Use of the Doppler Technique to Track Free-Roaming Animals from Satellites

JAMES C. MAXWELL
Smithsonian Institution

RADIOTELEMETRY has been developed over the years as a useful tool for the investigation of animals under natural field conditions. However, our present ground radiotelemetry has limited tracking range and the investigator must move with the animal to stay within range. A ground tracking range of 16 km is typical. The use of aircraft increases the tracking range to around 160 km but involves the expense and limitations imposed by the aircraft.

These range limitations of ground radiotelemetry will probably not be overcome with better technology. Fundamentally we are faced with a power-limited transmitter on the animal and a poor communication path made up of a conductive earth boundary, with hills, forests, and water to attenuate the transmitted wave. It takes less power to transmit a television picture from the Moon to Earth than to send the same picture 3200 km along the surface of the Earth. We can expect that our present ground-based tracking range of 16 to 160 km is representative of our technological capability and that this range will not soon significantly improve.

Satellites can be used to overcome this range limitation by providing a line-of-sight (LOS) communication path with the animal. The transmitted wave then suffers only the space loss and does not have to bend with the Earth's curvature or pass through interfering forests.

A satellite in a circular polar orbit of 800 km comes within LOS of any point on the surface of the Earth every 24 hr. At the equator, the satellite passes within LOS once every 12 hr; and at the poles, every 90 min. A satellite in a polar orbit "covers" the Earth. This is the reason the Nimbus satellites are placed in a polar orbit enabling them to "see" the weather conditions anywhere on the globe.

Similarly, an animal transmitter can communicate with a satellite in a polar orbit (such as Nimbus) at least once a day from the equator and every 90 min from the poles. After the investigator has mounted the package on an animal, a satellite with ground data-reduction facilities will produce a computer printout giving the animal's location and physiological data.

DESIRABLE CHARACTERISTICS OF AN ANIMAL-MONITORING SATELLITE SYSTEM

For a satellite system to find widespread application in wildlife research, it must be designed with the single goal of producing lightweight, low-cost animal packages. Requirements for accuracy in location, physiological data, and animal-package lifetime are secondary considerations. Figure 1 summarizes radiotelemetry animal experiments and the package weights.

A large variety of animals will be instrumented, and they will be capable of transmitting widely different amounts of radiofrequency power. Elephants can carry a heavy package capable of transmitting several watts. Large birds can transmit only 10^{-3} W for any reasonable tracking period.

A reasonable engineering compromise between the satellite capability, the limitation on animal-package output power, and the level of engineering difficulty (cost) suggests the following requirements for an animal-tracking satellite system.

(1) The satellite must be capable of monitoring up to several hundred animals at one time.

(2) The animal's position P must be determined to ± 1 km $< P < \pm 40$ km. Most experiments in long-range, continental animal tracking would be satisfied with $P \leqq \pm 10$ km.

(3) The animal must communicate with the satellite at least once every few days. When battery power is limited, an animal transmission to the satellite once a week can provide useful tracking information.

(4) In addition to the animal's position, the satellite must be capable of collecting at least five separate physiological parameters. The physiological parameters should be measured to within a ± 10 percent error of the physiological transducer output.

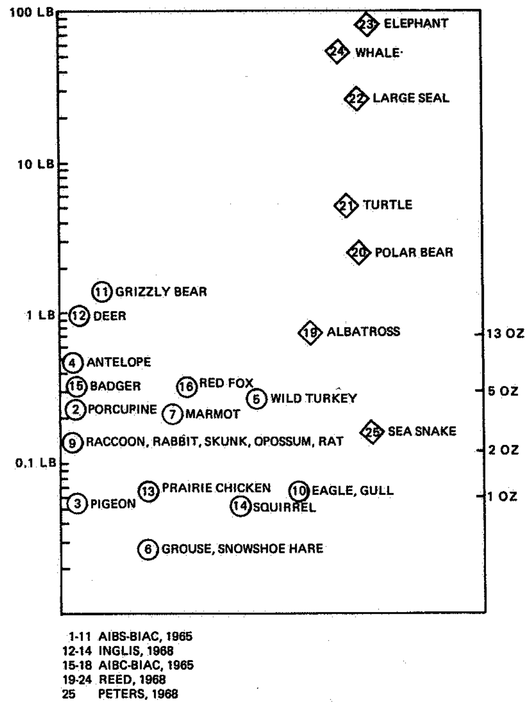

FIGURE. 1 Estimated weights animals can carry. The circle denotes experiments that have been done; weights include transmitter and batteries, but not harness. The diamond denotes rough estimates of what animals can carry.

(5) The weight W of the complete animal package must be as little as possible, 25 g $< W <$ 2 kg. This requires the satellite receiver to process different signal strengths transmitted from the animal package on Earth. Typically the transmitted power P will be 10^{-3} W $< P <$ 10 W.

(6) As a design goal, the animal package should cost only several hundred dollars.

(7) The lifetime of the animal package must be at least 3 months. Lifetimes of 1 yr or more are needed for long-term studies.

(8) The animal package should be simple and require no field adjustments.

RELEVANT EXISTING SATELLITE SYSTEMS FOR ANIMAL TRACKING

Three satellite systems currently either under development or being used by NASA satisfy some of these requirements.

(1) FR–2 (EOLE) a joint France-U.S. experiment;

(2) The Interrogation Recording and Location System (IRLS);

(3) The Omega Position Location Equipment (OPLE).

These systems determine the position of and collect physiological data on ground packages (table 1).

In the EOLE system, platform location is determined from the simultaneous measurement of satellite-platform range and indirect measurement of the angle between the propagation path and the satellite velocity vector. To accomplish this, the satellite broadcasts tone bursts, which are received by the package, translated in frequency, and retransmitted to the satellite. The satellite then measures the frequency difference (doppler) and time difference (range) between the transmitted and the returned signals. It stores in its memory these values, along with any transducer data included in the returned signal, for later retrieval by a ground station. The estimated uncertainty of the locations derived from these measurements is ± 2 km.

IRLS is similar in operation except that IRLS determines only satellite-to-package range by measuring the satellite-package radio-propagation delay. The uncertainty of the location derived from the measurement is ± 2 km.

In the OPLE project, the package receives VLF transmissions from the U.S. Navy's ground-based OMEGA navigation network, converts the signals to VHF frequencies, and transmits them to an OPLE Control Center via a synchronous-satellite transponder. The platform location is determined at the control center from the isophase contour lines generated by the phase difference between signals from the three OMEGA

TABLE 1.—*Summary of Characteristics of Present Satellite Tracking Systems*

	NASA systems		
	EOLE	IRLS	OPLE
Satellite:			
Designation	FR–2	Nimbus	ATS–3
Launch date	Dec. 1969 or July 1970	May 1969	Feb. 1968
Inclination	65°	90°	0°
Package required:			
Weight	4 lb	10 lb	44 lb
Cost	$10 000 each	$10 000 each	$25 000 each
Transmission power	4 W	5 W	35 W
Standby power	0.1 W	0.1 W	1.1 W
Transmission frequency	400 MHz	465 MHz	149 MHz
Reception frequency	460 MHz	400 MHz	136 MHz+VLF
Interrogation time	2×600 msec	2×3 sec	198 sec
Coverage of Earth's surface	Blind areas near poles	Complete	Part of western hemisphere
Accuracy	±2 km	±2 km	±500 m (potential)

transmitters. The potential uncertainty of OPLE location measurements is quoted as ± 500 m (800 km). The weight (20 kg) and large size (due to the necessarily large VLF antenna) of the present OPLE package eliminate it almost immediately from serious consideration as an animal package.

These three systems have two features in common that prevent them from being universally adaptable to tracking animals. The packages are too heavy to be carried by most animals and, because they are electronically complex, weight reduction is difficult. The cost of the packages prohibits any systematic use of these satellite systems, and again their complexity rules out any possible reduction in cost to approximately $100 per package.

THE DOPPLER TECHNIQUE: A GOOD SYSTEM FOR SATELLITE ANIMAL TRACKING

The doppler satellite-tracking technique is ideally suited for satellite monitoring of animals. No other satellite technique offers the same theoretical advantages of narrow bandwidth and has the same general system flexibility to meet the varied requirements of animal tracking.

Simplified Explanation of the Doppler Technique

Consider an observer O moving along a known path C with velocity V, and a transmitter located at L. The observer is located at $t_1, t_2 \cdots t_n$ as he moves along path C. The transmitter is radiating a single frequency f_0 (fig. 2).

The observer will measure a received frequency f_r, modified from f_0 by the observer's velocity. This is the well-known doppler effect and is readily observed by listening to the horn of a passing automobile. The meas-

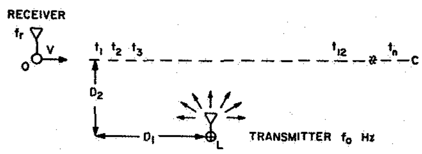

FIGURE 2. A receiver moving along *C*, with *L* fixed, measures the Doppler curve of figure 3.

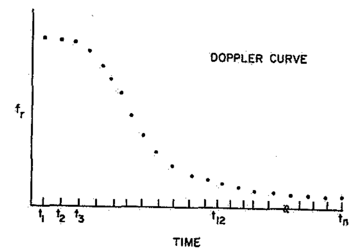

FIGURE 3. Doppler curve.

ured frequency f_r at each t_n is shown in figure 3.

If we are given only the doppler curve shape of figure 3 and path C — that is, if we know the location of the observer at t_1, $t_2 \cdots t_n$ — we can find the location of the transmitter L relative to C. For example, assume we can solve for D_1 and D_2 from the doppler curve and fix the transmitter relative to t_1. If at t_1 we are located 6 mi north (from some reference) and $D_1 = 1$ mile, $D_2 = \frac{1}{2}$ mile, then the transmitter is 7 miles north and 0.5 mile east or west. We obtain an east-or-west solution since the doppler curve is identical for both sides of path C; therefore, we always have two locations. One of the locations must be ruled out from some other knowledge. This is usually done from information on the earlier position of the transmitter, or its possible range of travel, or some physical characteristic of the location. For example, the transmitter is not east of C because there is a large lake there.

The problem is reversible. That is, we can interchange the transmitter and receiver and from L solve for path C. Indeed, an early method of measuring satellite orbits consisted of measuring the doppler shift received on the ground from the satellite transmitter moving with velocity V. This interdependency of transmitter location and measured doppler curve formed the basis for the Navy "Transit" satellite navigation system.

The Relationship Between the Doppler-Effect Curve Shape and the Transmitter Location

Figure 4 is an inverted doppler curve measured for 200 seconds of the Explorer 1 satellite pass. The received frequency f_r was measured at 1-second intervals, bad measurements were rejected, and the resultant curve was plotted.

As an aid in understanding the position/doppler relationship, consider figure 4 and the following steps:

(1) We connect the points with a smooth curve.

(2) We find the inflection point on the doppler curve and mark its time T_i. At T_i, the satellite must be at right angles to the transmitter. (Figure 5 presents the geometry of the problem.)

(3) The satellite orbit is known. We know the location of the transmitter plane from step 2.

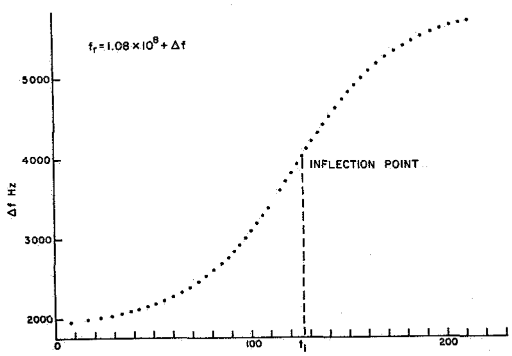

FIGURE 4. Doppler curve measured with the Explorer 1 satellite (1958).

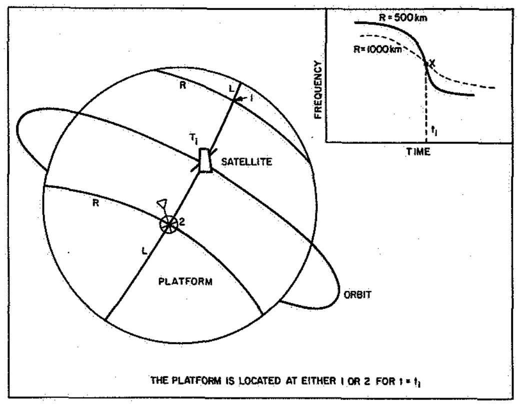

FIGURE 5. Doppler curve/platform location geometry.

(4) The transmitter is on the surface of the Earth. Then the transmitter must lie on the line L formed by the intersection of the plane and the surface of the Earth.

(5) The overall shape of the doppler curve gives the range R to the transmitter. For example, $R = 500$ and 1000 km is shown in figure 5 to illustrate how the Doppler shape changes with range. A computer is usually employed to fit the known Doppler curve for each range case. The range curve that produces the minimum errors is the range R to the transmitter. As a rough indication of range,

$$R = \frac{f_t f_r^2}{c(df_r/dt)}$$

where

f_t = transmitted frequency (Hz),
f_r = received frequency (Hz),
c = speed of light (3×10^8 m/sec),
df_r/dt = slope of doppler curve at T_i (Hz/sec).

(6) The animal transmitter is located at positions 1 or 2. Knowledge of a previous position will fix either 1 or 2 since they will be located hundreds of kilometers apart.

Measurement errors affect the location accuracy. A 1-sec error in locating the doppler inflection point moves the plane of the transmitter

$$7.6 \text{ km/sec (satellite velocity)} \times 1 \text{ sec} = 7.6 \text{ km error.}$$

From figure 4, the slope

$$\frac{\Delta f_r}{\Delta t} \doteq \frac{2000 \text{ Hz}}{67 \text{ sec}} \doteq 30 \text{ Hz/sec} \qquad (t = T_i)$$

or

$$30 \text{ Hz} = 7.6 \text{ km error}, f_0 = 108 \text{ MHz}$$

$$3 \times 10^{-7} \text{ frequency error} = 7.6 \text{ km location error.}$$

We are interested in the frequency stability for the 10 minutes while the satellite is in view:

$$\frac{3 \times 10^{-7} \text{ Hz}}{10 \text{ min}} \doteq 2 \times 10^{-6} \text{ Hz/hr}$$

and

$$2 \times 10^{-6} \text{ Hz/hr crystal stability} = 7.6 \text{ km location error.}$$

A crystal-controlled oscillator with no oven but with 2 inches of thermal insulation to hold the crystal and circuits to within 0.1° C for 10 minutes will provide sufficient frequency stability to limit our position error to $< \pm 3$ km.

Very small packages, such as for birds, will not be able to insulate fully the crystal unit and will therefore have a larger positional error. However, the positional error should remain less than ± 30 km except when very large changes in the ambient temperature occur during the 10-minute satellite pass.

Choices of Animal Package for Use with the Doppler Technique

A lightweight Doppler transmitter providing only position information is diagrammed in figure 6. The crystal oscillator will operate at the frequency assigned for the animal. The timer can be used to turn the transmitter on and off and thus conserve battery power, which will extend the transmitter lifetime for a given weight of batteries, thus providing the ultimate in lightweight transmitters for small animals. Figure 7 shows a second type of transmitter, in which a timer is used to

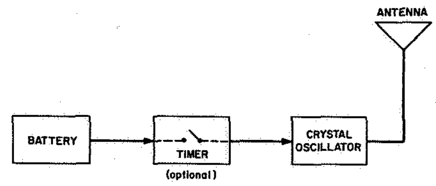

FIGURE 6. The lightweight (position only) animal package.

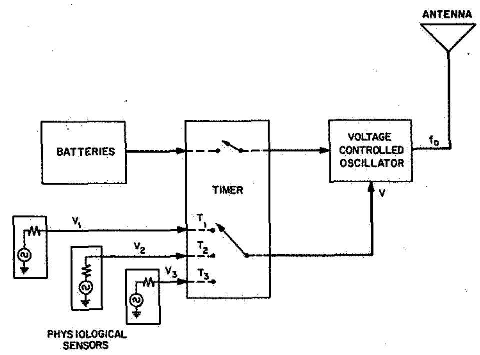

FIGURE 7. Position and physiological-data animal package.

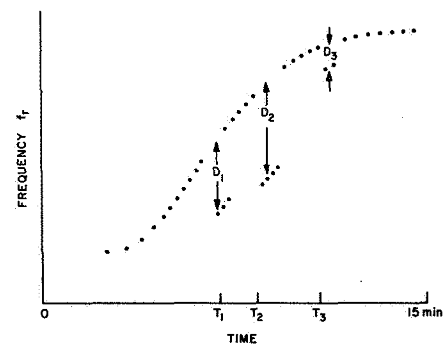

FIGURE 8. Doppler curve with physiological data, D_1, D_2, and D_3.

commutate physiological data into a voltage-controlled oscillator. This package will also give the animal's position.

The physiological data will appear on the Doppler curve as frequency deviations. Figure 8 is an example of such an output. We identify the channels by their time separations and order T_1, T_2, T_3, $T_2 - T_1 = 1$ min, $T_3 - T_2 = 2$ min. The amount of frequency deviation D is proportional to the physiological-sensor voltage output v. Then, from the Doppler curve we measure D_1, D_2, and D_3 and obtain v_1, v_2, and v_3. The f_r data points during the time that physiological data are transmitted are ignored when determining location.

We can estimate some sizes and weights for the animal packages for the doppler technique.

At the output of the satellite receiver tracking filters, having a bandwidth B, the S/N (signal-to-noise ratio) is given by

$$S/N = \frac{\lambda^2 P_T D_T D_R E_R I L}{(4\pi R)^2\, k\, T_{eq}\, B}$$

where k is Boltzmann's constant and the other quantities have the values noted in table 2. Then, with $R = 3 \times 10^6$ m, $T_{eq} =$ 1200 K, $P_T = 225$ mW, $B = 50$ Hz, $\lambda =$ 0.3 m,

$$S/N = 8.9 \text{ dB}.$$

For birds and other small animals, we must operate at the frequencies available from crystal units. This restricts our maximum frequency to $f_0 \leqq 100$ MHz, $\lambda \geqq 3$ m. For larger animals, where there is room for frequency-multiplication stages, we can choose f_0 at our convenience. A small λ enables us to work with small antennas. A $\lambda = 0.1$ m produces an antenna with circuit polarization that occupies less than $4 \times 4 \times$ 2 inches. Table 3 summarizes the design choices and the resultant animal packages.

Satellite Requirements for the Doppler Technique

As a reasonable design choice, the satellite system must receive and process 10 separate

TABLE 2.—*Values of Quantities Used in Determining* S/N *Limits*

Symbol	Quantity	Value	Remarks
λ	Operating wavelength	$0.1 < \lambda < 4$ m	Ionosphere restricts $\lambda < 4$, Electronics restricts $\lambda > 0.1$
P_T	Radiated power	$10^{-3} < P_T < 1$ W	Power level compatible with small animal packages
D_T, D_R	Directivity of transmitting and receiving antenna	1	Isotropic antennas
E_R	Receiving antenna efficiency	80%	Some loss in antenna-to-receiver cable
I	Ionospheric attenuation	1	$\lambda < 6$ m
L	Polarization loss	½	Linear antenna polarization assumed
R	Transmitter-to-satellite range	$R < 3 \times 10^6$ m	Satellite elevation $\phi = 10°$
B	Bandwidth of satellite receiver filter	5 Hz $< B <$ 50 Hz	$\lambda = 3$ m
T_{eq}	Satellite-receiver equivalent-noise temperature	$1200 < T_{eq} < 7900$ K	Satellite-receiver noise figure $F = 6$ dB

Table 3.—*Animal Packages for the Doppler Technique*

Animal (attachment)	Electrical power	Total animal package weight (~80% batteries)	Lifetime (days)	Rate of locating $1/T$	Remarks
Eagle	Hg battery	1.2 oz *	31	>1/day	$P_T = 10^{-3}$ W
Albatross	$50 \frac{W\text{-}H}{lb}$	1.7 oz t_1	217	1/week	$B = 0.5$ Hz, $f_0 = 100$ MHz $E = 20\%$
		3.4 oz *	88	>1/day	No physiological data
Caribou	Ag-Cd battery and solar cells	1.4 lb t_2	136 952	1/day 1/week	$P_T = 225 \times 10^{-3}$ W
Polar bear (collars)	$30 \frac{W\text{-}H}{lb}$	8.5 lb t_1	70	1/week	$B = 50$ Hz, $f_0 = 1$ GHz $E = 25\%$
		8.5 lb t_2	1000	1/day	With physiological data
Sea turtle	Ni-Cd battery	20 lb t_2	925	1/day	
Whale (marine float)	$13 \frac{W\text{-}H}{lb}$	(600 in.^{3})	6475	1/week	
Elephant (harness)	Ni-Cd battery and solar cells	20 lb t_2	Indefinite	1/day	

* = No timer
t_1 = With timer set for "on" for 24 hr, "off" for 1 week
t_2 = With timer set synchronous with the satellite pass, "on" for 15 min, "off" for T
P_T = Transmitted power (W)
B = Required satellite receiver (tracking filter) bandwidth (Hz)
f_0 = Transmitter frequency (Hz)
E = Efficiency of the animal package electronics

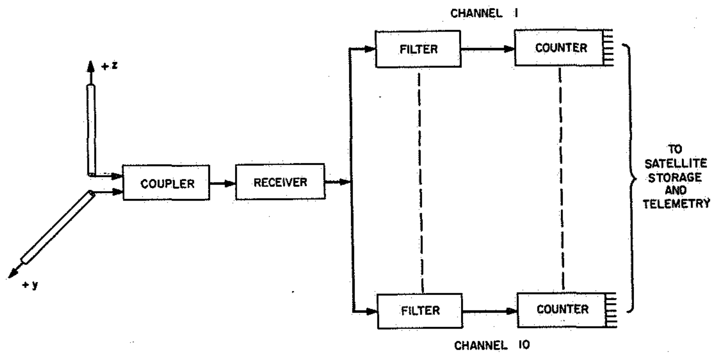

FIGURE 9. Block diagram of the equipment required in the satellite.

frequencies from the ground transmitters. The 10 frequencies will enable the satellite to track several hundred animals a day, although only 10 animals can be tracked in a small area that is within a single LOS of the satellite.

Figure 9 is a block diagram of the satellite receiving and processing system. The tracking filters have bandwidths of several hertz and are used to extract the transmission frequency of the animal package from the background electronic receiver noise. The counters measure and present the received frequency to the satellite telemetry system in digital form. Later the satellite will send the measured frequency to the ground station for analysis. The output of these counters is the frequency points f_r that make up the doppler curve.

The satellite telemetry must process a data rate R of 4 bits/sec $< R <$ 20 bits/sec. The data processor consists of 100 integrated circuits (flat packs). The tracking filters could be made up of the Signetics NE 561B phase-locked-loop integrated circuits. The satellite receiver must be a wideband UHF type. The 10 frequency bands will be widely separated in the UHF range and may require two separate mixing operations. The satellite antenna can be a crossed dipole configuration. Four arms, each 10 inches long, extending from the body of the satellite will satisfy the antenna-gain requirements. The following Doppler equipment characteristics are required in the satellite:

(1) Size: 66 in^3
(2) Weight: 1.5 lb
(3) Power consumed: 4.7 W
(4) Data rate to telemetry: 4 bits/sec $< R <$ 20 bits/sec

CONCLUSION

The Doppler technique is ideally suited for use in tracking animals from satellites. The narrow bandwidth inherent in the technique provides the electronic design flexibility needed in animal work. It also will result in the smallest, lightest, and simplest animal package possible. No other radio technique will offer a better animal package. In addition, the narrow bandwidth of the satellite receiver is much less sensitive to electrical interference when compared to more conventional wideband receiving systems.

I intend to continue the Smithsonian effort to help NASA provide for this satellite animal-tracking capability. We proposed this Doppler technique to NASA early in 1968, and I am encouraged by NASA's support for my design efforts in these years of shrinking budgets. We hope to make a rather simple test of this Doppler technique in early 1971 using Nimbus IV. I expect to see a satellite Doppler capability by 1974 that will enable investigators throughout the world to mount $100 transmitters on animals and obtain, in the mails, the daily location and condition of the animal.

DISCUSSION

GRIFFIN: What kind of an antenna must the animal carry for this apparatus to work effectively?

MAXWELL: For small animals a short piece of wire several inches long may be used. Since it is necessary to radiate a milliwatt (at 100 MHz, this is a fraction of a wave length) the efficiency will go down to 10 to 20 percent, a very low efficiency system. For larger animals a larger dipole will be used. At 1 GHz the antenna is four inches by four inches by three inches.

WILLIAMS: There is one problem to be considered if this system is used on birds. While the temperature stability can be solved by simply putting the unit underneath the feathers, the unit components are affected, particularly by antenna loading, by the wing beats of the bird. We get a 5-kHz change just in the motions of the bird; if the bird is actually touching the antenna you get many many times that.

MAXWELL: Your crystal oscillator is overly frequency sensitive to the varying antenna driving point impedence. The driving point impedance of the antenna changes with the relative position of the wings to the antenna.

WILLIAMS: How are you going to get around the frequency shift unless you have shielding?

MAXWELL: It may be necessary to add an active stage to buffer the crystal from the antenna. Certainly the frequency "pulling" of the crystal can be held to a few hertz.

WILLIAMS: The whole system is based on a very high degree of frequency stability. A very small transmitter near a small electromagnetic generator (the bird) makes it difficult to get frequency stability. Some thought must be given to this problem.

MACKAY: If the crystal of an oscillator is shaken up and down, as by the movements of a bird, some crystals will show a shift in frequency that is of the order of the required stability. Some crystals used in a fundamental mode will show less stability than an overtone crystal.

A separate output stage on the transmitter seems required, and some of these, as well as some frequency multipliers, are significantly less affected by changes in the surroundings than others. Light electrical shielding need not interfere with the bird. Perhaps a greater problem is reliable automatic release of an attachment to the bird that does not interfere with his normal activities. Some of the biological problems seem more difficult than the electrical ones.

WALCOTT: I would just like to emphasize the last problem. In designing these transmitter packages, it is absolutely crucial to work on both the biological as well as the engineering problems.

BUSSER: The very existence of the AIBS Bio-Instrumentation Advisory Council as a go-between or the catalyst in this area, shows that both sides are certainly not ignoring this problem of communication. It is very real.

GRIFFIN: How long a monitoring period is available?

MAXWELL: The satellite is in view for about 10 min every 12 hr. You could use most of this 10-minute period to monitor a transducer or a data storage device. However, you are limited to the 10 min if you wish real-time information.

GRIFFIN: Could you, for instance, use the closest part of the curve for position information while transmitting physiological data before and after, when it is still within range?

MAXWELL: No. The trouble is, you never know when the satellite is at right angles. You don't know when you are at the center of the Doppler curve.

BIBLIOGRAPHY

GILL, T. P.: The Doppler Effect: An Introduction to the Theory of the Effect. Logos Press, London, 1965, 149 pp.

GUIER, W. H.; AND WEIFFENBACH, G. C.: Satellite Doppler Navigation System, Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 507–516.

GUIER, W. H.: Ionospheric Contribution to the Doppler Shift at VHF from Near-Earth Satellites. Applied Physics Laboratory CM-1040, Jul. 1963, 58 pp.

GUIER, W. H.; NEWTON, R. R.; AND WEIFFENBACH, G. C.: Analysis of the Observational Contributions to the Errors of the Navy Satellite Doppler Geodetic System. Applied Physics Laboratory TG-653, Jan. 1965, 82 pp.

MAXWELL, JAMES C.: A Doppler Satellite System Design for Animal Tracking. IEEE National Telemetering Conference Record, April 1971, pp. 259–263.

SLATER, L. E., ed.: A Special Report on Biotelemetry. Bioscience, vol. 15, no. 2, Feb. 1965, pp. 81–157.