, there are many applications in air- or shipborne positioning where the trajectory is also of interest.

The use of phase measurements requires that there be no cycle slips in the data, or that they can be detected *and* removed.

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Table 4: RMS-Errors for the Different Differential GPS Kinematic Positioning Methods (Taken from Examples Given by HEIN et al., Ref. 7)

	Northing	Easting	Height
Differential corrections (pseudorange)	± 2.9 m	± 4.3 m	± 4.9 m
Phase–smoothed pseudoranges	± 0.90 m	± 0.92 m	± 1.45 m
Phase differencing	± 0.02 m	± 0.01 m	± 0.02 m

Cycle–slip fixing of carrier phase observations

It seems that geodetic GPS receivers of the last generation have cycle slips because of failures in hardware and internal software (register overflowing, internal cross-talk, aliasing, self-jamming, truncation, etc.), and that new sophisticated carrier phase receivers will never (?) have cycle slips. Nevertheless, such phenomena will happen if the antenna's view of the sky is obstructed. This can be the case during a terrestrial kinematic survey if trees or buildings along the traverse are shadowing satellites. It can also occur during marine applications in the harbour area or in airborne positioning when parts of the ship or aircraft may obstruct the intervisibility between antenna and satellites.

From our own experiences, we can state that it is therefore absolute necessary to deal with cycle slip correction methods or algorithms, even though pragmatic-thinking colleagues may argue that an appropriate observation plan should avoid cycle slips.

The following approaches for cycle slip repair are possible:

(i) *Use instruments with more than four channels* to get redundant observations. For this case also, single-frequency receivers are suited.

(ii) *Use the dual–frequency phase ratio method* – For cases in which two-frequency phase data are observed, advantage can be taken of the so-called ionospheric residual $\delta\phi$ (see Ref. 15):

$$\delta\phi(t) = \phi_1(t) - \frac{f_1}{f_2}\,\phi_2(t) \tag{3}$$

where ϕ_1, ϕ_2 are the carrier phases of the corresponding frequencies f_1, f_2 (L_1, L_2). This quantity has the property that it contains no terms depending on the station-to-satellite range and on the clock errors, and thus, has a linear, nearly constant behaviour. The ionospheric residual can be used for overbridging loss of lock and corresponding cycle slip correction.

(iii) *Checking of the receiver clock error* within the Kalman filter *and* prediction (especially suited for single-frequency receivers), see Ref. 5.

(iv) *Integrate GPS with INS or other sensors* – When the kinematic GPS positioning technique is used in urban areas, in woodlands, etc., especially also during flights, an interpolator is especially needed during times of loss of lock. For this purpose and for cycle slip detection and correction, the integration of GPS/INS is the appropriate surveying and navigation tool of the future.

It may be noted also that additional sensors, such as a laser or radar altimeter over sea, or an atomic clock or the inner orientation of stereo images of a photogrammetric GPS flight, may help to recover and to remove cycle slips.

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ABSTRACT

The application of kinematic airborne camera positioning using satellite observations to the Global Positioning System (GPS) and inertial navigation systems is discussed in detail. Based on two-years experiences of test flights within the research projects of the author requirements for the build-up of a camera positioning system for routine photogrammetric work are presented. Possible implications on satellite positioning in near future are outlined.

PRÄZISE KINEMATISCHE GPS/INS POSITIONIERUNG: DISKUSSION DER ANWENDUNG IN DER AEROPHOTOGRAMMETRIE

ZUSAMMENFASSUNG

Die Anwendung der kinematischen Positionierung von aerophotogrammetrischen Aufnahmekammern mit Hilfe von Satellitenbeobachtungen zum Global Positioning System (GPS) und inertialen Navigationssystemen wird detailliert diskutiert. Auf der Grundlage von zweijährigen Erfahrungen mit Testflügen innerhalb von Forschungsprojekten des Autors werden Anforderungen für den Aufbau eines Kamera-Positionierungssystems für photogrammetrische Routineaufgaben formuliert. Mögliche Beeinträchtigungen der Satellitenpositionierung in naher Zukunft werden erwähnt.

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