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*Technical report*

# BGDL-II—A GPS data logger for birds

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***Abstrct:*** We have developed a new GPS data logger consisting of a receiver, timer, memory, and battery. It is principally designed for long period tracking of migratory birds. It can fix 600 positions with one small lithium battery. We can set an arbitrary measuring schedule prior to each experiment. We can, for example, track a bird over six months, fixing positions three times a day. The whole unit weighs 67 g including battery and casing. The casing is pressure-resistant up to 3 bars. The main advantages compared to tracking methods based on the ARGOS system are: 1) several times cheaper equipment, 2) no charge for the use of satellite links, 3) the errors in the position data obtained are more than 10 times smaller, 4) the schedule setting has greater flexibility, and 5) the fixing has a lesser failure rate. However these advantages are realized at the cost of real time delivery of position data as users must re-capture the birds to obtain the stored data. In this paper, we explain the configuration of equipment, principles of operation, and the performance. We also discuss some results of albatross tracking. In the experiment the failure rate in the fixing of the albatross positions averaged 20%.

**key words:** GPS, data logger, tracking of migratory birds, albatross

## Introduction

Satellite tracking systems such as ARGOS are increasingly used in the study of bird migration. These systems are very powerful and have revolutionized the means of tracking migrating birds. However they do have some drawbacks: 1) high price of equipment, 2) fee for the use of satellite links, 3) large errors in measurement, sometimes up to a few kilometers (the extent of the errors is unknown in some cases), 4) restrictions on the schedule setting of the measurements, 5) occasional failure in the fixing of positions. In recent years, some attempts to use the global positioning system (GPS) (Enge *et al*., 1999) in the study of the traveling routes of birds have appeared in the literature (Steiner *et al.*, 2000; Weimerskirch *et al.*, 2002).

In an attempt to overcome some of the aforementioned weak points in the satellite tracking systems we have developed a new data logger called BGDL-II based on GPS (Fukuda *et al.*, 2002, 2003). The equipment is several times cheaper than that of ARGOS and data do not need to be transmitted, which enables us to reduce costs as we do not need to buy a license or pay for satellite links. The position measurement is also more accurate than when using the satellite system, with a possible error of up to only 10 m. These are advantages common to all GPS data loggers. Advantages specifically relating to our system include the ability to set a daily schedule of measurements beforehand using a personal computer (PC) temporarily connected to the unit, and due to the low cost of the equipment, which consists of a GPS receiver, timer, memory, and a lithium battery with the ability to fix a total of 600 positions, we can obtain accurate position data from many birds simultaneously for longer periods. This allows us, for example, to track each bird over six months, fixing positions three times a day.

Our unit is housed in a casing, which withstands pressure equivalent to 30 m water depth, sufficient for use on albatrosses. The whole unit weighs 67 g including battery. However, the small size and light weight of BGDL-II are realized at the cost of real time delivery of position data, as users must re-capture the birds to obtain the information stored in the equipment's memory.

In this paper, we explain the configuration, the principles of operation, and the performance of the BGDL-II. We also discuss some results of tracking experiments on albatrosses at different locations from a technical perspective.

## Equipment

### Configuration

Figure 1 illustrates the configuration of the equipment, which consists of a patch-type

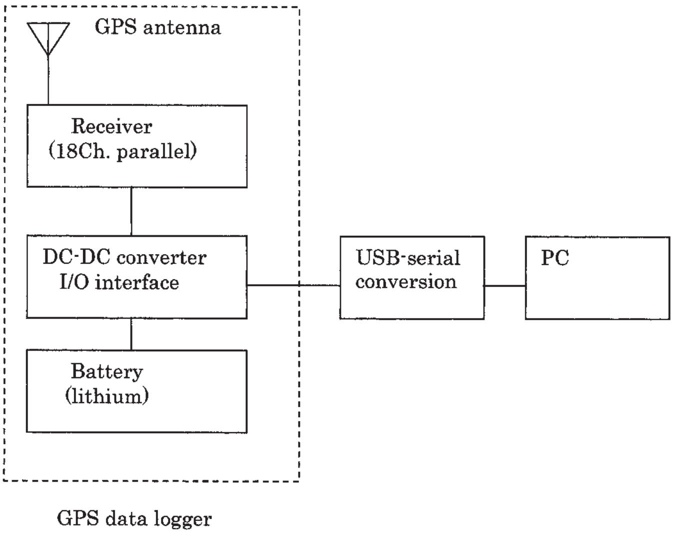



Fig. 1. Configuration of equipment. The computer is used to set the fixing schedule before an experiment and to read data after the experiment.

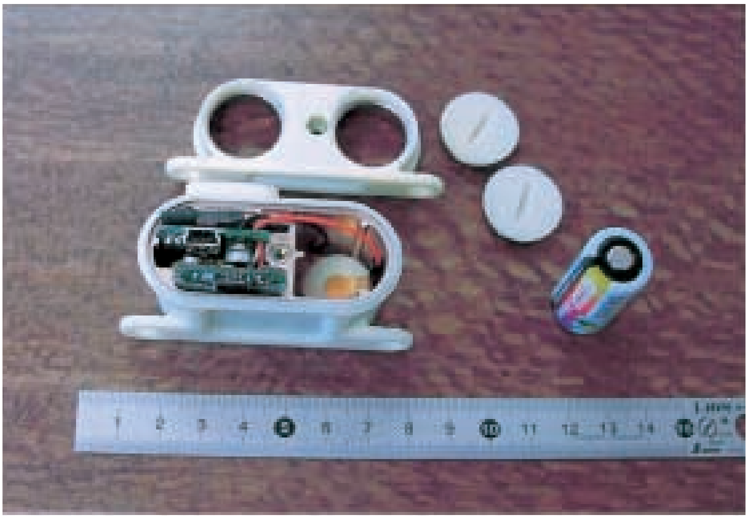


Fig. 2. Electronic devices, such as the GPS receiver, are housed in the left-hand space; space on the right houses the battery (CR123A).

GPS antenna, an 18 channel parallel GPS receiver, timer, memory, and battery. We use CR123A lithium batteries, of the kind normally used to power cameras. Figure 2 shows a photo of the equipment. A personal computer is temporary connected to the unit, via a cable, prior to each experiment to set the daily position fixing schedule and after each experiment to read the data.

The first model, named the BGDL-I, was developed in 2000. It weighed 100 g including battery and casing. It was developed to confirm the feasibility of the basic idea of BGDL's. Then, based on its principle, the BGDL-II was developed in 2001 using a lighter casing to reduce the weight to 66 g. The latest model (BGDL-II$^+$) developed in 2002 weighs 67 g. It is a modified version of the BGDL-II, taking into account many experimental results. In the BGDL-II$^+$, the weight of the antenna is 10 g, the battery 17 g, the casing 24 g, and the electronics: receiver, timer, memory, etc. weigh 16 g.

Principles of operation

Prior to an experiment we initialize the unit, inputting the time (any local time or UTC may be used) and the present position of the unit as well as the almanac data (coarse position information for the full constellation of the GPS satellites). These initial time and position references do not need to be completely accurate; even on errors in the order of tens of minutes or a few hundred kilometers, respectively, are acceptable, as the information is replaced by a precise version obtained every time the unit fixes a position (precise time is simultaneously obtained when a unit fixes a position). Thus, this initialization process can be omitted if the place of the new experiment is not far from the last position the unit fixed. The unit has a timer running continuously.

The next step is to arrange the daily fixing schedule by setting the first fixing time for each day and the desired interval between successive fixes. We also set the "working time" and "extension time". When a scheduled fixing time arrives, the unit activates and begins to receive ephemeris data (information broadcast from satellites from which a GPS unit can calculate its position relative to them) from some satellites in desirable positions for the unit. The unit uses the above mentioned almanac data to estimate which satellites are now in its receiving range and in desirable positions. If it has succeeded in receiving signals from at least three satellites when the working time expires, it stops, calculates the position, stores the information and returns to sleep mode. With information from three satellites, the logger is able to fix and record only its two dimensional position (longitude and latitude); however, if it obtains data from four or more satellites, it is able to fix and record its three dimensional position (longitude, latitude, and altitude). The unit can obtain and record precise time information in both cases. If the unit fails to receive data from three or more satellites before the working time expires it will continue the trial within the extension time. In this case, the logger will stop receiving data at the instant it succeeds in reaching three satellites. If the extension time expires before the logger has reached three satellites, the unit returns to sleep mode without position data. The recommended work time and extension time for BGDL-II$^+$ are

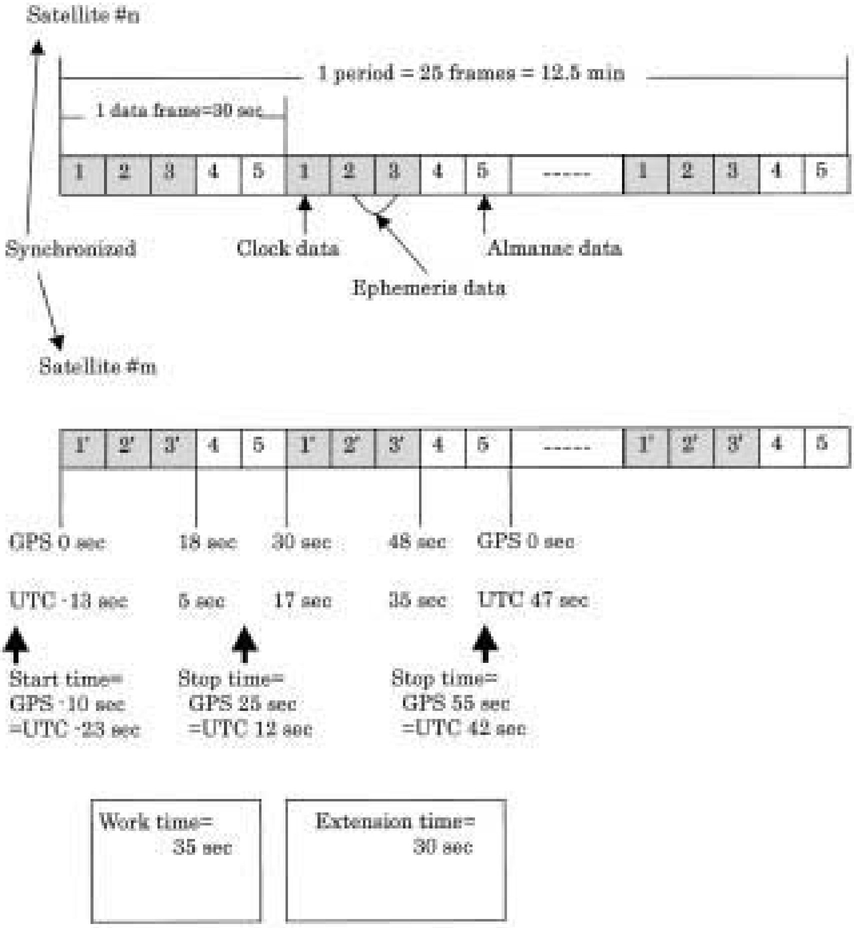



Fig. 3. Time chart of GPS transmitter and BGDL receiver. Transmitters of all the GPS satellites are synchronized. Each satellite starts transmission of its ephemeris data twice a minute (0 s and 30 s in GPS time). The transmission time of the ephemeris data is 18 s. BGDL starts receiving the signals 10 s before the start of the transmission of the ephemeris data. The 10 s are used to synchronize the receiver to the satellite signals.

35 s and 30 s, respectively.

Figure 3 illustrates the precise time chart of the operation. Note that the GPS time is accurate but does not include the leap second adopted in the UTC time system so the GPS time is 13 s ahead of the UTC time. When UTC time introduces another leap time the difference increases to 14 s.

The battery capacity is input into the unit on its first use, after which the unit calculates the time it has worked and estimates the remaining battery capacity. The operator can use this information to estimate the expected operation time for the next deployment. Moreover, this allows the unit to stop working automatically before the battery is exhausted. If the power supply were to be suddenly discontinued while the unit was receiving signals, the processor could malfunction, resulting in the loss of stored position data. Data stored in the memory do not disappear even if the battery is exhausted or removed while the unit is not receiving signals because the system also contains a small button type battery to power the timer and memory.

Specifications

Table 1 summarizes the specifications of BGDL-II$^+$. We can estimate the number of times the unit can try to fix positions ($N$) using one battery as

$$N = \frac{B \times 3600}{T \times C}, \tag{1}$$

where $B$ is the battery capacity in milli-ampere hours (mAh), $C$ is the current the equipment consumes while working in milli-amperes (mA), and $T$ is the receiving time of each trial in second. Power consumption during sleep mode is minimal and therefore not included in the above calculation.

In the case of BGDL- II$^+$, $C = 165$ mA and we usually use batteries for which $B = 1400$ mA h. We usually set the work time and extension time at 35 s and 30 s, respectively. So $T = 35$ s when the unit seldom uses extension time, or $T = 65$ s when the unit uses extension time to its full extent in almost all of the trials. Thus, the maximum and minimum for $N$ are 873, and 470 respectively.

The memory capacity of the unit is enough for 600 three dimensional positions. As will be seen later, both the failure rate and the number of times the unit uses extension time are

Table 1. Specifications of the BGDL-II$^+$.

| Item | Specification |
|---|---|
| Interface protocol | NMEA Ver.2.0 |
| Coordinate frame | WGS84 (changeable) |
| Power requirements | 550 mW (typical) |
| Stand-by current | < 7$\mu$A (+3V DC) |
| Operating temperature | −30 ~ +60°C |
| Depot temperature | −40 ~ +85°C |
| Water proof | 30 m |
| Size | 42×71×31 (mm) |
| Weight | 67 g (battery included) |
| Maximum fixing points | |
| Memory capacity | 600 |
| Battery capacity | 870 (SANYO CR123A, 35 s/measurement) |

low in the case of BGDL-II+. Consequently, the memory capacity is the ultimate restriction on the number of positions a unit can fix in each experiment. Of course we can reuse the unit after we have retrieved the data and, if necessary, replaced the battery.

There are three kinds of fixing schemes in GPS, termed cold start, warm start, and hot start. During cold start a unit starts position fixing with neither almanac data nor ephemeris data, needing a few minutes to fix a position. In warm start a unit has almanac data when it begins fixing and it needs about 35 s to fix a position. For hot start a unit has both almanac and ephemeris data from the beginning and subsequently takes only about 10 s to fix a position, using this time to synchronize the receiver to the satellite signals and calculate the distance between the satellite and itself. We programmed the unit to utilize old ephemeris data if they have been obtained within the last 4 hours, thereby saving time when fixing positions.

Figure 4 shows the ratio of times the BGDL-II+ fixed positions with hot start in relation to the total number of times it fixed a position. From this figure we can determine that there is a possibility of saving battery power when the fixing interval is less than 1 hour and the working time set shorter than 10 s. However, we did not adopt this strategy for our BGDL-II+ units because, as is mentioned above, it is the memory capacity which restricts performance of the unit.

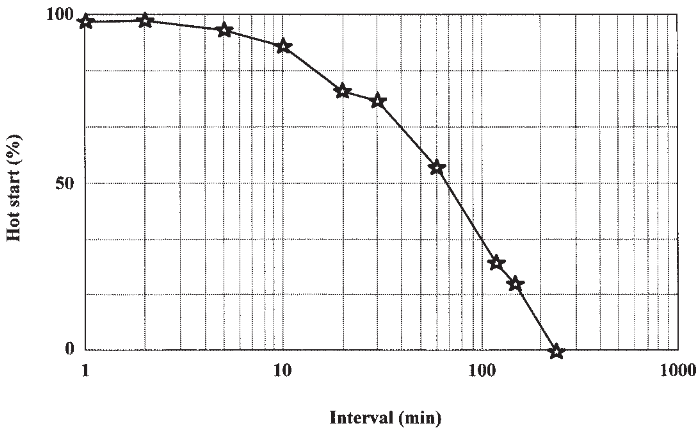



Fig. 4. Ratio of hot starts to the total number of starts *vs*. fixing interval.

## Accuracy of fixed positions

We saw no noticeable difference between accuracy of position data obtained by our units and that obtained by commercially available GPS receivers. For example in Fig. 5a, we show a plot of positions measured by two BGDL-II units placed a few meters apart to eliminate interference. Each unit measured its position 400 times at 4 min intervals.

The length of each axis in the figure is about 30 m. The 2 drms (twice the distance root mean square) values for the two units are 8.75 m and 9.71 m, respectively. We can expect that about 98% of the errors in the positions obtained by the unit are within these 2 drms values.

Figure 5b shows the fluctuation in the positioning errors. The horizontal axis in this figure is the fixing time. We can see a strong correlation between the slow components of the fluctuation of errors of the two units. However, there is no such correlation between the fast fluctuating components.

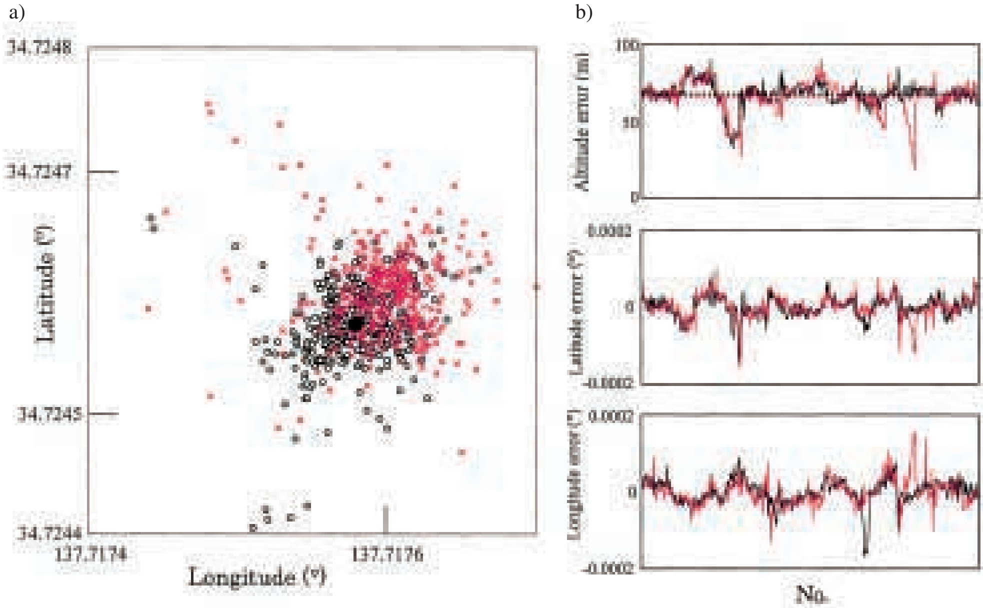



Fig. 5. Results of 400 measurements by two BGDL-II units at two fixed positions a few meters apart (August 2002). There is no noticeable difference in the fixing accuracy between BGDL-II units and BGDL-II+ units.
a) Plot of positions fixed by the two units. The 2 drms (see text) of units #20 (red cross) and #02 (open circle) were 9.71 m and 8.75 m, respectively.
b) Fluctuation of measured altitudes (m) and differences in measured and averaged latitude and longitude values (°). Red lines and black lines denote measurements by units #20 and #02, respectively.

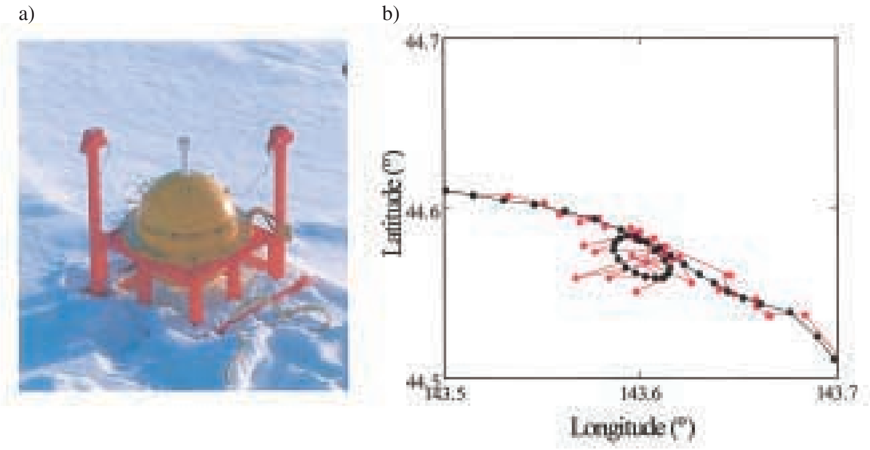



Fig. 6. Comparison of the performance of ARGOS and BGDL systems.
a) Setting the equipment on sea ice. Two BGDL's are placed on the top of sticks about 40 cm apart. The scheduled fixing time interval was 2 hours for both BGDL's, with 1 hour difference in the start time (photo by the Institute of Low Temperature Science, Hokkaido University).
b) Part of the trajectory of the sea ice fixed by the BGDL units (black dots) and ARGOS system (red dots).

It is typical in GPS measurements to record errors in altitude of around 20 m. This is sometimes too large to obtain meaningful data for the study of certain birds, for example the albatross, which usually does not fly high above the sea surface.

In order to compare the performances (accuracy and failure rate) of BGDL and ARGOS, we placed an ARGOS buoy on sea ice in February 2003 on the Sea of Okhotsk (143°0′E, 44°40′N, Fig. 6a). Two BGDL's were also put on the frame of the buoy. The ARGOS transmitter was set to transmit signals periodically without a lengthy rest time between successive transmissions. In comparison, each BGDL unit was scheduled to fix positions at two hour intervals. The start time of one unit was set at 0:00 and the other at 1:00. Thus, we could fix positions over two months at one hour intervals. In Fig. 6b, we show a partial sea ice drift trajectory, obtained using these two methods. The difference in the accuracy of the positions fixed by the two systems is obvious. As for the failure rate, BGDL succeeded in all the fixing trials. The ARGOS system failure rate is difficult to define in this case because the transmitter on the buoy sends signals periodically without taking into account the position of the ARGOS satellites. In some cases it succeeded in fixing within a very short interval, but in others it could not fix a position for many hours. The maximum interval between two successive fixings was 3 h and 26 min.

## Albatross tracking

Due to the weight of the units and the necessity of re-capture, we selected certain species of albatrosses for the first application of our units.

a)

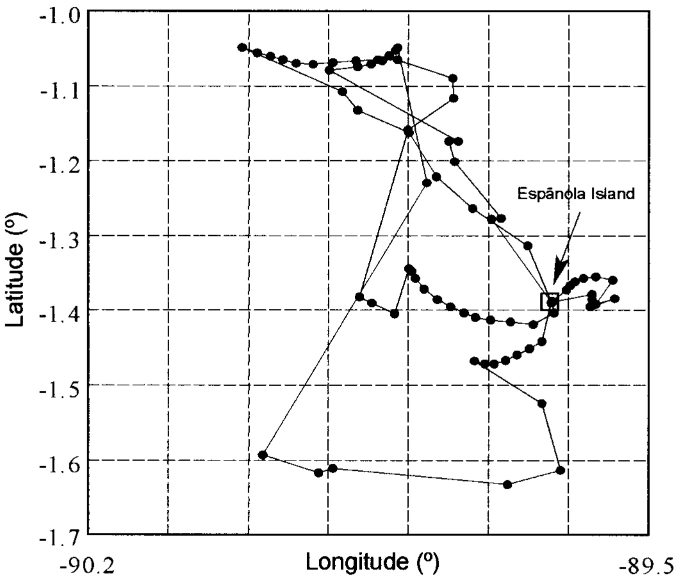
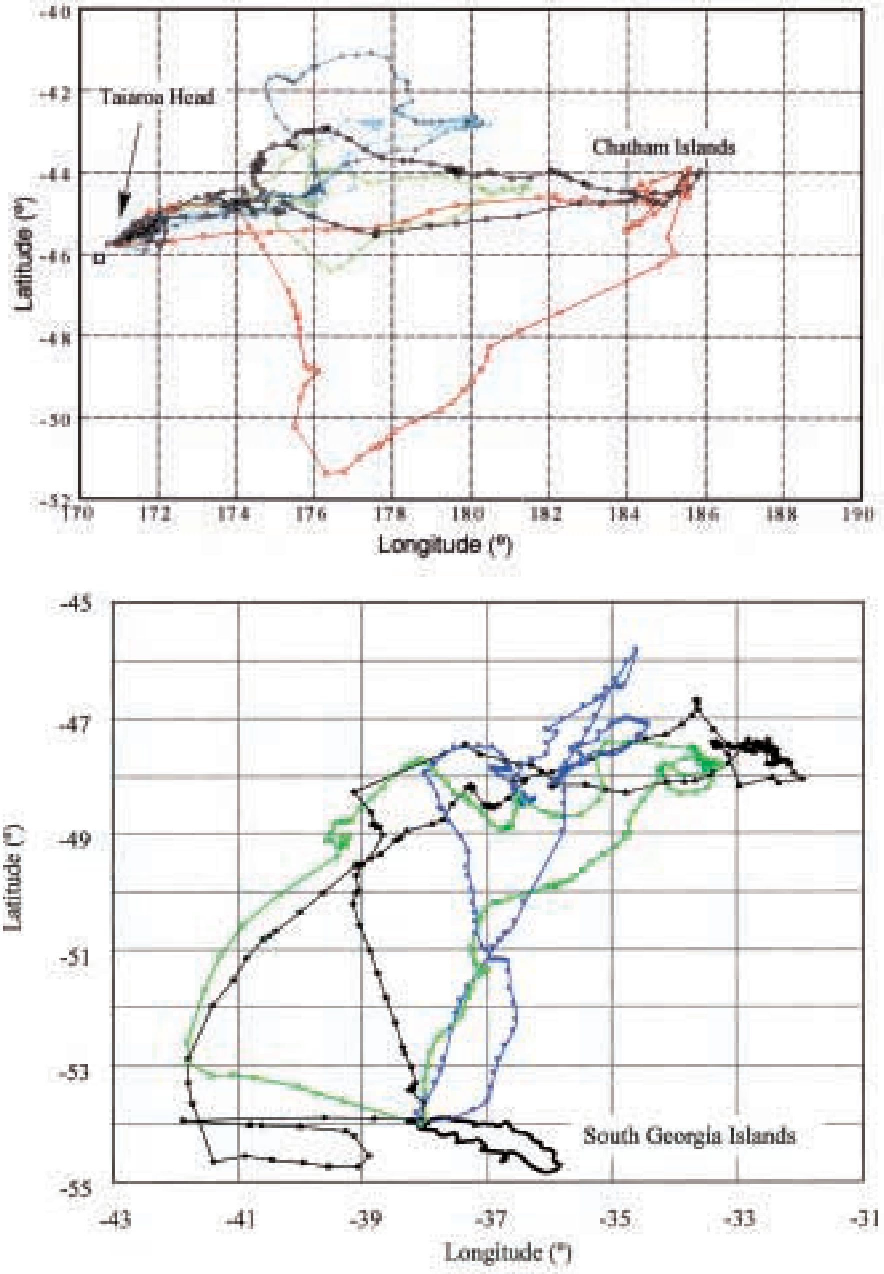



Fig. 7. Tracking of albatrosses
a) Tracking of a waved albatross around the Galapagos Islands (July 12–22, 2002). The bird made 3 trips during this period (the fixing interval was 1 hour). In this and the following figures, west longitude and south latitude are shown using minus signs.

b)




c)

Fig. 7. (continued)
b) Tracking of 5 royal albatrosses around Taiaroa Head (December 5, 2002–January 1, 2003). Light blue line: ID59007, dark blue line: ID69007, black line: ID72007, red line: ID75005, green line: ID80005.
c) Tracking of 3 grey-headed albatrosses around the South Georgia Islands (December 15–January 1, 2003). Black line: ID1320601, blue line: ID1318273, green line: ID1147616.

Waved albatross (*Diomedea irrorata*) tracking around the Galapagos Islands

In the year 2000 we began using our units for a study of albatross at Espãnola Island (1°23′S, 89°37′W). In 2001 we succeeded in obtaining data, using BGDL-I (weight 100 g), on the lengthy round trip of a bird from its nest to the west coast of South America (Fukuda *et al*., 2002). In 2002, using BGDL-II (weight 66 g), we concentrated on obtaining more detailed data on shorter trips. This new version was more reliable and successful than BGDLI. However, some problems occurred in the software, schedule setting, and deployment so that we obtained only fragmentary data from the deployment in this experiment (Fukuda *et al*., 2003).

Figure 7a shows only the most successful result obtained during the 2002 season. The failure rate was 38% in this case. There were no significant differences between the failure rate of fixings taken while the birds were traveling and those taken during their stays in the nest. In July 2003, we began to deploy more efficient and reliable BGDL-II$^+$ units.

Royal albatross (*Diomedea epomophora*) tracking around Taiaroa Head (Otago peninsula, New Zealand)

In December 2002, we deployed twenty BGDL-II$^+$ units on royal albatross at Taiaroa Head (45°40′S, 170°44′W). The results of this experiment confirmed that this version has a higher success rate than its predecessors. Reliable data were obtained from seventeen units (5 examples are shown in Fig. 7b, while in the other three cases we made mistakes in setting the schedule or the birds did not make a long journey. Details about the behavior of birds, some of which went beyond the Chatham Islands more than 1000 km away, will be reported elsewhere. The scheduled time interval between successive fixings was one hour for all the experiments.

Table 2 summarizes the failure rate, which we found to be only a little larger during the traveling phases than during the nest attendance phases. The average (± standard deviation) failure rate was 24 ± 19%. There were some cases with failure rates <10%, while it increased up to 50% or more in other cases. There were no significant differences between the conditions (days of the experiment, size of the birds, length of the trips, etc.) in which these experiments were conducted. This suggests that our unit is in itself very reliable and that the success or failure of an experiment largely depends on other elements, such as the users' skill in attaching the units to the birds, the state of the units after the bird dived into sea water, etc.

Grey-headed albatross (*Diomedea chrysostoma*) tracking around the South Georgia Islands

In December 2002, we deployed three BGDL-II$^+$ units on grey-headed albatrosses at Bird Island (54°01′S, 38°04′W) in the South Georgia Islands (Fig. 7c). This experiment gave us even better results than those from Taiaroa Head. The failure rate for the three units is shown in Table 3. The total average failure rate was 10 ± 4%. It is interesting to note that the rate was a little lower during the traveling phases than during the nest attendance phases. The fixing interval was one hour in experiment ID1320601 and 45 min in the other two.

## Conclusions

The failure rate in the fixing of positions during flight using the newest BGDL-II$^+$ was 26 ± 20% on average, but in many cases it was lower than 10%. In this regard, we believe

Table 2. Failure rate in the fixing of 17 royal albatrosses foraging around Taiaroa Head.

| Overall | | | | Travelling phase | | | | Nest attendance phase | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Success | Failure | Failure rate | ID | Success | Failure | Failure rate | ID | Success | Failure | Failure rate |
| 59007 | 212 | 147 | 0.41 | 59007 | 74 | 117 | 0.61 | 59007 | 138 | 30 | 0.18 |
| 61005 | 274 | 39 | 0.12 | 61005 | 214 | 30 | 0.12 | 61005 | 60 | 9 | 0.13 |
| 62007 | 256 | 104 | 0.29 | 62007 | 165 | 92 | 0.36 | 62007 | 91 | 12 | 0.12 |
| 69007 | 307 | 76 | 0.20 | 69007 | 156 | 66 | 0.30 | 69007 | 151 | 10 | 0.06 |
| 70005 | 127 | 19 | 0.13 | 70005 | 81 | 10 | 0.11 | 70005 | 46 | 9 | 0.16 |
| 71005 | 205 | 11 | 0.05 | 71005 | 138 | 8 | 0.05 | 71005 | 67 | 3 | 0.04 |
| 72007 | 371 | 12 | 0.03 | 72007 | 297 | 8 | 0.03 | 72007 | 74 | 4 | 0.05 |
| 73005 | 49 | 265 | 0.84 | 73005 | 25 | 233 | 0.90 | 73005 | 24 | 32 | 0.57 |
| 74007 | 131 | 33 | 0.20 | 74007 | 52 | 24 | 0.32 | 74007 | 79 | 9 | 0.10 |
| 75005 | 239 | 49 | 0.17 | 75005 | 156 | 32 | 0.17 | 75005 | 83 | 17 | 0.17 |
| 77005 | 113 | 53 | 0.32 | 77005 | 81 | 42 | 0.34 | 77005 | 32 | 11 | 0.26 |
| 78005 | 294 | 141 | 0.32 | 78005 | 130 | 125 | 0.49 | 78005 | 164 | 16 | 0.09 |
| 80005 | 221 | 21 | 0.09 | 80005 | 142 | 10 | 0.07 | 80005 | 79 | 11 | 0.12 |
| 82007 | 147 | 19 | 0.11 | 82007 | 44 | 11 | 0.20 | 82007 | 103 | 8 | 0.07 |
| 84005 | 211 | 30 | 0.12 | 84005 | 140 | 25 | 0.15 | 84005 | 71 | 5 | 0.07 |
| 87007 | 121 | 23 | 0.16 | 87007 | 72 | 22 | 0.23 | 87007 | 49 | 1 | 0.02 |
| 88005 | 479 | 119 | 0.20 | 88005 | 357 | 106 | 0.23 | 88005 | 122 | 13 | 0.10 |
| Total | 3757 | 1161 | 0.24 | Total | 2324 | 961 | 0.29 | Total | 1433 | 200 | 0.12 |

Table 3. Failure rate in the fixing of 3 grey-headed albatrosses foraging around the South Georgia Islands.

| Overall | | | | Travelling phase | | | | Nest attendance phase | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | Success | Failure | Failure rate | ID | Success | Failure | Failure rate | ID | Success | Failure | Failure rate |
| 1147616 | 439 | 66 | 0.13 | 1147616 | 210 | 32 | 0.13 | 1147616 | 229 | 34 | 0.13 |
| 1318273 | 344 | 17 | 0.05 | 1318273 | 277 | 12 | 0.04 | 1318273 | 67 | 5 | 0.07 |
| 1320601 | 296 | 38 | 0.11 | 1320601 | 203 | 30 | 0.13 | 1320601 | 93 | 8 | 0.08 |
| Total | 1079 | 121 | 0.10 | Total | 690 | 74 | 0.10 | Total | 389 | 47 | 0.11 |

that the performance of our unit is satisfactory. The following modifications are being considered for our GPS loggers.

1) Adding a limited ability to transmit stored data:

We will add to the unit a small transmitter with minimum transmitting power. It will start sending the stored data automatically when the unit comes within communication range of a receiver deployed in an area to which the bird will return. The transmitter will be powered by the remaining capacity of the battery and have a range of less than a few hundred meters. This development will render the recapture of birds unnecessary.

2) Adding continuous mode operation with larger memory capacity:

There is no technical problem in providing continuous mode operation in which a unit notes position data every second because it is the original mode of operation for the GPS receiver used for our loggers. However, such a design would require an upgraded memory chip with increased capacity to store all the data. There is again no technical problem in upgrading the memory. Moreover, as technology advances, memory chips are becoming smaller and lighter.

3) Developing a lighter version with limited ability:

In the cases of terrestrial bird studies and studies of sea birds smaller than albatrosses we can make a lighter unit with less waterproofing and decreased ability regarding the number of positions it is able to fix and store.

4) Developing a heavier but more powerful version:

In the tracking of larger subjects, such as mammals, a heavier but more powerful version with a bigger battery, more memory, and increased transmitting ability would be helpful. By using our unit as a base and linking it with various suitable sensors, we can develop further useful and interesting systems.

5) New application areas:

The principle we have developed here is applicable to many other fields. For example, alongside its use in the tracking of birds and mammals, the system can be used in the monitoring of sea ice drifts and sea water flow patterns.

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