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PHONING HOME—A NEW GSM MOBILE PHONE TELEMETRY SYSTEM TO COLLECT MARK-RECAPTURE DATA

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ABSTRACT

We describe and evaluate a new telemetry system based on GSM (Global System for Mobile Communications) mobile phone technology that may provide mark-recapture data for single year survivorship studies. These phone-tags automatically attempt to send an SMS text message once every two days. The successful receipt of a text message ashore constitutes a resighting event within the coastal zone of GSM coverage. Haul-out data and coastal location data are incorporated into the messages. Data are presented for a three-month period (January–March) following tag deployment on 59 gray seal (*Halichoerus grypus*) pups at the Isle of May (Scotland). An average of 15.5, 4.1, and 8.2 seals succeeded in registering within each three-day period in January, February, and March, respectively. Tags registered with a wide geographical range of GSM radio cells on the Scottish and English east coasts, and also from Norway and Germany. Haul-out records covering 54% of the animals' time were received. With future modifications to the tags, this figure should approach 100%. The median delay to network registration was 9.6 sec from a seal in the sea (not hauled out). These data show that GSM mobile phone telemetry is a useful technique to obtain haul-out and mark-recapture data.

Key words: survivorship, GSM, SMS, resighting effort, haul out, gray seal, *Halichoerus grypus*, Isle of May.

Survival probabilities from mark-recapture models have been estimated for seal populations using various marking methods. However the success of such studies depends upon obtaining a sufficient quantity and quality of resighting events. Apart from animal survival, the number of resightings depends upon the number of marked animals, the probabilities of tag retention and sightability and resighting effort. Flipper tagging is inexpensive, allowing large releases of tagged seals. However live resighting and dead recovery rates are often low, requiring long time series for sufficient data to be accumulated (Hastings and Testa 1998, Craig and Ragen 1999). Moreover, tag retention can be low and age-specific (Stobo and Horne 1994). Live resighting of branded animals has also been used (McMahon *et al.* 1999, Schwarz and Stobo 2000). While the mark retention is high, this marking technique is often restricted to species and to sex- or age-classes that predictably return to a breeding or molt colony each year where the resighting effort can be concentrated.

The development of the technique described here stems from a mark-recapture study carried out by Hall *et al.* (2001, 2002) to explore what factors (birth site, condition, sex, immune status) affect first year survivorship in gray seal (*Halichoerus grypus*) pups. They marked a cohort of newly weaned pups (Hall *et al.* 2000), some of which were subsequently resighted during monthly boat surveys or by the general public and the dataset was analyzed using a live-resighting, dead-recovery mark-recapture model (Barker 1997). However the surveys covered only a small part of the animals' potential range and the number of animals resighted was low and the inferential power of the model was limited.

Here we present a new telemetry system based on GSM (Global System for Mobile Communications) mobile phone technology that provides more detailed mark-recapture data over an extensive geographical range and thus may improve estimates of first year survival. Each seal is fitted with a mobile phone tag that is programmed to attempt to send a text message back to the laboratory at regular intervals. The thousands of GSM radio cells around the coast of Europe that are *continuously* listening for text messages from these seals now replace the human *monthly* survey effort in Hall *et al.*'s study. In the mark-recapture parlance, the successful receipt of a text message now replaces the conventional resighting event. GSM coastal coverage is variable, but usually extends to approximately 20 km offshore. We do not expect that live seals will remain continuously within the GSM coastal corridor. However, we do assume that there is a finite probability that a live animal will, at some time, return to the coastal corridor and succeed in sending a text message ashore. In addition to being a resighting event in its own right, each received text message contains location (GSM radio cell ID), haul-out, and diagnostic information. In this paper we describe the design and performance of these phone tags and evaluate the technical feasibility and effectiveness of relaying information from marine mammals using GSM mobile phone networks. While their operation is described in the context of a generalized Cormack-Jolly-Seber live-resighting mark-recapture framework (Seber 1982), a custom-made model will be developed which accounts for the particular properties of these resighting data.

METHODS

GSM Networks

GSM is an evolving set of protocols that control the operation of most mobile phones (Redl *et al.* 1998). GSM supports both voice and data communications.

Here we deal primarily with the Short Message Service (SMS), also know as text messaging. A text message can transfer up to 160 characters from one phone to another. The transfer includes data validation and notification to the originator of successful receipt of message. From a cold start, initiation of a text message transmission starts with the originating phone registering with an appropriate service provider (in our case O2) network. Successful registration requires, among other factors, that the phone is within radio contact of a GSM radio cell. The maximum theoretical range is 35 km, but is often less due to line of sight obstruction or radio interference. Registration is usually achieved within 10 sec of a cold start. However, if the phone is taken to a country with a different, roaming-partner service provider, the first (but not subsequent) registration may take up to one minute. After registration each text message transmission is usually completed within 2 sec. Thereafter the phone may deregister, which takes about 4 sec.

Hardware Design

A schematic diagram of the phone tag is shown in Figure 1. The central GSM phone component is a dual frequency (900/1800 MHz) Siemens TC35 GSM modem (Siemens Wireless Modules, Bracknell, UK). Its RF output is connected to a fully encapsulated dual-band planar, inverted-F antenna designed by the Centre for Mobile Communications at Sheffield University (Winkle *et al.*, in press). The TC35 GSM modem is controlled *via* a serial interface by a Microchip PIC16LF877 micro-controller. All commands are based on the Hayes AT command set. To reduce energy consumption the micro-controller switches power to the TC35 GSM modem only when network registration is attempted. A wet/dry sensor is used to inhibit network registration and text message transmission while underwater and to generate haul-out records. Up to 20 unsent 160-byte text messages (~40 d of operation outside GSM coverage) can be stored on the SIM card. A Saft LSH14 Lithium Thionyl Chloride C-size battery powers the tag (Saft, Bagnolet, France). Under the operating cycle described below, this will power the tag for at least 440 d. An external clock maintains time records to an accuracy of 1 sec/d. The tag is encapsulated in epoxy resin, weighs 230 g, and is 7 × 7 × 4 cm in size. A highly visible two-letter code on the leading edge of the tag enables individual identification at a distance.

Operation and Data Structure

The strategy of the controlling software is a compromise between minimizing energy consumption and obtaining a reasonable rate of text messages. Since the performance of the phone tag on gray seals was unknown initially we erred on the cautious side to ensure sufficient text messages were received. The parameter values described below will undoubtedly be altered in future applications on the basis of the performance of the first deployment.

Every 4 h the tag wakes from sleep mode, waits until it is dry and then attempts to register with a GSM network for a maximum of 95 sec (*reg_wait_timeout*). If registration is unsuccessful, only diagnostic data for that attempt are appended to a 160 character buffer. If registration is successful the delay from dry to registration (*reg_wait*) and the ID code of the radio cell with which it has registered are also appended to the buffer. O2 has provided the locations and identification codes of

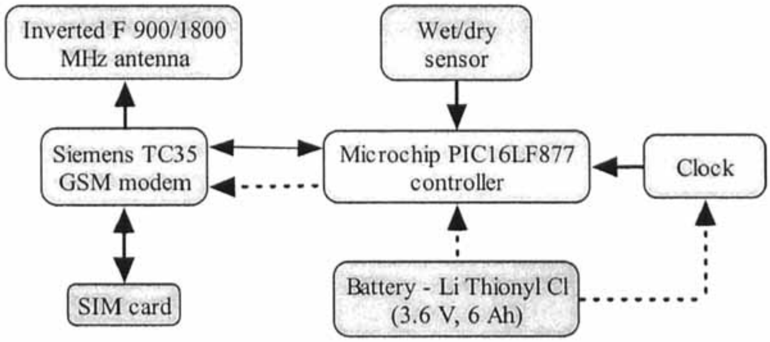

Figure 1. Schematic diagram of phone-tag. The dotted lines show power. The solid lines show data flow.

their GSM radio cells in Great Britain, enabling the location of the radio cell serving the tag to be determined.

The wet/dry sensor is interrogated every 2.3 sec. A *haul-out event* starts when the tag is continuously dry for 10 min and ends when it is continuously wet for 2 min. When the end of a haul-out is detected, its start and end times and a unique incremental number are appended to the buffer. When the buffer is full (approximately 2 d of operation) a text message is created and stored in the SIM card. Attempts to send this, and any previously unsent message(s) are made at the usual 4-h intervals.

Deployment

Fifty-nine newly weaned gray seal pups were fitted with phone tags at the Isle of May (56°11'N, 2°34'W, Firth of Forth, Scotland) breeding colony in December 2002. The phone tags were glued with fast-setting epoxy resin to the fur just posterior to the head. All procedures were carried out under UK Home Office licence.

RESULTS

Following their post-weaning fast all tagged pups departed the Isle of May by the end of December 2002 (McConnell, unpublished data). We present system performance measures for the following three months of operation (1 January to 1 April 2003).

Registration Performance

Figure 2 shows changes in the rate at which the initial 59 tags registered with the GSM network. Four-hour events were clumped into 3-d bins. For each tag, a 3-d bin was assigned a value of one if one or more of the 4-h attempts to register were successful. For each 3-d bin the scores were summed over all tags and are referred to as the 3-d registration rate. Through January, February, and March the mean rates (and SDs) were 15.5 (3.7), 4.1 (2.1), and 8.2 (2.1), respectively. Figure 3

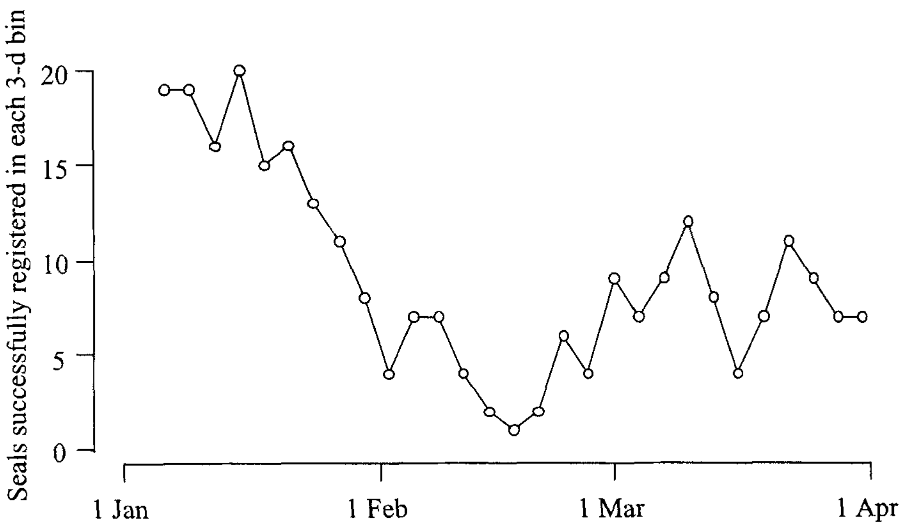

Figure 2. Changes in the *3-day registration rate* (see text) through time from the initial sample of 59 tagged seals.

shows the frequency distributions of the delay from the time the animal surfaced to successful registration (*reg_wait*) in each 4-h attempt. For attempts when the animal was known to be hauled out (from haul-out records in the received text messages) the median delay was 7.3 sec. From attempts when the animal was known to be not hauled out the median delay was 9.6 sec.

Geographical Coverage

The geographical coverage of the radio cells with which the tags registered is shown in Figure 4. In addition, two tagged seals registered with roaming partner radio cells in Norway and two with cells in Germany. This suggests that our "resighting" effort did indeed cover the GSM coastal corridor (albeit of variable extent) around north European waters and not just UK waters.

Haul-out Coverage

The stochastic nature of how often a tag succeeds in sending a text message means that not all haul-out records are received. In Figure 5 we show an example of haul-out records from one seal. The thick lines indicate haul-out records received. If two haul-out records have sequential numbers we know that there were no lost haul-out records during that interval, and this (non-haul-out record) is represented by the thin line. Absence of a line indicates we have no information available for that period. The combination of haul-out records and the complementary non-haul-out records are referred to as periods of haul-out coverage.

Quantifying the proportion of each seal's time over our three-month period for which we have haul-out coverage is complicated by two factors. First, a seal may register after 1 April following a prolonged period far out at sea (outside of

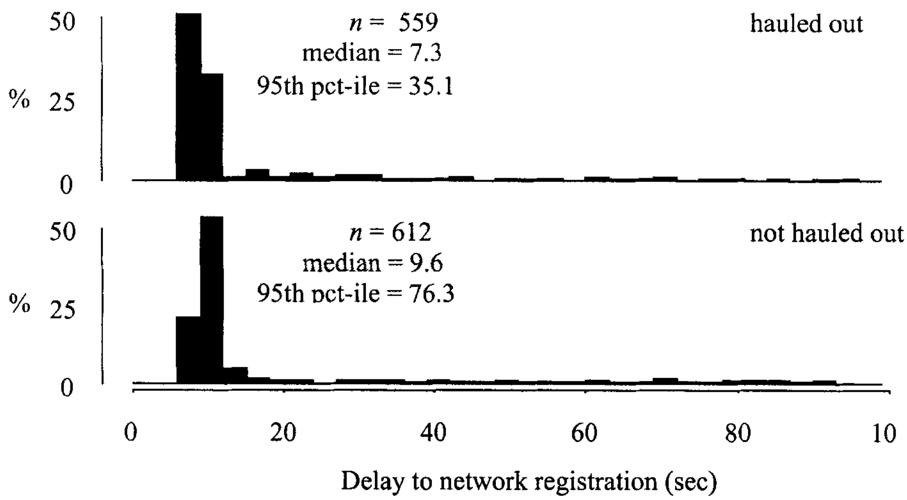

Figure 3. Frequency distributions, grouped by whether the seal was hauled out, of the delay from dry to network registration. Attempts to register timed out after 95 secs and only those successful registrations are included in this figure.

GSM coverage) and relay text messages that contain haul-out information prior to 1 April. Second, some of the initial 59 study seals may have died before 1 April. Thus, for each seal we consider only the period from 1 January to its last haul-out record prior to 1 April. Summing over all seals this is a period of 2,577.3 seal-days. Within this period a total duration of 1,152.4 seal-days were known to be hauled out and 252.1 seals-days were known to be not hauled out. That is, for the 54% of the time for which we have haul-out coverage the seals spent an average of 22% of their time hauled out.

Discussion

The first three months of data indicate that GSM mobile phone networks in general, and our design of a phone tag in particular, promise to provide useful resighting data on free-ranging pinnipeds. The quantity of the data we have obtained is determined not just by the efficiency of the phone tag telemetry system, but also by the behavior, movements, and survival of the study animals. The decreasing 3-d registration rate in January was probably due the pups initially remaining close to land before a staggered initiation of offshore foraging trips (McConnell *et al.* 1999). In January and February the 3-d registration rate stabilized somewhat to 4.1 and 8.2, respectively. This low rate probably reflects both offshore travel outside GSM coverage, and also the fact that even a live animal, with a functional tag, inside the GSM corridor does not guarantee the successful receipt of a text message. However, we do not expect our telemetry system to continuously track animals. Rather, it is presented as a new and efficient way to collect resighting data.

A custom-made modeling framework must be constructed which takes into account the novel nature of our data collection method. The details of model

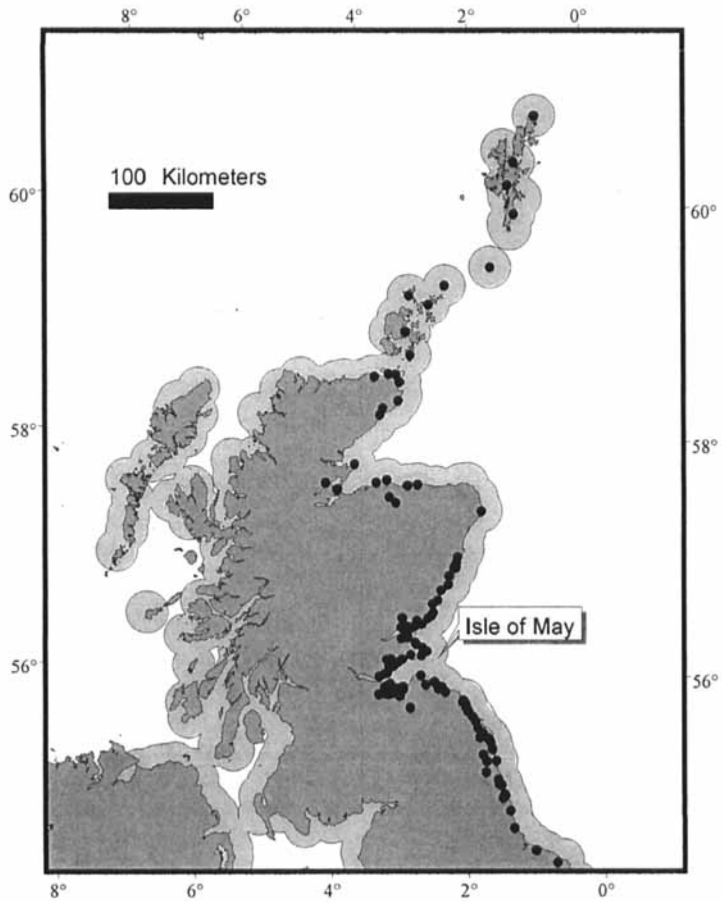

Figure 4. The locations of O2 GSM network radio cells within the UK with which the tags registered. The tags also registered with Norwegian and German cells. We also show approximate and simplified extent of O2 GSM coverage based on a 20-km buffer region centered on all O2 cells.

construction and choice and parameter estimation will be presented separately, as will methods to estimate tag detachment and failure rates. However we do make a general observation here about the requirement for emigration parameters in a mark-recapture survivorship model. The fact that text messages were successfully sent from Norway and Germany indicate that our resighting effort is not limited to UK waters but extends to the entire potential range of gray seal pups (all European coastal regions). Thus, although there are local blind areas of GSM network coverage, and the coverage (resighting effort) is not geographically heterogeneous, it is unlikely that any animal will permanently emigrate from this resighting region.

From these first three months of data we know the haul-out status of the seals for 54% of the time. Three future modifications will reduce the number of lost haul-out records and so increase the haul-out coverage. First, we will release the

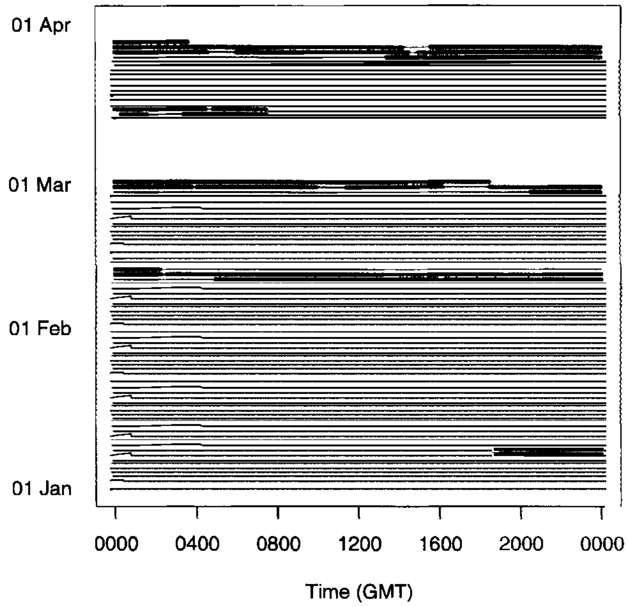

Figure 5. Example of haul-out records obtained from one seal. The thick lines indicate haul-out periods. The thin lines indicate the periods when the seal was known not to be hauled out (see text). Over the period 1 January to 1 April the haul-out status was known (haul-out coverage) for 81% of the time, of which 12% of the time was spent hauled out.

constraint in the current software that permits only one haul-out event to be recorded per 4-h period. Second, we will send less diagnostic information enabling each text message to span a greater period of time. Third, the addition of extra memory will release the current constraint that only 20 unsent text messages may be stored in the SIM card. Thus, many months of information can be stored without loss from those seals that register infrequently.

Neither registration locations nor the haul-out records (complete or otherwise) are essential inputs to a general CJS survivorship model. However their availability will allow the construction of models that are spatially explicit and can incorporate haul-out behavior through time. As well as describing the haul-out behavior *per se*, haul-out records also let us recognize text messages from a detached tag that is washed up on the beach. Data from such a tag would show continuous haul-out over a period of weeks—behavior that would be very unusual from a tag attached to a live seal. Subsequent data from such a tag would be excluded (right censored) in a survivorship model.

The longevity of the tag (or the size of the battery required) depends upon the current drawn. This is highest (an average of 40 mA) during the time that the TC35 modem is switched on and is trying to register. In the current software version, network registration is attempted for a maximum of 95 sec. The reasoning for choosing this value was that a shorter time-out might prohibit registration when the phone tag was at the edge of GSM coverage, was being intermittently washed by waves, or was attempting to register with a roaming partner for the first time. One the other hand, we expected that the seals would be outside GSM coverage for the bulk of their time, and thus a shorter time-out period would be preferable—the sooner the tag realized that registration was not possible the less energy would be expended. The frequency distribution of the delays to successful registration (*reg_wait*) in Figure 3 shows that the delays were less (especially the 95th percentile value) when a seal was known to be hauled out. This is probably due to the absence of wave wash and the slightly higher elevation (and thus better radio contact with GSM radio cells) of seals when hauled out. Overall, halving the registration timeout value to 47 sec would have lost only 8% of all successful registrations. While this would result in a significant reduction in tag energy requirements, it would also increase the risk of failing the more lengthy process of registering abroad for the first time. The registration delay could be reduced if the TC35 modem was switched on at the 4-h alarm, without waiting for the tag to become dry. The initial, non-radio part of powering up (3–4 sec) would thus be completed underwater, reducing the time that the animal had to be continuously at the surface for registration. However there would be an increased energy cost of maintaining the TC35 modem in a powered up state while waiting for the animal to surface.

This study has shown the potential of GSM networks to send information from marine mammals. The massive global investment in GSM networks and the huge growth in mobile phone usage have resulted in a telemetry technology with low capital and running costs. GSM networks phone-tags do not have the global coverage of the Argos satellite system (Fedak *et al.* 2002), and our method of location determination within the coastal GSM corridor is crude. However, for the many species of marine mammal that frequent coastal waters, the lower cost of phone tags allows larger sample sizes and thus more powerful inference to estimate population parameters. In addition, the ability of phone tags to relay haul-out information makes them a useful tool to adjust population sizes from seals counts on land (Thompson and Harwood 1990, Ries *et al.* 1998).

Our demonstration of proof of concept opens up the potential to exploit other data capabilities of GSM networks. General Packet Radio Service (GPRS) and Circuit Switched Data (CSD) channels allow data to be uplinked at a rate of between 1 and 2 Kbyte per sec, for unlimited duration. This removes the 160-byte constraint of sending information *via* SMS text messages. A potential application of this technology would be a time-depth recorder (TDR) which remotely uplinks data to the user whenever the animal comes within GSM network coverage. In addition, text messages could also be sent *to* the phone tags enabling changes in their operation to be executed remotely.

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