detailed studies of both fall and spring migration on the same birds are also already possible in the MOTUS-dense areas of the maritime provinces in eastern Canada and the province of Ontario (Fig. 3). We have been able to do this with eagles and waterfowl for a few years now, but the tags in these projects often weigh as much as two or three of our study organisms!

Even more exciting is the prospect that we can actually use the GPT system to directly study dispersal. For many years, we studied dispersal by the only direct means that we have available for small birds: mark-recapture. With an army of 100 volunteers across New York and surrounding states, we studied where young birds go to breed for the first time (Winkler et al 2005) and where breeders go when they shift breeding sites (Winkler et al 2004). This involved the capture of roughly 30,000 birds to produce fewer than 700 records of dispersal events. The GPT dispersal tag offers a direct and MUCH more efficient way to study this key population process. With this tag, birds can be tagged before they leave the nest and relocated the next season with MUCH higher probability than in a randomly distributed network of bird-banding volunteers. This opens up the possibility, for the first time, of experiments with birds in the nest (with, say brood size, or corticosterone levels) that can actually measure dispersal to the first breeding site as the response variable. Dispersal is arguably the most important yet least studied population process, and this new generation of tags will make direct studies of the causes of variation in the underlying behavior possible for the first time. It will also make possible for the first time studies of the heritability of key properties of small wild birds, since we will now be able to connect, with much higher probability, the phenotypes of parents with those of their young once they become breeders. Again, dispersal studies in dense areas of the MOTUS network are only waiting for the availability of long-lived tags.

And our smaller yet more powerful generation of solar-powered or solar-assisted tags such as the DTT opens up a whole new generation of possibilities for the direct study of moving birds and the environmental and physiological determinants of those movements (Winkler et al. 2014). I have used examples from my own work here, but the need for new techniques to study migration and dispersal has been broadly acknowledged by groups such as MOVEBANK and the Migratory Connectivity Project (< http://www.migratoryconnectivityproject.org/>). To the best of our knowledge, there are no tags available to serve the needs for which we are designing these tags. There is a battery-operated geolocator with an RF datalink available, but it is much larger and has a very limited means of initiating data download. And "coded nano-tags" are being used quite successfully in the MOTUS network, but they are battery operated and relatively short lived. The techniques and insights we are developing need to be brought to bear on the vast majority of all birds, not just those large enough to carry relatively huge tags, with large batteries.

Development Plan

There are several transformative developments that we propose for both the GPT and DTT, which involve the integration and refinement of the use of solar cells to reduce tag mass and/or increase productive tag life-time. We list these goals in the chronological order in which they will be prioritized. We generally do not work on a lower ordered task until the higher priority tasks are achieved, or until we reach a node where no further work is possible for a time (e.g., while a board is being spun), or until a student arrives with a keen special interest in, and qualifications for, one of the tasks further down the line. We develop Gantt charts for each of these tasks (e.g., Fig. 8), but there is not room for each of those here. Instead, we indicate in each task which of the two engineers will take the lead on overseeing that task, along with an estimate of how long it will take and how much supervisory and educational engineer time will be required.

GPT—General-purpose Programmable Tag

Year 1 *Automatic direction finding for tag localization* *(Gabrielson lead @ 6 weeks of his time, July - November 2016)*: Localization of radio tags becomes a major issue when much time has passed since the tags were last detected, and this is especially true in the long-life application to dispersal studies that we envision for the simple GPT beeper tags. Birds that fledged wearing a radio and return the next year to the general vicinity of their natal grounds will be searched for the

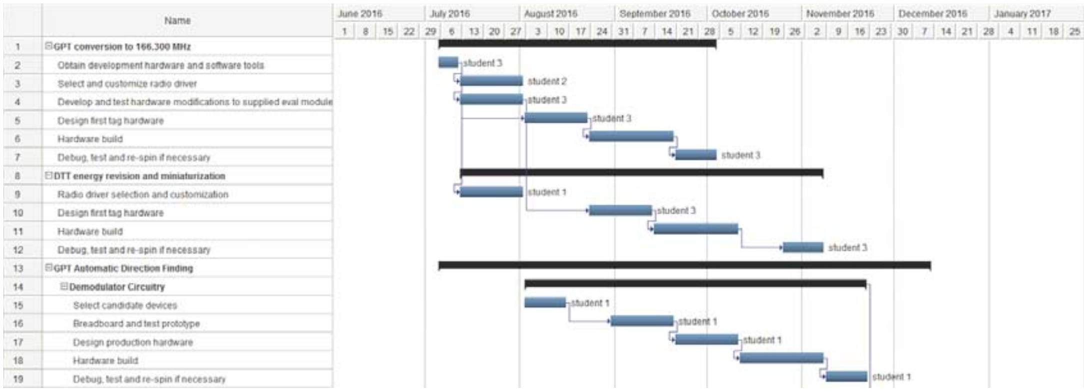

Figure 8. Gantt chart for representative development tasks in the first year of the proposed research.

following spring, and we need better methods to find them. Traditionally, analog radio tags have been localized by listening to the audio amplitude from a tag while a directional (usually Yagi)

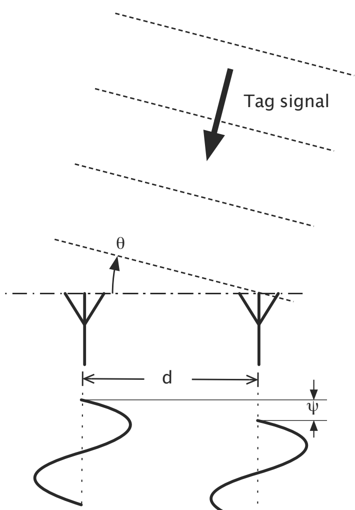

Figure 9. As the angle to the pair of receivers from the incoming signal increases, the phase difference between receivers increases.

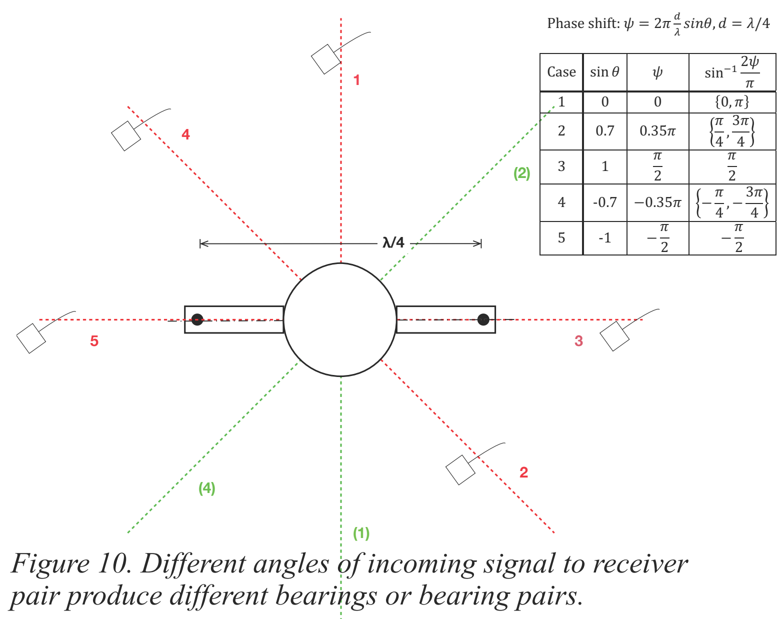

Figure 10. Different angles of incoming signal to receiver pair produce different bearings or bearing pairs.

antenna is being pointed in different directions. One of the problems with the very short transmission pulse lengths of the digital tags is that they do not provide long enough pulses to use this method of localization. The beeper informs a receiver in a zone of its presence, but for locating the tag and the bird that bears it, automatic radio-direction finding is going to be necessary.

Amateur radio operators have developed Doppler radio direction finders (e.g., Kossor 1999) with antennas placed into a four point circle and electrically switched to emulate the Doppler shift on a single rotating antenna. We have explored this solution by modifying an offthe-shelf unit for the frequency of our tags, and we confirmed what we feared: that this circuitry was not able to gather enough information on the 2.5 ms pulses during its virtual revolution to reliably estimate the pseudo-Doppler shift in their frequency, and thus direction. We have thus turned instead to an approach suggested by our colleague in ECE, Alyosha Molnar. We propose a direction-finding scheme that makes use of the digital coding to isolate individual tags along with signal processing to produce a persistent, visual indication of relative bearing to the tag. The localizing receiver will employ an array of two omnidirectional antennas separated by a quarter wavelength of the tags' center frequency. The tag signal will arrive at the two antennas with a phase difference, psi, that depends on the angle of arrival, theta, relative to the array (Fig. 9). The signals from the two antennas will be demodulated separately using a common local oscillator as a reference. Each demodulator produces in-phase and quadrature (I and Q) outputs which are converted to the signal's magnitude and phase relative to the local oscillator. The difference in phase between the two demodulated versions of the signal preserves the phase difference at the antennas. In most cases there will be two bearing solutions. So long as the separation between the antennas is one quarter wavelength, the formula in Fig. 10 will yield distinct solution pairs for each bearing angle, as shown in the table therein. The case numbers in the table correspond to the numbered pairs of bearing lines in the figure. At the maximum phase difference the bearing solutions converge to a line extending from only one end of the array toward the transmitter, unambiguously indicating the bearing to the tag (cases 3 and 5). In operation, the researcher will select the unique code of the tag of interest at the receiver, which will perform the signal processing whenever that tag code is received. The array can then be rotated until the maximal phase difference is detected and a straight-line to the tag is indicated (Fig. 11).

<u>Year 1 Conversion to 166.380 MHz</u> (Powell lead @ 6 weeks, 1 September 2016 - 1 March 2017): When we developed the first GPT over two years ago, we built it around the smallest and most efficient RF chip we could find at the time, the SX1230. This is one of the chips that is used in automobile key-fobs to give them remote locking capability, via an RF link at 434 MHz. This chip has served us very well, and we plan to continue to make these tags for the proximity-detection application. But for longer-distance wildlife telemetry, it will be better to develop a device at the lower frequencies typically used in wildlife telemetry applications, where lower frequencies yield better signal transmission in vegetation, etc. Working with Phil Taylor (head of

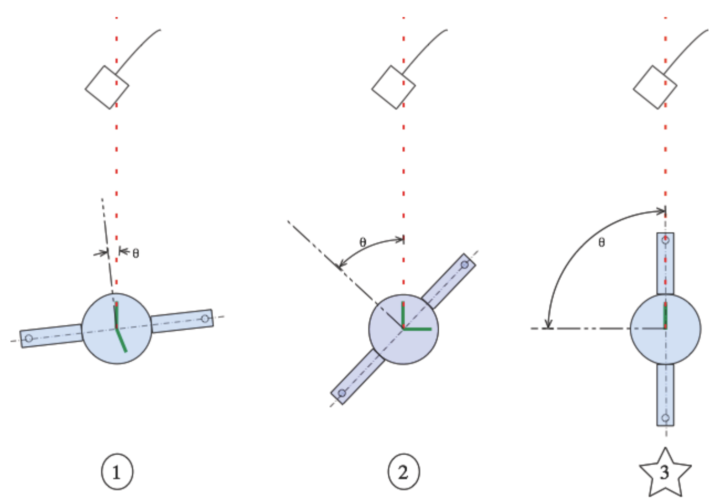

Figure 11. Rotating the receiver pair to find the maximal phase difference gives a way to sight to the tag.

the MOTUS system), we have already demonstrated that the MOTUS software-defined radio can detect and decode the signals from the GPT, but it would be a great advantage to produce GPT's that were transmitting at the "default" MOTUS frequency of 166.38 MHz that is used by all the tags detected now in MOTUS. We will thus be redesigning the GPT to use the Si1060 chip, which is a combined RF transceiver and microcontroller Silicon Labs. At the same time that this places us in a better frequency band, it brings a single-chip improvement in all functional realms of the GPT. The Si1060 is a modern chip (it first became available in 2014) with impressive capabilities and resources. It has 4 kB of RAM and 64 kB of flash memory, so there is plenty of space for

data storage, obviating the need for separate memory modules. For roughly the same PCB real estate, the built-in microcontroller gives many options to optimize data collection, analysis, and transmission that were not available with the previous key-fob chip. In addition, the Si1060 outperforms the SX1230's wireless capabilities. This new chip has a frequency range of 142 – 1050 MHz with a maximum bitrate of 1 Mbps, and previous tags could only reach as low as 290 MHz and could only transmit at 600 kbps. In addition, while the previous chip could only reach an output power of +17 dBm, the Si1060 can reach an output of +20 dBm. Furthermore, the current required to produce the +20 dBm output at its maximum frequency is 85 mA, a full 10 mA less than what was required for the SX1230 transmitter even at the significantly lower output power (+13dBm) at which we were running it. Extensive field tests with out current GPT indicate that our range when the tag is less than a meter above water (with a Yagi antenna on the base station on land) is about 1 km and line of sight in air, when the tag is ca. 400 m up in the air (hot air balloon) is about 2 km. Given that the current circuit on the GPT is running the SX1230 at +13dBm, we expect the ranges of the new tags with the Si 1060 to at least double.
Year 2 GPT ID field dongle (Gabrielson lead @ 10 weeks, July - December 2017): As indicated in Recent GPT progress above, we have developed a cloud-based database for all the codes that we have generated for the current generation of GPT tags, and we have a rough GUI prepared for field use on a laptop computer to record the details of deployment for each tag. This first-pass solution really needs refinements to the GUI and dataflow. Most importantly, we discovered when deploying tags this summer that it would be very useful to have a USB dongle that contained both a receiver to confirm the id of the tag being deployed and a GPS receiver to record at the same time the accurate coordinates of where the tag was being deployed. Maintaining an accurate database of the deployed tags will be invaluable in the near future as GPT's are made available to a much larger number of researchers. Because each tag will broadcast its own identity when exposed to light, the GUI will interface with a receiver USB-dongle that will be provided with the GPTs. Once the attached receiver dongle has received and decoded the ID, the GUI will display the tag's ID code and the date it was programmed, the date of shipping and the investigator or organization to whom the tags were shipped. When the tag is attached to a bird, the investigator will fill in relevant study data (date, time, location name, species, leg band code, etc.) in a fill-in table for each tag, with the GPS coordinates automatically provide by the dongle's GPS. Both at final tag assembly and at field deployment, data will be updated on a central cloud-based database that keeps the master database files up to date whenever the laptop computers have internet access. Because the base station units record detections in the form of ID codes, those records will easily be merged with the historical data in the master database for analysis.

DTT--Digital Turnstile Tag
Year 1 *DTT miniaturization and energy supplementation (Gabrielson lead @ 8 weeks, November 2016 - May 2017):* For the next generation DTT, we will use the same Si1060 wireless microcontroller chosen for the GPT re-design. This single chip will replace three like-sized chips on the current DTT, and require the addition only of a further tiny crystal to regulate the Si 1060's internal real time clock. This will allow us to dramatically reduce the PCB area by 25-30% and reduce the power requirement by 30-40%. These savings come with twice the flash memory and four times the RAM. The Si1060 is programmable in C, and most of the work in transferring the C code for our low-energy communications software will be in matching up the necessary functionality in our existing C code with the appropriate libraries and functions on the new chip. For most missions, the DTT must record enough light-level information to permit estimating positions over the period of a year. At a minimum, data in a 90-minute period surrounding each twilight should be recorded; the sample rate during that period could be as frequent as twice per minute, yielding 360 samples per day, or 131,400 samples for the year. Overnight no photovoltaic power is available to recharge the battery, so there must be enough energy to support two 90-minute measurement periods and real-time clock operation during the intervening night. For a reasonable worst-case scenario we shall assume that night will last for 16 hours. The proposed design will require 0.021 mAh of energy from the battery for combined overnight and