Contour Flying for Airborne Data Acquisition

MICHAEL MÖLLNEY, JENS KREMER, Kreuztal

ABSTRACT

Airborne data acquisition is typically done using flight patterns that allow "straight" movement during the data acquisition. This approach comes to its limits, if the modulation of the terrain reaches a certain magnitude relative to the desired flying height above ground. In this case, different approaches to reduce the effect of the modulating ground level are available. The most elegant and efficient way is to keep the altitude above ground constant and fly along the contour of the earth's surface. This contour flying allows to operate typical remote sensing and photogrammetry sensors to capture data at very high ground sample densities and it is a prerequisite for certain airborne geophysical surveys. However, this method has its physical and practical limitations that have to be considered to assure save flying operation.

With the *CCNS-5* and the related mission planing software *IGIplan*, IGI provides tools to exploit the advantages of contour flying in aerial surey missons.

1. INTRODUCTION

Airborne data acquisition is typically done using flight patterns that allow "straight" movement during the data acquisition. Consequently, straight lines with constant altitude are preferred. However, mainly for acquiring higher resolution data there is a clear trend toward flying at lower altitudes above ground.

1.1. Low Altitude Flying with Digital Cameras

For most digital frame cameras and line scanners there are no options to change the focal length to adapt the resolution of the acquired data. The ground sampling distance (GSD) determines the altitude above ground (AGL) that has to be flown. To double the resolution, it is required to fly with half the AGL.

Flying closer to the ground, the modulation of the ground level along a flown line has stronger effects in the change of the resolution. This can lead to an unacceptably wide range of GSD in the acquired data. As a consequence, the flying altitude has to be adapted to the changing of the ground level.

1.2. Low Altitude Flying with Airborne LiDAR

The point density and point distribution of an airborne LiDAR mission is dependent on different parameters: AGL, scan frequency, pulse repetition rate and the speed of the aircraft. The selection of all parameters should typically result in a homogenously distributed point cloud with the aspired point density.

To reduce flying time, typically all parameters are pushed to their limits resulting in maximal density per flying effort. Therefore, adjusting the altitude to regulate the density is the parameter of choice.

Analogously to the digital camera case, flying closer to the ground, the modulation of the ground level along a flown line has stronger effects in the change of the point density. To avoid inacceptable variations in the point density, the flying height has to be adapted to the changing ground level.

1.3. Geophysic Surveys

For certain airborne geophysical surveys, exact flight guidance is crucial not only for the horizontal, but also for the vertical position. Some of these surveys require data collection at a constant height above the earth's surface.

2. TERRAIN FOLLOWING IN AERIAL SURVEY

2.1. Classification of low Flying Altitudes

Flying by "terrain following" is a typical maneuver in military scenarios. In this domain, the following terms are used.

Term	Description	
Low Level	constant altitude	constant speed
Contour Flying	variable altitude	constant speed
Nap-of-earth (NOE)	variable altitude	variable speed

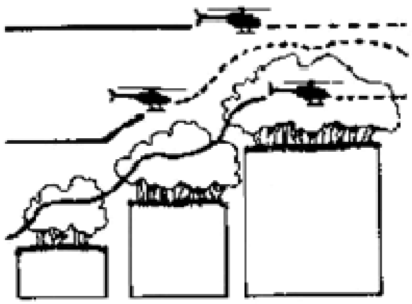


Figure 1: Terrain flight modes (classification) defined by US military [4].

2.2. Low Level, Multiple Levels

If the target area can be split into adequately large areas, where each one has a ground level range that can be acquired by one fixed flight level, an approach of multiple levels might be appropriate.

Advantage(s)	Operation of one level at a time is easier accepted in controlled / crowded air space.
Disadvantage(s)	Flying effort is high due to re-flying (partly) the same lines in different altitudes plus additional turn times.
	Multiple coverage of ground in different resolutions for overlapping levels of a line can result in additional effort to select the set of images that should be processed into the final product.
	Within the chosen level, the remaining ground altitude modulation is still affecting the GSD / point density along and across the flight line.

Table 1: Advantages and disadvantages of survey missions flown in multiple flight levels.

2.3. Contour Flying

Another approach is contour flying. The basic idea is to have constant AGL and constant speed, while flying straight (horizontally).

Advantage(s)	Resolution of acquired data is less modulated along the flight line.
	Extend of scanned ground is less modulated. Fewer problems in sideward and forward overlap.
	Constant line distance and grid spacing possible.
Disadvantage(s)	Permanent altitude change resulting in: - Significantly increased workload for the pilot. - Problems to get permission in controlled airspace.

Table 2: Advantages and disadvantages of survey missions flown along the surface contour.

3. FLIGHT PLANNING WITH CONTOUR FLYING CONSTRAINTS

In addition to flying at a fixed altitude, flying at constant AGL has some more constraints to be taken into account.

Topics that should be considered during the planning phase are:

- Selection of the Digital Terrain Model (DTM).
- Calculation of the altitude above ground.
- How strict should the modulation of the ground level be followed?
- Legal restrictions: minimum altitude above populated areas.
- Physical constraints of the aircraft: climb / descent rates.
- Speed of change of climb / descent rates.

For missions with extremely low AGL and military scenarios, additional constraints become important. These scenarios are not subject to this paper.

3.1. DTM Quality

Planning contour flights relies heavily on the resolution and quality of the DTM [2]. There are freely available DTMs which are often used for mission planning. This data is the result of an interpolation and resampling process at grid points.

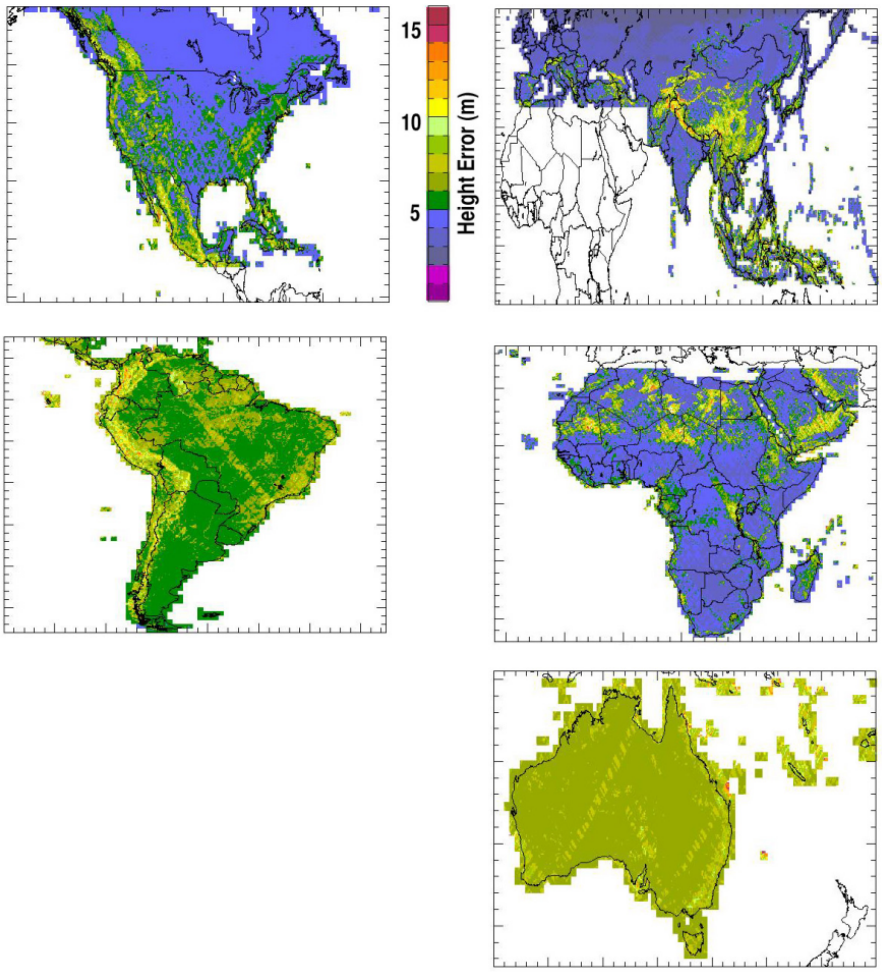


Figure 2: Estimated 90% vertical error of the SRTM DTM [8].

Parameters to consider are:
Resolution / Grid spacing:

- SRTM (Shuttle Radar Topography Mission [9]): ~90m (~30m CONUS)
- GDEM (Global Digital Elevation Map [10]): ~30m

Information / value quality of DTM at grid points:

- Interpolation mode for value at grid points: mean, maximum, spline?
- Quality in absolute value?
- What about solitary high objects: High antennas, wind turbines, industrial chimneys, power lines?

3.2. Range of Resolution / Altitude and Terrain Modulation

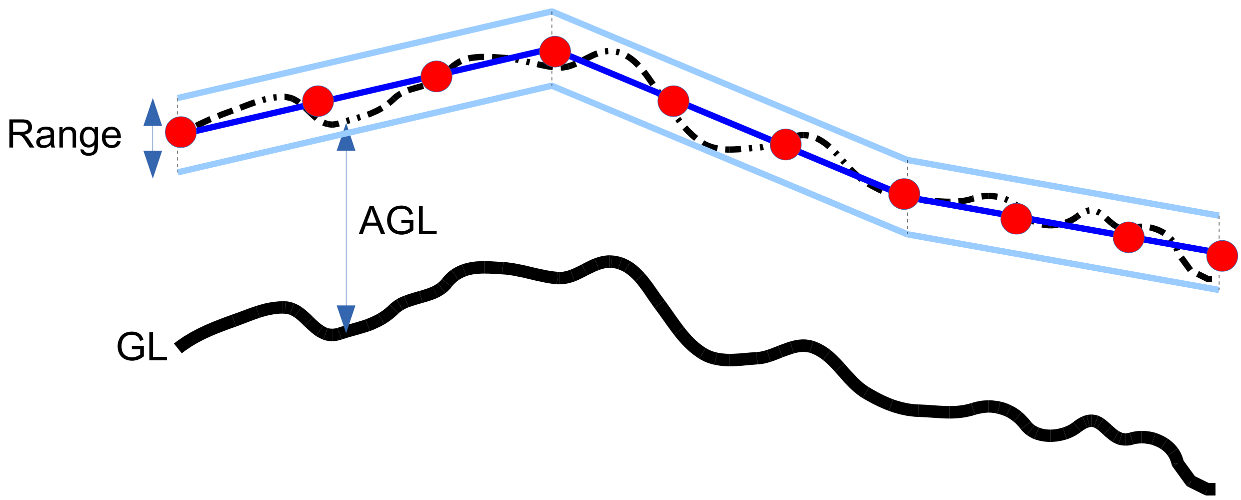


Figure 3: Schema of terrain adaption showing tradeoff between close contour following and constant ascent / descent.

Depending on the density and on the interpolation mode used in the DTM, the ground level shows high modulation frequencies. It is neither possible nor necessary to follow these modulations strictly. To avoid unnecessary stress for the pilot, the flight planning should be smoothed.
The angles of ascent and descent should be calculated not to follow the terrain strictly, but to allow the aircraft to stay in an acceptable range above / below the ideal AGL. This vertical corridor allows for some time of constant ascent and descent angle during operation. This planning gives the pilot some less stress and more important out the window visual scanning time [3].

3.3. Climb Rates of typical Survey Aircraft

In the following tables taken from Sander [1], the ascent/descent gradients of typical survey aircraft are shown at different altitudes. It has to be considered, that the capability for accent and descent differ. In Table 3 the minimum of both values are given, because during the mission planning phase, the direction in which a planned line will be flown is not known. The tables were extended for the Gyrocopter AutoGyro Cavalon [7].

Aircraft	Maximum Ascent/Descent Gradient Capability [m/km] vs Density Altitude				
	Sea Level	5000 ft	10,000 ft	15,000 ft	20,000 ft
Cessan 208B	62	52	41	35	21
Cessna 404	39	37	34	30	22
AutoGyro Cavalon	120	120			

Table 3: Maximum ascent/descent gradient capability of different survey aircraft at different altitudes ([1] and [7]).

Aircraft Type	Climb Gradient [m/km] (sea level)	Descent Gradient [m/km] (sea level)
Cessna 404	76	39
Cessna 402 STOL kit	68	37
Beechraft Queenair	58	37
BN Islander	115	74
Cessna Grand Caravan	99	62
AutoGyro Cavalon	120	120
Eurocopter ASTAR	247	165

Table 4: Climb/descent gradient capability of different survey aircraft at sea level (sources [1] and [7]).

3.4. Typical Flight Plan for Contour Flying

Keeping the AGL constant during contour flying leads to flight patterns, that look identical to flight plans in plane areas. The modulation of resolution is limited to the extent of the local camera footprint or scan line. In lowly modulated terrain, a locally rectangular coverage of a frame is a sufficient approximation of the real coverage.
As a consequence, the distance of the lines can be kept constant without having much trouble to keep a sufficient sideward overlap. The distance of the frame camera events within the flight line can be kept constant, too.

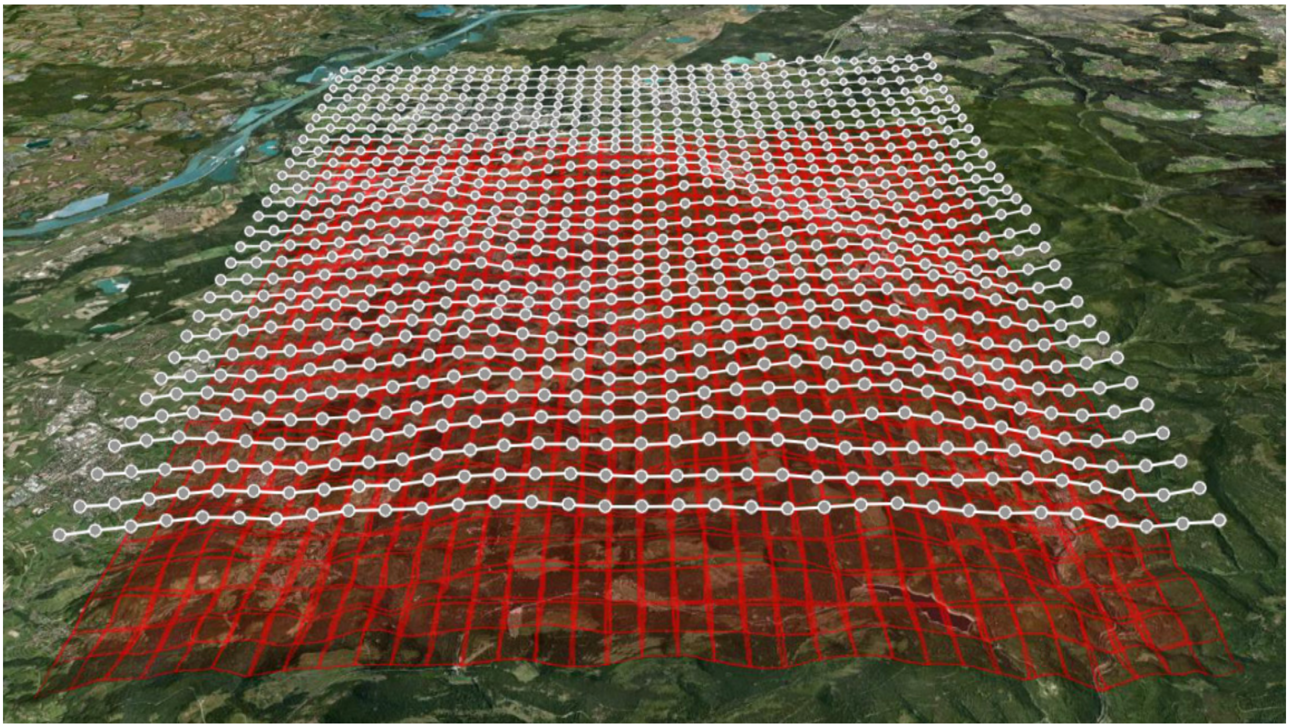


Figure 4: Flight pattern with fixed line distance and fixed event distance with AGL adaption. Terrain altitude range: 110m to 1000m.

4. CONTOUR FLYING WITH *CCNS-5*

For a terrain following mission, the pilot needs additional information to be able to follow the planned flight lines not only horizontally, but also vertically. The altitude information given by the actual aerial survey navigation systems is mostly not sufficient. In the following, some common aircraft instruments for vertical movement / altitude correction and different indicators implemented in the *CCNS-5* are described.

4.1. Common Aircraft Instrumentation for Vertical Movement / Altitude Correction

4.1.1. Vertical Speed Indicator (VSI)

Figure 5: Vertical Speed Indicator.

The vertical speed indicator – also known as “rate of climb and descent indicator” (RCDI) – shows the absolute vertical speed. This speed is typically given in the unit feet per minute. So the climb and descent angles depend on the actual speed over ground.
A planned contour flight normally contains the planned speed over ground. Therefore, the planned rate of climb and descent could be calculated. But depending on the actual wind situation, the same climb/descent rate can result in a different effective slope.
There is no correction indication available in this instrument. There is no direct indication for the pilot to correct his flight path.

4.1.2. Instrumental Landing System (Glide Path Correction Aspect)

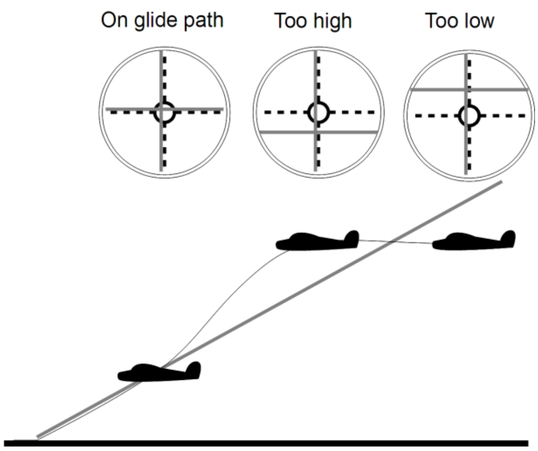


Figure 6: Glide path correction with an ILS instrument.

The ILS gives the pilot a help to follow a defined glide path. The indication shows if the planned path is above or below the aircraft. However, the ILS instrument relates to angle deviation. So if the pilot stays at a constant level relative to the glide path, the ILS will increase its deviation value.
This is adequate for landing help, as there is limited space for a safe touch down: no runway in front of touch down zone, limited runway length after touch down zone. For contour flying, it is not so critical to hit the exact altitude at a given position. A certain altitude range around the planned position is acceptable.
Indicating the angle to the planned position is not helpful, the airplane should pass in acceptable but calm movement.

4.2. *CCNS-5* as Pilot Instrument

The *CCNS-5,* as successor of the well-known *CCNS-4* guidance and flight management system, fulfills the same main tasks:

- Guide the pilot along the planned lines
- Control the connected sensors

As with the *CCNS-4,* the typical operation constellation of airborne data acquisition – a pilot and an operator as a team – is supported by two screens. However, the two screens of the *CCNS-5* can show different information at the same time. The pilot needs information to stay on the planned flight path, information to communicate with air traffic controllers, reference lines to access the next planned line and so on.

The sensor operator needs more information about how to navigate through the whole area. He needs status information of the sensors, while at the same time he has to cross check for good flight maneuvers.
At the *CCNS-5,* so called “info boxes” can be put around a moving map display. Pilot and operator can set up different boxes on their individual screens to give them optimal view on the map along with specific info boxes.

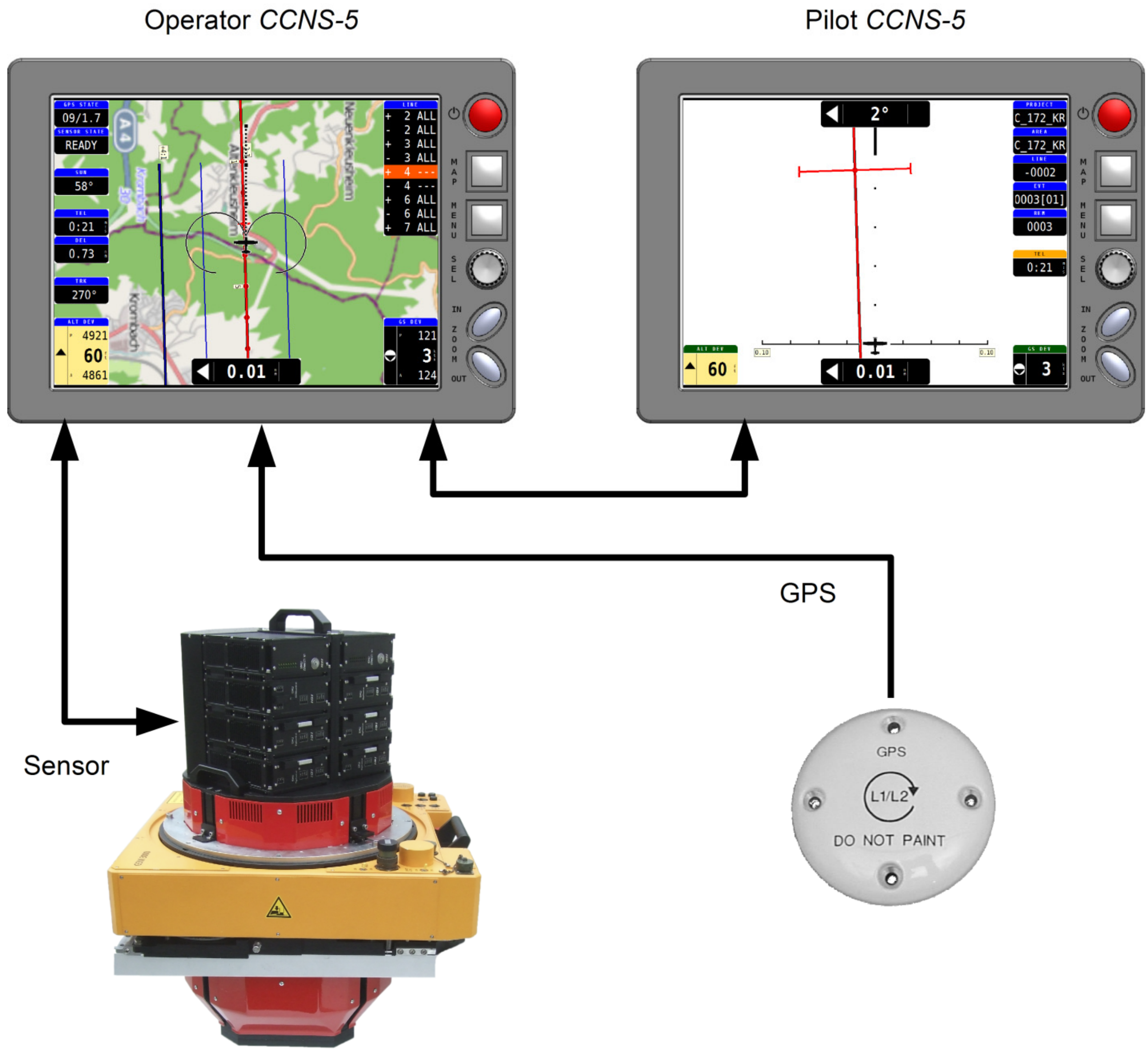


Figure 7: Connection schema *CCNS-5*. Pilot and Operator can have different views on the same operation status [5].

To ease the work of the pilot as good as possible, clear commands are given by the *CCNS-5* to correct possible offsets from position and speed.

4.2.1. *CCNS-5* Altitude Deviation Prediction bar

For contour flying, the deviation between airplane and planned position is to be kept in an acceptable range. It is not critical to fly with constant but acceptable altitude offset relative to the planned altitudes. This is contrary to the situation of a planned glide path for landing / touch down (see 4.1.2). However, the pilot must have a good indicator to keep the relative height towards the planned altitude change.

For the *CCNS-5*, IGI created an indicator that shows the altitude deviation of the coming planned events with the current ascent/descent path as reference.

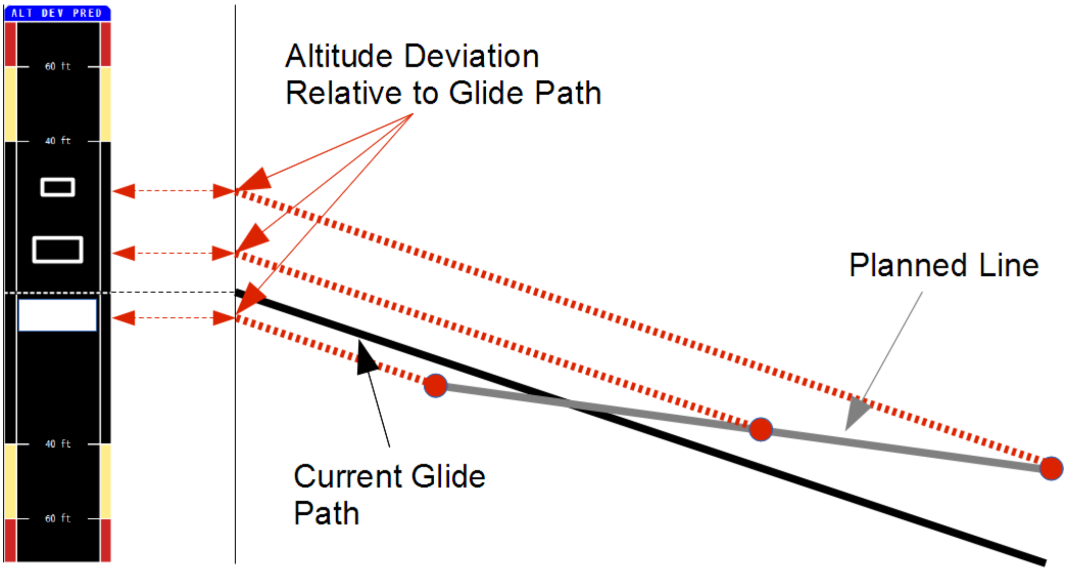


Figure 8: Altitude deviation prediction. Instrument predicts altitude deviation between planned and possible altitude when reaching the event, taking current ascent / descent in consideration.

In Figure 8, the pilot can read for his current ascent/descent, that the next planned event is just below him and the coming events will be above him. The instrument shows, that all three events are in an acceptable zone (outside yellow, red areas). However, there is also an indication that the pilot should pull the machine to reduce the trend of flying too low for coming events. This instrument is independent of the current speed and neutral to the current ascent/descent. So it gives the pilot a clear indication if the airplane will be below/above planned line and how to react (pull / push).
The warning (yellow) and critical (red) levels below and above the airplane can be set by the user. In a perfect flight on the planned line, only the bold bar would be seen in the center of the indicator, hiding the following events, as long as they lie on the same ascent/descent.

4.2.2. *CNS-5* Altitude Deviation Bar

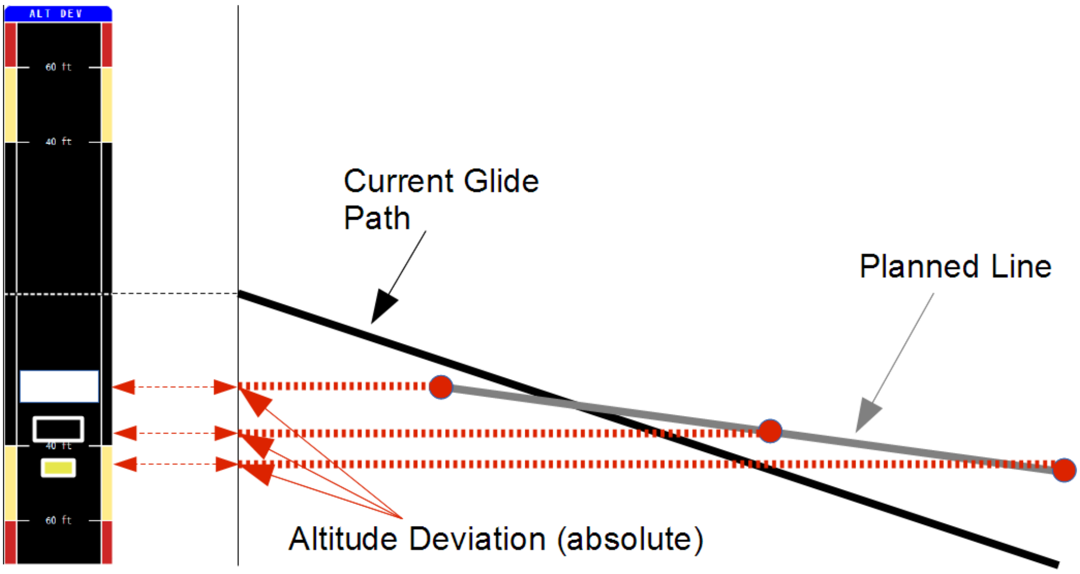


Figure 9: Altitude deviation. Instrument shows deviation between planned and current altitude not considering current ascent / descent.

The altitude deviation bar looks very similar to the altitude deviation prediction bar. The main difference is that the current ascent/descent is not taken as reference (see 4.2.1.). The current altitude difference between airplane altitude and the altitude for the next and following events is shown. In effect, the bars in the indicator move, even if the airplane flies perfectly on the planned flight line.

4.2.3. Additional *CCNS-5* info boxes regarding contour flying

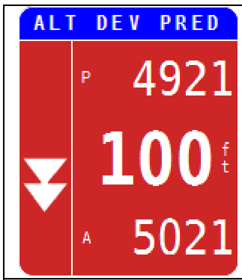
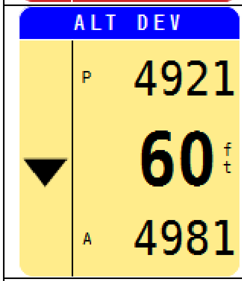
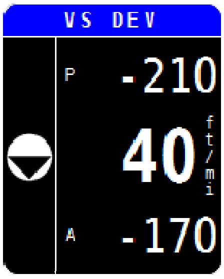
	ALT DEV PRED shows the predicted altitude deviation to the next planned event, taking current ascent / descent into consideration. In the example, the aircraft will be 100 ft above the planned altitude. The background color is red to indicate that the altitude deviation will be outside the acceptable range. The ranges are user settable. The indication shows a double-arrow pointing down to command the pilot to correct the glide path downwards.
	ALT DEV shows the altitude deviation for the next planned event. In the example, the aircraft is currently 60 ft above the planned altitude. The background color is yellow to indicate that the alt deviation is still acceptable, but close to an unacceptable value. The ranges are user settable. The indication shows a single arrow pointing down to command the pilot to push the aircraft down a little.
	VS DEV shows the vertical speed deviation between the planned ascent/descent and the actual one. In the example, the planned descent is 210 ft/min, the actual descent is 170 ft/min. There is a difference of 40 ft/min missing descent. The background color is black (no warn/error) to indicate that the slope is in an acceptable range. The ranges are user settable. A symbolized zero (white circle) contains a small arrow pointing down to give the pilot a hint that the aircraft should descent a little more to have the exact planned descent.

Table 5: Additional *CCNS-5* info boxes regarding contour flying.

4.2.4. *CCNS-5* screenshot with contour flying indication

Figure 10 shows a possible setup of a set of info boxes on a *CCNS-5* configured for the pilot. The appearance of the different objects can be configured by the user. In the given example, the following information is displayed.

- ALT DEV PRED bar: The next event is above the aircraft. The following events are even higher: Pull up.
- ALT DEV: aircraft should be 14 ft higher (indicated by small black arrow in circle) but is still sufficiently close to the planned altitude (indicated by black background). The planned altitude is 3883 ft.
- VS DEV box: The aircraft should be pulled up (arrow showing up, warning color) to reduce the current descent by 210 ft/min. Planned descent is -170 ft/min for the current speed.

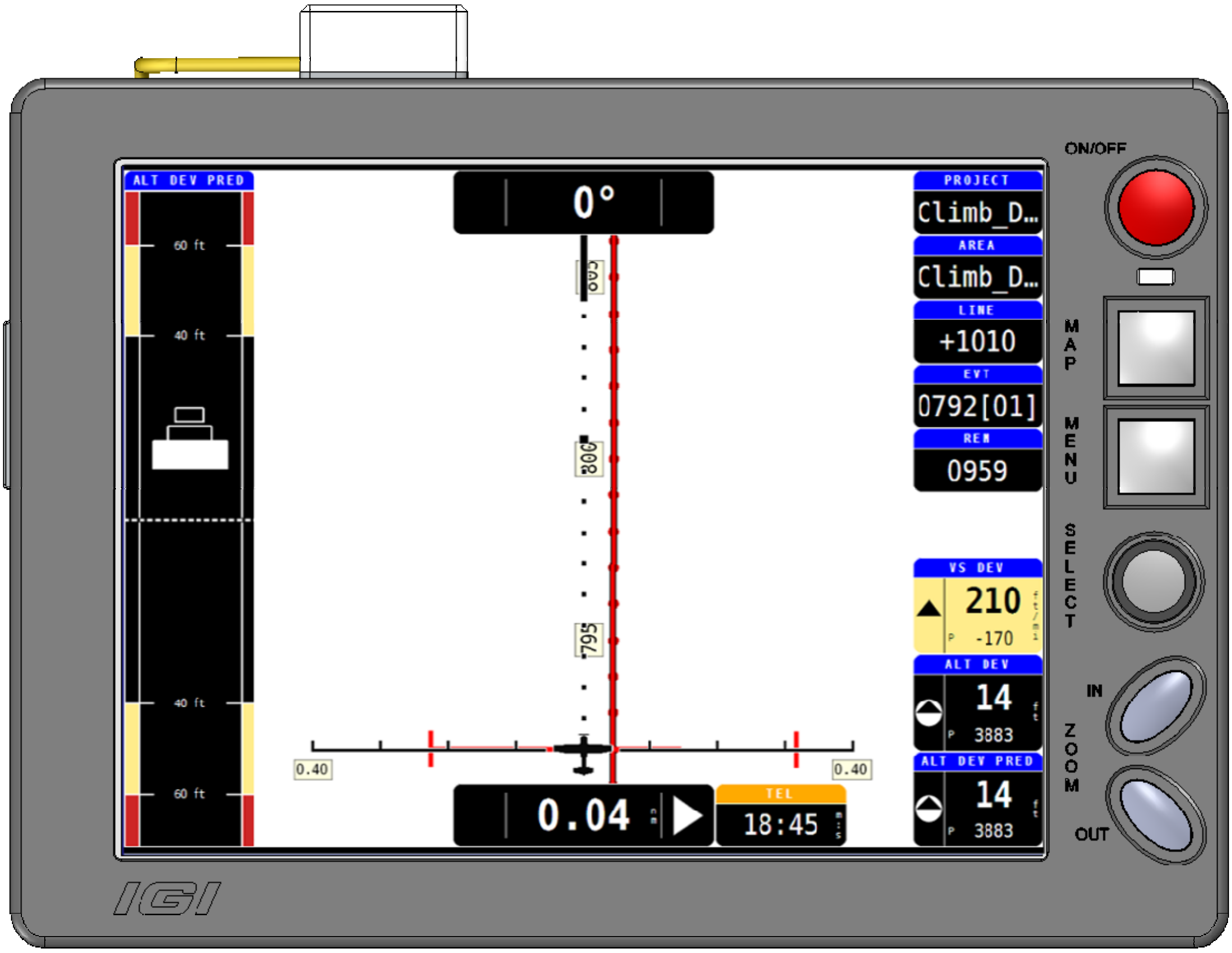


Figure 10: Possible setup of info boxes on the pilot screen for contour flying [5].

5. FLYING EFFORT – A PLANNING EXAMPLE

The mission planning for *CCNS-5* operations is generated in the software package *IGIplan*. All planning parameters are collected inside *IGIplan* to create the optimal flight planning. *IGIplan* provides tools for single level, multiple level and contour flying survey missions.
In the following section, the mission layout for these three approaches is compared for a hilly area near Karlsruhe in Germany. The ground level in the north-west is about 120m, while the top of the mountains in the south is about 1000m in altitude. The nominal ground sample distance (GSD) for this example is 15cm, the acceptable range is 14cm to 17cm.

5.1. Simple Block Planning

The most basic way to cover the target area with photos is to set an absolute aircraft altitude within whole block.
In this example, the altitude was determined by the highest point in the mission area. Using the GSD classification tool in *IGIplan*, it becomes clear that only a small area (green) can be covered with the desired GSD range. Most of the area is outside the acceptable range, the resolution is worse than 17cm (red).

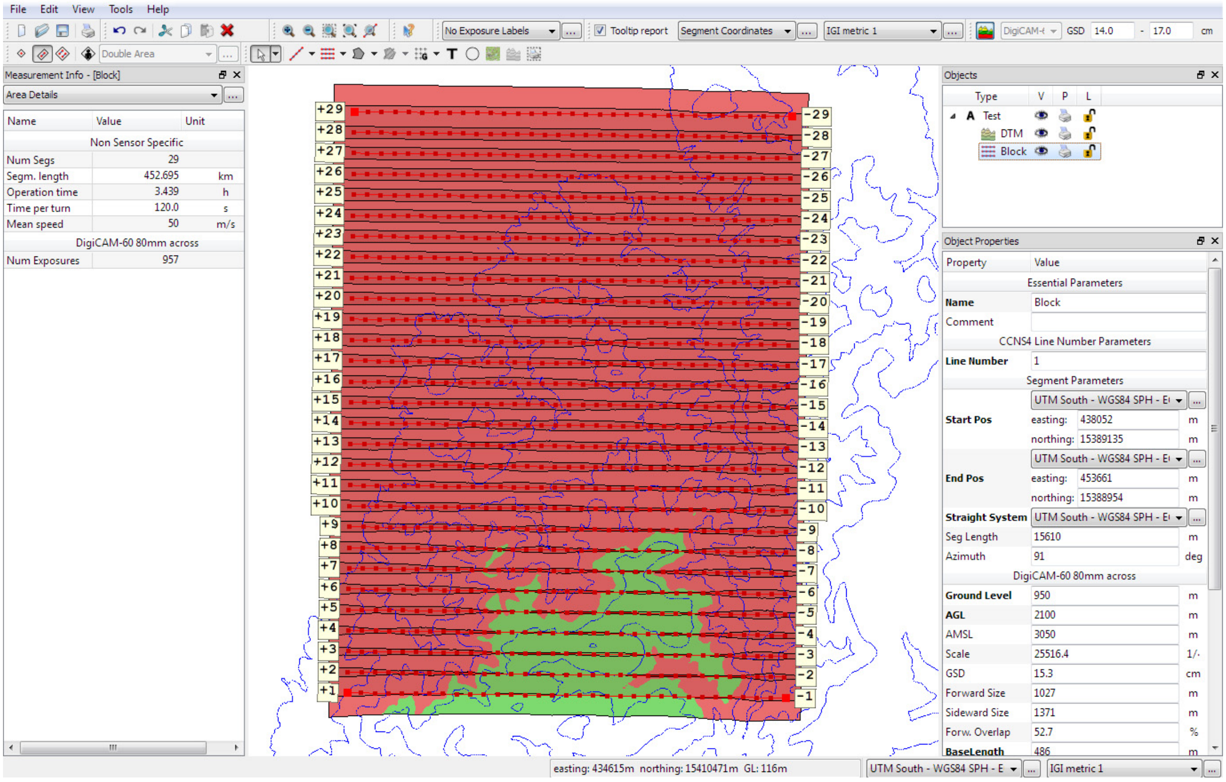


Figure 11: Screenshot of mission planning software *IGIplan* [6]. Block planning with fixed altitude. Wide areas have GSDs outside the requested range.

5.2. Adapt to Terrain by Introducing Additional Levels

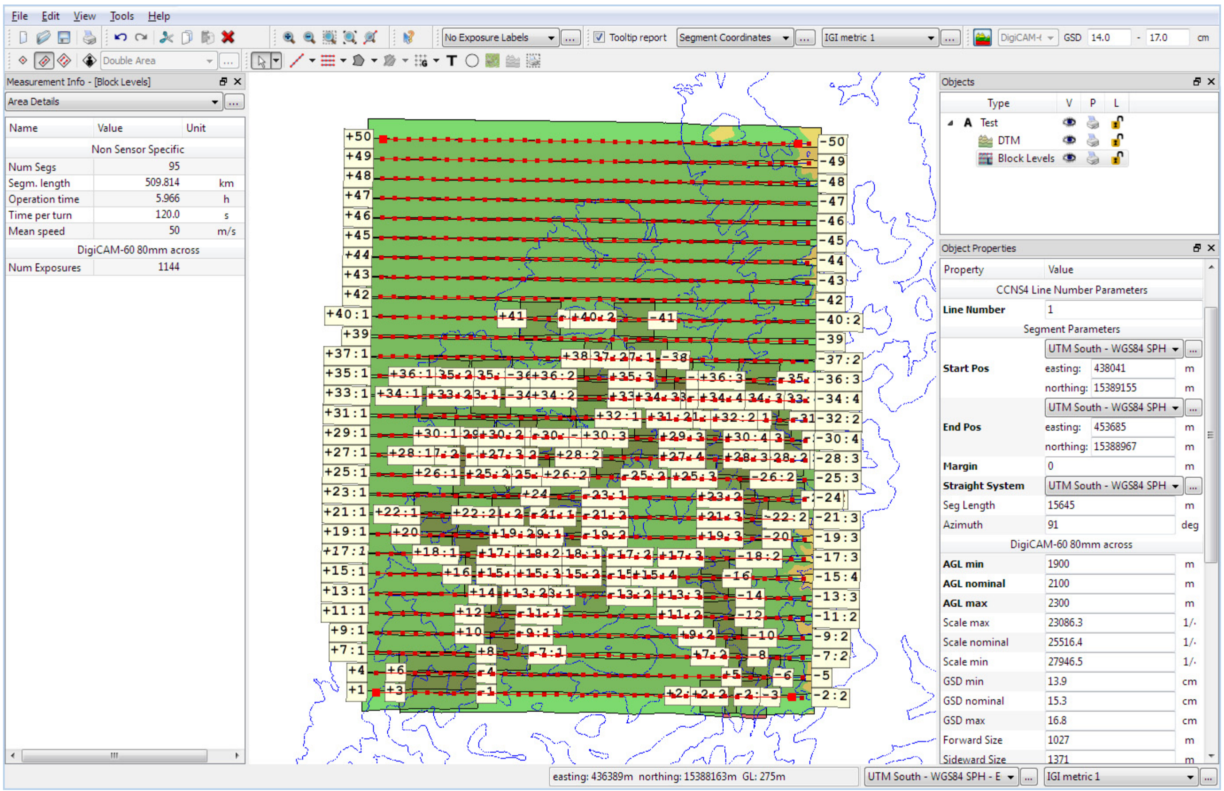


Figure 12: Screenshot of mission planning software *IGIplan* [6]. Block levels planning. Introduction of additional flight levels with constant absolute altitude to adapt to the change of ground level in terrain.

The next step is to split up the mission into areas of similar ground levels. To put most of the area into the acceptable GSD range, additional levels are introduced automatically. With this technique, the flying altitude is adapted to be constant in each line. This introduces new flight lines in new levels. Therefore the whole project area is in the acceptable range for the GSD (green).

Even though the levels of the area are flown one after the other, this approach introduces a lot of additional flying effort. The aircraft has to re-fly many lines in different altitudes. The work for the operator / pilot not to miss one of the lines in the different levels is not to be underestimated.

5.3. Adapt to Terrain by Contour Flying

If allowed in the project area, following the contour of the terrain has some significant advantages. The flying effort is the same as in the simple block. The GSD is adapted optimally. The project area is covered within the given GSD tolerance (green).

The coverage of the frames looks close to the pattern present in flat areas.

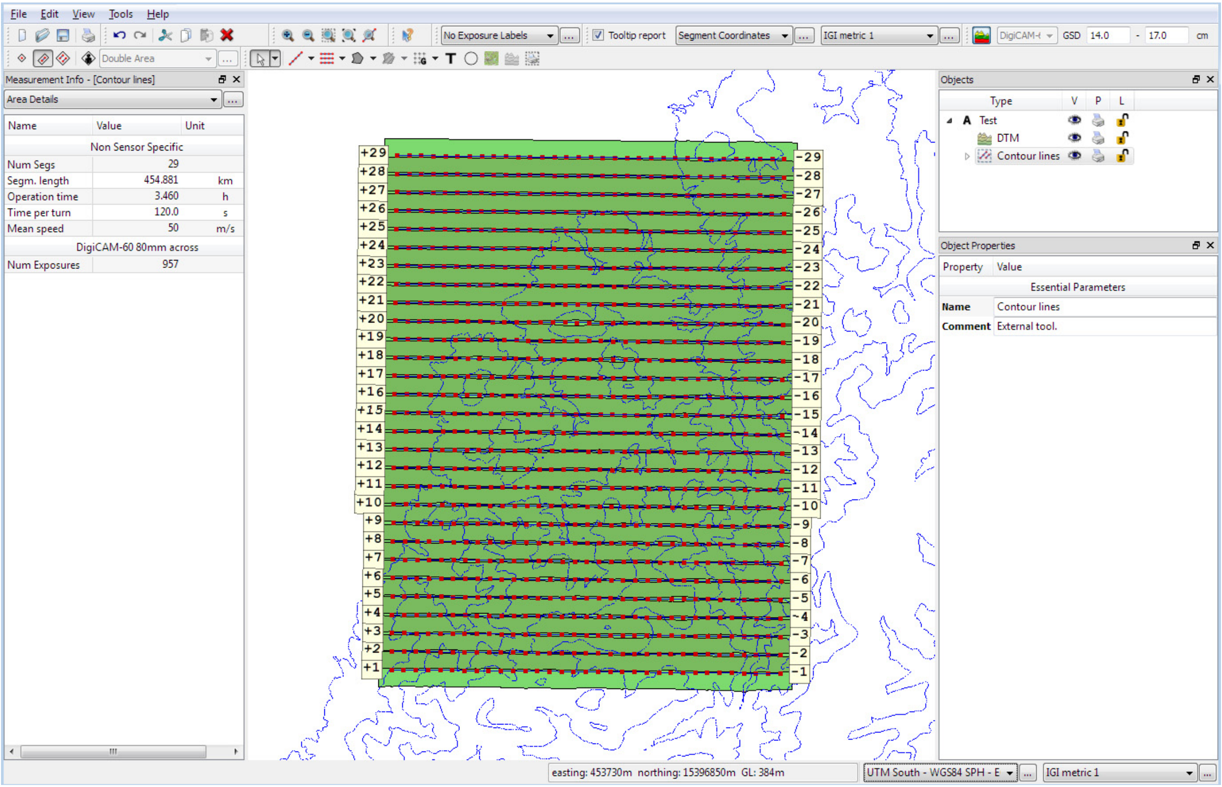


Figure 13: Screenshot of mission planning software *IGIplan* [6]. Contour flying planning. Aircraft altitude changes along the planned lines to keep within an acceptable range of AGL.

6. CONCLUSION

For high resolution aerial survey missions in low altitudes, the effect of the modulation of the underlying terrain on the quality of the final survey product introduces the desire to keep the aircraft's altitude above ground constant during the flight mission. Depending on the topography of the mission area, this contour flying can improve the efficiency of the data collection and the quality of the data production.

For some geophysical measurements, the measurement in constant altitude above ground is essential to maintain the necessary data quality.

The *CCNS-5* together with the *IGIplan* mission planning software provides tools to conduct efficient terrain following missions. Different graphical and alphanumeric info boxes give the pilot intuitive guidance information and the planning software includes the necessary tools to create flight plans for those missions. These improvements extend the well proven *CCNS* concept to the third dimension.

Although the *CCNS-5* provides the guidance to collect the optimal survey data, the practical applicability of this technique is mainly determined by practical safety constraints and by the local legal regulations.
Topics like the avoidance of solitary obstacles like chimneys or wind turbines, and the compliance with local legal regulations are not subject to a survey navigation system like the *CCNS-5*.

7. REFERENCES

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