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Small unmanned aerial vehicles for aeromagnetic surveys and their flights in the South Shetland Islands, Antarctica

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Abstract

We developed small computer-controlled unmanned aerial vehicles (UAVs, Ant-Plane) using parts and technology designed for model airplanes. These UAVs have a maximum flight range of 300—500 km. We planned aeromagnetic and aerial photographic surveys using the UAVs around Bransfield Basin, Antarctica, beginning from King George Island. However, we were unable to complete these flights due to unsuitable weather conditions and flight restrictions. Successful flights were subsequently conducted from Livingston Island to Deception Island in December 2011. This flight covered 302.4 km in 3:07:08, providing aeromagnetic and aerial photographic data from an altitude of 780 m over an area of 9 × 18 km around the northern region of Deception Island. The resulting magnetic anomaly map of Deception Island displayed higher resolution than the marine anomaly maps published already. The flight to South Bay in Livingston Island successfully captured aerial photographs that could be used for assessment of glacial and sea-ice conditions. It is unclear whether the cost-effectiveness of the airborne survey by UAV is superior to that of manned flight. Nonetheless, Ant-Plane 6-3 proved to be highly cost-effective for the Deception Island flight, considering the long downtime of the airplane in the Antarctic storm zone.

Keywords: UAV; Ant-Plane; Deception Island; Autonomous flight; Aeromagnetic survey

1. Introduction

In May 2000, the accuracy of global positioning systems (GPS) was improved horizontally from 100 m to approximately 10 m. Moreover, the reliability of computer and electronic devices increased, accompanied by a decrease in size, weight, and power consumption. These improvements have enabled small autonomous unmanned aerial vehicles (UAVs), controlled by computers and GPS, to be developed by researchers, companies, and amateur model airplane

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groups. The National Institute of Polar Research (NIPR) in Tokyo, in collaboration with Kyushu University (Fukuoka, Japan), private companies, and model airplane amateurs, started the Ant-Plane project to develop a UAV (Ant-Plane) for Antarctic research. The aims of this project were as follows.

(1) Develop a UAV to fly in coastal Antarctica during the summer season under calm weather conditions (wind speed < 7 m/s, temperature > −15 °C).
(2) Construct the Ant-Plane from model airplane parts, with a wingspan of less than 3 m.
(3) Complete a long-distance flight of more than 1000 km.
(4) Operate the Ant-Plane without the use of professional pilots or mechanics.
(5) Develop onboard scientific instruments, including magnetometers, meteorological devices, and cameras.

Funaki et al. (2006, 2008) listed the following benefits of the Ant-Plane.

1) It provides a safe and economical method for conducting airborne surveys.
2) In comparison with manned aircraft, it releases minimal environmental pollution.
3) Long-distance surveys can be completed from high altitude.
4) The Ant-Plane is relatively easy to transport to Antarctica because it is small and light.
5) Flights can be made over high-risk areas (e.g., crevasses and active volcanoes) without danger to personnel.
6) There are few legal restrictions for flying a UAV in Japan because it is classified as a model airplane. Civil Aviation Safety Authority (CASA) permission is only required for flights lower than 250 or 150 m altitude in Japan. However, the International Civil Aviation Organization (ICAO) has increased the restrictions on flying UAVs.
7) It is not necessary to submit flight plans to the CASA before conducting surveys, in Japan.
8) There are no restrictions on the length of flights, the scheduling of mechanical maintenance, or pilot training programs, in Japan.
9) The UAV can be operated by any member of an Antarctic expedition, and does not require a qualified pilot.
10) UAVs can be operated without radio control.
11) When surveying in high-risk areas, operations can be completed with a single UAV.
12) Takeoff and landing can be completed easily in challenging conditions (e.g., on short runways or snow fields) using a catapult, parachute, or net.

The following Ant-Plane flights have been completed in Japan: a 100 km flight with a magnetometer and a video camera above Sakurajima Volcano in Kagoshima Prefecture in 2003; a high-altitude flight to 5700 m with meteorological devices over Monbetsu City, Hokkaido, in 2005; and a 1108 km flight around the Goto Islands, Nagasaki Prefecture, in 2007. In 2006, Ant-Plane conducted an aeromagnetic survey along 500 km of survey lines in a 10 × 10 km area around Kalgoorlie, Western Australia. This produced a map of magnetic anomalies measured at altitude of 900 m.

Furthermore, the Japanese Antarctic Research Expedition (JARE) has completed the following flights from Syowa Station, Lützow-Holm Bay, East Antarctica.

1) The JARE 46th winter party planned an aeromagnetic survey using Ant-Plane 2-2 for January 2006, launching from a runway of sea ice. This was a tractor-type plane weighing 15 kg with a wingspan of 2.0 m and with an 86 cc gasoline engine. The intended maximum flight time was 1 h at a speed of 36.1 m/s (130 km/h); however, the flight failed because of wing damage sustained during taxiing on the rough sea-ice surface.
2) The JARE 48th summer party conducted meteorological research (measuring temperature, humidity, and concentration and size of aerosols) using an autonomous unmanned kite plane over a continental glacier near Syowa Station, in January 2007. The flight collected the data at altitudes between 300 and 1200 m. The plane had a wingspan of 2.3 m and an 80 cc gasoline engine, and flew for 2 h at speeds of 10–15.3 m/s (36–55 km/h, Hirasawa and Hara, 2007). Subsequently, Ant-Plane 4-2 flew over the same area but crashed after stalling, which was caused by an error in the registration of waypoints (WP; points on the flight route consisting of latitude, longitude, altitude, and speed). Ant-Plane 4-2 was a pusher-type plane with a tail propeller, an 86 cc gasoline engine, and a maximum range of 500 km in 5 h.
3) The JARE 49th winter party conducted meteorological research using Ant-Plane 4-3 over sea ice near Syowa Station. The plane flew for 1 h in a 1.5 × 1.5 km area at altitudes of 200, 400, 600, 800, and 1000 m in December 2008, and

successfully obtained data. However, Ant-Plane 4-4, equipped with meteorological devices and a magnetometer, crashed because of engine problems. Ant-Planes 4-3 and 4-4 were of the same construction as Ant-Plane 4-2.

In August 2007 a UAV developed by the British Antarctic Survey and the University of Braunschweig (Germany) was used for meteorological research at Halley Station, South Weddell Sea, Antarctica. The UAV (mini-UAV M2AV) flew 45 km in 40 min with a maximum altitude of 230 m. This plane was electric-motor driven, had a 2 m wingspan, and weighed 6 kg (BAS Press Releases, Issue date: 18 Mar 2008, No. 09/2008; BAS Press Releases, Issue date: 18 Mar, 2008, Number: 09/2008, http://www.antarctica.ac.uk/press/press_releases/press_release.php?id=352, Spiess et al., 2007). In September 2009, Aerosonde UAVs (Aerosonde Ltd; Australia, developed by the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration, USA) flew for 17 h in temperatures of −26 °C between McMurdo Station and Terra Nova Bay to survey katabatic wind and polynya (areas of open water surrounded by sea ice) (http://icestories.exploratorium.edu/dispatches/terra-nova-bay-or-bust/).

The Bransfield Strait is an interesting target for aeromagnetic research because there is poor coverage of high-resolution magnetic anomaly data in this region, despite its importance in terms of understanding the Mesozoic−Cenozoic tectonic evolution of the Antarctic Peninsula, and in particular understanding the processes of back-arc basin formation and evolution (Catalán et al., 2013). The flight range of Ant-Plane covers the width of the strait (about 100 km). The strait was formed by the separation of the South Shetland Islands from the Antarctic Peninsula, resulting from subduction of the Phoenix Plate (part of the Pacific Plate) beneath the Antarctic Plate (Fig. 1). The strait was actively formed from 200 to 4 Ma, based on evidence of the movement of the South American and Antarctic plates (Tanner et al., 1982; Barker and Dalziel, 1983; Pankhurst, 1983; Barker and Austin, 1994; Catalán et al., 2013). GPS data suggest that the South Shetland Islands are currently moving at a rate of 15−20 mm/yr to the NE relative to the Antarctic Peninsula (Dietrich et al., 2001). Intense volcanic activity has been reported along the spreading ridge in Bransfield Basin (Dziak et al., 2007). The pronounced positive alignment of the magnetic anomaly with a short wavelength and high amplitude reported by Kim et al. (1992) in the central Bransfield Basin

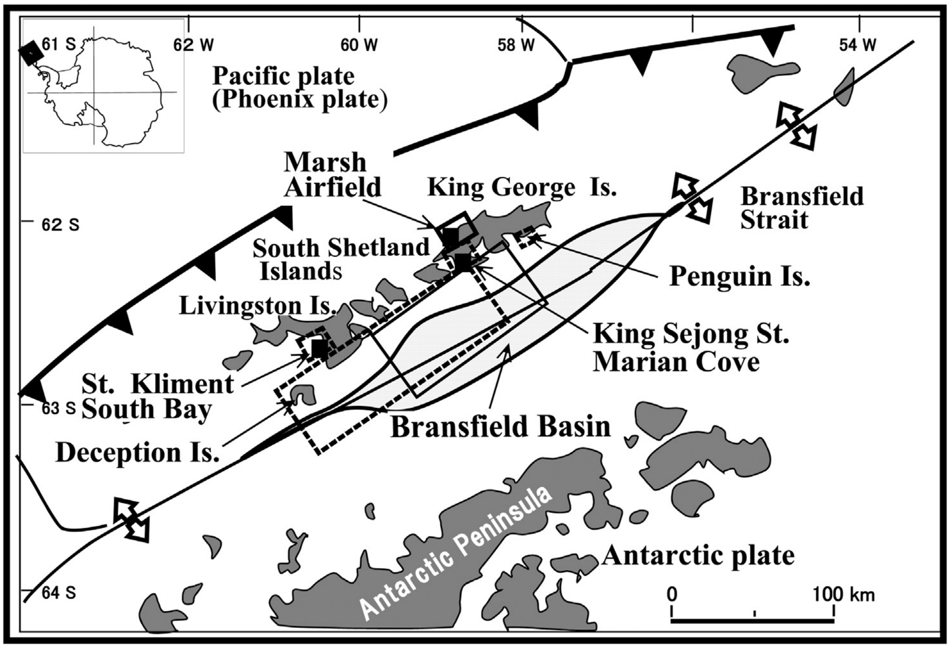

Fig. 1. Map of Bransfield Basin showing the plate boundary located between the South Shetland Islands and the Antarctic Peninsula (modified from Lawver et al., 1995 and Gracia et al., 1996). Solid squares indicate survey areas in January 2011, and dotted squares indicate survey areas from December 2011 to January 2012. Line with teeth: subduction zone located between the Pacific Plate (Phoenix Plate) and the Antarctic Plate. Line with white arrows: spreading ridge in the Bransfield Basin.

corresponded with the spreading ridge in many cases. However, the largest anomaly, recorded as more than 500 nT by Kim et al. (1992) and 1000 nT by Muñoz-Martín et al. (2005), observed around Deception Island was inconsistent with the ridge, because the island is located outside of Bransfield Basin. Catalán et al. (2013) proposed a model of the subsurface structure of the Bransfield Strait comprising a thin (1.5 km) and shallow (4 km b.s.l.) layer with a low total magnetization (2.6 A/m), as derived from seaborne magnetic and gravity data.

Deception Island (62°58′37″S, 60°39′00″W) is located between the spreading ridge in Bransfield Basin and Livingston Island (Fig. 1). The island is almost circular and has a diameter of 12 km; however, the eastern margin of the island is sub-linear. The island features a caldera in the center (Port Foster) measuring 9 × 6 km, and reaches its highest altitude at Mount Pond (539 m). A zone of high electrical conductivity, most likely associated with a fault, has been identified on the SE side of the island at 2–10 km depth, trending ENE–WSW (Pedrera et al., 2011). Lawver et al. (1995) detected the magnetic anomaly during a marine magnetic survey around Deception Island. The results revealed a strong negative anomaly to the north of the island trending ENE–WSW and a similar anomaly trending NW–SE around Port Foster. Positive anomalies were present offshore to the east of the island and on the west side of Port Foster. However, magnetic anomalies have not been reported from Deception Island itself. Therefore, to add to our understanding of the formation and evolution of the Bransfield Basin, an aeromagnetic survey was planned for the austral summers of 2010–2011 and 2011–2012.

2. Ant-Plane UAVs

Ant-Plane 6-3 is a pusher-type UAV with a 1 m aluminum pipe attached to the nose to hold a stinger magnetometer, as shown in Fig. 2a. The frame is 2100 mm long with a wingspan of 2890 mm (Fig. 3a). The control system and fuel tank are located inside the body, and scientific devices are stowed in the nose. The dry weight of the plane is 20 kg, rising to 28 kg with the addition of 10 l of gasoline (Table 1). The aircraft consists of the body, nose, main wings, vertical tail wings with booms, and a horizontal tail wing, and can be disassembled for transport and reassembled in the field. The propeller (reverse pitch, 24/10 l) and generator (25 W) are connected to a Fuji-Imvac BT-86 two-cycle flat engine (two-stroke horizontally opposed engine, Tokyo, Japan) at the rear of the body.

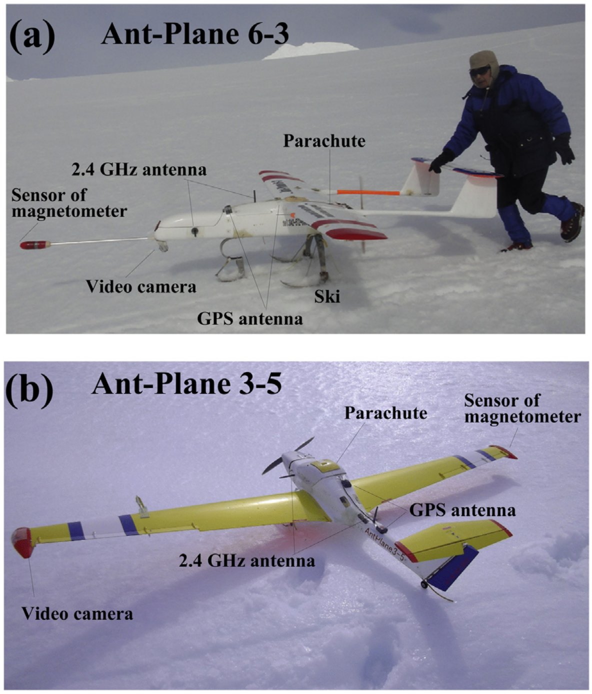

Fig. 2. Photos of the Ant-Plane. (a) Ant-Plane 6-3 and (b) Ant-Plane 3-5. Both photos were taken on the runway at St. Kliment Base.

Two booms connect to the main wings, and the horizontal tail wing connects to the vertical tail wing. The elevator is divided at the center and each side is controlled by a separate servomotor. The body is constructed of fiberglass hardened with polyester resin, and wooden framing is installed at key locations for structural reinforcement. The landing gear consists of a front wheel and a main gear with two wheels. These wheels are replaced with skis for takeoff and landing in snow. The fuel tank occupies approximately two-thirds of the body capacity, and is partitioned into three areas to avoid rapid changes in the center of balance during inclines. The wings and engine are controlled by a servomotor (Japan Remote Control Ltd. (JR) DS8421). Power is provided to the autonomous flight system (Higashino, 2006), the servomotors, and radio communication equipment by an NH 6 V 1600 mAh battery. AC power (7.4 V and 25 W at cruising speed from a Modelmotors Ltd AXi 4120/18 generator) is converted to DC by a Robotista RBT-NO440316, which then charges the battery. During manual flight, the signal from the proportional transmitter system (JR CPM9X II) at the ground station controls the servomotor through an onboard receiver (JR 9ch DR931, 2.4 GHz). Mutual communication between the ground station and the plane, within a radius of 5 km, is achieved via a 2.4 GHz wireless modem (Futaba FDA-

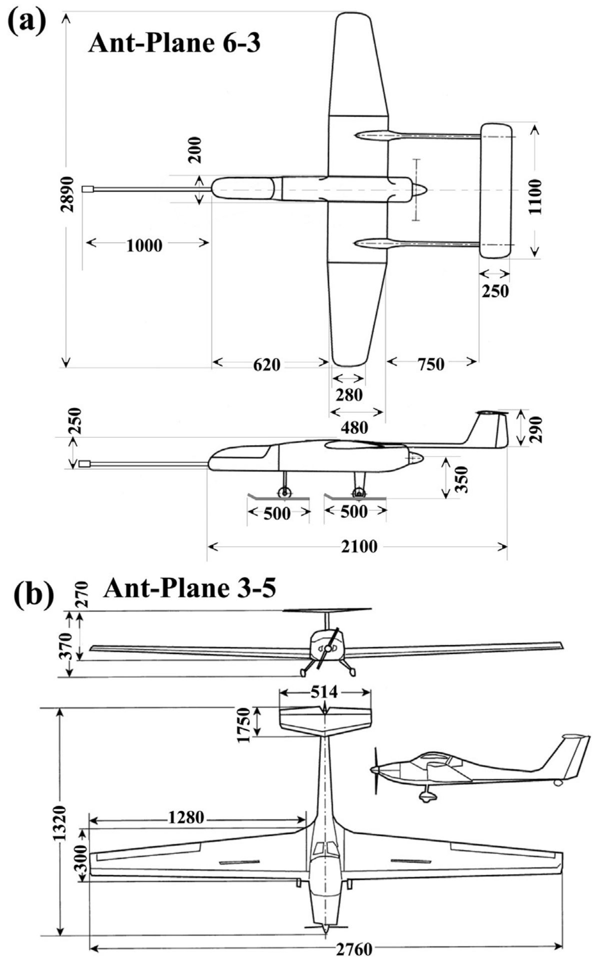

Fig. 3. Outline of the designs for (a) Ant-Plane 6-3 and (b) Ant-Plane 3-5 (units in mm).

01). The total cost of Ant-Plane 6-3, including the autonomous flight system and above-mentioned devices, was approximately US$20,000 (at an exchange rate of 100 Japanese Yen to US$1.00; all costs below are based on the same rate).

Ant-Plane 3-5 is a tractor-type scale model of the G-109 plane (Grob Aircraft, Germany; Fig. 2b). A magnetometer and video camera are installed at the tip of the main wings. The frame dimension is shown in Fig. 3b and Table 1. The plane weighs 9 kg when carrying 1.8 l of fuel, which provides a maximum flight distance of 300 km. The control and communication systems are essentially the same as those of Ant-Plane 6-3. The cost of Ant-Plane 3-5 is approximately US$20,000.

3. Magnetometers

The magnetometers generally used for geomagnetic surveys are not appropriate for use in the Ant-Plane because of their size, weight, and high power consumption; additionally, the strong vibrations from the engine may damage their circuitry. Installing these magnetometers in the Ant-Planes is risky because they are expensive and their flight reliability is not established. Accordingly, small, economical magnetometers have been developed for use in Ant-Planes, and are of two types.

3.1. Fluxgate magnetometer system (Tierra Tecnica FLFG 27-03)

This magnetometer system consists of a three-axis fluxgate magnetometer, GPS, data logger, and battery. The directions of the x-, y-, and z-axes of the magnetometer are calibrated by software to within 1°. The magnetometer has a sensitivity of 0.1 nT, and consumes 0.5 W. The system weighs 523 g, including a 7.4 V, 2100 mA lithium polymer battery. The GPS and magnetometer data are recorded on an SD memory card at 10 Hz.

3.2. Magneto-resistant (MR) magnetometer system (Robotista RBT-NO40081E)

This low-priced magnetometer system consists of a three-axis MR magnetometer (Honeywell HMR-2300, USA), GPS, data logger, and battery. The MR magnetometer has a sensitivity of 7 nT, and consumes 0.4 W of power. It weighs 400 g when using a 7.4 V, 1500 mA lithium polymer battery. Up to 3.5 h of GPS and magnetometer data can be recorded on an SD memory card. The angular accuracy of the z-axis is less than 2° against the x- and y-axes, and the accuracy between the x- and y-axes is significantly better than 2°.

The HMR-2300 magnetometer produces noisy data and substantial drift in comparison with the fluxgate magnetometer. However, it is useful for rough aeromagnetic surveys over periods of less than 1 h, and is less sensitive to noise derived from the airplane (Funaki et al., 2008).

For Ant-Plane 6-3, the sensor of a fluxgate magnetometer is attached to the tip of a 1 m aluminum pole to avoid the magnetic noise from the airplane and associated devices. The GPS antenna is attached to the outer surface of the plane on the upper side of the nose. The MR magnetometer is stowed in the center of the nose to monitor magnetic noise. In addition, an electrical signal from the MR magnetometer controls the shutter of a digital camera that is stowed near the center of the nose. A small Holux M-241 GPS logger

Table 1
Characteristics of Ant-Plane.

	Ant-Plane 3-5	Ant-Plane 6-3
Dry weight (kg)	6.8	20
Max. takeoff weight (kg)	9	28
Fuel (cc)	1800	10,000
Max payload (kg)	0.5	2
Fuel consumption (cc/h)	600	2000
Max distance (km)	300	500
Cruising speed (km/h)	100	100
Max. altitude (m)	2000	5000
Cruising time (h)	3	5
Stalling speed (km/h)	57	70
Engine	20 cc gasoline	86 cc gasoline
Power (HP)	1.5	7.5
Generator (W)	25	25
Max. rotation speed (rpm)	7000	6000
Emergency parachute	Equipped	Equipped
Communication distance (km)	5	5
Flight data	Radio to ground station	Radio to ground station
Autonomous navigation	Equipped	Equipped
Takeoff	Manual	Manual
Landing	Manual or parachute	Manual or parachute
Propeller	38 cm, 15/8, normal, polyvinyl chloride	61 cm, 24/10 l, reverse, wood

(63 g) is stowed in the center of the nose. This logger is significantly more sensitive than the GPS included in the magnetometer systems, and records data at 1 Hz.

To estimate the magnetization of the airplane, Ant-Plane 6-3 was horizontally turned around a three-axis flux magnetometer (FLFG 27-01) located 1 m from the tip of the nose. The magnetometer was consistently 40 cm above the ground, and the rotation speed of the engine was kept constant at 3000 rpm. The results indicated that the magnetization at the precise measurement site was 14 nT at an angle of 243° (given a nose direction of 0°).

4. Aeromagnetic survey flights

4.1. January 2011 flights from Marsh Airfield

The equipment required for the flight, other than the airframe and electrical devices, was sent to King Sejong Station (the South Korean Antarctic station on King George Island; Fig. 1) in October 2010 on the icebreaker *Araon*. The airframe and electrical devices were taken to Professor Julio Escudero Base (Escudero Base, the Chilean Antarctic base on King George Island; Fig. 1) on a commercial flight from Punta Arenas (Chile). The Ant-Plane was then assembled at Escudero Base.

We planned an aeromagnetic survey of the area of Bransfield Basin shown in Fig. 1. The survey was to be conducted from Marsh Airfield between 8 and 31 January 2011. We discussed the flight plan with the Chilean Antarctic Institute (INACH), and the plan was approved by the Chilean Air Force (FACH). The airfield control tower is located at 62°11′27″S, 58°59′12″W, at an altitude of 45 m. The airfield has one gravel runway with an area of 1292 × 38 m. We assembled Ant-Planes 6-2, 6-3, 3-4, and 3-5 at Escudero Base. However, we were unable to complete the survey for the following reasons.

1) Inclement weather, including rain, snow, and fog, with few fine days. The adverse weather was related to the location of the South Shetland Islands in the high-frequency zone of cyclone tracks (i.e., the storm zone), which is centered approximately along 65°S surrounding the Antarctic continent (e.g., King and Turner, 1997).
2) Wind strength consistently in excess of the 7 m/s limit for UAV flight.
3) Presence of clouds at altitude less than 200 m.
4) Lack of access to the runway due to prioritization of civilian and military flights.
5) Lack of permission to operate the UAV on the runway with other aircraft on the runway or apron.

Weather conditions were suitable for UAV flight on 15 January 2011. Furthermore, there were no commercial or military flights operating from Punta Arenas to Marsh Airfield on that day. Ant-Plane 6-3 completed a successful 1 h test flight in the afternoon, reaching an altitude of 300 m and a maximum speed of 27.8 m/s (100 km/h) over the 600 × 800 m flight area. The mechanics of the body, autonomous flight system, radio communication systems, and magnetometer were tested during and after the flight.

Although the wind speed was >7 m/s on 24 January 2011, we attempted an aeromagnetic survey above King George Island using Ant-Plane 6-3. However, the flight experienced problems after the accidental release of a parachute, which damaged the nose and boom. Vibrations resulting from wind turbulence (15 m/s at 300 m altitude) had broken the plastic latch securing the parachute hatch.

We also attempted an aeromagnetic survey using Ant-Plane 3-4 on 25 January 2011, despite strong winds (7 m/s at the runway, >15 m/s at 300 m altitude). Autonomous flight was confirmed above the runway before the plane flew to the survey area, located 1.0–3.5 km north of the runway. Survey lines of 3 km long and orientated E–W were defined at 500 m intervals, starting at the southern end of the survey area. The flight reached 500 m altitude with a constant speed of 100 km/h (27.8 m/s). In total, the area surveyed was approximately 27 km^2. For the first 15 min of the flight, aeromagnetic data were successfully collected. However, the number of GPS satellites from which the plane received signals decreased gradually. Consequently, we lost control of Ant-Plane 3-4 and were unable to find it. It may have landed in Drake Passage after deploying its parachute. GPS positioning requires a minimum of four satellites; however, receiving data from so few satellites may result in substantial inaccuracies during rapid heading changes while the system switches between satellites and takes time to stabilize. At least four satellites were present at an elevation angle greater than 20° during the flight of Ant-Plane 3-4. However, it is likely that the autonomous system was unable to control the plane while the satellite signals were disrupted during quick banks caused by wind turbulence. Ant-Planes 6-2 and 3-5 were assembled for subsequent flights, but conditions prior to 30 January 2011 were unsuitable for flights. Consequently, a successful flight was only made from Marsh Airfield on 1 of the 22 scheduled days.

4.2. December 2011 flights from St. Kliment Base

4.2.1. Flight preparation

An aeromagnetic survey of Deception Island and South Bay (Livingston Island) was planned for December 2011 from St. Kliment Ohridski Base (St. Kliment Base, the Bulgarian Antarctic station on Livingston Island; Fig. 1). There are no restrictions on UAV flights from St. Kliment Base because it is located 100 km from the control tower of Marsh Airfield. We expected weather conditions to be more suitable around Livingston Island than at King George Island on the advice of the members of the Bulgarian expedition at St. Kliment Base, who were in contact with a ship that had left Escudero Base for St. Kliment Base.

Ant-Planes 6-3, 6-4, 3-5, and 3-6, along with four research team members, were transferred to St. Kliment Base on 4 December 2011 by the Spanish Antarctic ship *Las Palmas*. The temperature at the base ranged from 1 to 5 °C during the day and 0 to −5 °C at night. Snow in the area was coarse-grained firn. The ski attachment on Ant-Plane 6-3 (30 cm long and 7 cm wide) broke after sinking into snow during taxiing on a glacier. We fixed this problem by constructing a longer ski (50 cm) and stronger attachment. A wooden propeller was also chipped by the granular snow during taxiing. We reduced the likelihood of this reoccurring by bonding fiberglass to the edge of the propeller. Preflight checks (Appendix) were conducted before each flight to assess the condition of the plane and communication equipment.

4.2.2. Deception Island flight plans

Nine liters of fuel were added to Ant-Plane 6-3 for 450 km of continuous flight. St. Kliment Base is located 35 km from the center of Deception Island (Fig. 4a). East–west survey lines of 18 km in length were established to investigate the island and adjacent offshore areas. Given intervals of 1 km between survey lines, we required 19 lines to cover the study area (Fig. 4b). As this would require a cruising range of approximately 500 km, we planned two flights: one to the northern part of the island and one to the southern part. Waypoints 0–27 were assigned to the northern flight course. The flight plan was for Ant-Plane 6-3 to takeoff under manual control from the glacier behind St. Kliment Base. Once safe flight conditions were established, autonomous flight would be initiated at 250 m altitude. The plane would then ascend to 800 m altitude and fly 8 km to the southwest before turning south toward Deception Island. The nominal flight altitude exceeded the elevation of the highest mountain (Mount Pond, 539 m) in the survey area. Survey Lines 0–9 progressed from north to south at 1 km intervals, over an area of 9 × 18 km. After completing Line 9, the plane would then fly Lines 10 and 11, which are repeats of Lines 1 and 0, respectively, flown in the opposite direction (Fig. 4b). These repeat lines are performed for assessment of magnetic heading errors. The plane would then return to the runway using the same route. We planned to conduct the southern flight after successful completion of the northern flight. Both flights had an intended cruising speed of 33 m/s (118.8 km/h).

4.2.3. Flight results

A 1 h test flight of Ant-Plane 6-3 was conducted at 500 m altitude in the afternoon of 17 December 2011. This confirmed the successful operation of the autonomous flight system, radio communication equipment, fluxgate magnetometer, and digital camera. Ant-Plane 6-3 took off from the glacier runway (62°43′8″S, 60°21′27″W; 25.9 m altitude) at 05:20:20 UT on 18 December 2011. Although a cloud ceiling was present, it lay above 1000 m. The wind at the time of takeoff was 4 m/s, and the outside temperature was −3.5 °C. Ant-Plane 6-3 returned to the runway at 08:27:28 UT after flying 302.4 km in a flight time of 3:07:08 (Table 2). The flight path, as recorded by the fluxgate magnetometer system, is shown in Fig. 5a. Data were received from between 9 and 10 GPS satellites throughout the survey area. The plane flew along WP0–2 and entered the survey area on schedule. It successfully completed Lines 0 and 1 along WP2–6 before suddenly changing course to the south at 4.5 km from WP7 (Line 2). The plane changed course to fly east on Line 3. The flight was subsequently successful on Lines 4 and 5 (WP9–13). The flight was then cut short again at 10.5 km from WP15 on Line 6. The original course was recovered on Line 7, and Lines 8–11 were surveyed successfully before the UAV returned to the runway on schedule. The altered flight course was recorded by the Holux GPS logger, the MR magnetometer system, and a video camera. To identify the cause of the course changes, we checked the waypoint data entered into the autonomous control system, but found no errors.

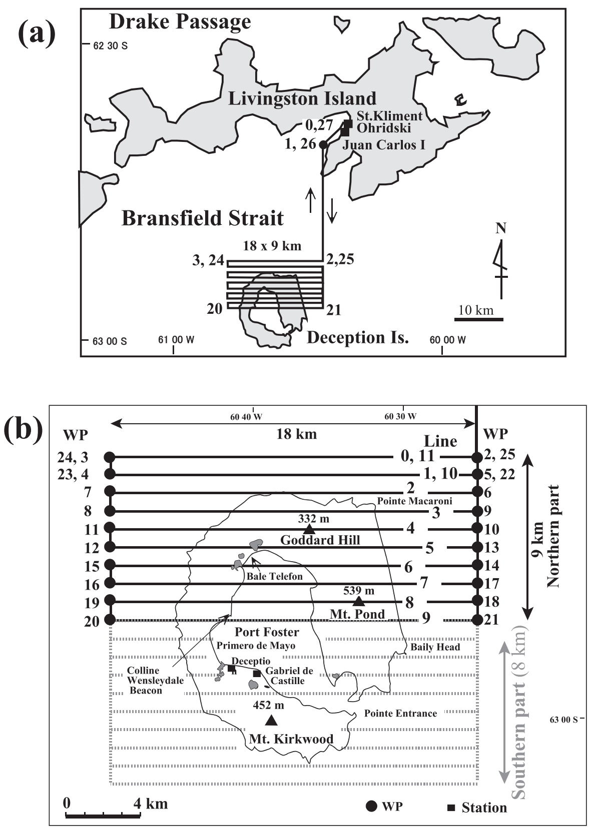

Fig. 4. (a) Map showing St. Kliment Base on Livingston Island, and Deception Island. Solid line: proposed flight path, with waypoints marked by numbers. (b) Map of Deception Island showing the planned survey path. Solid line: flight plan for the northern part of the island. Dotted line: flight plan for the southern part. Survey lines and waypoints are denoted.

The altitude throughout the flight recorded by the Holux GPS logger is shown in Fig. 6a. It appears that Ant-Plane 6-3 ascended to 780 m, maintained a consistent cruising level, and finally descended quickly to the runway under manual control. The cruising altitude was 20 m lower than the target altitude as a result of a calibration error between the atmospheric pressure and GPS altitude. This difference is, however, within the margin of error for single-point GPS positioning. Fig. 6b shows that the flight altitude varied by less than 5 m along the survey lines. It also shows more significant changes at the limits of the survey lines where turning resulted in descents of up to 15 m and ascents of up to 8 m in comparison with the cruising altitude.

Four different types of GPS were installed in Ant-Plane 6-3. Because the Holux GPS is the most sensitive among them, we used the positioning data recorded by the Holux GPS logger for flight analyses. The ground speed is shown in Fig. 7. The average speed over the survey area was 27 m/s (97.2 km/h), which is slower than the planned cruising speed of 33 m/s. The ground speed was 25–28 m/s when the plane flew west, and increased to 30–33 m/s when it flew east due to tail winds. When the plane flew south from WP1 to WP2, the speed increased to 38 m/s (137 km/h), but decreased to 19 m/s (68 km/h) when returning from WP25 to WP26. An average wind speed of 10 m/s and wind direction of 340° were estimated from these changes in ground speed.

We noted the following problems during the flight.

(1) According to the video footage, 14 min before landing Ant-Plane 6-3 flew through a cloud for 3 min. Based on the air temperature at ground level (−3.5 °C), the temperature at 780 m altitude was estimated as −10 °C, using the dry adiabatic lapse rate (about 1 °C/100 m). The cloud froze onto the camera lens, indicating that icing occurred. If the plane had remained in the cloud for a longer period, it may have crashed as a result of icing. Cloud and fog are extremely dangerous for UAVs.
(2) Ant-Plane 6-3 returned to the runway 18 min early because of changes in the flight course. A snowstorm reached St. Kliment Base 20 min after the landing. If the plane had been on schedule, landing under manual control may have been difficult.
(3) After the flight, we were unable to rotate the engine smoothly by hand. After disassembling the engine, we found that the cause was insufficient oil supply to the crank case.
(4) Following the flight, the piano wire connecting the servomotor to the engine throttle had experienced metal fatigue and was on the verge of breaking.

These issues demonstrate the hazardous conditions under which the Deception Island flight operated. The engine of Ant-Plane 6-3 had completed less than 10 h work before the flight, but was maintenance necessary for weaker part to metal fatigue. The flight consumed 6 l of fuel, with 3 l remaining in the tank. The fuel consumption rate of 50 km/l was consistent with Ant-Plane flights completed in Japan. Because we were not permitted to stay at St. Kliment Base after 19 December 2011, further surveys of the southern portion of Deception Island could not be pursued.

4.2.4. Aeromagnetic survey

The precise bearing of Ant-Plane 6-3 cannot be reported because of the low degree of accuracy of the onboard gyroscope (±2°). Therefore, the magnetic data collected by the fluxgate magnetometer were not attributed to geographical coordinates. The total magnetic field intensity (F) was used for magnetic analysis in this study. As the altitude varied considerably during turns in the flight path, we used only the data that were collected when the bearing was within 5° of the E–W survey lines.

In general, the variation between consecutive F values measured by the fluxgate magnetometer was less than 10 nT. However, there were some rare instances of dramatic changes as a result of magnetic noise. For example, in Line 0, the F value suddenly increased by 63 nT and remained at that level for 17 s, as shown in Fig. 8. We removed easily recognizable noise such as this from the data. The difference in F values between Lines 0 and 11 (the same course, but flown in the opposite direction) reflects the magnetization of the plane, daily variation in the geomagnetic field, and positioning errors. The variation between consecutive data points in these lines was similar, aside from the occurrence of noise (Fig. 8). The average F value in Line 0 (west-directed) was 15 nT larger than in Line 11 (east-directed). Similarly, there was a consistent pattern in F values between Line 1 (east-directed) and Line 10 (west-directed), but the average value was 32 nT higher in Line 1. Therefore, it seems that the magnetization of Ant-Plane 6-3 is relatively insignificant. There was a period of 1:54:00 between the time when the survey of Line 0 started and when Line 11 was completed. The geomagnetic variation during this time was <5 nT, as measured at King Sejong Station. Magnetic variation during the day may, therefore, provide a minimal contribution to the differences noted. The majority of the difference in F

Table 2
Time table during flights.

	Deception island Ant-Plane 6-3 18. 12. 0.2012 UT (AM)	Remarks	South bay Ant-plane 3-5 17. 12. 0.2012 UT	Remarks
Takeoff	5:20:20		22:22:27	
Autonomous flight at 260 m	5:29:02		22:31:36	
Reach to planed height	5:40:00	800 m	22:40:11	350 m
To the survey area	5:43:20		22:41:15	
In the survey area	5:56:09	Survey time: 2:03:40	22:41:51	Survey time: 0:45:45
Out the survey area	7:59:49		23:27:36	
Start of descent	8:22:19		23:28:32	
Manual flight	8:24:49		23:29:00	
Landing	8:27:28	Total flight time 3:07:08	23:29:34	Total flight time 1:07:07

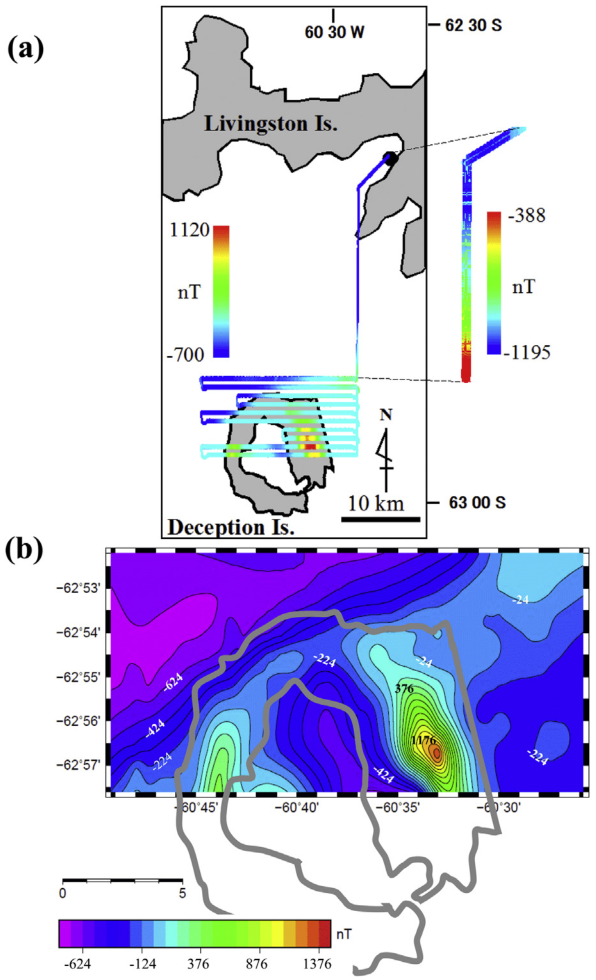

Fig. 5. (a) Magnetic anomalies as measured along the flight path. (b) Magnetic anomaly map of Deception Island and surrounding offshore area.

values measured along the same survey lines may be attributed to irregular magnetic noise from the plane and noise resulting from positioning errors. The largest variation in the F value observed along a single survey line was 1860 nT in Line 8 (Fig. 8). Compared with this, the difference between average F values in Lines 0 and 10 was relatively small (1.7%).

The F value recorded by the MR magnetometer stowed in the center of the nose showed similar variation to that measured by the fluxgate magnetometer. However, the data from the MR magnetometer included significant and irregular noise. The stinger sensor was, therefore, effective in reducing the magnetic noise.

The international geomagnetic reference field (IGRF-11) at the center of Deception Island for 2010 (62°54′36″S, 60°36′36″W) above 800 m was F = 36623.5 nT, declination (D) = 12.666°, and inclination (I) = −55.919°. We calculated the magnetic anomaly by subtracting the IGRF F value from the F values observed at Deception Island. The magnetic anomaly for the flight path is shown in Fig. 5a. Fig. 5b shows the magnetic anomaly for the survey area, which was obtained by smoothing the anomaly values using a 500 m^2 moving average. The following characteristics of the magnetic anomaly are evident in Fig. 5.

1) A higher-resolution magnetic anomaly pattern, compared with the seaborne anomaly map published by Lawver et al. (1995), was obtained.
2) The highest positive anomaly (1387.0 nT, at the summit of Mount Pond) and the strongest negative anomaly (−774.5 nT) were observed in the northwestern part of the survey area. The F value increases gradually from north to south between St. Kliment Base (WP0) and the survey area (WP2).
3) These results show that Ant-Plane 6-3, equipped with a fluxgate magnetometer, obtained reliable aeromagnetic data. The anomaly pattern will be analyzed based on geological and geophysical data from Bransfield Basin and the results will be published in a subsequent paper.

4.2.5. *Estimation of the cost-effectiveness of the flight for Deception Island by Ant-Plane 6-3*

In the case of the Deception Island flight by Ant-Plane 6-3, the line-km cost for full mobilization was roughly US$1.36/km: fuel consumption of 8.0 l (gasoline calculated at US$1.50/l) and manpower costs of US$400 for four members. However, the cost increased to US$168.7/km when the total budget of this project (US$31,000, Grant-in Aid for Scientific Research B (2011) awarded by the Japan Society for the Promotion of Science) and airplane cost (US$20,000) were included. Ferraccioli et al. (2005) conducted an aeromagnetic survey in Antarctica by manned airplane, obtaining a high-resolution aeromagnetic survey along a 1 km line-spacing grid using a manned Twin Otter (British Antarctic Survey) airplane in the Jutulstraumen area, western Dronning Maud Land, Antarctica. The airplane simultaneously acquired aeromagnetic and aerogravity data and partially airborne radio-echo sounding data along 15,500 km of survey lines over 25 flights, using a total of 100 survey hours. The flights were managed from the SANAE (South African National Antarctic Expedition) base. Although it is impossible for us to estimate the line-km cost of the

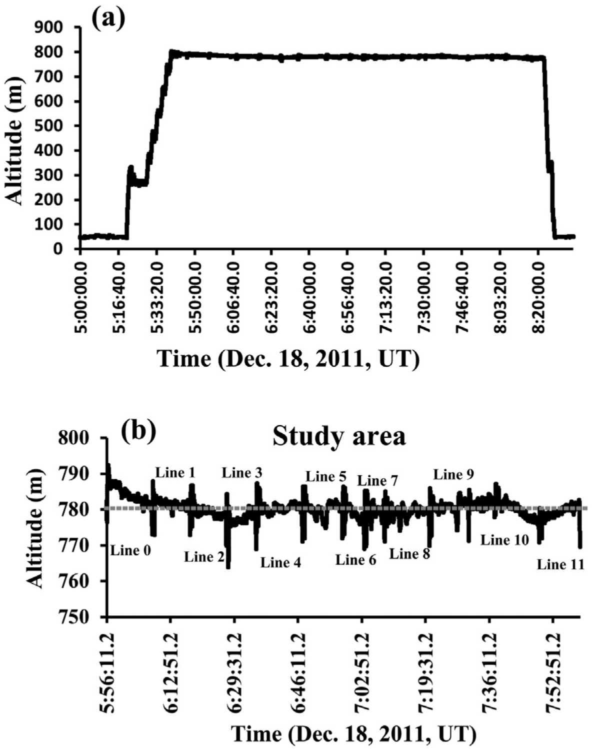

Fig. 6. (a) Flight altitude, as recorded by GPS equipment. (b) Flight altitude in the survey area. Dotted line: average altitude of the flight in the survey area (780 m).

full mobilization of their flights, it would appear to be lower that that for Ant-Plane 6-3 because these flights enabled large amounts of high-quality data to be obtained simultaneously with several scientific devices. However, the estimation becomes more complicated when the manpower fees, transportation, and airplane charter costs are included.

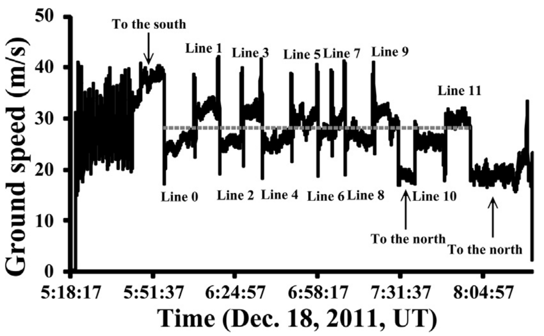

Fig. 7. Ground speed (m/s) of the Deception Island flight, showing changes in speed along the survey lines. Dotted line: average ground speed in the survey area.

In the case of Antarctic airborne surveys, comprehensive evaluation of the cost-effectiveness by manned flight and unmanned flight would generally difficult. We do not claim that airborne survey by UAV is significantly more cost-effective overall than manned flight at any time. However, greater cost-effectiveness is expected for UAVs in the Antarctic storm zone when airplane downtime is taken into consideration. Therefore, we concluded that Ant-Plane 6-3 was highly cost-effective for the Deception Island flight because the area is located far from airfields and is also in the Antarctic storm zone. In terms of safety, UAVs would generally yield greater cost-effectiveness in remote areas far from existing infrastructure.

4.3. Flight above South Bay, Livingston Island

We planned an aeromagnetic survey to cover the area of South Bay, Livingston Island (Fig. 9) using Ant-Plane 3-5 flying at an altitude of 350 m and speed of 27.8 m/s (100 km/h) on 17 December 2011. The flight plan included takeoff from the same glacier runway as the previous flight (WP0), progressing through WP1–24, and returning to WP25. We defined survey lines 5 km long, oriented NW–SE, with 12 lines (Lines 0–11) spaced at 500 m intervals. The final line (Line 11) is the same as Line 2, but flown in the opposite direction.

Ant-Plane 3-5 took off at 22:22:27 UT, flew along the waypoints on schedule, and landed at 23:29:34 UT. The total flight time was 1:07:07 and covered 105.4 km, while the flight time in the survey area was 0:45:45. The time sequence for the flight is shown in Table 2. Fig. 10 shows that the flight course recorded

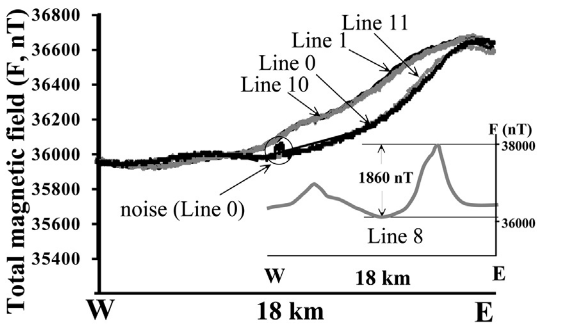

Fig. 8. Total geomagnetic field intensity obtained during flights along the same route in opposite directions. (a): Line 0 (west-directed flight) and Line 11 (east-directed). (b) Line 1 (east-directed) and 10 (west-directed). Circled area highlighting noise observed along Line 0. The inset shows spatial variations in total geomagnetic field intensity along Line 8.

by the Holux GPS logger was largely consistent with the scheduled course, although deviations of up to 150 m appeared in the survey lines. Again, turns by the plane resulted in considerable deviations from the planned course, but each time the plane recovered within approximately 300 m.

The average GPS altitude of the plane in the survey area was 363 m. Aside from a 56 m increase in altitude in Line 6 (Fig. 11), the dramatic changes in elevation during turns observed in the Ant-Plane 6-3 flight were not evident in this flight. The ground speed of the plane ranged from 16 to 34 m/s during turns in the flight path, while the average speed was 26 m/s (93.6 km/h) in the survey area (Fig. 12). The wind speed and direction were estimated at 3.5 m/s and 240°, respectively, based on variations in the ground speed measured in different flight directions.

We attached a downward-directed video camera to the tip of one wing and the MR magnetometer to the tip of the other wing. The camera operated successfully throughout the flight (Funaki et al., 2013) to capture the glacial and sea-ice conditions. However, the magnetometer ceased recording at 125 m altitude during the ascent, possibly as a result of communication errors between the magnetometer and the data logger. Consequently, the magnetic survey in South Bay was unsuccessful. We were unable to schedule any additional flights from St. Kliment Base.

4.4. Flight from King Sejong Station

Ant-Planes 6-3 and 3-5 were assembled at King Sejong Station for aeromagnetic surveys of southern Deception Island (Fig. 4b), Penguin Island (46 km ENE of the station), and a 12 × 7 km area around Marian Cove (Fig. 1). Ant-Plane 3-5 was scheduled to complete 12 lines in a 5 × 5 km area around Penguin Island on 3 January 2012. We used a 250 × 300 m snowfield located 1.7 km SW of the station as a runway. The ground station was established at 62°13′53″S, 58°45′32″W, at an altitude of 174 m. However, Ant-Plane 3-5 was damaged during transportation from the station to the runway. Consequently, Ant-Plane 6-3 took off for Penguin Island at 23:39:00 (UT) instead. The weather conditions were partly cloudy, with a temperature of 1.0 °C and wind of 3.2 m/s from the WNW. Snow levels increased significantly 30 min after takeoff, and the plane did not return to the runway. The plane probably crashed as a result of icing. We were unable to conduct further flights from King Sejong Station as conditions remained unsuitable during the research period.

5. Weather

Weather conditions were measured at Escudero Base from 8 to 31 January 2011 and at King Sejong Station from 1 to 27 February 2011. In general, the wind speed exceeded 7 m/s in February, but was lower in January. Cloud, rain, snow, and fog were the dominant weather types. These conditions are difficult for UAVs, which do not perform well when cloud layers are as low as 100–200 m altitude. Humidity remained high during cloudy conditions, and was usually between 80 and 100%. The average temperature recorded was −3 °C in the early morning and 6 °C in the middle of the day. During the 22 days we were at Escudero Base, only 1 day (15 January 2011) was suitable for UAV flights. Despite this, we attempted flights on three other days.

At St. Kliment Base (3–18 December 2011), weather conditions were generally breezy and cloudy. The cloud layer was usually below 300 m, which restricted flying to the visible area. However, weather conditions were good for UAV flights for 18 h from 17 to 18 December 2011, enabling us to fly beyond the immediately visible area. On the remaining days, conditions were unsuitable for flights and patches of fine weather lasted less than 3 h. The weather at King Sejong Station (19 December 2011–19 January 2012) was less suitable for UAV flights than that at St. Kliment Base.

6. Some lessons learnt regarding UAV flights

Throughout the development of Ant-Plane UAVs and the flights in Antarctica, we encountered several problems. Some were solved before the flights, but others remain. The main problems and proposed solutions are listed below.

1) Ant-Plane 3-4 crashed, probably because of problems with the autonomous flight system due to disruption of satellite signals when it was affected by strong turbulence. The Ant-Plane is controlled by single-point GPS positioning that requires a minimum of four satellites. Because no satellites have flight paths over high-latitude areas, the satellite signals may be disrupted by rapid banking related to positioning problems. Even if new satellite signals are received after banking, at least several seconds are required for the positioning to stabilize. To address this problem, several GPS antennae oriented in different directions should be included in the positioning system.

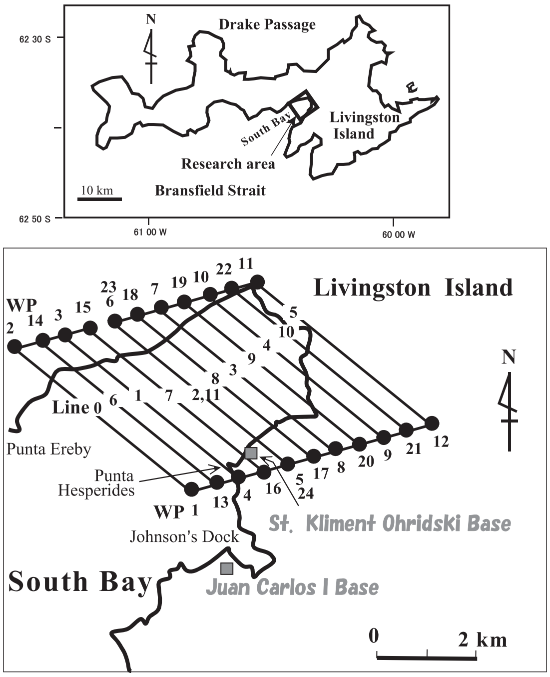

Fig. 9. (a) Location of South Bay, where the survey route was planned. (b) Locations of waypoint (solid circles) and proposed survey line.

2) It remains unclear why the flight course of Ant-Plane 6-3 was not correctly followed during the Deception Island flight. As no such problem was encountered during more than 10 h of flight in Japan, the cause of the altered course may be related to the peculiar environment in Antarctica. The most plausible reason is disruption of the GPS signals (see explanation above). This problem could be avoided by improving the software running the autonomous flight system and by reconfiguring the GPS antennae of the autonomous control system.

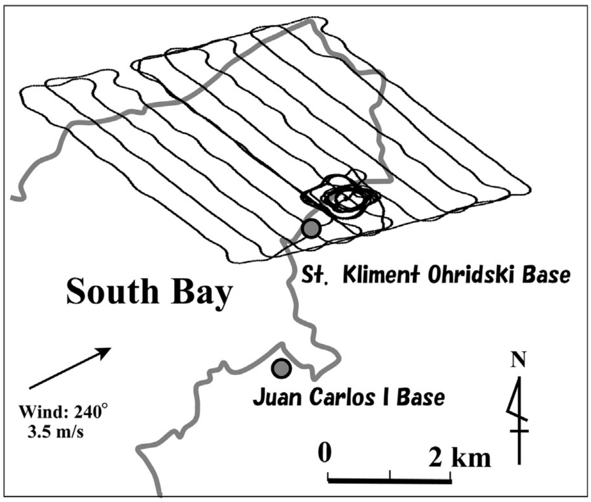

Fig. 10. Actual flight path of the South Bay flight.

3) During the aeromagnetic survey using Ant-Plane 6-3 above Marsh Airfield on King George Island, a parachute was accidentally released after breakage of the plastic latch securing the parachute hatch. The strong vibrations arising from wind turbulence caused the latch to break. We replaced the plastic latch with a more rigid metal one. This problem highlights the fact that ideal flight conditions are calm winds of less than 7 m/s, whereas only a few days of such good weather can be expected in the Antarctic summer season on King George Island.
4) The video footage captured during the Deception Island flight of Ant-Plane 6-3 showed icing on the camera lens when flying in cloud at an air temperature of approximately −10 °C. The plane was lost in snowfall during a flight to Penguin Island. Therefore, we conclude that Ant-Plane 6-3 crashed because control of the plane was compromised by icing. Flights in cloud should be avoided.
5) The ski attachment of Ant-Plane 6-3 broke after sinking into snow during taxiing on a glacier. We solved this problem by constructing longer skis made of aluminum and stronger ski attachments made of wood. As the ground-snow conditions change with the weather, various types of ski have been prepared.
6) A wooden propeller was chipped by granular snow during taxiing. We solved this problem by bonding fiberglass to the edge of the propeller. A plastic propeller may be ideal.
7) For gasoline-driven UAVs, metal fatigue is a serious problem that arises from severe vibrations; in

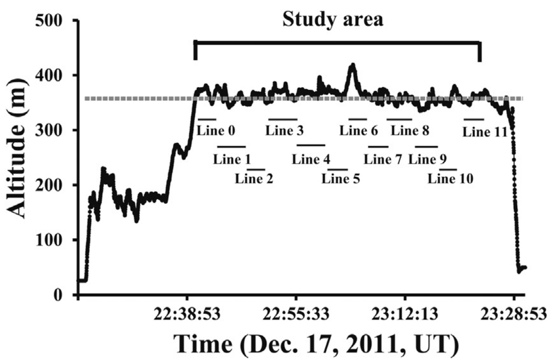

Fig. 11. Flight altitude over South Bay recorded by GPS. Dotted line: average flight altitude in the study area (363 m).

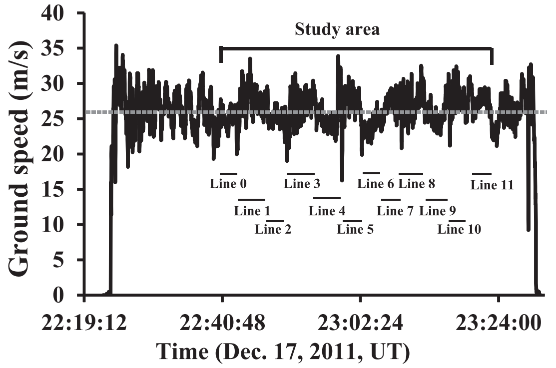

Fig. 12. Ground speed of the South Bay flight. Dotted line: average ground speed in the study area (26 m/s).

comparison, the vibrations in electricity-driven UAVs are relatively mild. To avoid metal fatigue, it is important to check the airframe and the assembly before and after each flight, using the check list (supplementary material). The Ant-Plane 6-3 requires maintenance before every 10 h of flight time, including replacement of weaker parts to avoid metal fatigue.

7. Summary

Using model airplane technology, we developed two types of small autonomous UAVs, Ant-Plane 6 and Ant-Plane 3, to conduct scientific research in coastal regions of Antarctica during the summer season. These planes employed onboard magnetometer systems using three-axis fluxgate and MR magnetometers. We planned to deploy the UAVs (Ant-Planes 6-2, 6-3, 3-4, and 3-5) for aeromagnetic surveys and aerial photography over Bransfield Basin during the austral summer seasons of 2010–2011 and 2011–2012. The flights of Ant-Plane 6-3 from Marsh Airfield on King George Island did not produce satisfactory results due to unsuitable weather conditions and flight restrictions. Ant-Plane 3-4 was lost after the GPS unit was unable to maintain contact with satellites in strong winds while undertaking an aeromagnetic survey around King George Island. Ant-Plane 6-3 subsequently completed a successful flight between St. Kliment Base and Deception Island, covering a total of 302.4 km in 3:07:08 at a cruising altitude of 780 m. From the aeromagnetic data collected during the flight, we were able to construct a new magnetic anomaly map of the northern region around Deception Island. This map covered an area in which Lawver et al. (1995) were unable to collect data. However, we were unable to collect data from the southern region of the island in a subsequent flight due to unsuitable weather conditions. Ant-Plane 3-5 successfully obtained video footage from a flight around South Bay, Livingston Island, but was unable to collect aeromagnetic data following equipment failure. The flight covered 105.4 km in 1:07:07 at an altitude of 363 m. We were unable to launch further flights from King Sejong Station because of poor weather. Ant-Plane 6-3 was later lost while flying toward Penguin Island, probably as a result of icing.

We successfully completed one aeromagnetic survey in the storm zone, which is the least suitable place in Antarctica for UAV operation. This confirmed that it is possible to use UAVs for scientific research in coastal Antarctica during summer. Benefits include the low rate of fuel consumption (50 km/l) and lack of flight safety concerns. From a general perspective, we cannot conclude whether the cost-effectiveness of the airborne survey by UAV is significantly better than that of manned flight. Although it is difficult to numerically evaluate the cost-effectiveness (line-km cost) of the UAV flights in our studies, for remote locations in the Antarctic storm zone, Ant-Plane may be more cost-effective compared with manned flights when taking into account factors such as personnel expenses, transportation, fuel consumption, insurance, and airplane cost. The flights also demonstrated the importance of maintenance before and after UAV flights, because parts are subjected to significant stress arising from engine vibrations. Sensitive parts require replacement before reaching 10 h of operation, regardless of their visible state. Successful flights in Antarctica require weak winds and cloud-free conditions to maintain contact with GPS satellites and to avoid icing. Finally, for safety reasons, it is advisable to operate UAVs in remote areas away from existing infrastructure.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.polar.2014.07.001.

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