Canadian Aeronautics and Space Journal   Le Journal Aéronautique et Spatial du Canada

Horizontal and Vertical Guidance for Airborne Geophysics

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ABSTRACT

Accurate aircraft positioning is vital to the production of useful geophysical maps based on data acquired from the air. Sander Geophysics Ltd. has used GPS for horizontal positioning for many years by applying differential corrections acquired at a ground station to recorded airborne data. The corrections are usually applied during post processing and the guidance signal is, therefore, uncorrected. Recent requests for very close line spacing have dictated the need to use "real time" differential corrections for accurate guidance and the company has used several techniques to implement this technique, including a UHF radio link with the ground station, and commercially available corrections which are received via a communications satellite. Improvements in line flying are dramatically illustrated by examples of recorded flight path data.

Recently, clients have been demanding an improvement to vertical positioning and guidance in order to reduce the levelling corrections which must be applied to the geophysical data. In general, geophysical aircraft are flown so that they contour the terrain and guidance is provided by a radar altimeter. In areas of steep terrain, this may not be possible because the terrain gradient exceeds the climb/descent capability of the aircraft. This means that the area must be "draped." Traditionally, drape flying requires the pilot to determine when to begin a climb or descent and no guidance is provided. It is a difficult task when considering the requirement that adjacent lines, which may be flown in opposite directions and perhaps on different days, must not differ significantly in height. Furthermore, the principal survey lines and their perpendicular control lines should intersect, meaning that the gradients in all directions must be considered to achieve the same heights at the crossover points. SGL has developed software to provide positive vertical guidance to pilots while drape flying using barometric or differentially corrected GPS height data. An overview of the technique and some results are given demonstrating the improvements achieved.

INTRODUCTION

Airborne geophysics consists of flying aircraft carrying various sensors along well defined paths close to the ground. The more accurately one can "recover" the actual flight path of the aircraft, the more useful the resulting map. In general, aeroplanes and helicopters used for these surveys are quite small, with relatively unsophisticated navigation systems which are designed for point-to-point navigation. For the purposes of geophysical surveys, purpose-built systems are required to achieve more accurate navigation. This paper describes the system in use at Sander Geophysics Limited (SGL) including recent developments to improve pilot guidance.

HISTORICAL REVIEW

The guidance provided to pilots flying the aircraft has evolved considerably over recent years as a result of numerous technological advances. Traditionally, a pilot would follow lines drawn on topographic maps or aerial photographs, usually with the aid of a navigator, and a frame or strip film camera would record the actual ground track. Flight path recovery consisted of a painstaking review of the film with reference to aerial photographs. This was a labour intensive and time consuming process with plenty of possibilities for errors.

Improvements in radio navigation equipment such as Doppler radar, Omega, and LORAN helped improve guidance and reduce the errors somewhat but none of these systems is sufficiently accurate to satisfy the needs of airborne surveying and the flight path recovery techniques described above were still required.

Some companies have had success in the use of microwave transponders, several of which (usually three) are placed in the survey area. Distance from each of these can be measured and the aircraft's position thus determined. This technique has the disadvantage of requiring considerable investment in ground equipment and the extra effort of setting it all up for each area to be surveyed.

Inertial navigation systems (INS) are also used with corrections applied for the inevitable drift but such equipment is expensive, heavy and reasonably challenging to operate in small aircraft. The main advantage of INS is its complete autonomy from any ground based equipment.

With the advent of GPS the situation has changed dramatically. With GPS, the navigation system has a constant, accurate reference of both position and time usable at low altitudes and under all kinds of radio reception conditions. Furthermore, even early receivers were small, lightweight, and had low power requirements relative to the systems mentioned above.

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RÉSUMÉ

Un positionnement exact par aéronef est essentiel à la production de cartes géophysiques utiles basées sur les données obtenues à partir de l'air. Depuis quelques années, Sander Geophysics Ltd. utilise le GPS pour obtenir le positionnement horizontal en appliquant des corrections différentielles acquises à partir d'une station terrestre à des données aériennes enregistrées. Les corrections sont en général appliquées après le traitement et le signal de guidage est, par conséquent, non corrigé. Des demandes récentes dues au rapprochement des lignes ont occasionné un besoin d'utiliser des corrections différentielles en temps réel pour un guidage précis et la compagnie a utilisé plusieurs techniques pour pouvoir utiliser cette technique, y compris un lien radio UHF avec la station terrestre, et des corrections commerciales reçues par l'intermédiaire d'un satellite de communications. Les améliorations apportées aux vols de lignes sont très bien illustrées par les exemples de données enregistrées de chemin de vol.

Récemment, les clients se sont mis à demander des améliorations au positionnement et au guidage vertical pour réduire les corrections de niveaux que l'on doit appliquer aux données géophysiques. En général, les aéronefs géophysiques volent de manière à contourner le terrain et le guidage est fourni par un altimètre au radar. Dans les zones de terrains accidentés, cela peut ne pas être possible parce que la pente du terrain dépasse la capacité de monter ou de descendre de l'aéronef. Cela signifie que la zone doit être «drapée». Traditionnellement, le vol drapé nécessite du pilote qu'il décide quand commencer à monter ou à descendre, sans aucune indication. C'est une tâche difficile, si l'on considère le fait que les lignes adjacentes, où l'on doit voler dans des directions opposées et parfois des jours différents, diffèrent beaucoup de hauteur. En outre, les lignes principales de levée et leurs lignes perpendiculaires de contrôle doivent se couper, ce qui signifie qu'il faut considérer que les déclivités dans toutes les directions ont la même hauteur aux points de jonction. SGL a élaboré un logiciel qui fournit une orientation positive verticale aux pilotes qui font du vol drapé, à l'aide de données de hauteur corrigées différentiellement ou barométriquement. Une vue d'ensemble de la technique et certains résultats sont donnés pour démontrer les améliorations obtenues.

Sander Geophysics Ltd. (SGL) was an early user of GPS, implementing GPS/INS integration by Kalman filtering. This permitted the GPS system to correct for drift in the INS when enough satellites were in view, while the INS could handle the job alone during GPS outages. As the satellite constellation was completed, GPS alone became sufficient to do the entire job and this is the mode now used by SGL and most of its competitors.

CURRENT PRACTICE

With the advent of "Operational Status" of GPS, with 21 active satellites and 3 or more on-orbit spares, three dimensional positioning with good geometry is available 24 hours a day in almost all parts of the world. This has removed the need for using inertial or Doppler radar systems to augment the GPS solution. The positioning accuracy achieved using a single receiver in the survey aircraft was on the order of 10 to 15 metres RMS, which was accurate enough for in-flight horizontal guidance for almost all applications. With the implementation of Selective Availability (SA), the mechanism by which positioning accuracy is deliberately degraded for US national security reasons, the single receiver accuracy has dropped to about 50 metres RMS. This is still adequate for in-flight guidance for most surveys, but is much worse than the accuracy needed for geophysical data processing.

Figure 1 illustrates in block diagram form the current GPS based navigation and flight path recovery system. The airborne GPS receiver data, including pseudoranges and calculated position, are recorded in flight along with the geophysical data. These are then combined with data recorded at a reference "ground station" and processed to yield an aircraft trajectory accurate to between 2 and 5 metres. This processing removes errors common to the two GPS receivers, namely the common part of the ionospheric and tropospheric delays and the Selective Availability error for each satellite. It is the latter error which dominates, being on the order of tens of metres RMS.

The flight guidance system used at SGL consists of a PC type computer containing a Novatel 10 or 12 channel GPSCard (TM), or communicating via serial link with any other GPS

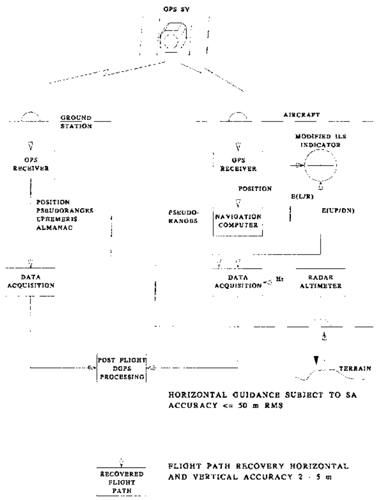

Figure 1.
Block Diagram of Current GPS-based Nav system.

receiver. The computer is uploaded with a file containing a description of a set of parallel lines to be flown, and the desired ground clearance for the flight. The calculated position from the GPS receiver is compared with the designated flight line, and a cross track error and distance to go is generated. A hand held serial terminal ("Mini Terminal") is used to present this and other data to the pilot, and to accept commands such as to change line; and the cross track error is used to drive the localizer (left/right) needle of a modified ILS indicator. **Figure 2** shows the miniterminal and modified ILS indicator installations. The output from a radar altimeter is compared to the desired ground clearance and the error signal drives the glide path (up/down) needle of the same indicator. The sensitivity of each needle is pilot adjustable to suit the prevailing conditions. The indicator is mounted on the top of the aircraft instrument panel so that it is in the pilot's peripheral field of view, allowing frequent reference to it. All flying is done "by hand", (i.e. the autopilot is not coupled into the system). Use of an autopilot for this type of flying is hampered by several factors. The magnetic noise created by the servo motors would interfere with the signal to be measured. The close proximity to the ground during most surveys would provide little time for the pilot to recover from a "runaway" autopilot condition. Furthermore, duty cycle limitation of the pitch and pitch trim servos is not conducive to frequent pitch command changes. Finally, the turbulence associated with low level flying would often prohibit use of an autopilot in any case.

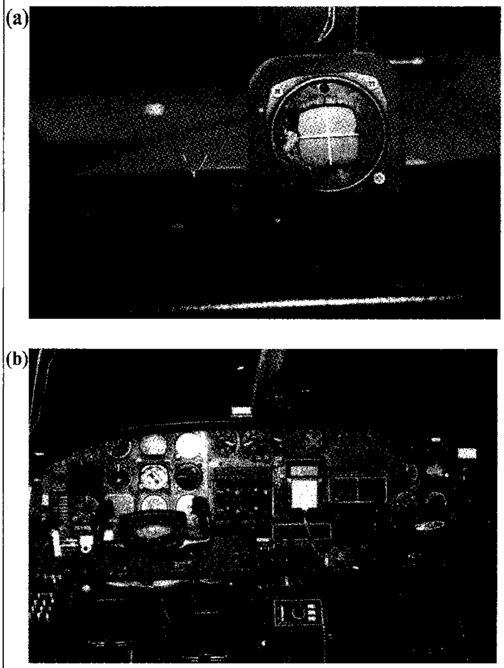

Figure 2.
Photo of a) modified ILS indicator and b) Pilot/Nav system interface - Miniterminal.

RECENT DEVELOPMENTS IN HORIZONTAL GUIDANCE

The line spacing required in some surveys is as close as 100 metres, which is getting close to the errors of single receiver (non differential) GPS. A pilot using this for flight guidance will dutifully follow the needle, but the actual ground track will have errors large enough to cause adjacent lines to come too close to each other, or occasionally even overlap. There is a real need for improved flight guidance in such cases. Single receiver GPS positioning can be greatly improved by transmitting corrections from a fixed, accurately located reference station. These corrections normally consist of the measured error in the range to each satellite, and some other ancillary data. The airborne receiver then corrects the pseudorange it measures, producing a calculated position with an accuracy of about 2 to 5 metres. This system is termed Real-Time Differential GPS (RTDGPS).

A number of possibilities are available for transmitting the differential correction data to the aircraft. The format of the messages can also take any number of forms, however a standard frequently used is referred to as "RTCM type 2". Some of the data link options are as follows:

1. Establish a private radio link using MF, HF, VHF, or UHF radios and appropriate modems. This requires a GPS receiver at an accurately known location on the ground and capable of generating pseudorange corrections. Setting up a transmitter requires considerable effort and range of the link is frequently a problem, since survey operations can be hundreds of kilometres from the transmitter. Licensing is an additional complication.

2. Use the radio beacons provided by the Coast Guard in Canada, the US, and several other countries. A receiver and demodulator are the only extra equipment required but the area in which reception is possible is limited to coastal areas and the Great Lakes.

3. Use the services of commercial providers transmitting on the subcarrier of broadcast FM stations. This is limited to the areas around larger cities where the service has been set up and by the limits of signal reception.

4. Use the services of commercial providers transmitting via satellite. A special antenna and receiver are required for the aircraft, and the area of coverage is limited to the "footprint" of the satellite used.

SGL has used options (1) and (4) above; these are illustrated in block diagram form in **Figures 3** and **4**, respectively. The private link used was set up for an offshore survey in Norway. A UHF transmitter feeding a highly directional antenna was used to beam the signal to the survey area. A range of about

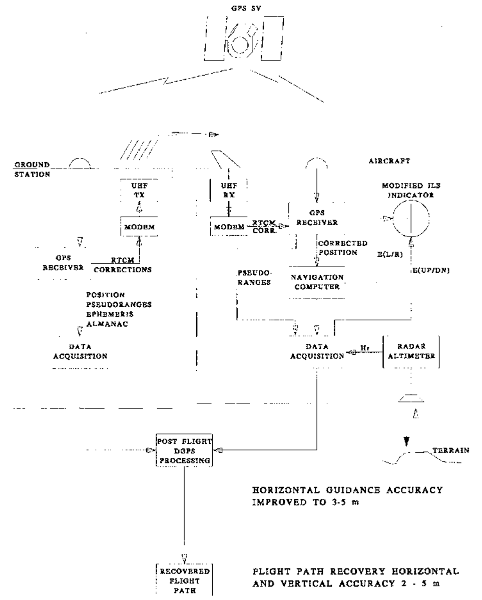

Figure 3.
Block Diagram of RTDGPS setup with Private Radio Data Link.

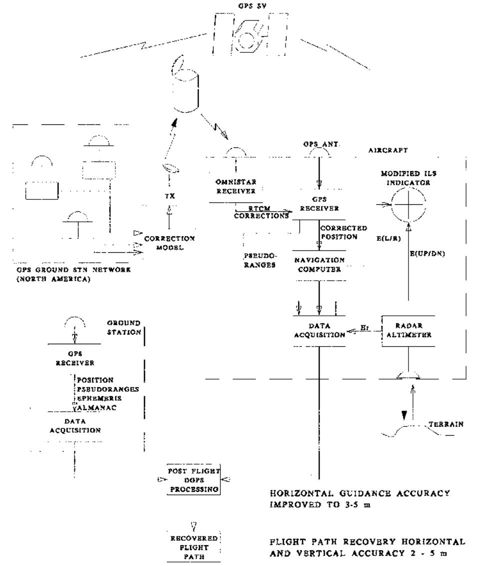

Figure 4.
Block Diagram of RTDGPS setup with Satellite Data Link.

120 km was achieved with 15 watts of transmitter power. For surveys in North America, the Omnistar(TM) service of John E. Chance Associates is being used with good success. The signal received is very weak and an omnidirectional, low gain aircraft antenna is used, however reception is available for about 95% of the time and the advantage of using it almost anywhere in North America is significant.

Figure 5 gives statistical data relevant to the flight path errors experienced during the Norway survey with and without RTDGPS guidance. These data are presented as the single sided distribution of the average cross track error (absolute value) along each flight line determined by comparing the planned flight path to that actually flown. The actual flight path was determined using post-processed differential GPS positions as described above. On average, of course, the error along each flight line is zero with deviations both left and right of the planned line. Note that the effect of removing selective availability (SA) errors has reduced the mean flight path error from 16 metres to 9 metres. Most of the remaining errors are attributable to the pilots' ability to minimize indicated cross track errors. In addition, note the considerably reduced spread of the distribution. The cause of the outlier at nearly 60m average line deviation is not known but is suspected to be either a recording error or reflects a requirement to deviate around an offshore oil rig.

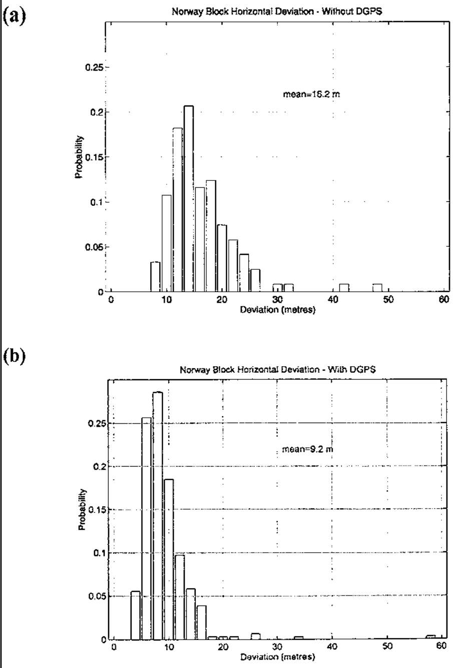

Figure 5.
Horizontal flight path error summary with and without RTDGPS.

RECENT DEVELOPMENTS IN VERTICAL (DRAPING) GUIDANCE

The main survey data are acquired by flying along closely spaced "traverse" lines. More widely spaced "control" lines are flown perpendicular to the traverse lines and, of course, the geological data recorded at each intersection is expected to be identical regardless of which direction it is flown. In general, this is only true if the intersections occur at the same height (i.e. the lines intersect in the true sense, that is, in three dimensional space). The control line data are used to adjust traverse line data by accounting for diurnal signal variations and other slowly varying quantities. The geophysical quantities being measured are generally quite height sensitive. **Figure 6** illustrates qualitatively, the apparent shape of a magnetic anomaly, for instance, if measured at two significantly different heights. In this context, significantly different may mean as little as 20 metres.

The developments described in the previous section refer only to horizontal guidance improvements; in the vertical sense the pilot continues to fly by radar altimeter height and tries to achieve a constant height above the terrain as specified in a given contract. This is known as contouring. For flight over flat terrain or a body of water (such as the Norway offshore survey data discussed), radar altimetry is an appropriate guidance method to achieve the desired result. Flight over increasingly steep terrain means that contouring becomes more difficult and much of the survey area will be flown at terrain clearance heights exceeding the desired value. The severity of this effect is dependent upon both the terrain and the aircraft. A helicopter, for example, is much better at contouring steep terrain than an aeroplane, though certain types of aeroplanes are also better than others in this regard.

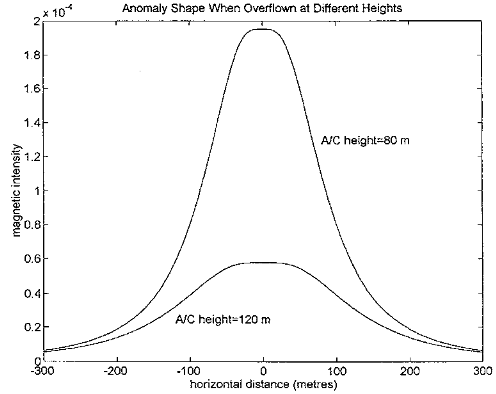

Figure 6.
Typical observed anomaly shapes when overflown at different heights.

The SGL fleet consists of four broad classes of aircraft including: single engine, turbine powered light helicopter (Eurocopter AS350D ASTAR); single engine, turbine powered aeroplane (Cessna 208B Grand Caravan); twin piston engine, fixed gear aeroplane (Britten Norman BN2 Islander); twin piston engine, retractable gear aeroplane (Cessna 404 Titan). These classes of aircraft have widely disparate climb / descent gradient capabilities. Each has advantages over the others depending on the area to be surveyed and the type of survey to be conducted. Radiometric surveys, for example, require much better contouring than magnetic total field surveys; helicopter operating costs are significantly higher than those of the aeroplanes; the piston powered retractable gear aeroplane can cover much more territory in a given period of time than the fixed gear aeroplane but cannot contour as well; the turbine engines cannot match the endurance of the piston engines at low altitudes but are much more tolerant of frequent power changes. **Table 1** illustrates the relevant figures for these aircraft types. Note that in general the descent capability is somewhat less than the climb capability. For the fixed wing aircraft this is due to higher groundspeed and, with piston engines, the reluctance to reduce power excessively in order to prevent shock cooling of the engines. For the helicopter, the avoidance of "settling with power" becomes important during rapid descents.

Table 1.
SGL fleet sustained climb / descent gradient capability.
(Sea level, standard day with allowances for typical winds and power settings)

A/C Classification	A/C Type and typical level flight speed (KTAS)	Max climb gradient (feet/nm) (m/km) (deg)	Max descent gradient (feet/nm) (m/km) (deg)
Retractable gear, piston twin aeroplane	Cessna 404 Titan (150)	460 76 4.3	225 37 2.1
Fixed gear, piston twin aeroplane	Britten Norman BN2 Islander (110)	700 115 6.6	450 74 4.3
Single engine turbine aeroplane	Cessna 208BGrand Caravan(110 to 150)	600 99 5.7	350 58 3.3
Single engine turbine helicopter	Eurocopter AS 350D ASTAR(70)	1500 * 247 14.3	1000 * 165 9.5

Clearly, anywhere the terrain gradient exceeds the maximum descent gradient capability of the aircraft in use, the pilot will have to start climbs early and accept higher than specified terrain clearance (radar altitude) during descents. This is known as "draping" or "drape flying". The term is descriptive if one considers the analogy of a tarpaulin draped over the terrain to be flown. The tension on the tarpaulin is analogous to the climb / descent gradient capability of the aircraft to be used and determines how low into the valleys the tarpaulin will fall. The final shape of the tarpaulin defines a flyable surface.

In the absence of any form of guidance, drape flying is left entirely up to the pilot's judgement. Such a situation presents difficulties since adjacent lines may be flown in opposite directions and therefore with differing groundspeeds particularly if wind is significant. Furthermore, the pilot has to visually account for terrain off the line being flown in anticipation of flying the perpendicular lines at some later time or date.

SGL has developed a system to implement the flyable surface and provide reliable vertical guidance to the pilot in an effort to improve flying height consistency. The process of creating a flyable surface is summarized in block diagram form in **Figure 7** and described as follows:

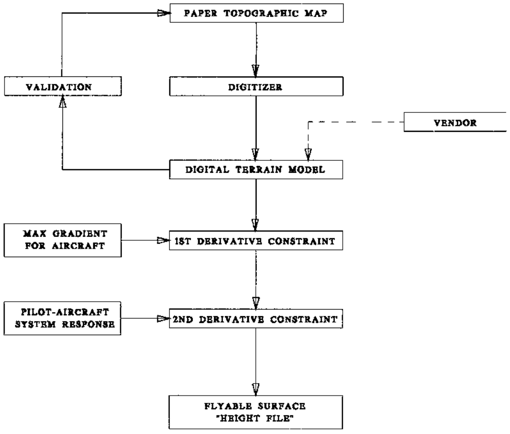

Figure 7.
Block diagram of Terrain Modelling and Smoothing Process.

1. A digital terrain model of the survey area is generated. Sometimes such models of adequate resolution are available commercially but more often they are not. In this case, paper topographical maps are manually digitized. This requires time and effort but it should be noted that it is not necessary to *fully* digitize such a map since many features are to be smoothed. The most important elements to be included are all the peaks and some representation of the areas around each peak. The digitized map can then be contoured and plotted for checking against the source map for veracity of the principal features.
2. The digital terrain model is smoothed by raising any low points as necessary to ensure that the maximum acceptable gradient is not exceeded anywhere. Thus, the first derivative of the surface elevation with respect to any horizontal direction is constrained by the performance capability of the aircraft.
3. The smoothed surface is then further smoothed to eliminate sudden transitions from maximum climb command to maximum descent command and vice versa. Essentially, this means setting an upper limit on the second derivative of elevation with respect to any horizontal direction. The value of this upper limit is determined by observing the wavelength of the typical pilot-aircraft system response to such a command sequence as determined from recorded in-flight data.

It should be noted that the smoothed surface model is general in the sense that it is not tied in any way to the planned flight lines. The final version of the smoothed terrain model constituting a flyable surface is called a "height file". **Figures 8** and **9** provide an example of digital terrain data before and after the smoothing process. The area shown is in the foothills of the Rocky Mountains of Northeastern British Columbia and was flown with the Cessna 404 Titan. Further discussion of data from this survey appears later in the paper. This particular height file did not have the second derivative constraint imposed.

Figure 10 is a block diagram illustrating the use of the height file in the vertical guidance system. Segments of the height file are loaded into the navigation computer as required based on the current position. For each position determination (twice per second) the computer looks up the appropriate flying surface height, Hs, from the height file and adds to it the contract specified terrain clearance height, Hc, to compute the desired flying height, (Hd=Hs+Hc). The desired flying height, Hd, is compared with the measured flying height, Hm,

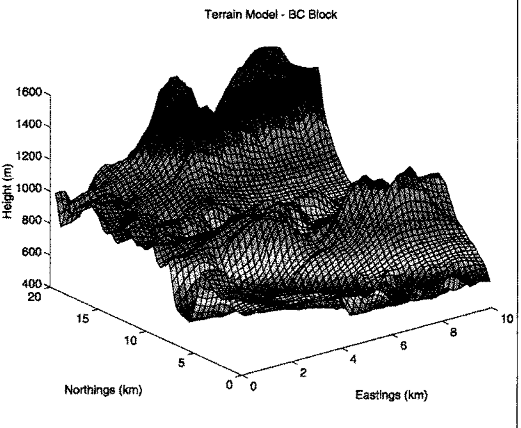

Figure 8.
3D view of portion of digital terrain model - BC Block.

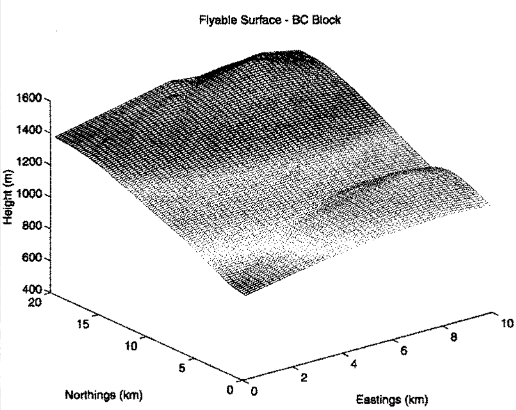

Figure 9.
3D view of smoothed flyable surface - BC Block.

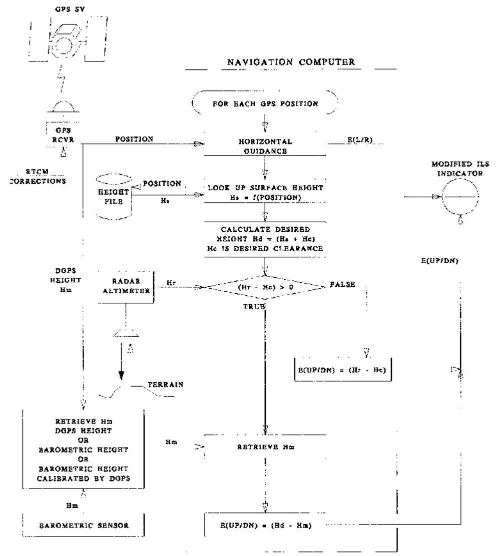

Figure 10.
Block diagram of nav computer function - drape guidance.

and the difference generates an error signal, (Hd-Hm), indicated to the pilot on the glide path (up/down) needle of the modified ILS indicator.

In addition to all of the above, the computer checks the current reading of the radar altimeter, Hr, to ensure that the actual terrain clearance is not less than the expected minimum value, Hc. This can occur as a result of either an incorrect terrain model or an error in measured flying height, Hm. Despite the efforts to ensure accuracy, it is possible for the digital terrain model not to include one or more high points, particularly if the source data is questionable and has been manually digitized. Furthermore, tall trees or structures may be present where the terrain model is based on the ground elevation. Potential errors in measured height, Hm, are discussed below. In either case, if the quantity (Hr - Hc) is less than zero, the system will revert automatically to radar altimeter guidance, usually causing an immediate "fly-up" command until the condition is satisfied. A suitable buffer on this test is incorporated to prevent unnecessary vertical guidance mode changes.

Measured flying height, Hm, is determined in one of three ways listed below:

1. Barometric altimetry:

   The navigation system includes a barometric sensor plumbed into the aircraft's static pressure system and corrected by the pilot for diurnal variation (i.e. altimeter setting). The output of this sensor is based on the ICAO standard atmosphere and is subject to all the usual barometric altimetry problems; notably, non-standard temperature lapse rates with altitude, static source position error, and mountain wave effects. This sensor provides an adequate measure of Hm, subject to the above sources of error which may be sufficient to trigger the system to revert to radar altimeter guidance mode.

2. Real Time Differential GPS:

   If the aircraft is receiving real time differential GPS corrections (RTDGPS), the GPS altitude becomes a usable quantity which is repeatable under all atmospheric conditions. It relies on the GPS corrections data link described earlier which may be subject to outages of varying duration. In addition, a suitable vertical datum adjustment must be made to account for differences between mean sea level and the WGS-84 ellipsoid, which are the "zero" elevations for most terrain maps and the GPS, respectively.

3. Barometric altimetry calibrated by RTDGPS:

   While operating in RTDGPS mode, the corrected GPS altitude is used to calibrate the barometric sensor in real time such that its accuracy is sufficient to handle RTDGPS outages of short duration without causing a step in the pilot's command signal. "Short duration" may actually be quite a long time provided the aircraft it not climbing or descending a great deal and the atmospheric pressure is not changing rapidly.

The navigation system supports two other modes if draping is not required. These are the traditional ones of radar altimeter guidance and fixed altitude. The fixed altitude mode may use either the barometric sensor or RTDGPS as the height reference and also includes the automatic reversion to radar altimeter guidance in the event radar altitude falls below a predetermined limit.

To illustrate the effectiveness of the system, **Figure 11** includes profile data for two pairs of adjacent lines flown in opposite directions in a region of considerable terrain relief

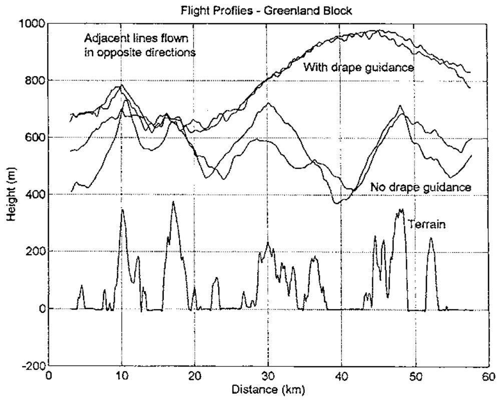

Figure 11.
Profiles for two pairs of adjacent lines flown with and without drape guidance - Greenland.

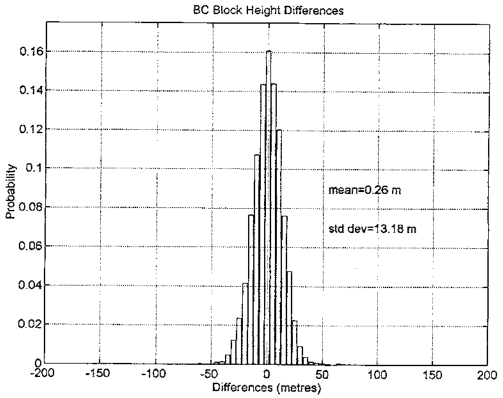

Figure 13.
Distribution of height differences at intersections with drape guidance - BC Block.

(southern Greenland). In the first case, the pilot was not receiving draping guidance while in the second case he was. The difficulties of manual draping and the subsequent improvement in line-to-line consistency with draping guidance are evident. Furthermore, the influence of terrain off the line flown is evident. It must be noted from this effect that the quality of geophysical data acquired may suffer when using the draping guidance described herein in the sense that the terrain clearance is greater than would seem possible. On the other hand, if the control lines can not intersect the traverse lines, the data suffer from excessive levelling corrections. Additional discussion of this dilemma appears at the end of the paper.

A good measure of the overall performance of the system is provided by the comparison of **Figures 12** and **13**. Here the distribution of height differences at all line crossover points in the survey area are given for two surveys over similar types of terrain; the first flown without drape guidance in an area of Bolivia called the Corazon block; the second with drape guidance in the BC block of **Figure 8**. The mean of all the height differences should be close to zero in either case. However, due to the previously mentioned difficulties of manual draping, the mean height difference for the Corazon block is nearly 10 metres and the standard deviation over 70 metres; this despite the efforts of a highly experienced survey pilot who put considerable planning effort into the job. Contrast that with the BC block data whose sample size is similar, was acquired by the same pilot flying the same aircraft over similar (although not identical) terrain but with the aid of draping guidance. The mean and standard deviation of the height differences are 0.3 metres and 13.2 metres, respectively.

Finally, **Figures 14** through **16** show profiles of actual (post-processed DGPS) aircraft heights, smoothed terrain model, and

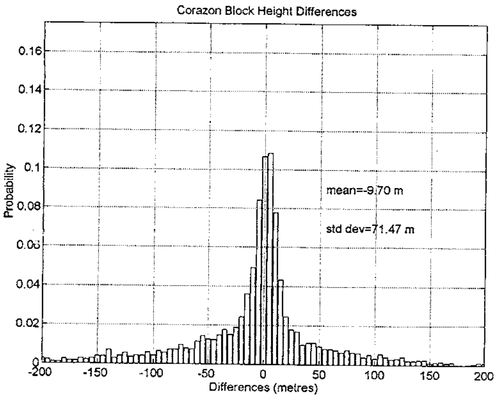

Figure 12.
Distribution of height differences at intersections without drape guidance - Corazon.

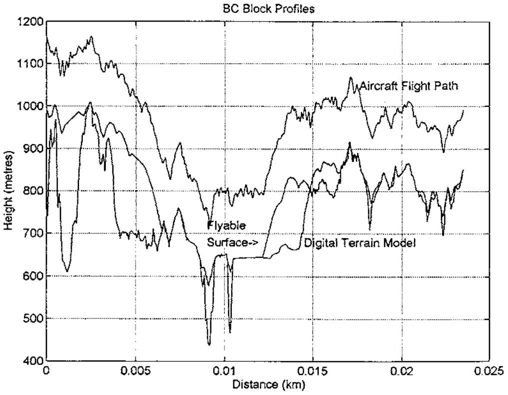

Figure 14.
Profiles of BC Block showing terrain model, flyable surface, actual flight path.

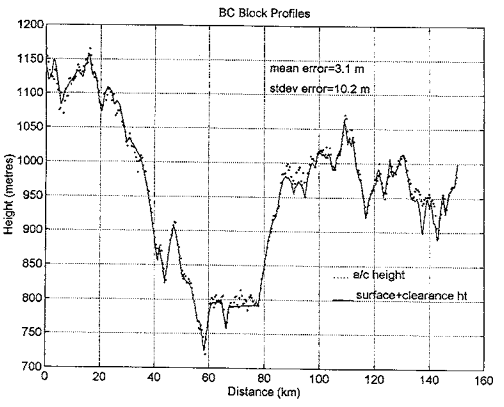

Figure 15.
Profile comparing command surface and actual flight path.

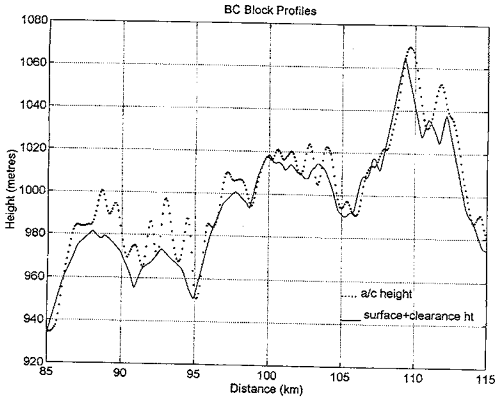

Figure 16.
Detail of figure 15.

digital terrain height for a typical survey flight line recorded in the BC block described in **Figures 8** and **9**. **Figure 14** clearly illustrates valleys which are ignored by the smoothed model. The effectiveness of the guidance system is demonstrated by the close agreement between the flight path data and the smoothed model in **Figure 15**. Statistically, the mean height error along this flight line was 3.1 metres and the standard deviation of the error was 10.1 metres. Finally, **Figure 16** is a detail of **Figure 15** which illustrates the pilot-aircraft response to the command signal changes. Recall that this particular terrain model was not smoothed in terms of the second derivative; this feature has only recently been added and has resulted in even better agreement between the flyable surface and the actual flight path, however these data were not available for publication at time of writing.

FUTURE ENHANCEMENTS

Development of the systems described in this paper are continuing. Among these is the use of combined GPS/GLONASS receivers. These hold the potential for eliminating the requirement to receive differential corrections for guidance purposes, particularly in the horizontal sense. Such receivers have recently become available on the market and SGL is actively testing one of them. As described earlier, the vertical draping guidance system currently implemented is general in that it is not tied to any particular flight path plan. This can cause difficulties such as those illustrated by the Greenland data discussed earlier. Work is underway to develop flight path optimization schemes in order to retain the benefits of draping guidance while reducing terrain clearance in certain areas. It may be of more benefit, for instance, to eliminate control lines in some areas in order to permit the traverse lines to be flown much closer to the surface. This requires only the gradients in the flight line directions to be reduced.

SUMMARY

Clearly, the improvements in pilot guidance reduce flight path errors in both the horizontal and vertical senses. The end result is improved data requiring fewer reflights and less data processing effort to produce the final product. This lowers the cost of production for a moderate increase in investment in hardware and software and some pre-survey planning. The pilot's workload is also greatly reduced in areas which would otherwise be manually draped thus enhancing safety in a demanding flying environment. Feedback from clients served with these improvements to date has been very positive. It should be noted that the traditional methods of single GPS receiver horizontal guidance and radar altimeter vertical guidance are still used by SGL for those surveys where they are appropriate.