Ultra-light bird tracking system based on BGPS™

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BIOGRAPHY

Dr. Ivan G. Petrovski has been in the GNSS field for more than 25 years. He holds a Ph.D. degree from the Moscow Aviation Institute. He worked as an Associate Professor there before being invited in 1997 by the Japan Science and Technology Agency to join the National Aerospace Laboratory as a research fellow. At present he is concentrating on developing software receiver and simulator technology for iP-Solutions, Tokyo, Japan.

Charles Bishop is a lecturer in animal locomotion and energetics at Bangor University, North Wales, UK. He has an interest in the limits to animal flight performance and has been researching into the biology of the migratory bar-headed goose (Anser indicus), funded by the Biotechnology and Biology Research Council (BBSRC), UK.

R. J. Spivey designed the hardware and wrote the firmware for the miniature GPS tracking system and is currently funded by the BBSRC, UK.

INTRODUCTION

The paper describes ultra-light tracking system designed to serve for tracking bar-headed geese (*Anser Indicus*) and other types of birds for a period of about one year. The paper describes motivations behind the project, achieved results, underlying technology, as well as the hardware and software components of the system. It also presents initial test results.

1. IMPORTANCE OF BIRD TRACKING

Since the industrial revolution, human civilization has had an unduly adverse impact on the planet's ecology. Restraining this impact benefits from knowledge of ecological changes. The migratory pathways and habitats selected by avian species are sensitive, amongst other things, to anthropogenic climate change, and contamination of the environment. Thus, it is important to be able to quantify the strategies deployed, and the effort expended, on these long distances journeys.

Figure 1 Bar-headed gees (Anser indicus)

High resolution, high frequency positional fixes of birds over a twelve month period allows the foraging habits, diurnal activity, flight physiology and migratory routes of wild birds to be studied. The advent of power-efficient miniaturised positioning technology, particularly in conjunction with systems capable of monitoring such things as cardiac activity, temperature and tri-axial acceleration, permits the collection of far more detailed data than has hitherto been possible. Such knowledge can help determine the degree of difficulty involved, particularly in the climbing phases of the migratory flights

Animals that locomote using flight have to address the formidable physiological challenge of overcoming the weight of gravity. In order to have a minimal impact on their ability to sustain flight, perhaps alongside unloaded birds who are navigationally important companions during migrations, it is imperative that any tracking system be as lightweight as possible. This requirement becomes particularly acute for systems that must collect data with high frequency since this has repercussions both for memory needs and battery size. Apart from being very lightweight, such a system must also be unobtrusive so as not to interfere with the flight aerodynamics, muscle mechanics or ability to dive or swim underwater (buoyancy). It must be weatherproof, waterproof, capable of tolerating extreme environments and sufficiently robust to withstand attack by other birds.

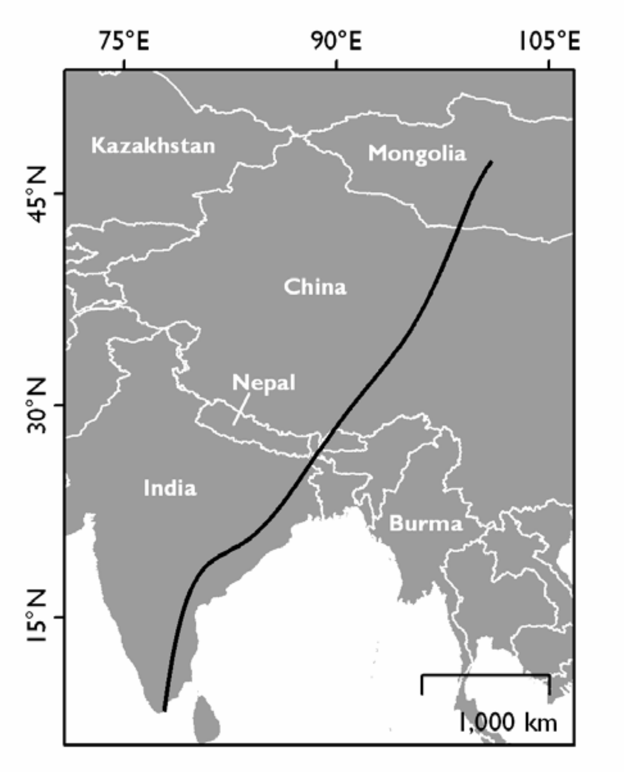

Figure 2. Bar-headed gees (Anser indicus) migratory pathway.

2. HISTORY OF THE PROJECT

A significant population of bar-headed geese (*Anser Indicus*) (see Figure 1) spend their winters in India and summers in Mongolia. The migrations involve crossing the Himalaya at altitudes of some 6000m where high winds, low oxygen density and sub-zero temperatures pose particular challenges (Figure 2). The very early ancestors of these geese did not have to cross the Himalaya before India underwent a geological collision with mainland Asia. In evolutionary terms, this was a recent event, and led to rapid adaptations spurring extreme athleticism in this species of goose.

The project's main aim was to study these migrations and determine how challenging the migrations are, particularly those sections of the migration demanding prolonged ascending flight at high altitudes. Initial studies deployed Argos transmitters powered by solar panels that attempted to relay an hourly positional fix via satellite telemetry. These systems proved somewhat unreliable, and providing at best intermittent results. Where positional fixes were available, the altitude and speed data was not always. The results were sufficient to demonstrate that the geese invariably follow a single broad corridor through the eastern Himalayan mountains, but insufficient to allow the pattern of ascending flight to be studied in any detail.

Since the geese are flightless for a few weeks each summer, and tend to return faithfully to a complex of lakes in Mongolia, it is possible to consider deploying recoverable systems that need not attempt to relay their data via power-hungry satellite links. The recapture of geese is possible without causing stress to the geese. Kayaks are used to gently persuade the geese floating on the lakes to paddle towards the shore where fenced enclosures await them.

3. BGPS

The BGPS technology [1] has been adapted for the presented system in order to process very short chunks (tens of milliseconds) of recorded GPS signal and find a correspondent antenna positions. The BGPS is an approach to global positioning that confers ultimate advantages over alternative methods when it is required that a position fix should be done after a few milliseconds of GPS signal reception. The BGPS also allows to meet real-time requirements. Providing an initial estimate of time within seconds or even tens of seconds is available, the raw signals from a constellation of GPS satellites need only be sampled for a few milliseconds in order that a antenna position can be obtained in real-time or in post-processing. The presented system requires only the post-processing mode, which ease some restrictions for initial time constrains. This processing can be performed using a fast desktop PC whose power consumption is unimportant, while the raw data is collected and stored very efficiently in bursts by the system in the field. Unlike other approaches common in battery powered GPS systems, there is no need for a lengthy warm-up interval of the order of 30-120 seconds while satellite navigation message is obtained.

Normally a receiver can find its position (i.e. antenna phase center position), because it knows distances to satellites and position of these satellites. The receiver can determine a satellite position because it knows satellite ephemeris and the epoch of signal transmission. The satellite position and epoch of transmission are encoded in navigation message in the satellite signal. It takes 36 seconds to ensure that the receiver has received enough information in order to find its position.

The BGPS uses ephemeris, which are delivered outside of the receiver. In particular we can use IGS ephemeris [2] or ephemeris, which we download from live satellites on a different receiver, which operates continuously. For real-time implementations ephemeris can be predicted for 3-10 days in advance or even longer.

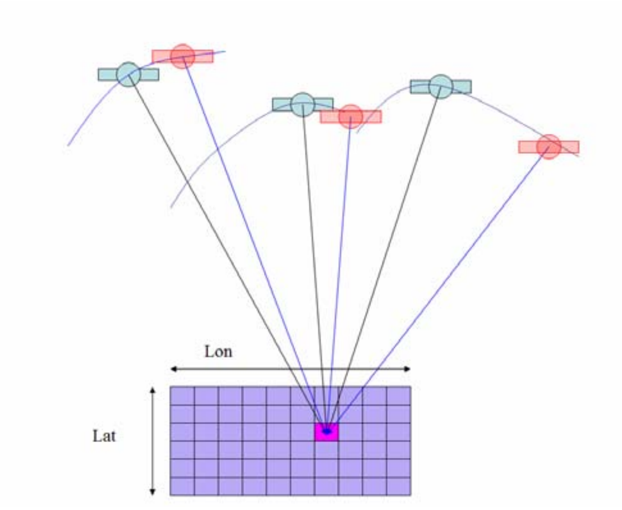

Figure 3 Search grid for brute force algorithm in 2D+1.

If we also can avoid a decoding of the time of transmission, then it allows us to reduce time of receiver operation required for one position fix from 6 seconds down to 1 millisecond. To ensure good acquisition results the records of up to 20 millisecond of signal or longer are required. If for example the receiver operates for only 36 millisecond to record GPS signal, then it means that power consumption goes down about 1,000 times in comparison to a receiver, which operates for 36 second to receive all data from the navigation message. Actually, the power consumption in case of using BGPS is even smaller, because the receiver doesn't need a navigation processor, which also reduces overall weight significantly.

One cannot provide predicted ephemerides for the length of one year or even a month, therefore the system operates essentially in post-processing mode, collecting short, records of GPS signal and storing them in the memory. Later these records are processed using external ephemeris information and positions for each record are recovered.

Now we consider how we can avoid a necessity of decoding a time mark in navigation message. The GPS equations can be presented in the following form using matrix form for convenience as follows.

$$\overline{Z} = \left[A(\overline{X}) \right]$$

where $\overline{X}$ is a state vector consist of receiver antenna coordinates and receiver clock error

$$\overline{X} = \begin{bmatrix} x_r \\ y_r \\ z_r \\ \delta t_r \end{bmatrix}$$

and $\overline{Z}$ is an observation vector constructed from measured pseudoranges

$$\overline{Z} = \begin{bmatrix} \rho_{s_1} \\ \rho_{s_2} \\ \cdots \\ \rho_{s_n} \end{bmatrix}$$

In order to solve a positioning task we need to find 4th order vector $\overline{X}$ using vector of pseudorange measurements $\overline{Z}$ of *n-th* order.

The core of the problem is in that without a time mark we now need to introduce an extra variable into the equations. When the time of transmission from navigation message is unavailable, the new state vector $\overline{X}'$ is now extended state vector

$$\overline{X}' = \begin{bmatrix} x_r \\ y_r \\ z_r \\ \delta t_r \\ t_r \end{bmatrix}$$

An additional variable , which is a time of signal reception t_r, is introduced now into the state vector. Previously, the time of signal reception was assumed to be known as it is derived from navigation message with certain accuracy.

The observation vector is also changed because the receiver cannot restore pseudoranges unambiguously without the time mark.

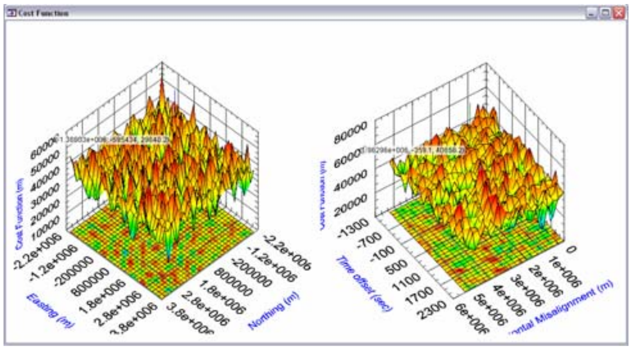

Figure 4. Cost function for Latitude-Longitude search area (on the left) and time offset-position misalignment (on the right).

$$\bar{Z} = \begin{bmatrix} \Delta\rho_{s_1} + N_{s_1} \\ \Delta\rho_{s_2} + N_{s_2} \\ \cdots \\ \Delta\rho_{s_n} + N_{s_n} \end{bmatrix}$$

The equations became essentially non-linear, because we don't have fixed satellite positions anymore and they should be introduced also as functions of this additional variable. The straight implementation can use brute forth method to check assumed position, satellite orbits and time variables (both clock error and time of reception) for consistency. Figure 3 shows 2-dimensional search space and schematically introduce 4th (5th in 3D case) search dimension as alternative satellite positions. The 3rd (and correspondently 4th in 3D case) variable is clock error. Processing software essentially needs to minimize a criterion, which is formed as a cost function based on residual pseudoranges. The simplified criterion can be expressed as follows.

$$CF = (\bar{Z} - \tilde{\tilde{Z}})^T \times (\bar{Z} - \tilde{\tilde{Z}})$$

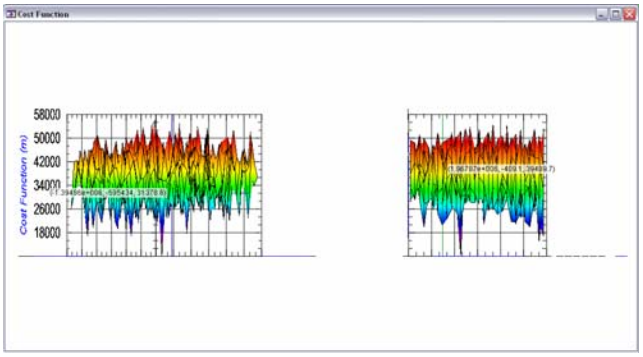

Figure 5. Cost function for Latitude-Longitude search area (on the left) and time offset-position misalignment (on the right). Lateral view.

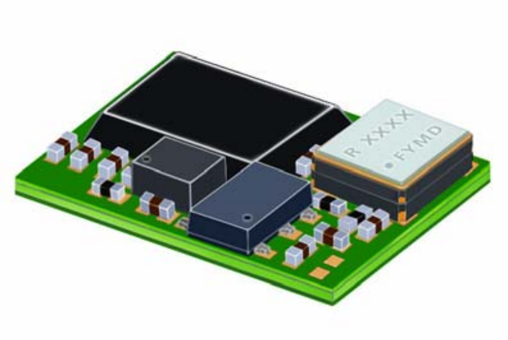

Figure 6 Rakon GPS module with integrated TCXO.

where

$$\tilde{\tilde{Z}} = \left[A(\hat{\hat{X}}') \right]$$

Implementation of the brute force algorithm is limited to pure academic purposes due to the prohibitive calculation cost. BGPS applies advanced heuristic algorithm along with additional extended criterions formed of the pseudorange derivatives. The global minimum of cost function *CF* gives the sought position. It is very important that the CF has multiple local minima (see Figures 4,5), so standard optimization algorithms are not applicable for this task.

4. IMPLEMENTATION

4.1 System design and specification

After initial feasibility review of applying BGPS technology to study the iconic migrations of bar-headed geese, the decision was taken to design a miniature datalogger that could be mounted on a neck collar worn by the geese. The system records regular snapshots of raw GPS data for post-processing following recapture. The deferral of post-processing provided a substantial advantage in terms of battery size and life.

The goal was ideally to develop a system capable of acquiring several GPS fixes per hour for an entire year, with a system weight of less than 2% of the goose body mass. It was known from previous studies that short flights are barely influenced if pigeons are loaded with a mass of 5% their body weight.

The target for power consumption was approximately 100mA per fix, with the system remaining active for around a quarter of a second per GPS snapshot. With the battery specifically selected for this system, this enabled up to 20 snapshots to be obtained per hour.

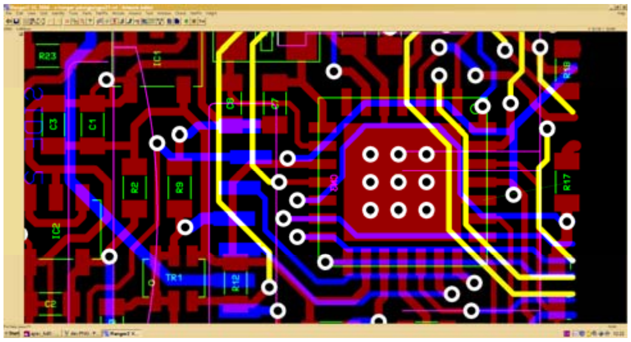

Figure 7 PCB layout for data loggers

4.2 Hardware

An extremely compact GPS Rakon front-end with on-board temperature compensated crystal oscillator (Figure 6) was used. It was capable of outputting a continuous stream of raw data following the configuration of internal registers. This data stream was interfaced directly to a high performance microcontroller capable of simultaneously accepting the incoming data and writing it to a memory storage device. Some intermediate buffering of the data was performed within the microcontroller, with precautions against buffer overruns being implemented in the code so that unpredictable latencies in the memory storage device could be confidently identified during post-processing. With this approach, less than 10% of the recorded data was corrupted due to storage overheads. A barometer and temperature sensor were also included. The barometer provided independent altitude estimates capable of assisting the GPS altitude fixes, and its fine resolution translated into altitude changes of some 0.1 meters, useful in the study of ascending flight. The temperature sensor provided an indication of the ambient air temperature.

Figure 8 Collars assembled

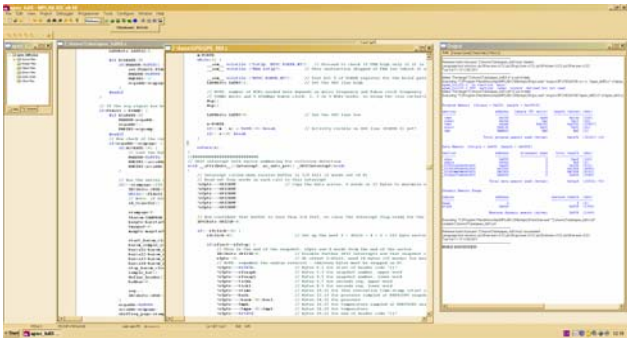

Figure 9 MPLAB IDE for firmware programming, used for creating dataloggers firmware.

4.3 Firmware

The firmware was written mainly in C, with some time-critical portions of the code in assembly language (Figure 9). Particular attention was paid to minimizing power consumption and eliminating unnecessary delays in the communication protocol to the memory storage device. Sleep modes reduced the power consumption to a negligible level between GPS snapshots. The start time of each snapshot was logged and had a resolution of 30 micro seconds.

4.4 Software

A processing software applies three steps to provide a position fix

1) orbit preparation,

2) signal acquisition,

3) raw data processing.

Orbit preparation step is using IGS products, which are tabular orbits in SP3 format. The orbit coordinates and

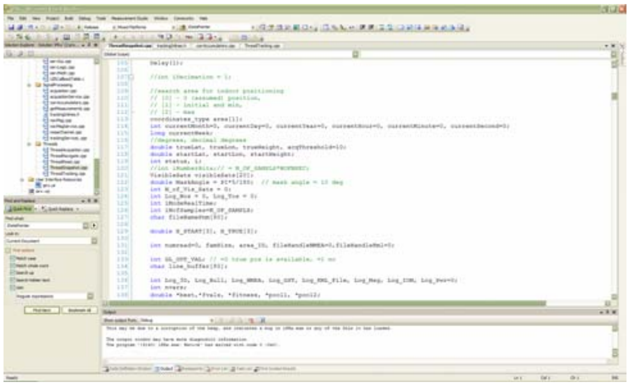

Figure 10. MS Visual Studio IDE for post-processing software programming.

Figure 11. Team of biologists in the field (Mongolia).

clocks are given for each 30 seconds. The orbits are preprocessed by the software, which creates continuous interpolated orbit representation, using optimized trigonometric interpolation.

The signal acquisition part acquires the signal using FFT algorithms. The acquisition algorithms are designed to implement non-coherent, differential and coherent acquisition and their combination to improve sensitivity and allow shorter records.

Acquisition part outputs raw data, which are measured pseudorange differences. Note that we don't have pseudoranges as such, because those cannot be restored without reading a time mark from navigation message.

Figure 12 . Gees with collars on.

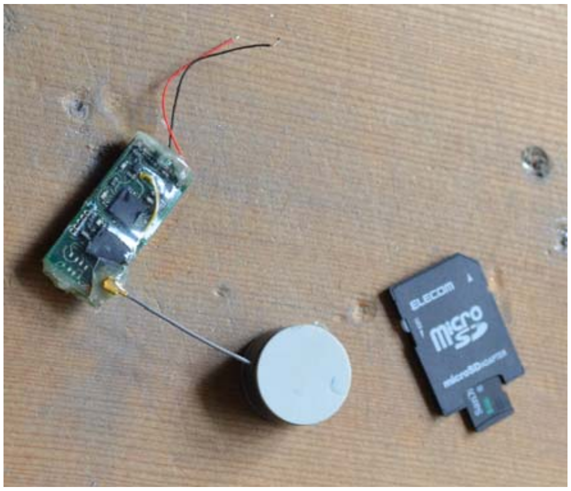

Figure 13. Datalogger, antenna and SD card with an adapter.

The accuracies of the pseudoranges are limited by the sampling rate, which is chosen to minimize memory requirements for the records. The essential difference between acquisition and tracking in terms of accuracy is that acquisition accuracy is usually limited by the distance between the samples, whereas the tracking accuracy is defined by the signal bandwidth, and therefore usually much higher. The processing software however applies further processing, which allows to refine pseudorange accuracy down to acceptable level. The software is written in C++ in Microsoft Visual Studio Environment.

5. TEST

Figure 11 and 12 shows how the field test with gees receiving colors with dataloggers. Initial test are conducted using a modified iPRx software receiver and prototype dataloggers (Figure 13). The first series of tests have been aimed to ensure that dataloggers operate correctly and GPS signal is recorded.

A further consideration was the choice of an antenna. Second series of tests were conducted in order to test antenna performance. High gain active antennas allow the duration of a GPS snapshot to be decreased, but are incompatible with the size and weight constraints. After much experimentation, a compromise capable of meeting the design goals was eventually identified. Further refinement of the antenna design will be one aim of future work since further weight savings appear possible.

Figure 14. Result of positioning test with processing software in Google Earth. Accuracy is within 20 meters.

Finally, the position fix has been obtained using the records from a datalogger (Figure 14). The accuracy currently is about 25 meters, but can be further improved with signal processing.

CONCLUSION

The further steps we are undertaken now include system refinement before conducting field tests next year.

These refinements include improvements of accuracy and sensitivity of the post –processing software along with providing it with more user friendly interface.

The other goal is a refinement of antenna. One of the solutions under consideration is an addition of on-board amplifier.

We plan to conduct also a feasibility study of mounting modified datloggers on tail feathers. Further adaptations in terms of weight are required for very small birds. Even the current design allows some weight reductions by choosing different butteries.

ACKNOWLEDGEMENT

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