THOMAS E. STRIKWERDA, HAROLD D. BLACK, NADAV LEVANON, and PAUL W. HOWEY

THE BIRD-BORNE TRANSMITTER

APL has developed a small, lightweight transmitter to track the positions of migratory birds by satellite. Solar-powered prototype units weighing less than 170 grams have been built and used to position free-flying birds. Future plans include the development of smaller, lighter units having microprocessor-based environmental sensors.

INTRODUCTION

In mid-1982, biologists from the U.S. Fish and Wildlife Service asked APL to design a small transmitter to track the position of migrating birds with a satellite.

APL had had much experience in satellite positioning using the Doppler effect, but little in tracking animals.[1] In principle, it should be possible to track birds that way, but we could not respond with confidence about the practicality of such a task. After a four-month feasibility study, our answer was a qualified "yes." We identified several critical elements that would require design and test. On the other hand, we believed there was a good chance of success. We began work on the design of a bird-borne transmitter in January 1983 and, after a year and a half, are nearing our goal.

The Fish and Wildlife Service is particularly interested in tracking endangered birds of prey during their migration. Satellite tracking would provide information about the routes between their summer and winter habitats. Conventional tracking by ground or airplane is expensive, time consuming, and limited.

The biologists' tracking requirements are not particularly stringent: (a) locate the birds once per day with an accuracy of about 1 kilometer and (b) track them for one entire migration cycle (roughly 200 days). The weight and volume restrictions on the transmitter were a challenge: the weight should be no more than 10 percent (preferably closer to 5 percent) of the bird's weight, typically 1 kilogram for the birds of interest, and the package should be small enough to avoid interfering with the bird's activities. Although the transmitter must be small, it must also radiate enough power to transmit to a satellite.

FEASIBILITY STUDY

During the study phase, we examined three major questions:

1. Could an existing satellite system be used or would we have to consider building a satellite, receiver, and ground support facilities?
2. How much power would be required, and how would it be supplied?
3. Could we develop an RF design that would be small, stable, and powerful?

The results of the feasibility study were encouraging. We determined that the Argos satellite system, which uses Doppler positioning, would be suitable for tracking birds. Rechargeable batteries in combination with solar cells could probably provide enough power. The major risk areas were the power supply system and the frequency stability needed to locate the bird accurately.

THE ARGOS SYSTEM

Shortly after we began our study, we learned of the Argos system[2] on board the National Oceanic and Atmospheric Administration's Tiros satellites. The Argos system is similar to the Navy Transit system[3] but inverted. A transmitter on the earth sends short messages to a satellite; the frequencies, as measured by a satellite receiver, are used to determine the transmitter's location. As the satellite approaches and then passes over the transmitter, the measured frequencies drop because of the Doppler shift. The change in frequency is caused by the change in relative velocity along the line of sight between the transmitter and the receiver. The rate at which the frequency drops and the time when the drop occurs are related to the geometry of the satellite path relative to the transmitter. The position of the transmitter on the earth can be determined if the satellite's orbit is known. The location calculations are performed in Toulouse, France, by Service Argos and are disseminated quickly (typically in 4 hours) to users around the world via a computer and telephone network (Fig. 1).

There are two Tiros satellites in the Argos system, in (approximately) 850-kilometer sun-synchronous orbits; their orbits intersect the equatorial plane at points 67° apart and are inclined 98.7° relative to the equator. Depending on the transmitter's latitude, it is possible to determine its location between 6 and 20 times a day.

Each transmitter is assigned an identification number that is encoded in the signal, making it possible to track hundreds of transmitters around the world. The Argos system was designed for tracking weather

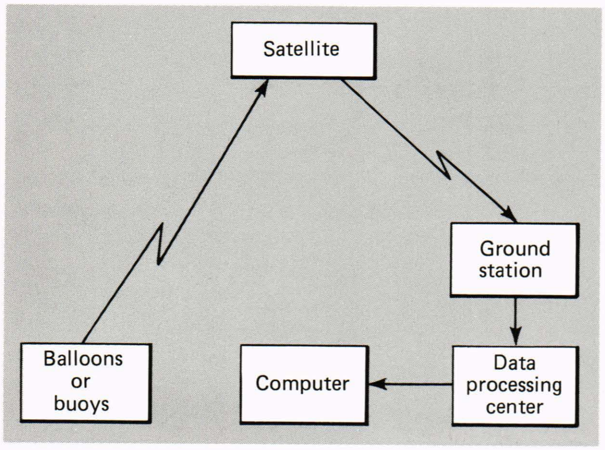


Figure 1—The Argos system is used primarily for collecting weather data from balloons and buoys, but there are other uses such as locating wildlife. The Tiros satellite measures the frequency of signals it receives as it passes over each transmitter and records the transmission data and frequency along with the time on magnetic tape. When the satellite passes over a ground station, the data are transmitted to the ground and relayed to France for processing. The transmitter location and message data for each pass are then sent to a computer, which can be accessed by users. The total elapsed time from data transmission to computer is 3 to 4 hours.

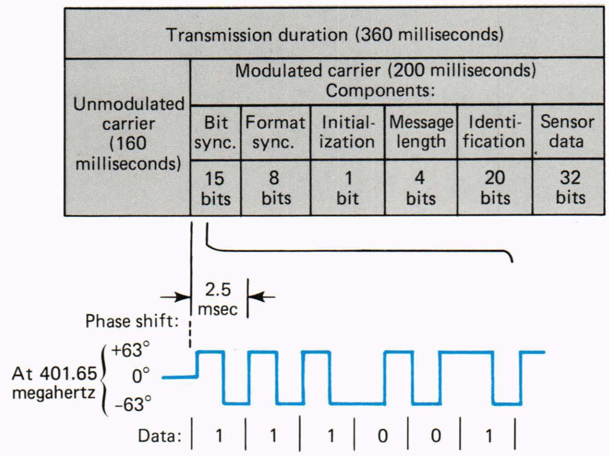


Figure 2—The Argos signal format. The system accommodates a large number of users by having each transmitter send a short signal every 40 to 60 seconds. Each transmission has two parts: a carrier portion followed by a phase-modulated portion. The satellite receiver locks onto the signal during the 160 millisecond carrier. This portion is followed by synchronization patterns, a transmitter identification code, and finally the sensor data. The shortest transmission allowed is 360 milliseconds for 32 bits of sensor data; the longest is 960 milliseconds for 256 bits.

balloons and buoys. Transmitters have also been placed on sailboats participating in transoceanic races and on icebergs for studies of ocean currents. There are about 400 transmitters in use, most of them on weather buoys.

In addition to an identification number, there is provision in the satellite system for receiving data encoded in the signal. Therefore, sensors incorporated in the transmitter could provide information about the bird and its environment. The Argos signal format is shown in Fig. 2.

Permission to use the Argos system is granted if the transmitter meets certain specifications (see Table 1). Although the specifications are strict, especially considering the size, weight, and power limits that are necessary when tracking birds, the near-real-time Argos system allowed us to focus our efforts on the transmitter.

Table 1—Basic Argos specifications (from the *Argos User's Guide*).

Nominal frequency	401.65 megahertz ±1.2 kilohertz
Aging	±2 kilohertz per lifetime
Short-term stability, df/f	10^{-9}
Medium-term stability	10^{-8} per 20 minutes
Effective radiated power	1 to 10 watts
Phase modulation:	
Levels	0°, + 63°, −63° (±6°)
Symmetry	≤5°
Modulation rate	400 ±5 hertz
Transmission duration	360 + ($N \times 80$) milliseconds (N = 0, 1, ... , 7)
Repetition period	40 to 60 seconds

BIRD-BORNE TRANSMITTER COMPONENTS

The transmitter can be divided into the following major modules (Fig. 3): a power supply consisting of rechargeable batteries and a solar array; an encoder containing a clock that controls the transmitter timing; a precision oscillator that provides a precise frequency for Doppler positioning; a phase modulator for incorporating a message in the signal; and an amplifier to provide enough power for the signal to be received by the satellite and an antenna.

The packaging of the transmitter is also very important in this application. While designing each section, we had to keep in mind the weight, volume, and power of the transmitter. Compromises had to be made to keep the transmitter small.

Power System

One major concern was power. Argos requires approximately 1 to 10 watts of radiated power compared to the several milliwatts radiated by conventional transmitters used to track wildlife from the ground or from airplanes. The milliwatt transmitters have ranges of kilometers or a few tens of kilometers, while the range to a satellite is typically several thousand kilometers. However, the average power of the bird-borne Argos transmitter is quite low because each transmission lasts

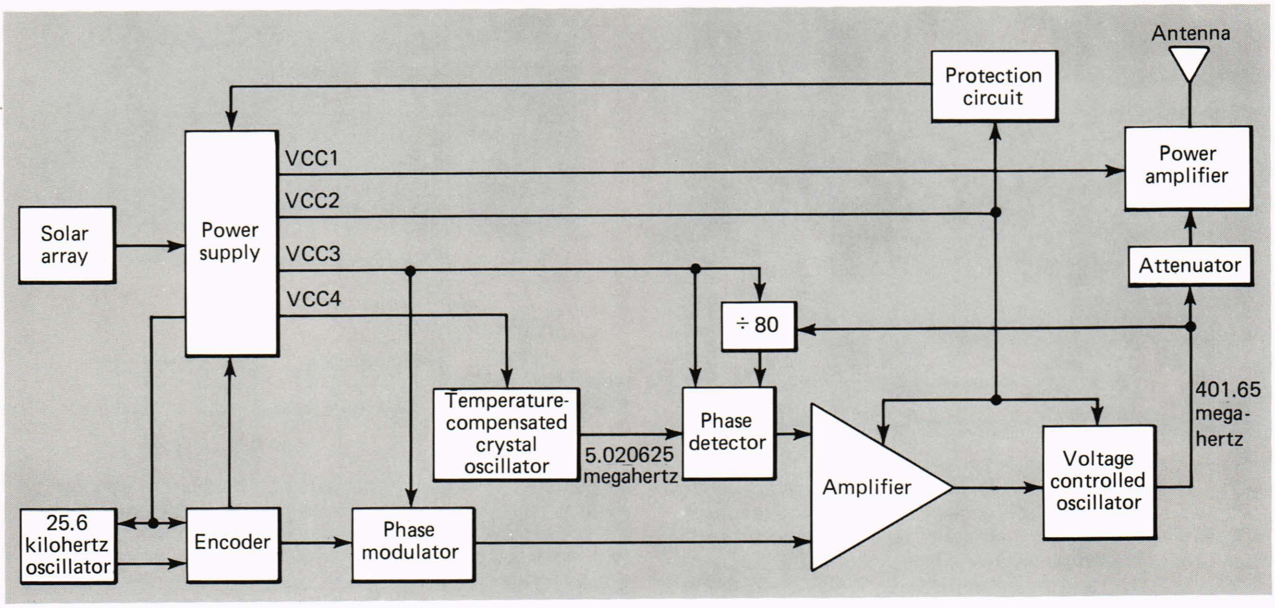


Figure 3—The five main transmitter subassemblies: power supply, encoder, temperature-compensated crystal oscillator, voltage-controlled oscillator, and power amplifier. When the batteries are nearly drained, all components except the charge control circuitry in the power supply are turned off. The charge control circuit is on at all times and draws very little current. If the batteries are charged, the encoder is turned on. The encoder controls all other timing in the transmitter. The temperature-compensated crystal oscillator and voltage-controlled oscillator are turned on just before each transmission. The most power-consuming device, the power amplifier, is on only during actual transmission. The average current is only 4 milliamperes.

only 0.360 second and repeats every 40 to 60 seconds (giving a duty cycle of approximately 1/150). Further (average) power reductions are possible. It is unnecessary for the transmitter to radiate all day because only one location is needed per day. If we assume a 30 percent efficiency, a duty cycle of 1/150, and 1 watt of radiated power, the average consumed power of the transmitter would be about 24 milliwatts.

Two methods are possible for supplying power: high-energy-density primary batteries or secondary (rechargeable) batteries in conjunction with solar cells. The best primary batteries (lithium–thionyl chloride) have 20 times the energy density of nickel-cadmium secondary batteries (500 versus 25 watt-hours per kilogram). However, the 200-day lifetime of the transmitter (one migration cycle) and the average power of 24 milliwatts imply a primary battery weight of 200 grams. A duty cycle reduced by half would still require batteries that would weigh too much. Therefore, the secondary batteries were chosen, provided that we could show that they could be recharged daily by a small solar array.

Batteries charged daily must supply about 0.50 watt-hour and would weigh about 22 grams. To avoid deep discharge, the battery should be 50 percent larger than this. Even after adding the weight of a solar array, the secondary battery system is lighter than one with primary batteries. Six nickel-cadmium cells are needed to supply the current and voltage, each supplying 1.4 volts, for a total weight of 35 grams. Other types of secondary batteries were considered but were rejected for various reasons.

The size of the solar cell array was determined from solar radiation studies. The solar constant is approximately 110 milliwatts per square centimeter for direct, vertical sunshine. Solar cells are about 10 percent efficient, and battery charging efficiency is roughly 75 percent. Thus, if the equivalent number of hours of direct sunshine in a day is 4 hours (and the solar array is horizontal), we would need 15 square centimeters of solar cells. Each cell provides about 0.6 volt, so the number of cells determines the voltage supplied to the batteries whereas the area determines the current. Therefore, roughly 22 solar cells are needed to charge the battery. To give some performance margin, we used twenty four 1 × 1 centimeter cells.

Power System Tests

To test our estimates of the solar power system, we placed a solar array and a battery-charging circuit on the roof of a building and measured the charge current and battery voltage. A load resistor drained the battery at the average rate. Figure 4 shows data from a typical test day. The test convinced us that enough power could be generated for the transmitter if the bird stayed in the open. On cloudy days, however, little power would be received, and the transmitter would not be on very long.

The tests helped us refine the power supply design. We felt that the transmitter should transmit for at least 2 to 4 hours before turning off with a drained battery. This makes it likely that the period of transmission will overlap a satellite pass (a fix is possible about every 3 hours). A small circuit was added to the power system to switch the transmitter on or off, depending on the battery voltage. The voltage must be above a certain threshold before the transmitter switches on, and

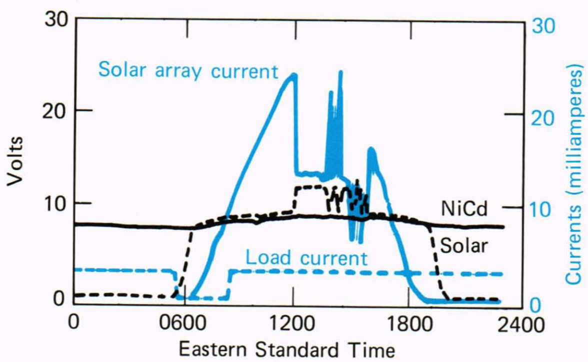


Figure 4—Data from a typical test day. The charging circuit must store the power received from the sun and release it slowly. Tests of the charge control circuit showed that, on that particular day, the simulated transmitter was on on the previous day and ran until 0600 hours (load). Meanwhile, the battery voltage was dropping throughout the night until 0600 hours (NiCd). At about 0600 hours, the sun rose, but charging did not start until the solar array voltage was higher than that of batteries—at about 0730 hours (solar array current). The charging current grew as the sun rose higher. At about 1230 hours the charge control circuit sensed that the battery was nearly fully charged. To prevent battery damage, a current limiter was switched on. Between 1330 and 1700 hours, there were clouds that further slowed the charging. That, in turn, allowed the battery to drain slightly, so the current limiter was removed for short periods. The limiter was removed permanently at 1700 hours. The solar array voltage dropped as the sun set at about 2100 hours, and the transmitter remained on into the next day.

once on, the battery voltage must drop below a lower threshold before the transmitter switches off. The battery charge characteristics make this approach possible because the voltage rises slowly as it is charged and falls slowly and predictably as it discharges. With this strategy, the transmitter will not switch on on rainy, cloudy days but will store the little charge it does get until the next day. Although this strategy does not meet the goal of one location determination per day, there is some compensation because birds are unlikely to migrate in poor weather.

A more realistic test of the power system was designed next. In a plastic box (of the size we hoped to use for the bird-borne package), we placed a small, conventional wildlife transmitter powered by the solar cells and batteries and controlled in the same way as was done for the roof test. A load resistor was added so that the total load matched that of the Argos transmitter. The box was strapped on the back of a captive Andean condor at the Patuxent Wildlife Research Center (Fig. 5); an identical transmitter was placed on a shelf nearby to serve as a reference.

The test ran for several months in the spring of 1983. Because the bird was caged, it perched nearly the whole day, in many cases with its back away from the sun. Even though the weather during this period was quite cloudy, the transmitter was on for an average of 8.4 hours per day.

The tests helped to clarify one risk with the solar cell approach: feather coverage. Because the condor is a very large bird, its feathers could completely cover the package; we had to cut part of the neck feathers to keep the transmitter exposed. After the test had run for several weeks, we placed the reference unit on a captive golden eagle at the Patuxent Wildlife Research Center to obtain better information on the feather problem. Although the eagle is large (3 kilograms), its shape is more nearly that of the birds of prey that biologists intend to track. We concluded from the study of both birds that feathers would not be a big problem but that it may be wise to trim some neck feathers to reduce the risk. We also expect that feathers will not interfere very much with the solar cells while the bird is flying.

Figure 5—Test of the solar power design with a captive subadult Andean condor at the Patuxent Wildlife Research Center. The bird wore a small plastic box containing a solar array, batteries, charge control circuitry, a battery load, and a small transmitter to indicate whether the batteries were charged. The test provided valuable data on the amount of sunlight received under more realistic conditions than laboratory tests. The small transmitter in the package also provided temperature data needed for the design of the crystal oscillator of the satellite transmitter. The bird tended to keep the temperature in the box regulated within a 20°C range.

Encoder

The encoder provides both long-term and short-term timing, switching subsystems on and off at the appropriate times; it also controls the phase modulator. Our design was implemented in digital circuitry using a small number of integrated circuits. The encoder has its own low-power crystal oscillator to provide precise timing. A programmable read-only memory is used to store the transmitter identification number and, for test purposes, a dummy sensor message.

As was mentioned above, the Argos system is designed to receive sensor data from the transmitter. Biologists eventually want sensors to be included in the bird-borne transmitters. However, we made the sensor development a parallel effort, along with the development of a more "intelligent" encoder, to allow us to concentrate on the other transmitter sections.

Crystal Oscillator

The Argos system uses the Doppler shift of a 401.65 megahertz signal to locate a platform. To get an accurate location, a very stable frequency is required (in this case, a df/f of 10^{-9} during transmission and less than 4 hertz change during a typical pass of 20 minutes). This stability is not great by usual satellite standards. Typically, when crystals are placed in an oven with a precisely controlled temperature they achieve stabilities of 10^{-11} to 10^{-12}. Obviously, we could not afford the weight, volume, or power of an oven.

Another choice, a temperature-compensated crystal oscillator (TCXO), compensates for changes in crystal temperature to keep the oscillator on frequency. A TCXO could just meet the Argos requirements for stability and noise. We selected an oscillator frequency of 5.020625 megahertz—1/80th of the 401.65 megahertz needed for Argos—and then multiplied by 80.

A TCXO can be made stable over a limited temperature range, typically 30°C. Obviously, many birds live in environments in which the temperature ranges are wider than this. To help decide what temperature range to choose, we placed a thermistor that changed the repetition rate of the wildlife transmitter in the power system test package on the condor. We could then infer the package temperature. The bird's body and feathers kept the transmitter package quite well regulated. On the basis of this experiment, we tentatively set our range from 20 to 40°C. Whether this will be satisfactory for all uses remains to be seen.

Phase Modulation and RF Design

The radio frequency design was the most difficult. The Argos signal format begins with a 0.160 second signal (carrier) followed by a phase-modulated portion that contains an identification number and digital data from sensors or other devices (Fig. 2). The phase modulation specifications are very strict.

After trying several methods, we settled on a voltage-controlled oscillator at 400 megahertz. The output signal is divided by 80 to produce a 5 megahertz signal that is compared to the TCXO signal. Any phase or frequency difference is used to control the voltage on the oscillator to maintain the frequency at the 401.65 megahertz required by Argos. The phase modulation is generated by modulating the loop control voltage with signals from the encoder.

Amplification

An amplifier is needed to boost the low power signal produced by the voltage-controlled oscillator to the 1 watt required for Argos. It also isolates the oscillator from impedence changes in case the antenna comes into contact with other objects. We are using a commercial amplifier that is very small and lightweight, although it is not the most efficient one.

TRANSMITTER TESTS

In July 1983, the various sections of the transmitter were combined, and the transmitter was tested with the Argos system. The components were not packaged then, and a power supply was used instead of the solar array. The transmitter was placed in a laboratory, and a whip antenna was put on the roof. The measure of success involved several values: the transmitter's latitude and longitude (both within the 0.5 to 1 kilometer error limits usually quoted for Argos transmitters) and the correct dummy sensor message. Several days of testing showed a scatter of 300 meters in latitude and longitude and uniformly correct messages.

In October 1983, the transmitter was taken to France to be tested and certified by Service Argos. Any transmitter using the system must meet certain minimum standards before Service Argos will issue identification numbers. Figure 6 shows one of two transmitters used for the tests.

PACKAGE DESIGN

During the feasibility study, we realized that packaging the transmitter would be a major part of the development. We relied heavily on our sponsors for guidance because of their experience in tracking animals using conventional transmitters. The primary packaging issues have already been mentioned, but package integrity is also a concern. It must remain watertight in the presence of height-associated pressure changes, it must not be affected by extremes in temperature, and the solar array cover must not degrade with exposure to sunlight.

There are other packaging considerations. The oscillator is placed on the bottom of the package, close to the bird's back, to take advantage of the bird's thermal inertia and thermal regulation. Our tests with the Andean condor and the golden eagle showed that the temperature in the test package was maintained within a 20°C range. Short-term temperature behavior (on the order of seconds to minutes) could not be obtained

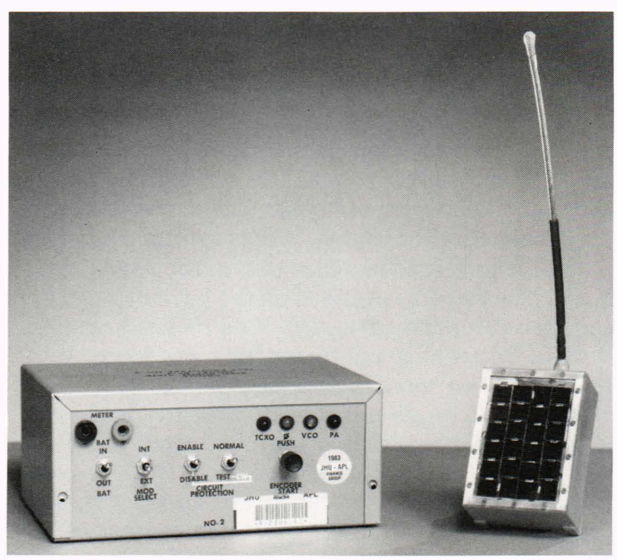


Figure 6—Two prototype transmitters were taken to Service Argos for certification tests. Each transmitter design must be checked to ensure that the transmitter will perform well with the Argos satellite receiver.

from the data. Some lightweight insulation for the temperature-controlled oscillator may be necessary to minimize the short-term changes.

Package shape also was of some concern. Ideally, the package should be streamlined, but a number of factors limit this. The solar array size determines the size of the top of the package. It must be raised a little so it will not be covered by feathers; if even one cell is completely covered by feathers, the current generated by the array drops substantially. If the package is too high or too wide, it could interfere with the bird's flying and be a serious problem for birds that rely on their flying ability to catch food. We chose a 4 × 6 arrangement of the solar cells, and the other dimensions followed from that choice.

In addition, a streamlined package shape may be difficult to fill efficiently. We have made the first flight units compact while preserving the modularity of discrete subsystems. Optimum use of space within the package will wait until we have gained some experience with the transmitters. For the first design, the electronics have been laid out on four circuit boards with flexible connections between boards (Fig. 7). Some form of shielding is necessary to prevent RF from entering the package. Two options for packaging the transmitter are being evaluated: a thin but strong metal box and a lightweight plastic box. The metal box provides the necessary shielding whereas the plastic box requires a thin metal shield or screen inside.

A relatively large transmitter such as that must be worn like a backpack except that the straps crisscross on the bird's breast and are stitched together there. Teflon ribbon is used because it is strong and flexible and resists icing in freezing weather.

The only practical antenna for the package is a wire whip made of galvanized cable with a very tough coating and extending down the bird's back. The design has been used successfully on conventional wildlife transmitters for tracking California condors. The antenna must be very tough because birds often will pull and bend it repeatedly. It is also the most likely route

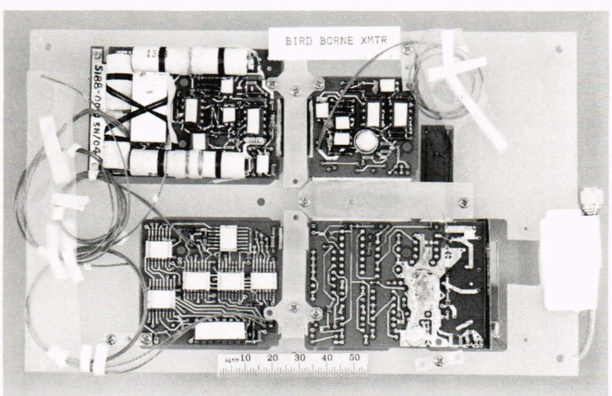


Figure 7—The four circuit boards that comprise the bird-borne transmitter, mounted on an assembly fixture. Clearly visible are the six NiCd batteries and the TCXO (rectangular object near the batteries). The encoder is the lower left board; the power supply, the upper two boards; and the 5 and 400 megahertz section, the lower right board (most components are on the reverse side).

for water to enter the package. Water, of course, would destroy the sensitive components.

Our success with the packages for our first tests with birds is quite encouraging (Fig. 8). The weight is approximately 160 grams, well within our hopes for the first units. As expected, four components contribute more than half the weight: the nickel-cadmium batteries, temperature-controlled oscillator, circuit boards, and box. Although we are within our initial weight budget, few birds could comfortably carry the package, particularly on a long migration. First tests are being made with swans and eagles.

TESTS OF THE FLIGHT PACKAGE

Our first laboratory test of the transmitter with the Argos system was important in verifying the electronic design, but it did not test the transmitter under realistic conditions. The first transmitter made with the small circuit boards was placed in a large, clear plastic box with a heater at the back of the package to simulate the bird's body heat, and it was attached to the solar array. The assembly (Fig. 9) underwent roof-top tests in February 1984 to verify that the transmitter would function properly with the solar array. The transmitter survived some very cold weather and transmitted for up to 20 hours after a full day of sun.

The position errors from the test were within the 1 kilometer requirement but showed somewhat larger scatter than was found during tests with the transmitter in the laboratory, probably because of small temperature fluctuations that affect the temperature-controlled oscillator.

The next transmitter was used for the tests of the captive bird. We modified a plastic box by attaching an antenna and holders for harness straps and also attached a solar array. The package was worn by a captive golden eagle at the Patuxent Wildlife Research Center (Fig. 10) during March and April 1984. The test was very successful in that many location determinations were made and the transmitter operated normally.

Then, in May 1984, the first flight unit was attached to a wild mute swan living in a wildlife refuge on the eastern shore of the Chesapeake Bay. This species was

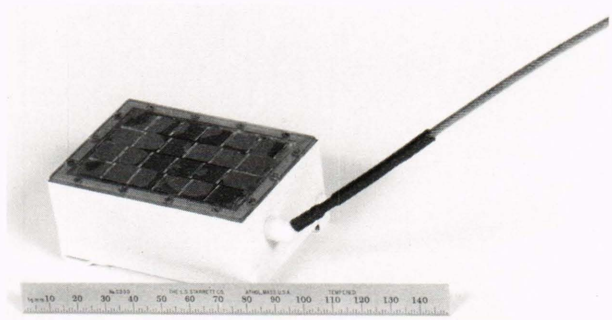


Figure 8—A completed transmitter. Note the metal clips for the harness on the four corners. The transmitter is painted white, a color similar to that of the bird; this transmitter was placed on a swan.

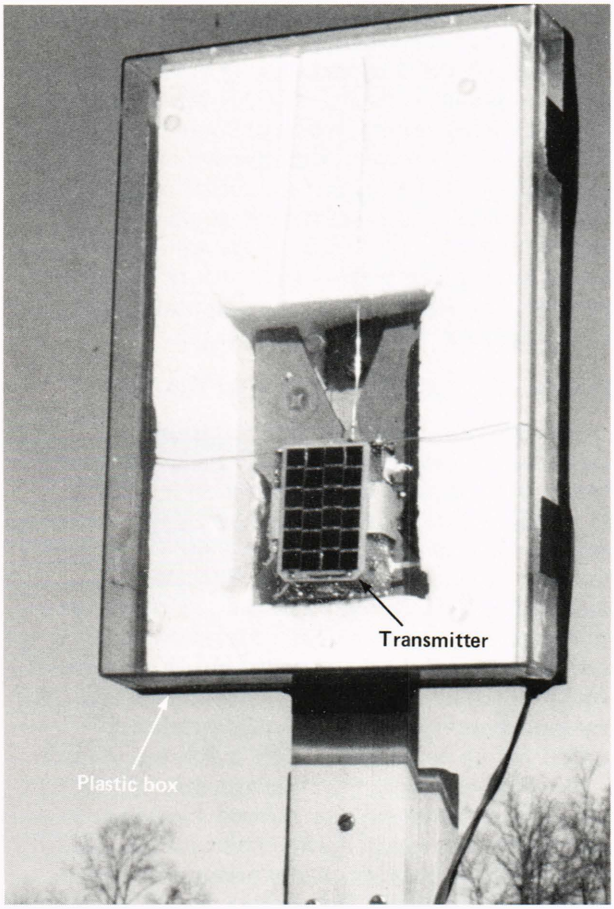


Figure 9—The first small prototype, tested on a roof at APL in February 1984. A heater was placed near the transmitter to keep the TCXO within its most stable temperature range.

Figure 10—The first Argos bird transmitter on a captive golden eagle for field tests. The bird wore the transmitter for five weeks and provided information on accuracy, solar powered design, and bird adaptation.

chosen because it does not range very far, enabling biologists to monitor its position and adaptation to the transmitter. We obtained an average of one location a day (Fig. 11). Plans are being made to release more birds with transmitters in 1985.

ENHANCED PERFORMANCE ENCODER

The Argos system, as mentioned previously, can receive data from sensors. However, for data transmission a somewhat more sophisticated encoder is needed. A microprocessor encoder has been designed that allows flexibility in the choice of sensors. It is essential that the encoder not take any more room (basically one circuit board) or weigh more than the original encoder. Therefore, it is being built using silicon chips in chip carriers, while other elements have been incorporated in a custom-made gate-array device.

The second-generation transmitter, with the microprocessor encoder, will include several environmental and housekeeping sensors. With them, we will be able to monitor air and package temperature, air pressure, and battery voltage. Some of that information will be useful for the study of migration, while other data will give us information on transmitter performance.

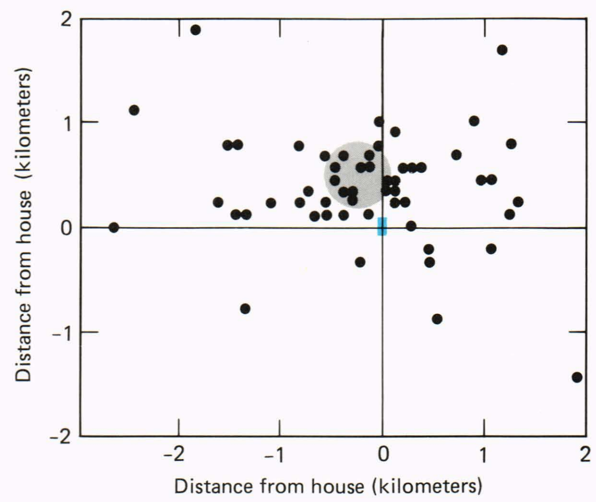


Figure 11—The first transmitter attached to a free-flying bird was placed on a mute swan living on a pond near the Chesapeake Bay. The swan remained on the pond while it raised its young, permitting biologists to monitor its adaptation to the transmitter. The locations were determined by Argos during the months-long test. The circle represents the approximate size and location of the pond on which the swan lived, and the positions are relative to a house on which a reference transmitter was placed. The root-mean-square scatter in location is about 1 kilometer.

FUTURE DEVELOPMENTS

What are the prospects for a smaller, lighter package? It is clear that the four major components must shrink significantly. Packing the electronics more densely will lower the circuit board and box weight. Producing the voltage-controlled oscillator and power supply in microcircuitry will also reduce weight. However, decreasing the heaviest item, the batteries, must await new, higher power density cells. The temperature-controlled oscillator may be replaced by a very stable, small oscillator being developed at APL in which it may be possible to include the phase modulator. However, it is too early to report on those developments.

APL has filed for a patent for the transmitter design and will seek companies to produce the transmitter under license.

REFERENCES

[1] W. A. Good and J. W. Hamblen, "How High Does the Whistling Swan Fly?" *APL Tech. Dig.* **10**, 2-10 (1970).
[2] J. L. Bessis, "Operational Data Collection and Platform Location by Satellite," *Remote Sensing Environ.* **11**, 93-111 (1981).
[3] H. D. Black, "Satellites for Earth Surveying and Ocean Navigating," *Johns Hopkins APL Tech. Dig.* **2**, 3-13 (1981).

ACKNOWLEDGMENTS—The authors thank other members of the APL research team, in particular, Joseph G. Wall and John Daniels. The enthusiasm of the sponsors, Mark R. Fuller and William S. Seegar, has made the project an especially enjoyable and satisfying one.

THE AUTHORS

THOMAS STRIKWERDA (left) joined APL in 1981 as a senior staff physicist in the Space Analysis and Computation Group. He was born in Grand Rapids, Mich., in 1948. Tom received a B.S. degree in physics from Calvin College in 1971 and a Masters degree (1974) and Ph.D. degree (1977) in astronomy from the University of Virginia. After leaving the university, he was a Research Associate and then Assistant Professor at Virginia Polytechnic Institute and State University in the Engineering Science and Mechanics Department.

In addition to his work on the Bird-Borne Transmitter, he has recently worked on the design study for the Space Telescope Alternate Fine Guidance Sensor, with primary responsibility for the simulation and evaluation of electro-optical sensors.

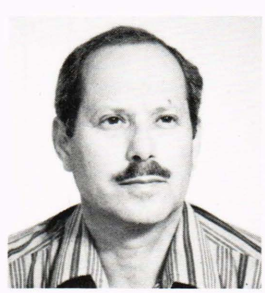
He is a member of the American Astronomical Society, American Institute of Aeronautics and Astronautics, and Society of Photo-Optical Instrumentation Engineers.

For fun, Tom goes birding.

HAROLD D. BLACK (center) is supervisor of the Space Analysis and Computation Group and a member of the principal professional staff. He was born in North Carolina in 1926 and earned an M.S. in engineering at the Carnegie Institute of Technology in 1952, with postgraduate education in applied mathematics at the Illinois Institute of Technology and the University of Maryland. He worked at Rohm and Haas Co. in Huntsville, Ala. (1952-54), and at the Armour Research Foundation of the Illinois Institute of Technology during 1954-57.

Mr. Black joined APL in 1957 and the Space Department in 1958. During 1970-71, he was a Parsons Fellow in biomedical engineering.

PAUL W. HOWEY (right) joined APL to work on the Bird-Borne Transmitter program in 1983. He had previously developed a miniature remote-sensing and radiotelemetry system to study microclimates at the University of Bath (U.K.), where he received a Ph.D. degree in 1982. Paul was born in 1952 in Newcastle-upon-Tyne and from an early age has been interested in things that "work," which eventually led him to study the life sciences at the University of Liverpool where he specialized in neurophysiology. He received a B.S. degree there in 1974. In his free time, he designs and builds miniature radio and electronic control systems for model helicopters and aircraft.



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