LIGHT AIRBORNE PLATFORMS FOR MONITORING MINES AND MINERALS

L Ameglio[1,2], F Durufle[3], G Jacobs[2] and C Cavern[3]

1. MAusIMM, Managing Director, EXIGE, South Africa. Email: laurent@exigesa.com
2. GyroLAG, South Africa and Botswana.
3. ECA Group, France.

ABSTRACT

Airborne geophysics and geomatics is at a crossroads as to whether it remains a viable mapping tool, both technically and commercially, and broaden its potential for new applications (eg environmental monitoring, civil engineering and precision farming). The use of small and stable multisensor aerial platforms to conduct highly flexible surveys flown at a low/reasonable cost of operation is a recurrent wish of many stakeholders in the natural resources exploration and mining industry. Through its Fly Light Airborne Geophysics research program, EXIGE and partners have pushed the development and testing of two new airborne carriers with unique capabilities for geo-surveys: GyroLAG's gyrocopter and ECA Group's unmanned aerial vehicle (UAV). These carriers are the next generation of versatile and innovative aerial vehicles for remote sensing and monitoring. They are rotary, smart tailored, ultra-high resolution manned (gyrocopter) or autonomous (UAV) airborne platforms that combine the merits of dense data sampling, accurate position location, very low clearance above ground or sea level, slow speed, interchangeable and combined multiple geo-sensors, automatic data quality control and real-time quality assurance. They also have the benefits of being highly efficient, cost-effective, commercially attractive, safe, reliable and easy to deploy and operate. Their technical specifications and multiple advantages compared to traditional aircraft and/or ground crews are presented in this paper. An overview of various geo-sensors (magnetic, gamma-spectrometry, visual, near-infrared and LiDAR) carried on-board is also provided.

INTRODUCTION

Over the past 30 years, airborne geophysics and geomatics have become an effective and accepted technology for mapping various signatures on the Earth's surface and subsurface. Airborne geophysics has notably been recognised as a key contributor to grassroots regional and subregional natural resources exploration programs. However, its contribution to resource evaluation of minerals projects, new frontier areas, small concessions or targets and further downstream to mining operations and to site remediation, remains only subpractical for a number of reasons. These include:

- impractical character of traditional airborne geophysics
- cost ineffectiveness of traditional surveying aircraft and geo-sensors
- lack of truly integrated multisensor mapping solutions
- limitation of some geo-technologies
- user/mining industry unawareness of the availability and capabilities of new geo-technology
- lack of demonstrated tangible economic benefits to miners
- time and expertise required for data/image interpretation
- large gap between acquisition and interpretation of data (not real time)
- lack of real-time transformation of geophysical data into information useful for mining management
- cultural and economic impediments to the adoption of radical new technology by mining players
- effective size of investigated areas
- cost of repeat monitoring (4D) using traditional airborne solutions.

A recurrent wish of many stakeholders in the natural resources industry consists of using a small and stable multisensor aerial platform. This platform should also allow highly flexible surveys flown at a low/reasonable cost of operation. The success in the development of such an airborne geophysics/geomatics platform is based on the efficient and versatile integration of three main components: carriers, sensors and data. In this paper, we introduce the results of more than ten years of research and development, trials and commercial applications of two new light airborne carriers. A selection of their geo-sensors and mapping and imaging results is also presented.

NEW VERSATILE AIRBORNE SURVEY CARRIERS

Ultra-detailed airborne surveys are usually required for medium to small greenfield and brownfields exploration, operating mine sites and site remediation following mine closure. For example, they help define mineral targets, resource upgrades, sterilisation and the monitoring of tailings dams (eg fluid leakage) in a quantitative manner. This cannot be sufficiently achieved by either a manned helicopter (even less a fixed-wing aircraft) or ground crew. Both are of low effectiveness operationally and from a cost perspective. There is a missing link in the resolution of geophysical and geomatics mapping between regional/subregional traditional airborne surveys (from satellite to traditional aircraft platforms at hundreds of kilometres to 60–80 m above the ground/sea level respectively) and ground geophysics follow-up or detailed investigations.
Conventional wisdom dictates that when looking for an aerial observation or survey platform, either a rotary-wing or a small fixed-wing aircraft will be most suitable as

a carrier. However, it is worth pointing out that these aircraft types were not designed to do this in the first place, which means that they require a lot of adaptations and compromises. Furthermore, aviation has also gone through a revolution in recent years. The perception of aviation consisting of either expensive factory-produced aircraft or cheap and dicey backyard-produced microlight contraptions have been turned upside down. Today, there are a host of brand new factory- produced very light aircraft (VLA) and remotely piloted aircraft systems (RPAS) available. Some of these aircraft have proved themselves to be equal, and in some cases far superior, to their more expensive and aging heavy counterparts for geo- surveying. In the next sections, we present two new versatile airborne carriers: GyroLAG's VLA gyrocopter and ECA Group's RPAS.

GyroLAG gyrocopter

While the GyroLAG aircraft (Figure 1) may resemble well- known 'recreational' aeroplanes, under the skin it is a generation ahead, conforming to military specifications and commercial aviation certification. The platform is hereafter referred to as a gyroplane, gyrocopter or autogyro. The machine is designed and built in South Africa and is currently undergoing type certification under FAR 27. It is also operated under Part 96 of the South Africa Civil Aviation Authority and a traditional Part 135.
It is only natural that some confusion might exist between the helicopter and the gyrocopter because the appearance of the two machines is quite similar. The main difference is that the true autogyro never has any power applied to the rotor (Figure 2a) when the machine is in flight. It relies entirely on aerodynamic forces to keep the blades turning and provide lift. This situation is referred to as autorotation. Thrust from a propeller driven by an engine (either in the front (puller mode) or on the back (pusher mode); see example in Figure 1) moves the gyroplane forward (Figure 2b). When air flows over a wing (in this case the rotor blade), it creates low and high pressure areas (see Figure 2 insert). These areas generate lift, but a part of it also pulls the wing forward (Figure 2c and d). This causes the free-wheeling gyrocopter rotor to automatically rotate.

Autorotation can be sustained at a very low airspeed. Even with no forward airspeed, only a slight rate of descent is be required to sustain autorotation. In other words, a properly designed autogyro cannot 'just loose lift', contrary to a fixed- wing aircraft when confronted with a stall. The significance of this is the increased safety during very slow flight and the aerodynamic impossibility of a potentially deadly stall or spin at low altitude. This allows pilots to concentrate on flying rather than stressing over stall speeds and instrument readouts (although they must still fulfil their professional obligations in these respects).
Helicopters and fixed-wing aircraft have the advantage of being able to carry a

larger number of passengers over a longer distance faster. This makes them good as transporters, but less suitable or cost-effective as geo-survey carriers. While it carries fewer passengers, the gyrocopter, with its auto-rotating, flexing rotary-wing, is a much more stable and less demanding platform in adverse weather conditions. The simplicity of the design converts directly to a lower operating cost.

The GyroLAG gyroplane for geophysical operations originates from years of various designs and developments which details are presented in Ameglio *et al* (2009). The main technical characteristics of the GyroLAG autogyro presently used for airborne geophysics are presented in Table 1. The aircraft is also fitted with an integrated UHF and Bluetooth communications package, day and night glass cockpit, satellite tracking unit with real-time online tracking, a GPS precision navigation system (Agnav) with horizontal and vertical light bars for the pilot's survey guidance, laser and radar altimeters and a GPS receiver (Novatel).
The GyroLAG gyrocopter platform has now reached a level of manufacturing readiness so that mines can operate it themselves. It is made of the Trojan carrier, and standard and tailored geo-sensor packages are interchangeable between geophysics and geomatics missions. Special data processing and interpretation can be performed remotely at GyroLAG's data processing centre in South Africa or independently by mine staff or third-party specialists.

FIG 1 – GyroLAG South African gyroplane Trojan type with GyroLAG's FLAME (fluxgate airborne magnetics) gradient magnetic system. Inset: cockpit view with navigation computer (centre) and data acquisition pilot display (left).

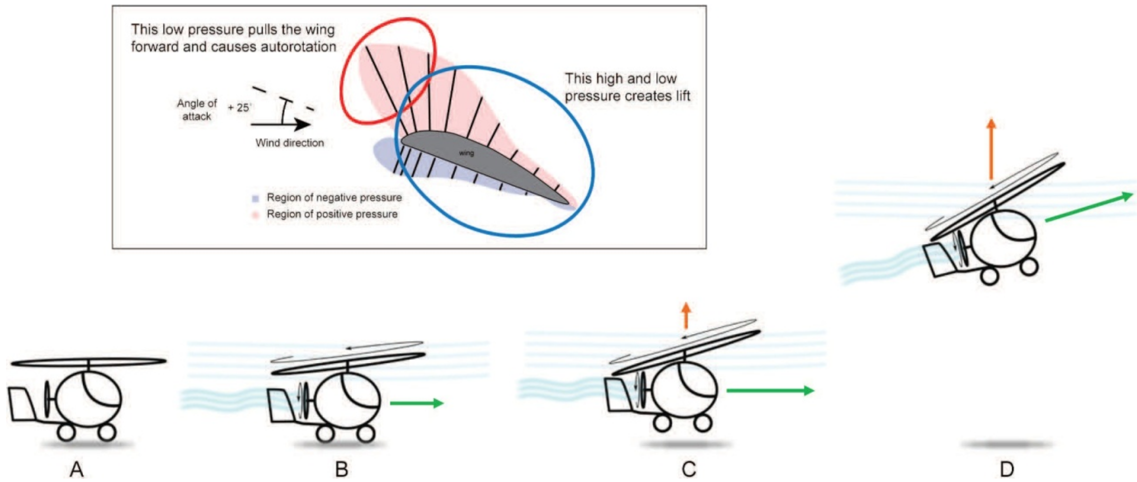


FIG 2 – Flying principles of a gyrocopter. (A) Standing still; (B) propeller generates forward motion (green arrow) and air flows over the rotor blade; (C) rotation generates lift (orange arrow) - see insert; (D) lift overcomes gravity. Insert - schematic of pressure distribution around a wing.

Number of seats		2
Endurance (h)		>4
Fuel consumption		24 (unleaded 95)
Aircraft range (km)		>400 (at average cruise
Engine type		Subaru 2.2 L
Tank capacity (L)		120 (+ 5 L reserve)
Speed (km/h)		50 to 150 (average 100
Landing distance		5 to 30 m
Speed (VNE) (km/h)		160
Size	Length (m)	4
	Width (m)	1.6
	Height (m)	2.6
Weight	MTOW (kg)	680
	Empty (kg)	400
	Useful (kg)	280

MTOW – maximum take-off weight. VNE - Velocity Never Exceed

TABLE 1 – Salient technical specifications of GyroLAG's Trojan gyrocopter.

ECA Group unmanned aircraft system

The recent deployment of RPASs (also interchangeably known as an unmanned aerial vehicle (UAV) or unmanned aircraft system (UAS)) for civil applications has increased significantly over the past few years. The development of such small (ie smaller than traditional aircraft) fully automated flying systems was mainly driven by technology miniaturisation and the decrease in size of integrated circuits. Micro- and mini-UAVs (as per classification from the European Association of Unmanned Vehicles Systems; see Table 2) have also been proposed for security missions such as surveillance or reconnaissance. This is the native market for RPAS. Moreover, this commercial technology is of a lower cost (both for purchase and operations) compared to traditional airborne carriers such as fixed-wing aircraft and helicopters. The use of mini-UAVs for the civil market was the next natural step in their development. Aerial photography and video are amongst the most widespread applications. However, most do not provide geo-referenced and gyro-stabilised images. They are also limited to carrying single sensors due to the low payload capability of most UAVs (usually much lower than 0.5 kg; see Table 2). The next application of UAVs is geophysical mapping with multiple sensors. However, this requires more effective range, endurance and payload capabilities of UAVs that fall in the close range (CR) category (see Table 2). The CR category is less versatile (ie it is heavier, bulkier etc) than mini-UAVs. A rare exception identified by EXIGE is the ECA Group' IT180 rotary machine. This UAV boasts excellent value for money and offers powerful and effective flying capabilities. This machine constitutes the present core of EXIGE's wingless autonomous survey probe research and development activities in UAV- borne geophysics and geomatics.

The IT180 (Figures 3a, 3b and 3c) is a vertical take-off and landing hybrid between the mini- and CR UAV categories (see Table 2). It has a take-off mass of less than 30 kg, which is characteristic of mini-UAVs, but a range of over 10 km, a flight altitude of up to 3000 m above sea level or 300 m above ground level (agl) and an endurance of up to two hours, which can only be achieved by CR UAVs. The technical specifications of the two key IT180 models for mineral exploration and mining operations are summarised in Table 3. The IT180 has a co-axial counter-rotating double rotor (1.8 m diameter) that provides a stable platform in strong winds and lower levels of rotor vibrations for geo-sensors. It is equipped with either a two- stroke 46 cm^3 engine running at 10 000 rev/min (with one or two fuel tanks) or a lithium polymer (or Lithium Ion) battery-powered brushless and gearless motor (10 000 rev/min, 0.5 h autonomy). The noise emission at 3 m agl is 95 dBA and 74 dBA for the petrol and the electrical models respectively. The maximum cruise speed is 80 km/h, reduced to a low of 30 km/h (or lower since the machine can hover) while on survey line.

The IT180 is capable of flying in extreme environments (desert, rain or snow) with the following flight performances: maximum constant wind speed of 50 km/h and a maximum wind gust of 60 km/h.

Both the electrical and petrol models carry full digital autopilot with rate gyro, differential GPS and acceleration, altitude, temperature, anti-collision and ground distance sensors. Common piloting features include altitude stabilisation, GPS position hold, automatic return to base, manual flight mode, instrument flight rules with real-time wireless video control and fully autonomous waypoint flight.

The ground control station (GCS) is embedded on a toughbook (Figure 3d) that allows for flight control, data analysis and mission planning using the touchscreen or the keyboard and a joystick for manual piloting or payload turret commands.

The intuitive graphical user interface provides easy and quick learning ergonomics (Figure 3d) for the main operations. The operator can control and manage the IT180 from up to 10 km (with tracking antenna) thanks to the video feedback display and cartography mission follow-up. The communication between the IT180 and the GCS is done via a set of modem transceivers embedded in the data link terminal (DLT; see Figure 3d) that are supported by omnidirectional antennas. The DLT is linked to the GCS trough a specific cable. The DLT is provided with a magnetic base allowing for quick set-up on top of vehicles.

Due to its architecture, the IT180 can embark payloads on its top and/or bottom side, which is a unique feature of UAVs.

The IT180 useful payload (ie excluding fuel or batteries) is 5 kg for the petrol model and 3 kg for the electrical model. Associated endurances are 30–50 minutes and up to two hours for the electrical and petrol models respectively.

The IT180 is packaged in dedicated ruggedised transportation boxes (Figure 3e). This results in a very small logistic footprint compared to regular helicopter UAVs of the same category due to its contra-rotating architecture with no tail rotor. This also further simplifies maintenance and reduces the cost of parts.

Unmanned aerial vehicle categories	Acronym	Range (km)	Flight altitude (m)	Endurance (h)	Take-off mass (kg)
Micro	Micro	<10	250	1	<5
Mini	Mini	<10	150 to 300	<2	<30
Close range	CR	10 to 30	3000	2–4	150
Short range	SR	30 to 70	3000	3–6	200

TABLE 2 - Main characteristics of selected unmanned aerial vehicle categories with possible geo-survey capabilities.

FIG 3 – IT180 remotely piloted aircraft system from manufacturer ECA Group. (A) Electrical model tethered during a real-time wireless video monitoring (security purpose) of a soccer game in France; (B) petrol model on a manual flight for visual inspection of a nuclear tower (France); (C) Nelson Mandela Metropolitan University and GyroLAG AGEO's (airborne geophysics observatory) petrol IT180 with two fluxgate magnetic sensors gradient system; (D) IT180 ground control station (GCS) (left), graphical user interface (right) and data link terminal (DLT) (bottom); (E) dedicated small footprint ruggedised transportation boxes – 25 kg, 1121 × 409 × 355 mm box for rotor blades, feet, DLT and GCS (top) and 25 kg, 673 × 673 × 642 mm for IT180 body (bottom).

		IT180-5TH (petrol model)	IT180-3TET (tethered model)
Endurance		Up to 120 min	Unlimited
Range		Up to 10 km (with tracking	Ground fixed
Deployment		<6 min	<10 min
Engine		2-stroke, 46	DC brushless
Fuel type		Synthetic	Li-po 26Ah
Fuel capacity		1.2 L + extra	N/A
Operating		-10°C up to +45°C	
Maximum		80 km/h	
Wind		Up to 60 km/h	
Noise		65 dBA (at 100	44 dBA (at 100
Maximum		3000 m (9000	Up to 150 m (length of
Size	Rotor	1.8 m	
	Feet	1.3 m	
	Height	75.5 cm	
Weig	MTOW	22 kg	18 kg
	Empty	14 kg	15 kg
	Useful	5 kg	3 kg

MTOW – maximum take-off weight; agl – above ground level.

TABLE 3 - Technical specifications of ECA Group' IT180 remotely piloted aircraft system.

SELECTED GEO-SENSORS AND APPLICATIONS

Geo-sensors allow the recording of meaningful information for the end product of any airborne geo-surveys. However, new sensing technologies and combinations of those technologies must be enhanced from the traditional off-the-shelf offers by manufacturers or traditional airborne geophysics service providers. Existing geophysical sensors are expensive, heavy, bulky, not necessarily fit-for-purpose (notably for mining operations) and rarely integrated (since they are produced by different manufacturers). This situation prevents easy-to-use multi-sensor application for the wide range of requirements during the life cycle of mine operations. A short selection and overview of geo-sensing hardware and/or applications in use on or developed for the two airborne platforms presented in the previous section of this paper is provided hereafter. These results come from years of ongoing testing and surveys performed by EXIGE, GyroLAG and their respective scientific and technical partners worldwide (ie the Earth Stewardship

Science Research Institute at Nelson Mandela Metropolitan University, South Africa; the University of Strasbourg and Ecole et Observatoire des Sciences de la Terre, France and Fraunhofer-FHR /Anwendungszentrum für multimodale und luftgestützte Sensorik (AMLS), Germany).

Geophysics – magnetic mapping (gyrocopter and remotely piloted aircraft system)

Magnetic data on GyroLAG's gyrocopter and the IT180 (within the framework of the Airborne Geophysics Observatory joint venture with the Nelson Mandela Metropolitan University in South Africa) platforms are collected using single or multiple (up to three) fluxgate vector magnetometers instead of the traditional Cesium magnetic sensor. As they are lightweight and have low power requirements, the fluxgate sensors allow for the development of affordable multi-sensor use without compromises on the data quality (despite the intrinsic lower manufacturing resolution of fluxgate sensors). This innovative method (Munschy and Ameglio, 2013) also has the advantage of compensating for permanent and induced magnetic fields generated by magnetised objects carried with the sensors (eg the aircraft). The main challenge in using fluxgate magnetometers arises from calibration errors and drift, but these are overcome using a quick and simple method of calibration in the field (using algorithms for satellite-based magnetic sensors corrections; see Munschy *et al,* 2007). Measurement accuracy is similar to that obtained with traditional scalar magnetometers (eg Cesium vapour sensors), particularly if one looks into the real source of magnetic noise in any airborne magnetic surveys being best estimated by the analysis of line and tie-line cross-over values more than the absolute accuracy of the sensors themselves.
A comparison of GyroLAG's magnetic mapping (on-board a gyrocopter) against traditional Cesium magnetic airborne mapping is presented in Figure 4. The two maps are similar and it is difficult to form an opinion about their respective qualities.
Another comparison of the fluxgate sensor magnetic airborne mapping (on-board a UAS this time) against traditional Cesium ground mapping is presented in Figure 5. Both maps show similar anomalies. However, theuav borne map displays a better spatial resolution.

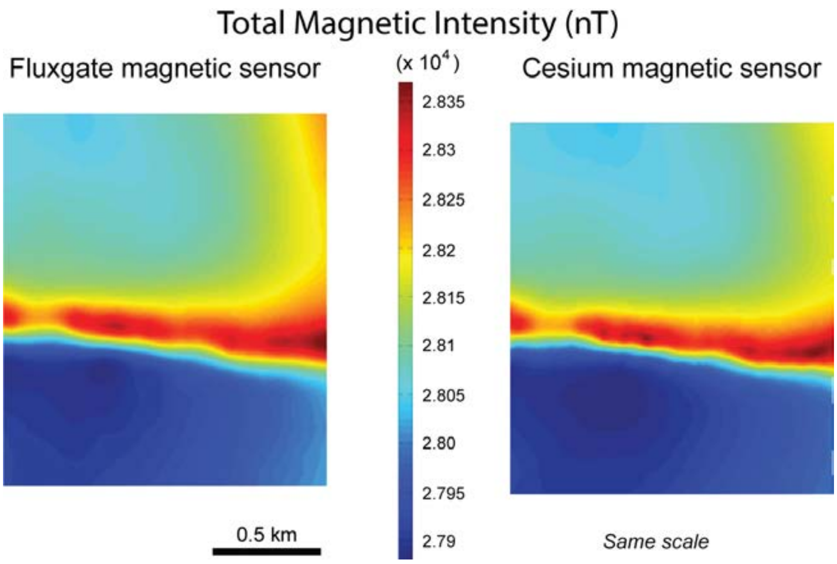


FIG 4 – GyroLAG fluxgate on-board a gyrocopter (left) versus traditional Cesium airborne magnetic mapping on-board a fixed-wing aircraft (right; data from South Africa Council of Geosciences).

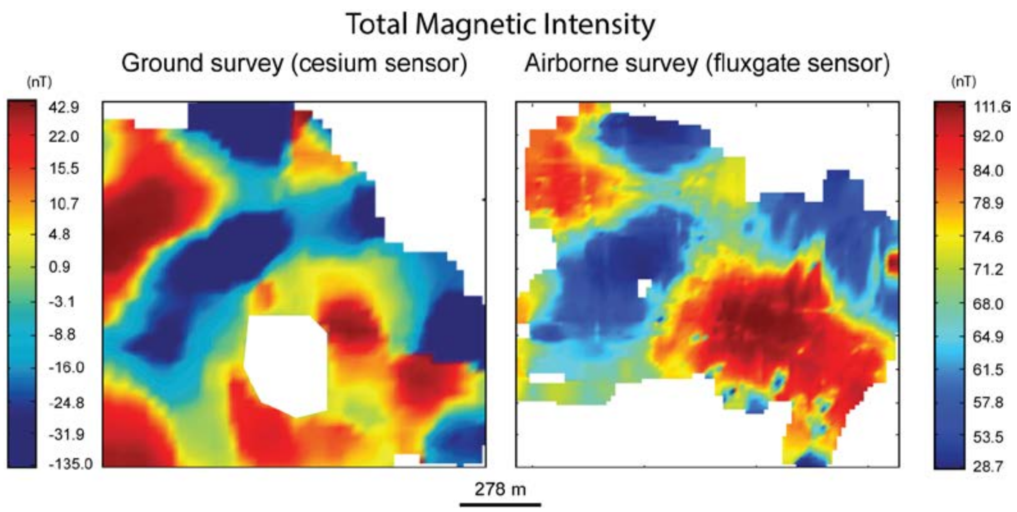


FIG 5 – Airborne fluxgate magnetic mapping (right) versus Cesium ground magnetic mapping (left) (after Bouiflane, 2008). Both maps cover the same area but the effective surface surveyed varied slightly.

Geomatics – VNIR, TIR, SWIR and LiDAR (gyrocopter and remotely piloted aircraft system)

Some of the geomatics sensors that have been used on the IT180 include:

- 10–14 megapixel (MP) digital still camera (fixed
- 35 or 50 mm and 20–70 mn vibration reduction zooms)

(Figure 5a)

- daylight colour video camera such as the Controp D-Stamp gyro-stabilised on two axis (resolution 752 × 582, zoom ×10, 48° to 5°) and the LWIR FLIR Photon 320 (resolution 324 × 256, fixed 35 mm lens, 36°)
- infrared video camera such as the Photon 320 long- wave infrared (LWIR)/forward looking infrared (FLIR) (resolution 324 × 256, fixed 19 mm lens, 36°).

LiDAR sensors for UASs are now available off-the-shelf but have not yet been tested on the IT180. However, LiDAR surveys are routinely performed on-board the gyrocopter, with some results displayed in Figures 6b and 6c. With respect to data resolution and accuracy, the following is routinely obtained at 40 knots (75 km/h) :

- point density of 3.1 and 1.5 point/m^2 at 100 and 200 m agl respectively
- pixel size of 6.4 cm and 12.8 cm at 100 and 200 m agl respectively
- actual/usable swath width of 160/100 and 320/200 m at 100 and 200 m agl respectively.

Accuracy can then be further improved using surveyed reference points on the ground. It is worth noting that similar accuracy might be achieved with the more casual and less expensive photogrametric technology. However, the multiple reflections of a laser beam from a LiDAR sensor will allow both the bare earth terrain model (DTM) and a surface model (DSM) to be produced with ease. Both DTM and DSM are of critical importance for natural resources exploration and production projects.

One of the latest developments on-board GyroLAG's gyrocopter, in collaboration with German partner Fraunhofer-FHR / AMLS, is a multi-camera set-up called PanX system (Figure 6d) that consists of up to five visible and near-infrared cameras (VIS-NIR) (Allied Vision Mako G-419B NIR) combined with a panchromatic model (Allied Vision Mako G-419B). Each NIR-enhanced camera is equipped with a custom-built filter in order to select the requested spectral bands. Each camera has a resolution of 4 MP. At a flying altitude of 300 m agl, the swath width is about 300 m with a ground resolution of 0.15 m per pixel. The acquired data sets of the sensors are fused to multi- channel images using the workflow by Weber *et al* (2015). The resulting images can be processed a lot easier with photogrammetric tools as the panchromatic channel is used for image alignment and processing. Ongoing development will allow for a thermal infrared (TIR) and short-wave infrared (SWIR) (up to 2500 nm) camera to be added to the PanX system.

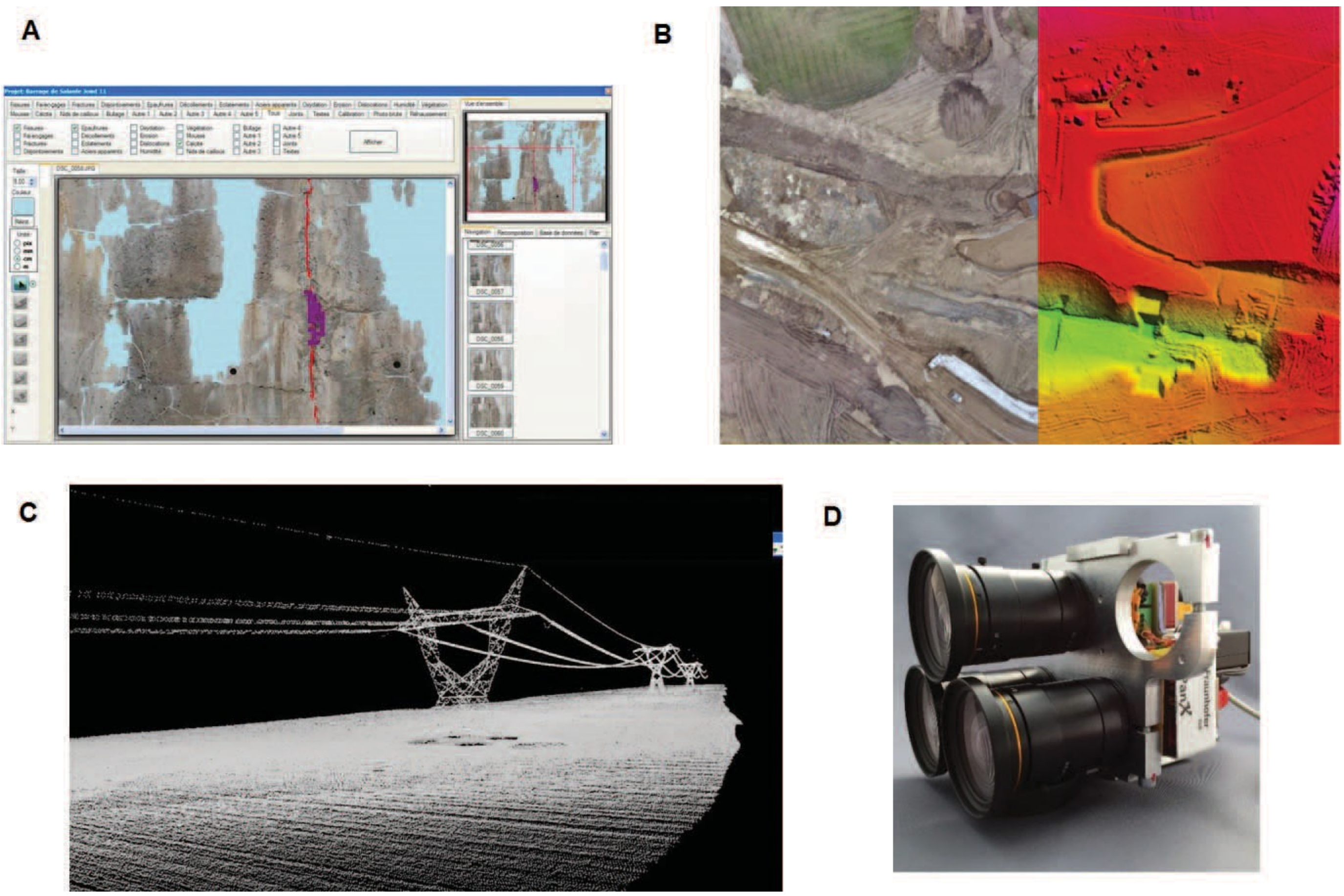
Geophysics – gamma-ray spectrometry (gyrocopter)

To reduce the large payload imposed by traditional NaI airborne gamma-ray spectrometers (GRS), GyroLAG selected Medusa's off-the-shelf novel equipment and methodology, which uses a much smaller detector made of CsI crystals and performs acquisition of the full spectrum. A comparison by Limburg *et al* (2011) of airborne acquisition performed on a fixed-wing aircraft (at 100 m agl) using a traditional 48 L NaI GRS and a Medusa 4 L CsI GRS is illustrated in Figure 7. Inspection of the maps demonstrate that overall geological structures are clearly visible in both data sets and that the maps for each of the elements (ie U, Th and K) are virtually similar. A detailed analysis of the strengths and weaknesses of the NaI and CsI systems can be found in Limburg *et al* (2011). This demonstrates that a smaller and lighter CsI GRS outperforms a larger and heavier (and also more expensive) traditional NaI GRS and provides almost similar efficiencies to a NaI GRS that is four times larger. This dispels the industry myth that 'the bigger and more expensive, the better' when it comes to airborne GRSs.

DISCUSSION

Light airborne platforms within the competitive landscape

As an airborne mobile carrier for geomatics and geophysical instruments for non-military applications, the VLA market is only emerging. It does so into a competitive landscape where airborne geophysics is at a crossroads as to whether it remains a viable mapping tool. In addition to other competitive aerial platforms, VLAs also face competition from space, terrestrial and maritime platforms. In the following sections, we discuss the unique advantages of the two new airborne carriers presented in this paper and their respective competitive edges for geo-surveys compared to traditional aircraft and terrestrial platforms.



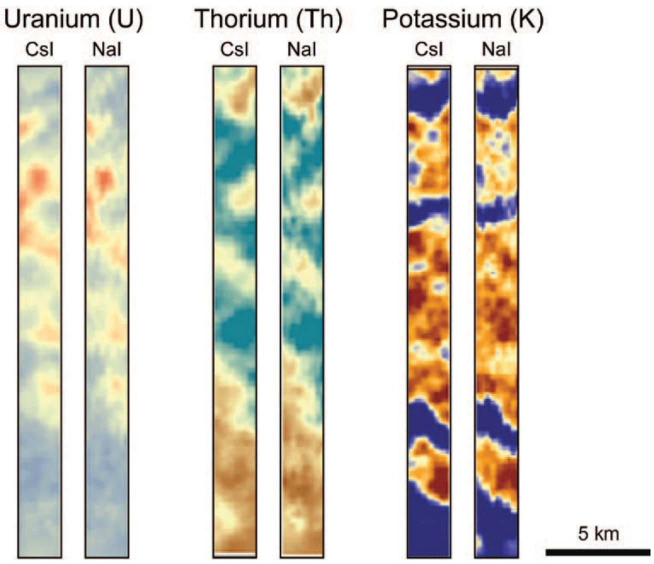


FIG 6 – Selected hardware and images acquired on gyrocopter and IT180. (A) Image analysis of infrastructure defects by Helios (Infotron's project partner) using unmanned aerial vehicle-acquired vertical ortho-photos over a cement dam wall; (B) ortho-photo (left) and bare earth terrain model/surface model of classified point cloud LiDAR data set over an opencast operation in Europe (from GyroLAG's partner Laser Survey in Scandinavia); (C) unclassified 3D point cloud over a power line acquired on board GyroLAG gyrocopter; (D) FHR/AMLS PanX system.

FIG 7 – Maps of interpolated (kriging) 238U, 232Th and 40K data from Medusa (left) CsI (4 L crystal) versus traditional (right) NaI
(48 L crystal) gamma-ray spectrometer (after Limburg *et al*, 2011).

Gyrocopter advantages over traditional aircraft for geo-surveys

Autogyros were very important in the development of the helicopter. Many technologies essential for practical helicopters were first developed for the autogyro. The first gyrocopter was indeed designed 20 years before the first helicopter ever flew (Lewis, 2002). The gyrocopter was designed specifically to be safe at slow speeds and at low levels of flying, which are the critical components of airborne geophysical surveying to acquire the best data resolution. The helicopter was designed as a troop and material transporter instead.
Gyrocopters actually have a great safety record mechanically. The pilots, however,

cannot claim the same safety record. This is the reason why gyrocopters have never been widely accepted by the public or industry. Gyrocopter pilots are usually recreational pilots and only need to hold a sport-pilot license. Therefore, it is no surprise that the vast majority of gyro accidents are related to pilot error, including hitting wires, hitting trees, landing too fast or trying to take off too short. As a result, gyroplanes have suffered an unjustified perception of being unsafe machines. All GyroLAG pilots are commercially rated, gyrocopter proficient and receive extensive training in low-level operations. With over 8000 hours accident-free on operation with various gyrocopter types, this approach has proved to be the right way forward.

From an engineering and aerodynamic perspective, because the gyrocopter is in permanent autorotation, it cannot 'just loose lift', contrary to other aircraft when confronted with a stall (as with a fixed-wing aircraft) or when the motor powering the rotor loses power (as in a helicopter). The significance of this is the increased safety during very slow flight and the aerodynamic impossibility of a potentially deadly stall or spin at low altitude. Aerodynamically stable gyroplane designs are also much safer in turbulent winds. As landings are typically made at very slow airspeeds, they can be made safely in very short distances (less than 50 m). A gyrocopter is also a much less mechanically complicated machine than a helicopter or fixed-wing aircraft. With new gyrocopter designs like the GyroLAG, which has been specifically designed for airborne geo-surveys, the gyroplane is here to claim its share of the sky in the mining and mineral exploration industry.

A few other advantages of using gyrocopters for geo-survey applications include:

- ideal for following close terrain for better data resolution
- very manoeuvrable in the air
- single pilot operation
- large view from front seat/open cockpit
- very low kit prices compared to aeroplanes/helicopters
- low fuel (unleaded) costs
- low maintenance costs compared to aeroplanes/helicopters
- the gyroplane can be taken to the survey site on a small trailer
- in an emergency, the gyroplane can land on a 15 m square spot
- easy to operate and cost-effective (ie at or lower than the cost of a fixed-wing aircraft with the resolution of a helicopter)
- lower carbon footprint, with a consumption of only 24 L/h of unleaded petrol (ie five to ten times lower than traditional airborne platforms for geo-surveys)
- lower ground clearances (5 to 20 m) than what is commonly used in the airborne geophysics industry (25 m agl for helicopters and 60 to 100 m agl for fixed-wing), resulting in a significant improvement in data resolution
- slower survey speed (75 to 120 km/h), improving sampling footprint.

IT180 *advantages for geo-surveys and mining operations*

The two key advantages of the petrol model of the IT180 UAV compared to other UAVs in the same category are its endurance of up to two hours flying and its payload capability of up to 5 kg. The IT180 also offers a number of other advantages for geophysical and geomatics applications in the mining industry. Some of those advantages are:

- field proven (already in use in Panama, France, Russia, Finland, Thailand, United Arab Emirates and South Africa), with a total of over 1000 flying hours (excluding military use) in many weather conditions (wind, rain, snow, sand/dust and heat)
- already used by governmental institutions (eg the Engineering Unit of the French Army and counter terrorism units in Thailand) and also by civil companies such as EDF (electricity provider) and SNCF (railway company) in France
- longest endurance, with the electrical version capable of flying up to 50 minutes and the petrol model up to two hours
- in tethered mode (electrical model), autonomy is unlimited since the UAV is permanently powered from the ground and stability is further increased for monitoring and remote sensing tasks
- environmentally friendly, with very low noise emissions

(only 42 dBA at 100 m agl for the electrical model)

- multiple payload capability, widening the spectrum of achievable missions (see previous section of the paper)
- payload capability of 3 kg for the electrical model and 5 kg for the petrol model, which is significantly higher than the less than 0.5 kg of many other UAVs in the same mini- UAV category (see Table 2)
- dual-mount configuration of payloads fastened on the bottom and/or top of the machine, enabling multiple missions and flights with different payload types to acquire different types of data
- range of up to 10 km with a tracking antenna, which can be further enhanced by the mobile capability of the GCS (see Figure 3d) when carried on naval or terrestrial vehicles
- high stability due to its unique co-axial counter rotating architecture, which allows the machine to withstand wind speeds of up to 60 km/h (17 m/s)
- quick and simple deployment in a maximum of six minutes
- ease of use, with many integrated automatic functions and touch-to-fly operator touchscreen interface for fully autonomous operation.

With over 70 per cent of mine operations worldwide being open pit (Magnus and Hodge, 2012), mining is very much an open surface business. Safer mine monitoring can then only benefit from the capabilities of VLAs. This is particularly true for tethered hovering UAVs such as the IT180-3TET model (see Table 3). Propelled by an electrical generator situated on the ground and connected to the carrier by a communication cable (see Figure 3a), the advantage of the tethered IT180 is its capability to fly for an unlimited period of time. It can be operated to complete permanent surveillance and monitoring missions over the entire mine operations and/or can be used as a radio communication relay. With its small and compact ground system unit, it can be deployed from different manned or unmanned platforms such as maritime vessels or ground vehicles. Another critical advantage of a tethered UAV is that it is considered in a special category by civil aviation authorities. For example, in France, tethered UAVs are enabled to fly in urban areas, which is not possible with non-tethered models.

Unmanned aerial vehicles versus traditional aircraft and terrestrial vehicles

UAVs have several competitive advantages over traditional airborne carriers such as aircraft and helicopters. The most significant is economics, with the cost of a UAV mission for imaging often being a tenth of that of an aircraft or helicopter mission. They also have advantages in dangerous and hazardous tasks, where the removal of the pilot from the carrier is very desirable. However, the UAV is a less mature airborne technology when it comes to operational effectiveness. Furthermore, civilian aviation regulatory constraints (eg not allowing a UAV to fly beyond line of sight (BLOS) in an airspace shared with manned aircraft or over populated areas) and the limited autonomy and range of UAVs mean that they are competitors to ground platforms instead. UAV-borne geo-surveys performed by the authors displayed an effectiveness improvement ratio of 8–9 in survey time and 12 in operational costs compared to ground crew operations. As shown in Figure 5, magnetic results acquired by a UAV are also comparable, and to some extent better (eg spatial distribution) than those provided by ground crew surveys.

Role of space-borne carriers

Satellite-based Earth observation instrumentation and resolution is developing rapidly. It is frequently perceived as a competitive challenge to VLAs both in terms of capability and scale of deployment. This technology may be possible in the near future, particularly for climate change and civil security monitoring. However, effective satellite applications for natural resources exploration and mine operations is hampered by limitations such as:

- spatial coverage in swathes and often not geographically complete
- temporal coverage, where observation is in predetermined orbits and also limited by night-time (imaging) and cloud cover
- data resolution (x/y axes) from 100 m to kilometre scale is only adequate at a regional scale
- data resolution (z axes), with satellite sensitivity becoming more limited as the atmosphere thickens towards the surface of the Earth.

When comparing these strengths and weaknesses with those of RPAS and gyrocopters (see previous sections), capabilities turn out to be very complementary, creating opportunities for many applications and products that utilise both technologies.

Cost estimates and effectiveness

It is always difficult to make a general estimate of the cost of conducting airborne surveys. This is because cost is influenced by many parameters, including type of target, type of carrier used, survey flight tolerances, expected data resolution, fuel cost, survey geographic location, time frame constraints, number of geo-sensing technologies on-board the carrier, size of the survey, distance from carrier base to survey area, operator business model and commercial strategies. However, analysis of press releases in the mineral exploration industry will set the cost of airborne surveys at somewhere between US$10/km and US$200/km (or much more in very remote conditions). For comparison, a seismic survey will cost around US$1500/km and a non-seismic (eg magnetic or gravity) ground survey approximately US$55–95/km. Of course, the geophysical information yielded by the airborne and ground surveys is very different. The data resolution is usually better when using ground crews. However, the VLA platforms are bridging the gap between airborne and ground-based surveys (at least for some of the non-seismic technologies).

Comparative ratios might prove to be a better illustration of the cost effectiveness of VLA platforms. For similar geo- technology sensors (eg magnetic and gamma spectrometric), a helicopter-borne survey will cost two to four times that of a fixed-wing survey. A gyrocopter-borne survey (Figure 1) provides a helicopter-borne survey/resolution at the cost, or lower, of a fixed-wing survey. A similar comparison will apply to a UAV-borne survey with a carrier in the mini category (see Table 3). The initial purchase price of a mini- UAV is, however, 1.5 to two times the price of a gyrocopter. The UAV is also a far less mature technology when it comes to operational effectiveness. Furthermore, aviation regulations don't allow UAVs to fly BLOS in an airspace shared with manned aircraft. The limited autonomy and range of UAVs makes them a competitor to a ground platform (man or vehicle). UAV-borne surveys performed by the authors displayed an effectiveness improvement ratio of 8 to 12 in survey time and operational costs respectively when compared to ground crew operations.

CONCLUSIONS

Ultra-high resolution airborne imaging of the textural, geological and geochemical characteristics of the ground and infrastructure is a recurrent wish of stakeholders in the natural resources sector. This wish cannot be met by conventional airborne hardware, which is too expensive and unpractical. Little to almost no research and applications have been performed to allow highly flexible and operationally reliable airborne geomatics and geophysical surveys to be flown at a low/reasonable cost. By utilising tried and tested technologies and in-house and collaborative developments in the domains where it is most needed (ie carriers and geo- sensors), the GyroLAG gyrocopter and ECA Group UAS now provide the industry with unique, inexpensive and practical platforms.

However, the carrier in any airborne platform remains only a means to an end. The geo-sensor is the main hardware component that will allow the recording of meaningful data. Due to the intrinsic limitation of light airborne vehicles such as gyrocopters or UAVs (ie payload and autonomy), specific geo-sensors have also been developed by GyroLAG and its partners and integrated into the new carriers. Sensors include magnetic, gamma-spectrometry, ortho-photo, VNIR and TIR applications, and an SWIR camera is under development.

Gyrocopters (and also UASs) are not intended to take over all the tasks of manned aircraft. They mark a departure from conventional fixed-wing or rotary aircraft and provide a solution to fill a role that traditional aeroplanes cannot due to the safety risks and excessive costs involved. In particular, the gyrocopter bridges the gap between traditional airborne and ground survey resolutions. In the same way, UASs are not intended to completely replace ground crews. Instead, they can fly close enough to the ground, cover faster and homogeneously small survey areas and reach inaccessible spots that cannot be done by walking ground crews, particularly in rugged and/or hazardous areas.

With the advent of such versatile carriers and geo-sensors, EXIGE and partners are now also turning their attention to the data component of the airborne platforms. The focus is to turn data into more valuable information. In a raw form, airborne geophysics information is still highly complex and unintelligible to all but a few specialists. Geophysicists need to create information that is more relevant and suitable for business decisions by the mining industry. This means going beyond amplitude and structure maps. It will require embracing and integrating new processes such as, to quote a few, real-time automatic airborne data quality control, autonomous map generation on-board the airborne carrier and data visualisation using the computer gaming virtual reality technology.

ACKNOWLEDGEMENTS

GyroLAG wishes to thank its crew and representatives for their dedicated contributions through the years developing and promoting the gyrocopter platform for geophysics and remote sensing applications. GyroLAG also wishes to acknowledge its research partners worldwide: ESSRI at Nelson Mandela Metropolitan University (South Africa), UNISTRA and EOST (France) and Fraunhofer-FHR/AMLS (Germany).

REFERENCES

Ameglio, L, Jacobs, G, de Cabissole, B and von Ludwig, J, 2009. GyroLAG: versatile multi-sensor airborne geophysics platform, presented to 11th SAGA Biennial Technical Meeting and Exhibition 2009, Swaziland, 11–18 September.

Bouiflane, M, 2008. Aeromagnetic and magnetic multi-scale mapping: structural study in an area of Rhine graben, PhD thesis, Institut de Physique du Globe de Strasbourg, France, 206 p.

Lewis, J, 2002. Autogyro history and theory [online]. Available from:

<http://jefflewis.net/autogyros.html> [Accessed: 11 September 2015].
Limburg, J, Ibs-von Seht, M, Barrie, C, Tijs, G, Koomans, R L, Siemon, B and van der Graaf, E, 2011. Benchmarking a small footprint detector system for airborne surveying [online]. Available from:
<http://www.medusa-systems.com>.
Magnus, E and Hodge, A, 2012. Trends in the mining and metals industries, in *Mining's Contribution to Sustainable Development*, 16 p (International Council on Mining and Metals: London).
Munschy, M and Ameglio, L, 2013. Airborne vector magnetic field measurements from fluxgate sensors, presented to 13th SAGA Biennial Technical Meeting and Exhibition 2013, South Africa, 7–9 October.
Munschy, M, Boulanger, D, Ulrich, P and Bouiflane, M, 2007. Magnetic mapping for the detection and characterization of UXO: use of multi-sensor fluxgate 3-axis magnetometers and methods of interpretation, *Journal of Applied Geophysics*, 61:168–183.
Weber, I, Jenal, A, Kneer, C and Bongartz, J, 2015. PanTIR – a dual camera setup for precise georeferencing and mosaicing of thermal aerial images, in *Proceedings Workshop of Photogrammetric Image Analysis*, pp 269–272 (International Society for Photogrammetry and Remote Sensing: Hannover).