March 13, 2011

Dr. Andrew Rawicz
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Re: ENSC 440/305W Design Specification for a GPS Ice Tracking System

To Whom It May Concern:

We enclose a design specification for ArcTech's Integrated Climate Evaluator (ICE) system that provides long-term, autonomous asset tracking and environmental monitoring in the high arctic. This specification provides design solutions to the functional requirements described in a related document, ArcTech's functional specification for a GPS ice tracking system.

This document provides an outline of the design considerations made by the ArcTech design team in selecting certain electronic components, choosing housing materials and designing the mechanical enclosures and circuit layouts. A general system test plan is also provided with a prototype expected to be complete by early April 2011.

If you have any questions about this document, please contact me by email at bjm11@sfu.ca.

Sincerely,

Brendan Moran
CEO, ArcTech

encl: Design specification for a GPS ice tracking system.

Design Specification for GPS Ice Tracking System

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Executive Summary

While the nature of climate change is a matter of some debate, the need for a better understanding of our climate is undeniable. To understand the arctic environment, we need more information about the climate in the form of the behaviour of large ice floes. The formation of these large sheets of arctic sea ice can tell us quite a bit about an environment which is very sensitive to climate change but typically very difficult to monitor, particularly in the winter.

The ArcTech Integrated Climate Evaluator (ICE) system, in combination with the ArcTech ICE Cap sensor module, provides a comprehensive autonomous weather, position and velocity monitoring solution in a cost envelope which is inexpensive and environmentally friendly enough to be deployed yearly without need for expensive retrieval operations. The ArcTech ICE is a cylindrical base module while the ICE Cap is a sensor module mounted to the top of the ICE system. The base module contains a power supply large enough to maintain the operation of the system for a minimum of eight months.

Using the ArcTech ICE platform, climate researchers will be able to gain a more complete understanding of the movement and properties of arctic ice floes. This knowledge is of paramount importance in understanding the climate of such a sensitive arctic region. Deployment consists of drilling a small hole in an ice floe that is approximately 9 inches wide and 18 inches deep and installing the system in the hole. This will be carried out by a team of researchers based on a Canadian ice breaker which serves as a research platform in the arctic. The researchers are flown out onto the ice floes by helicopter to collect ice core samples, so the deployment of the ArcTech ICE system can be done in tandem with existing research operations.

While the primary goal of the system is to provide movement tracking and environmental monitoring for ice floes, its features allow for appplication to remote weather stations, weather balloon operations, ocean current monitoring buoys, and asset tracking. The ArcTech ICE system provides a single integrated platform which can be deployed in any of these situations simply by varying the deployed software and the sensors deployed on the ICE Cap.

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Glossary

DMA Direct memory access allows peripherals and subsystems to access system memory independently of a microcontroller or CPU

EEPROM Electrically erasable programmable read-only memory is a type of non-volatile memory found in many microcontrollers.

EMI Electromagnetic interference

GPS The Global Positioning System is a network of 32 low-orbit satellites maintained by the US government that can determine the location of a receiver to, depending on the quality of the receiver, within 1 metre. [1]

Heave One of the six degrees of freedom of a rigid body; heave is the measure of motion in the z direction, or "up and down". It can be roughly measured by double-integrating the output of an accelerometer. [2]

I^{2}C Inter-integrated circuit is a multi-master serial computer bus often used for interfacing between peripherals (e.g. sensors) and a microcontroller or CPU

Ice floe Also known as sea ice, an ice floe is a floating piece of ice that can be up to 10 kilometres in width or length. [3]

IP-67 An international protection or ingress protection rating that indicates a vessel is dust tight and water sealed for immersion up to 1 metre. [4]

Iridium Iridium refers to the Iridium Network, a privately maintained network of low-orbit satellites that provides global data and voice communication to users with an Iridium account. [5]

RoHS This standard regulates the Restriction of Hazardous Substances in electrical and electronic equipment and is maintained by the Environmental Agency of the British government. [6]

RTC A real time clock allows for the timing of a microcontroller to be based on the date rather than an internal oscillator.

RTOS Real-time operating system

SPI Serial peripheral interface bus is a synchronous serial data link that allows for communication between devices in master/slave mode

UART Universal asynchronous receiver/transmitter is an integrated circuit that allows for parallel data to be transmitted in serial form

1 Introduction

The ArcTech Integated Climate Evaluator (ICE) system is an autonomous monitoring station intended to provide GPS location and environmental data for objects in the remote arctic location. The primary objects these are intended to track are ice floes but the system is intended to be capable of marine asset tracking as well. The ICE system is designed to monitor any particular asset for eight months while taking data samples on an hourly basis. This data will then be communicated with an end user via a satellite modem.

This document will outline the approach for meeting the functional requirements as described above and in ArcTech's functional specification document. [7] The design choices for the system will be discussed in relevant sections pertaining to the mechanical, electronic and software requirements. Where applicable, other design choices will be discussed with reasons given for why a particular solution was chosen.

This design specification is intended to be used by the ArcTech design team. It will function as a reference to ensure the requirements as outlined in the functional specification document are met. Furthermore, during the testing phase the quality assurance engineers will refer to this document for test criteria and ensure the unit behaves as designed.

2 System Specifications

2.1 General Requirements

The ICE system will be an autonomous, self powered tracking system capable of determining its location through a GPS receiver and broadcasting it to an end user via an Iridium modem. It will also collect data about its surrounding environment and communicate this information along with its location. The system must also be capable of withstanding a marine environment and maintain functionality at temperatures as low as -20° Celsius.

2.2 Physical Requirements

Due to constraints of installation and handling, the system must be at least 50 cm in length and no more than 6 inches in diameter due to limitations of installation equipment. It must also have a flotation collar in the event of fall through or for tracking marine assets. Accordingly, it must be water-resistant or waterproof in the event of fall-through or if it is used for marine asset tracking. The mechanical design of our system that addresses these requirements is discussed in Section 4.

2.3 Sensor Requirements

From [7],

The unit must provide information about the following environmental conditions:

- Air temperature in cap of unit
- Air temperature in bottom of unit
- Relative humidity
- Barometric pressure
- Heave (via a three-axis accelerometer with the output filtered and integrated twice)
- Temperature of ice below unit/fall through detection (to determine if unit is in ice or water)

Each sensor requirement is addressed in Sections 7 and 8.

2.4 Communication Requirements

The communication requirements were partially mandated by the client in that using the GPS system is a simple, low-cost and accurate way to determine location. The use of the Iridium network for communication with the end user was mandated for its commercial availability and ease of use. Specifically, in terms of power conservation, a requirement of the GPS receiver is that it have a time to first fix of 40 seconds or less. This requirement will be addressed in the selection of the specific GPS receiver, which is described in Section 5.2. Additionally, the client's requirement that the system communicate its position and environmental data at an hourly interval places a design constraint on the microcontroller; this is addressed in Section 5.1.

2.5 Performance, Reliability and Durability Requirements

The system is required to have an air temperature sensitivity of at least ±0.5° Celsius for the research purposes of the end user. This is addressed in our selection of an appropriate air temperature sensor, described in Section 8.3 The system must also be able to avoid irreparable damage at temperatures down to -40° Celsius and return to functionality once the temperature returns to -20° Celsius. The general requirement that the system be operational at -20° Celsius is addressed in the selection of the electronics, in that all must be operational in this range and all must have storage temperature ranges that accommodate this -40° Celsius limit.

The system must also be able to power itself for a duration of eight months. This raises a significant design challenge in terms of power budgeting which is specifically outlined in Sections 5.1 and 5.3. In that vein, if the system is to be recovered after an initial eight-month deployment, all other components should be still working properly with the exception of the battery power source(s). This design issue is addressed in the selection of the enclosure material (see Section 4) and the decision to seal the unit to IP-67 standards.

2.6 Usability Requirements

Our usability requirements pertain to the message format and the physical installation of the unit. The former is addressed in Section 7.4 whereas the latter is a general design consideration that is met by providing a fully assembled, calibrated and functioning unit to the end user that requires little activation outside of turning the unit on via a magnetic switch.

3 System Design

3.1 System Overview

A schematic of our system is shown in Fig. 1. It shows the required sensors as specified by the client and end user and gives an overview of the interfacing between the microcontroller and its inputs and outputs. For the proof-of-concept unit, the unit will be capable of broadcasting its location, all specified environmental data with integration and communication to the client.

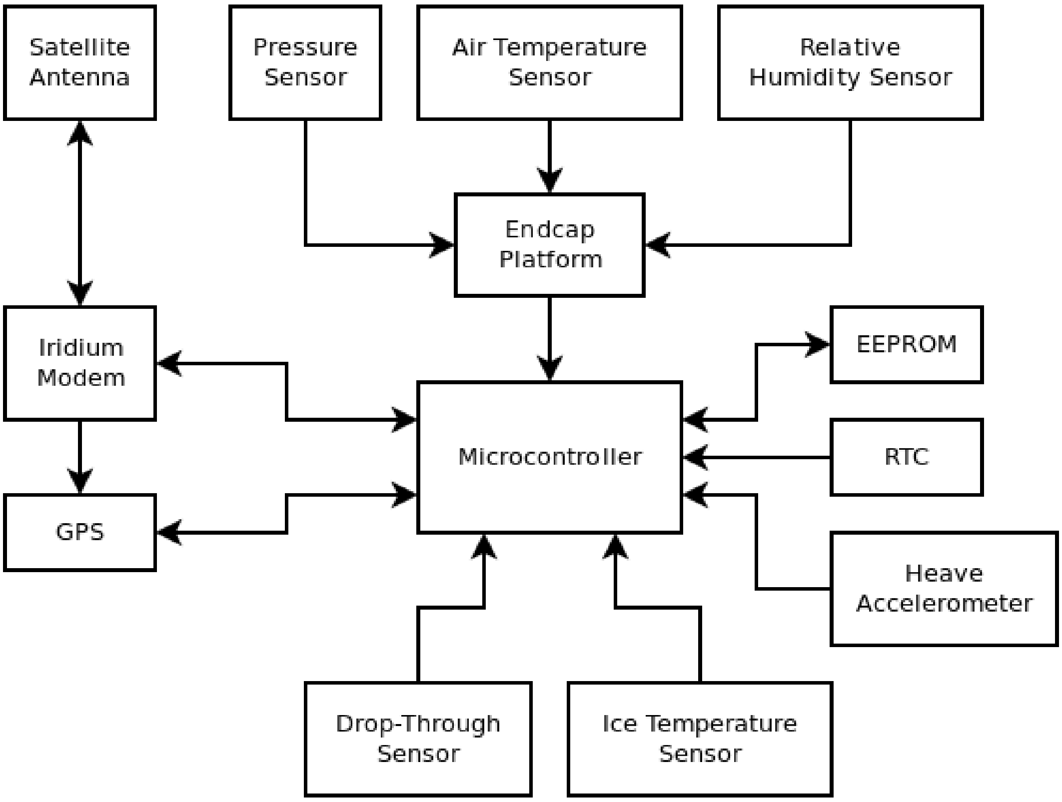

Figure 1: Block diagram of ice tracking system illustrating data flow and required sensors

3.2 Mechanical Design

The system will be enclosed in a cylindrical housing as dictated by the end user's installation procedure, specifically drilling a hole in an ice floe and placing the unit inside said hole for tracking. The environmental constraints present significant design challenges in choosing the housing material and sealing the unit from incident moisture. These challenges and our proposed solutions are presented in Section 4.

3.3 Electronics

The electronics (sensors and microcontroller) are divided into two printed circuit boards, one of which is internal and sealed from the environment, and the other which contains all sensors that must be exposed to collect data as well as the antenna(s). Doing so reduces the number of sensitive electronic components that could potentially be damaged by exposure to incident weather. The internal PCB contains the microcontroller, accelerometer, GPS module and power control circuitry with connectors to the external PCB/sensor pod, battery pack and fall through/ice temperature sensor. The layouts and specific sensors that were chosen are described fully in Section 7 and 8.

3.4 Software

Interfacing with each sensor and communication module is done through a microcontroller running a real-time operating system (RTOS). This allows for software development by multiple members of the ArcTech design team in a high-level programming language. The microcontroller chosen for this purpose also features a real-time clock (RTC) which allows us to easily address the requirement that data be transmitted on an hourly basis while operating in a deep sleep mode to conserve power. A discussion of our specific software design considerations is given in Section 3.4.

4 Enclosure

4.1 Overview

The ArcTech ICE is manufactured with an aluminium housing, which encloses and protects the internal electronics as well as shielding the external sensors from snow and severe weather conditions. The housing is composed of a cylindrical, tubular profile measuring 5" in external diameter and 20" in length, and having a wall thickness of 0.5". Two end caps, fitted with sealing provisions guarantee the device's sealing, and prevent any moisture from coming into contact with electronic parts. The unit will be assembled in a dry room so that there will be no humidity upon assembly. Figure 2 shows the final design chosen for the enclosure.

Figure 2: Perspective view of the final enclosure design (exploded view)

4.2 Cap Design

As many of the sensors need to be exposed to accurately monitor the environment, the internal electronics must be able to communicate with the outside sensors and still remain protected. As a result, the ICE system is equipped with a HR30-7R-12PC pass through connector and a 132284 - SMA passthrough connector (See Figs. 4 and 5). Specifically, the 12-point circular connector is used to support communication lines between the internal MCU and the external temperature, pressure and relative humidity sensors, while the SMA connector supports the dual band GPS-Iridium antenna. These are both IP-67 rated and will allow the exterior and interior electronics to communicate. Fig. 3 shows the overall cap design and the associated mounting holes for these connectors. The cap design is engineered around the topology of these connectors, providing recesses where necessary to avoid water pool formation and ensure maximum contact of the connectors' sealing devices with the cap surface. Fig 3 details the cap design and the mounting holes for these connectors.

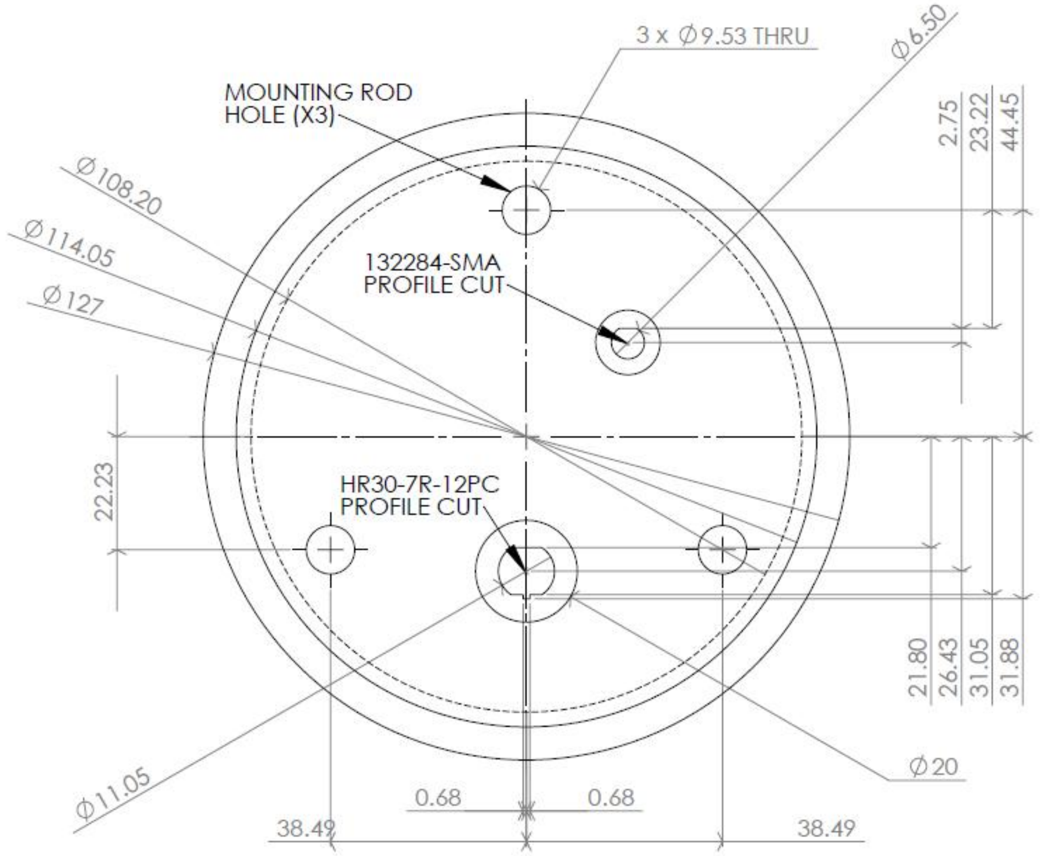

Figure 3: Top view of the cap showing the mounting holes

The outside three holes are for threaded rods that will run through the whole cylinder as support beams for the interior PCB and the battery pack. These support rods will ensure the wires do not stretch or tangle as the cap is screwed in. They will also provide mechanical stability should the unit be moved vigorously during installation, fall through or recovery.

Figure 4: HR30-7R-12PC circular connector

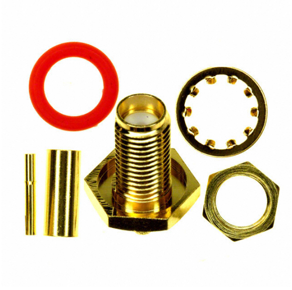

Figure 5: 132284-SMA coaxial connector

4.3 Locking and Sealing Provisions

In addition to providing mechanical support for the internal components, the threaded rods also serve as a locking mechanism for the unit. Sealing nuts are tightened externally on the rods, which presses the end-caps against the enclosure cylinder and seals the mounting rod holes to exterior water and humidity. Fig. 6 shows a view of the sealing nut (SEELnut^{TM}) in use.

Figure 6: The SEELnut^{TM} sealing nut. Note the red, self sealing O-ring already mounted at the bottom of the nut.

In order to provide a seal for the cylinder-cap interface, we have chosen to implement a radial O-ring seal. The seal uses an AS568-244 O-ring with an internal diameter of 4.234" and a cross section of 0.139". The groove is machined on the cap's side according to the AS568 standard. Fig 7 shows a side view of the cap, detailing groove measurements, while Fig 8 shows the assembled radial seal.
Finally, the cold temperatures faced by the system present an encapsulation problem: any humidity in the air during assembly could cause condensation in the ICE system once deployed. Condensation could potentially cause a catastrophic system failure if the condensation were to bridge connections on the internal PCB or batteries. In order to prevent these potential system failures, we will pack a strong dessicant into the ICE and ensure that the O-rings form an air-tight seal.

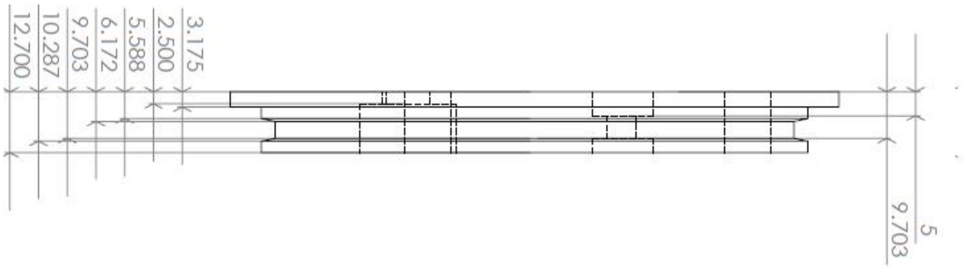

Figure 7: Showing the O-ring groove between the cap and cylinder

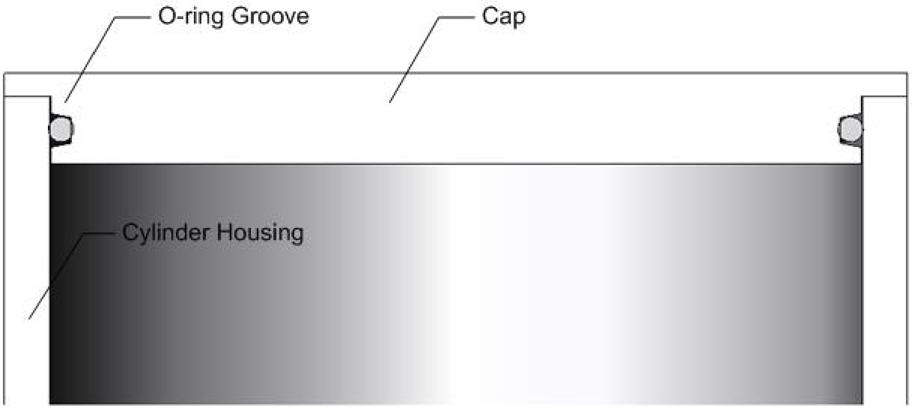

Figure 8: Sealing detail for the assembled radial seal

4.4 Material

The system enclosure will be machined out of 6061 grade aluminum. One reason for this choice is price as aluminum is much cheaper than stainless steel ($30/unit for this grade of aluminum in comparison to stainless steel at $150/unit). In terms of durability, for an eight month deployment the corrosion will be negligible; this particular aluminum alloy is widely used in marine applications for its resistance to corrosion. It is also light weight (4.5 kg/unit in comparison to 10 kg/unit for stainless steel) which is an important design consideration for deployment and buoyancy. As the units will be deployed via helicopter, the system's mass becomes a factor in terms of payload. Additionally, a lighter enclosure will be more buoyant possibly avoiding the need for a flotation collar. Finally, 6061 grade aluminum was chosen for ease of machining. Aluminum is soft relative to stainless steel and will thus bring machining costs down. [8]

4.5 Flotation Devices

The three support threaded rods will also be the anchoring position for an optional flotation device. The flotation collar will consist of a buoy type device that is large enough to keep the unit afloat. The unit has an estimated weight of 4.5 kg which allows for the use of standard type IV ring buoys as a flotation device. These buoys can be easily anchored through aluminium ribbons to the three mounting rods and will provide a minimum buoyancy of 21 lb (10 kg) in case of fall through or the use of the system to track marine assets.

4.6 Environmental Considerations

Although the device comes with a flotation device, it might be the case that the client does not have sufficient economic resources or motivation to recover the unit. The possibility that the ICE system will be released into the ocean motivated our decision to ensure that all materials comply with RoHS standards. Furthermore, the enclosure design does not have any features in which marine life could get trapped, or parts that might be easily broken off and eaten by wildlife.

4.7 Alternative Designs

Prior to choosing the current cap design, several different options were explored. Initially we planned on having a twist cap similar to a plastic pop bottle to screw on the cap. This design was later discarded for several reasons:

- Difficulty and cost of machining custom threads on both the cap and the cylinder
- Necessity of a thicker housing to accommodate threads
- Possibility of O-ring “squeezing” and subsequent rupture during cap tightening

Our next design was to have the cap bolted down to the enclosure along its perimeter, using a crush seal O-ring (see [9]) rather than a radial O-ring design. The crush seal would make machining much easier but we decided against this design due to the requirement of axial holes in the cylinder which would have required further sealing and the consequent need for a thicker housing.

In terms of materials, consideration went to 304-grade stainless steel which was discarded due to cost, weight, and difficult in machining. Another material we considered was PVC for its lightness and ease in fabrication. However, PVC was discarded due to its brittleness and poor elasticity at low temperatures.

5 Internal Printed Circuit Board

The ICE system will have two printed circuit boards. One PCB will be inside the enclosure hosting all circuitry which can operate without exposure to the external atmosphere, while the other PCB will be exposed to the environment in an exterior sensor pod. The exterior sensor pod is described in Section 8. The internal PCB is a standard RoHS FR-4 PCB with 1oz copper thickness and gold connection plating in accordance with satisfy RoHS standards.

The internal PCB houses several subcircuits: the power module (Section 5.3), the microcontroller (Section 5.1), the accelerometer (Section 7.1), the GPS (Section 5.2), and the satellite modem (Section 7.4). The internal PCB connects each of these devices with the microcontroller coordinating all subcircuits. A full circuit diagram is included in Appendix A. The current version of the internal PCB hosts several development boards, but the future version will host individual devices instead at reduced manufacturing costs.

5.1 Microcontroller

The functional requirements of the ICE unit led us to consider a number of different microcontrollers. Specifically, the requirements provided us with specific design considerations:

- Low operating and sleep currents
- Appropriate supply voltages to accommodate battery power source
- Functionality at -20° Celsius
- Real-time clock for waking up from power-down mode at an appropriate time
- Large number of interface ports for communicating with sensors
- As much memory as possible for storage of an operating system and/or data if multiple data sets are transmitted at a less frequent rate

The number of sensors involved and the associated complexity of interfacing with them indicates that programming the microcontroller in assembly language may be too cumbersome. In addition, since software design will be carried out by several ArcTech members, an operating system with high-level programming capability seems necessary. This will be discussed further in Section 3.4. Table 1 lists several microcontrollers that were considered for our system illustrating these design considerations and how they were addressed. All of these units featured a real-time clock and guaranteed functionality between -40 and -20° Celsius.

Table 1: Comparison of several microcontrollers considered for use in ICE system

Component Name	**Flash (kB)**	**RAM (kB)**	**I_{Peak} (mA)**	**I_{Sleep} (μA)**	**V_{DD} Range (V)**	**Ports (UART/ SPI/I^{2}C)**	**Price (@25 units)**
LPC1769	512	64	42	31	2.4 - 3.6	4/1/3	$10.92
AT32UC3-A2UR	512	96	18.5	13.9	1.65 - 1.95	3/1/1	$10.26
STM32CBT6B	128	8	15.4	2.6	2 - 3.6	3/2/2	$4.30
PIC32MX795	512	128	98	50	2.3 - 3.6	6/4/5	$9.06

When choosing a device, we considered these parameters in addition to availability and ease of development. The LPC1769 was available from a reliable retailer with a user-friendly breakout board and free development software (LPCXpresso). While its cost and operating currents were not ideal, it has adequate RAM to accommodate the operating system and a deep power-down mode. It also has flexible clock management capabilities that allow the oscillator to run at lower frequencies, thus reducing the operating current. These factors influenced our choice of the LPC1769 as the microcontroller for the ICE system.

5.2 Global Positioning System Module

The GPS module was selected based on three factors: power consumption, time to first fix, and availability of suitable breakout boards. We selected the Skytraq Venus634 because it has a cold-start time to first fix of 29 seconds, a current consumption of 28 mA and a sensitivity of -164 dBm. In addition to these features, the Venus634 is available on a breakout board with an SMA antenna connector, which eased its inclusion into our design. We will connect the V_{Bat} terminal of the Venus634 to improve the time to fix beyond 29 seconds.

After the GPS obtains its first fix, it improves in accuracy, which is reported by the GPGSA NMEA string in the dilution of precision fields. We will not take the first fix reported by the GPS; instead we will wait until the horizontal dilution of precision is less than 5.0. This is the maximum recommended dilution of precision for making business decisions and is thus an appropriate level of accuracy for scientific measurement.

5.3 Power Module

The ICE system must operate for eight months without any opportunity to exchange or recharge batteries or to harvest energy from any ambient source. With these constraints, power efficiency is a primary concern in the design of the system. Extra care has been taken to select power converters which minimize the quiescent current and maximize the efficiency of the supply. The tracker operates in two modes: active and sleep. In active mode, the microcontroller is running and power is delivered to all sensors. In sleep mode, the microcontroller enters deep power down mode and power is not supplied to any sensors.

The microcontroller and all sensors use a 3.3 V supply, while the Iridium modem requires a 5 V supply due to the satellite transmitter. The current consumption of each component is outlined in Table 2. The total current required for each voltage rail was used in order to design the power supplies. A composite solution was necessary and is outlined in Fig. 9.

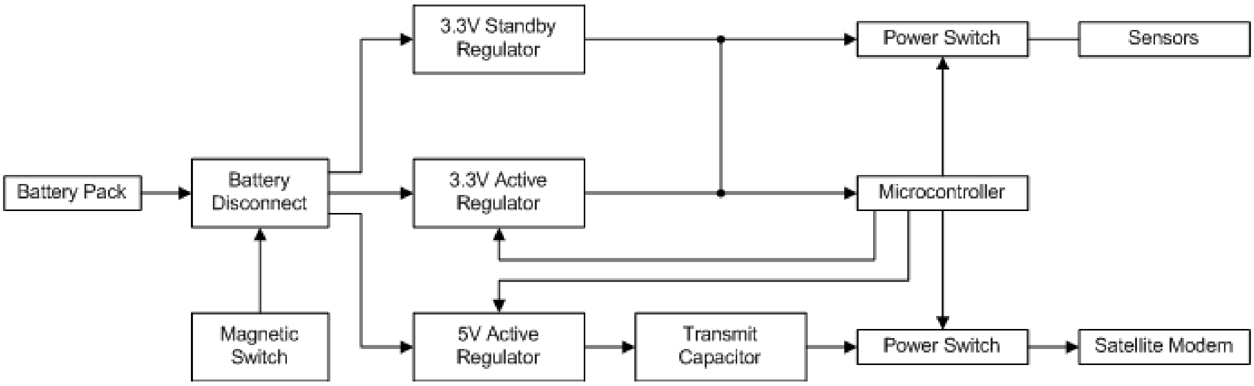

Figure 9: Power module block diagram

Battery Disconnect

To allow for ease of deployment, we will seal the units before shipping them to our end customer. In order for the customer to be able to deploy the unit in a very cold, remote location without having to open the unit and connect power, we have provided a magnetic switch. Units will be shipped with a magnetic toggle attached to the sensor pod which, when removed, will connect battery power to the unit. To prevent false removals from requiring maintenance, reconnecting the magnet toggle to the unit will disable it again.

Table 2: Power consumption of sensors, microcontroller and communication devices

Device	**3.3 V Current**	**3.3V Sleep Current**	**5 V Current**
Microcontroller	42mA	651 nA	-
Accelerometer	975 μA	-	-
Pressure Sensor	12 μA	-	-
Humidity/Temperature Sensor	30 μA	-	-
Ice Temperature Sensor	15 μA	-	-
GPS	28 mA	-	-
Satellite Modem	-	-	45 mA
Total	**72 mA**	**651 nA**	**45 mA**

To accomplish this task, we developed the circuit shown in Fig. 10. Application of the magnetic toggle grounds the PWRSW node, which turns off Q1, turns on Q2, reverse-biases D1 and turns off Q6. If the magnetic toggle is removed, a small amount of current flows through R3, charging the gate of Q1. As Q1 turns on, a voltage will develop across R1, which will cause Q2 to turn off. As Q1 turns on and Q2 turns off, the gate of Q6 will start to be pulled down. As Q6 turns on, D1 will become forward biased and accelerates the turn-on of Q1 and, thus Q6, creating a positive feedback loop. Because R3 is very large, the current drawn by application of the magnetic toggle will be 12V/10 MΩ = 1.2 μA. Despite this small current, the circuit is immune to EMI because Q1 is held on by R2. Furthermore, none of these components consume any current once the magnetic toggle has been removed and Q1 and Q2 have reached steady-state.

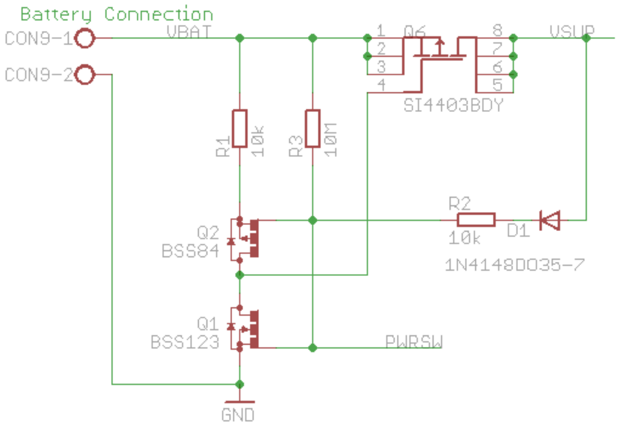

Figure 10: Battery disconnect circuit

3.3 V Supply

First, we selected regulators based on the requirements of the active mode. We chose the LTC3631 power regulator because it can supply 100 mA, has high efficiency, low quiescent current, internal MOSFETs, and easily available development boards. This regulator is suitable for powering both the 3.3 V rail and the 5 V rail. Next, we examined this regulator's performance when our system is in sleep mode. In this mode, our system will only consume 651 nA, which places the LTC3631's quiescent current (12 μA) far higher than our system load. To correct this, we place the LT3631 into shutdown mode, reducing the current consumption to 3 μA. To supply power to the sleeping microcontroller, we then need a backup regulator. Selecting the lowest quiescent current linear regulator we could, we chose the LT3008, which has a quiescent current of only 3 μA. The LT3008 has the further advantage that it is designed to be used as a backup regulator, requiring no switching circuit or coupling diodes between it and the other regulators in the system. This combination lowers the quiescent current of the configuration from 12 μA to 6 μA.

The LT3008 creates a further difficulty, however. As it only provides 20 mA maximum, the LT3008 is not capable of powering the microcontroller at its maximum operating frequency. The microcontroller's clock multiplier must thus be disabled before it disables the LTC3631 and can only be re-enabled after the LTC3631 has started up again. A single regulator solution is not viable due to the high dynamic range of our power supply requirement:

$$20 \log \left(\frac{71 \text{ mA}}{651 \text{ nA}} \right) = 100.8 \text{ dB}.$$

Further improvements to this configuration are possible but are more complex and more expensive for little overall improvement in system lifetime. To judge whether the power regulation subsystem needed to be improved, we compared the savings in the battery pack the cost of the improvement. If the savings in the battery pack were less than the cost of the solution, we did not implement the improvement to the power regulator. To reduce power consumption in sleep mode, we have provided a power switch to disable the peripherals. Because the GPS time to fix can benefit significantly from maintaining its memory, a connection from the GPS V_{bat} to the standby regulator has been provided.

5 V Supply

The 5V supply only powers the satellite modem. The satellite modem is powered at the end of each cycle only in order to keep quiescent current to a minimum. The modem is placed into power-down mode when not in use. The current consumption of the power down mode is not listed in the modem's development guide. The 5 V supply has very challenging requirements. The Iridium 9206SBD Satellite modem has a variety of power requirements at different stages in its operating cycle, as shown in Table 3. The Iridium modem requires an average of 45 mA in idle and a peak of 1.5 A in transmit. Over this range of current draws, the modem requires that its power supply remain within 5.0 ± 0.5 V DC. During transmit, the power supply droop shall be no greater than 0.2 V DC.

Table 3: Current consumption of Iridium modem in different modes

Mode	Current Consumption	Duration
Background	40 mA	41 ms
Transmitter data burst	1.5 A	8.3 ms
Post-transmit burst	100 mA	6 ms
Receive data burst	195 mA	8.3 ms
Post-receive burst	100 mA	7 ms
Idle	45 mA	30 s

To accommodate these stringent requirements, we considered several options: design the power supply for 1.5 A, design for a large fraction of 1.5A with a small capacitor to maintain the supply during transmit or design the power supply for 100 mA with a large capacitor to maintain the supply during the entire transmit phase. We eventually decided on the last option due to a comparison of required capacitor sizes and their costs.

$$C = (I - I_{\text{supply}}) \frac{dT}{dV} = (1.5 \text{ A} - 0.1 \text{ A}) \frac{8.3 \text{ ms}}{0.2 \text{ V}} = 0.0581 \text{ F}$$

Calculating a minimum capacitor size of 60 mF, we searched for closely sized supercapacitors with low effective series resistance (ESR) which also contributes to power supply droop. We chose a 1.5 F capacitor (much larger than the requirement) based on price and ESR. This created a new problem, in that this capacitor stores a large amount of energy:

$$E_{\text{stored}} = \frac{1}{2}CV^2 = (0.5)(1.5\text{ F})(5\text{ V})^2 = 18.75\text{ J}.$$

18.75 J is a significant fraction of the energy required to operate the system on each cycle, so we cannot allow the capacitor to discharge after each cycle. To guarantee that the capacitor does not discharge through the powered-down satellite modem, we have provided a power switch to disconnect the power supply to the satellite modem. The leakage current in the supercapacitor we selected is $I_{\text{leakage}} \leq 20\ \mu\text{A} = E_{\text{leakage}} \leq 0.36$ J/cycle which is a significant improvement over the 18.75 J from a full discharge. The modem also has a restriction of a maximum of 4 A of inrush current. To reduce the inrush current, the switch has been fitted with a loading capacitor and a current limiting resistor on its gate. This will cause the switch to turn on slowly, reducing the inrush current seen by the modem. Finally, a measurement connection has been provided so that the microcontroller can measure the voltage which will be applied to the satellite modem and guarantee that the 5 V rail is within 5.0 ± 0.5 V DC before enabling power to the modem.

6 Battery Pack

The battery pack must be specified to operate over the entire range of temperatures expected and it must provide a minimum of 5 V so that it can supply the regulators. We will avoid using rechargeable batteries as they tend to have higher self-discharge rates and there are no facilities for re-charging them as the unit will be completely autonomous for the duration of its deployment. Since we require batteries which operate down to −40° Celsius, we selected Tadrian Lithium Primary cells. These batteries are rated to −55° Celsius and are not rechargeable.

6.1 Characteristics

The battery pack's requirements have been obtained from the estimated power consumption of each component of our sensor package. The energy requirements of each device have been compiled in order to calculate a total energy requirement for the unit over its required lifetime. These energy requirements are shown in Table 4, 5, and 6. The supercap is only charged during the active mode of the 5 V regulator, so it is included in the 5 V active mode table. Table 7 shows the energy per cycle required from the batteries once regulator efficiency and quiescent current are factored in.

Table 4: Device current consumption for 3.3 V (active mode)

3.3 V Loads	**Current**	**Active Time**	**Active Charge**
MCU	42 mA	60 s	2.52 C
Accelerometer	975 μA	45 s	43.88 mC
Pressure Sensor	12 μA	45 s	540 μC
RH sensor	27.3 μA	45 s	1.227mC
GPS	28 mA	45 s	1.26 C
Ice Temp Sensor	15 μA	45 s	675 μC
Misc.	500 μA	45 s	22.5 mC
Total			**3.849 C**

Table 5: Device current consumption for 3.3 V (sleep mode)

3.3V Loads	**Current**	**Active Time**	**Active Charge**
MCU	652 nA	3540 s	2.30 mC

Table 6: Device current consumption for 5 V (active mode)

Modem Modes(5V)	**Current**	**Active Time**	**Active Charge**
Background	40mA	10 ms	400 μC
Transmitter data burst	1.5 A	8.3 ms	12.45 mC
Post-transmit burst	100 mA	6 ms	600 μC
Background	40mA	31 ms	1.24 mC
Receive data burst	195mA	10 ms	1.95 mC
Post-receive burst	100mA	7 ms	700 μC
Idle	45mA	30s	1.35 C
Supercap drain	20 μA	3600s	72 mC
Total			**1.439 C**

Table 7: Energy consumption per cycle

Power Sink	**Voltage**	**Charge /cycle**	**Energy Output /cycle**	**Efficiency**	**Energy Input /cycle**
3.3 V (active)	3.3 V	3.85 C	12.7 J	87.00%	14.599 J
3.3 V I_{CC} (active)	14.4V	7.5 mC	-	-	108 mJ
3.3 V I_{CC} (sleep)	14.4V	10.62 mC	-	-	153 mJ
5 V (active)	5 V	1.44 C	7.2 J	90.00%	7.996 J
5 V I_{CC} (active)	14.4 V	3.75 mC	-	-	54 mJ
5 V I_{CC} (sleep)	14.4 V	10.71 mC	-	-	154 mJ
3.3 V (standby)	3.3 V	2.31 mC	-	-	7.617 mJ
3.3 V I_{CC} (standby)	14.4 V	10.8 mC	-	-	156 mJ
Total	-	-	-	-	**23.228 J**

Using the total energy per cycle which we calculated in Table 7 and a 50% overdesign factor, we calculated the lifetime energy of the unit:

$$E_{\text{lifetime}} = 8\text{ months}\left(\frac{730.5\text{ h}}{\text{month}}\right)\left(\frac{1\text{ cycle}}{\text{hour}}\right)\left(\frac{23.228\text{ J}}{\text{cycle}}\right)(1+50\%)\left(\frac{1\text{ W}\cdot\text{h}}{3600\text{ J}}\right) = 56.6\text{ W}\cdot\text{h}$$

Our selected batteries have a terminal voltage of 3.6 V and a rated capacity of 2100 mA·h, yielding an energy capacity of 7.56 W·h. We selected the the number of batteries necessary by dividing the required energy by the cell energy:

$$N_{\text{cells}} = \left\lceil \frac{56.6\text{ W}\cdot\text{h}}{7.56\text{ W}\cdot\text{h}} \right\rceil = \lceil 7.382 \rceil = 8\text{ cells} \tag{1}$$

Because we require an even number of cells, we will connect four pairs of parallel cells in series to form the battery pack.

6.2 Environmental Considerations

We were very concerned with the possible side effects of leaving batteries to fall into the ocean, so we took special care to select lead-free/RoHS compliant batteries. Tadiran Lithium Primary cells meet this requirement.

7 Internal Sensors

7.1 Accelerometer

The ArcTech ICE system uses a Bosch BMA-180 accelerometer to estimate the ice heave caused by seawaves and in the case of fall through, to estimate sea conditions. The BMA-180 is a three-axis, digital-output, highly-configurable accelerometer. We chose this accelerometer for its high accuracy (4096 LSB/g), wide operating temperature range ($-40°$ to $+85°$ Celsius), and low cost compared to other devices with similar characteristics. The BMA-180 is shipped in a LGA package, which would constitute a problem for assembly on our side. Nevertheless, we were able to find a version equipped with a breakout board, which eliminated soldering concerns.

The BMA-180 can be configured to use both SPI and I^2C communication protocols. Due to the abundance of general purpose I/O pins in our microcontroller and to the need to quickly perform a large number of measurements with this device, we opted to interface the BMA-180 and our microcontroller using the SPI protocol. This protocol, compared to I^2C, provides much lower overhead at the expense of being able to address only two peripherals per port.

The BMA-180 gives the user the option of configuring its power consumption mode, its measurement range, and its bandwidth. This is achieved by writing specific control words into the accelerometer's EEPROM memory. In order to obtain the highest measurement precision while limiting our power consumption, we chose to configure the device as follows:

- Measurement range: ±2g
- Bandwidth: 75 Hz (37.5 Hz effective)
- Operating mode: ultra-low noise Mode (supply current = 650-975 μA)
- Advanced interrupts: disabled
- Main interrupt: on new data present

In this configuration, the accelerometer reads data at a rate of 40 Hz and triggers an external interrupt in the microcontroller every time a new set of data is present in its registers. The microcontroller then performs, through the aid of a previously set-up DMA channel, and SPI read. The data is read in the form of three 14 bit registers (x,y and z acceleration), processed to calculate a net acceleration vector, and stored in an array in 16 bit format. Once the microcontroller has collected sufficient data ($\approx$ 10 seconds), the accelerometer is put in sleep mode (supply current: 0.5 μA), and wakes up only when a new read cycle is needed.

The data is collected in the form of an array of three accelerations: $[x_{\text{acc}}, y_{\text{acc}}, z_{\text{acc}}]$. The microcontroller processes this data at every read cycle, obtaining a net magnitude for the acceleration according to

$$A_{\text{NET}} = \sqrt{x_{\text{acc}}^2 + y_{\text{acc}}^2 + z_{\text{acc}}^2} - 9.81 \text{ m/s}^2.$$

The microcontroller then interprets the case $A_{\text{NET}} > 0$ as a positive (upwards) acceleration, and the case $A_{\text{NET}} < 0$ as a negative acceleration. The array A_{NET} is then integrated twice to obtain the relative displacement X_{NET}, and the maximum and minimum values of this array are subtracted from each other to obtain the maximum heave. This calculation assumes negligible horizontal movement in our time scale (10 s), which is a reasonable assumption for both static (in-ice) and weak marine current conditions.

7.2 Ice Temperature Sensor

The ArcTech ICE system measures the environmental temperature using Texas Instruments' TMP102 temperature sensor. The main considerations taken into account when choosing this temperature sensor were low cost, low power, and high accuracy. The TMP102 sensor was deemed to be the best choice among competitors with these characteristics in mind.

The TMP102's notable features are:

- Accuracy: ±0.5° Celsius
- Resolution: 0.0625° Celsius
- Temperature Range: $-40°$ Celsius to $+125°$ Celsius
- Low quiescent current (10 μA)
- Low cost

The TMP102 can communicate with a microcontroller using one of two two-wire interfaces: system management bus (SMB) or the I^2C bus. Since there exists a driver for the I^2C protocol already in FreeRTOS's device library, we decided to use the I^2C communication protocol.

The sensor can be configured to acquire a data ouput of 12 or 13 bits of temperature data, corresponding to normal and extended mode respectively. In extended mode, the sensors allows for temperatures above $+128°$ Celsius to be measured. Since arctic conditions do not usually present a temperature range above $+128°$C, normal 12-bit mode is used. Each minimal bit increment corresponds to an increase in resolution of 0.0625° Celsius. This result is obtained by sending a read request over the I^2C bus to the temperature register and awaiting two bytes of temperature information to be returned.

Once the read request has been sent by the microcontroller, the 12 most significant bits of the two bytes returned are used to extract the temperature value. Based on this binary value, the temperature data can be determined using the following conversion method. If the most significant bit of the 12 temperature bits is a 0, the temperature is positive:

$$T = 0.0625 * (\text{12-bit data in decimal format})$$

Otherwise, if the most significant bit is a 1, the temperature is negative and is in two's complement:

$$T = |0.0625 * (\overline{((\text{12-bit data in decimal format}) - 1)})|$$

7.3 Fallthrough Detection Sensor

Falthrough detection will be performed with the aid of the ice temperature sensor. The fall-through can be detected by an abrupt change to near-zero Celsius temperatures. We will store the previous measurement of the ice temperature at each reading and, if the ice temperature abruptly changes to within 4 degrees of zero, we will conclude that the sensor has fallen through the ice and is now floating.

7.4 Communication Module

We researched several satellite communication vendors, eventually settling on the Iridium satellite network for their Short Burst Data service. This service is similar to SMS text messaging but with binary data. It also allows for email delivery which will make communication with our end user much simpler. Specifically, we chose the Iridium 9206SBD satellite modem because it is a low-power, low-cost unit of smaller size than other Iridium modules. It also offers tight integration with GPS modules provided that a suitable antenna is available.

8 External Sensor Pod

8.1 External PCB

Several of our environmental sensors require physical contact with the air. In order to accommodate these devices, we designed a second PCB which is connected to the internal control electronics via a waterproof connector. This PCB houses the barometric pressure sensor, the air temperature sensor, and the relative humidity sensor. It also houses an LED and a magnetic switch which are provided on the external PCB so that the cap has as few holes as possible. The external PCB will house a debug/upgrade serial port for the prototype version.

We considered mounting the sensors inside the main housing, but this method would leave vertical holes for the sensors exposed to the elements. This increases the chances of water, ice, snow or particulate matter becoming trapped in the sensor openings. To avoid this, we will mount the external PCB upside-down so that all sensor openings are facing downwards, and any contaminants will be cleared by gravity. In addition, the PCB itself will be coated with a waterproof conformal coating, leaving only the sensor openings exposed to the environment. A PCB schematic is provided in Appendix B.

8.2 Pressure Sensor

The pressure sensor we chose (BMP085) communicates via I^{2}C. One additional signal communicates the end of a conversion. The BMP085 is a calibrated sensor, so Bosch stores calibration data in a ROM internal to the sensor. First, we read this calibration data and store it. For each reading taken by the BMP085, a read sequence is followed:

1. Write the “start temperature conversion” command via I^{2}C
2. Wait for a conversion complete interrupt
3. Read the raw temperature via I^{2}C
4. Write the “start pressure conversion” command via I^{2}C
5. Wait for a conversion complete interrupt
6. Read the raw pressure via I^{2}C
7. Use the calibration routine to convert raw temperature and raw pressure to temperature and pressure

The temperature supplied by the BMP085 is less accurate and lower resolution than that supplied by the SHT15 (see Section 8.3) so we discard the temperature reported by the BMP085. The calibration routine we use is suggested by Bosch in order to make proper use of the calibration data stored in the sensor’s internal ROM.

In order to minimize the power spent by the microcontroller on managing communication with the BMP085, the communication process is entirely interrupt driven. The task which manages communication will be suspended while the read process completes. One disadvantage of this approach is that it opens the possibility of race conditions, which we must be careful to avoid.

8.3 Relative Humidity and Air Temperature Sensor

The relative humidity sensor presented a significant challenge. Most relative humidity sensors are built using air-gap capacitors which are exposed to the ambient air. The capacitance of the device will change dependent on the ambient humidity and measuring this change gives a measurement of the relative humidity.

The typical method for measuring this capacitance is in the form of an oscillator and the measurement of capacitance is simply a count of the pulses generated by the oscillator over a fixed time duration.

In a complex multitasking environment such as the one we are using, this kind of timing based measurement can introduce additional complications to the system which are not desirable. We thus chose a relative humidity sensor that manages its own measurement process. The Sensirion SHT15 integrates a high accuracy temperature sensor and a relative humidity sensor with a serial data interface. The SHT15's temperature sensor is accurate to ±0.3° Celsius and its relative humidity sensor is accurate to ±2% over the 10% – 90% range. The relative humidity sensor is temperature corrected internally, without need for external calibration.

While the SHT15 has many redeeming qualities, its communication interface is convoluted and does not conform to any existing standard. To communicate with this sensor, we use a combination of an SPI port, an external interrupt and a MOSFET to force the SPI data output to be open-collector (electrical connections shown in Fig. 11). Although this combination works efficiently in a fully interrupt driven manner, it does require quite specialized software to manage inverting output data, transitions from one SPI mode to another, and disabling of one SPI line to act as an interrupt for part of the communication procedure. Fortunately we were able to create the SHT15 interface with built-in peripherals, preventing the need to "bit-bang" the interface which, while effective, would have taken much more processing power.

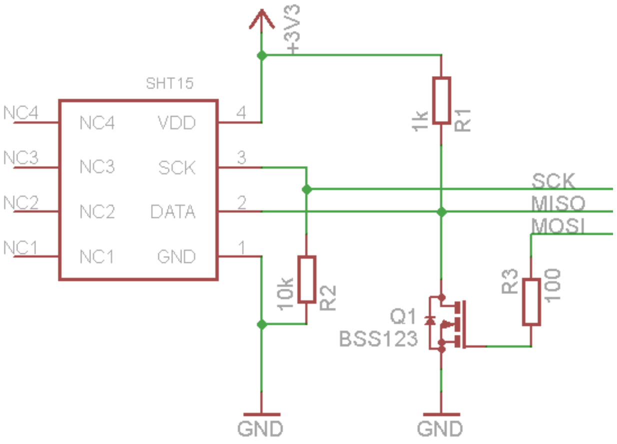

Figure 11: SHT15 Connection Diagram

8.4 Antenna

In order to minimize cost and space requirement on the top end-cap, we opted for a dual band, GPS-Iridium antenna. Our antenna of choice is the UC-1614-341RS, fabricated by Myers Engineering International. This antenna can operate in both the 1565-1585 MHz and the 1600-1630 MHz bands, making it suitable for both GPS and Iridium uplink. The antenna has a standard impedance of 50 ω with a +2 dBi gain and hemispherical coverage. Its quadrifilar helical design results in dimensions that are remarkably small for a dual band antenna, with just 1.5" of external diameter and a height of 4.5". Its range, size and cost (approximately $100) make it an excellent choice for our system.

9 Software Architecture

We chose to implement our design using a real-time operating system (RTOS) called FreeRTOS. Using an RTOS provides us with a simplified software design cycle. Several operating systems were considered in addition to FreeRTOS. The main considerations were support for the ARM Cortex-M3 microcontroller, minimal footprint, multi-threading support and availability. Other potential candidates were ChibiOS/RT, FreeRTOS, RTLinux, uC/OS-II and uCLinux. The memory requirements of RTLinux and uCLinux were too large to be viable candidates on a low-power microcontroller. uC/OS-II does not have a free license and has a somewhat larger memory footprint than ChibiOS/RT and FreeRTOS. Ultimately, FreeRTOS was chosen as it is very lightweight (between 4 and 8 kB), is royalty free, has extensive driver support and most importantly, is already ported to the LPC1769.

The ability to do multi-threaded programming allows tasks to be distributed into separate threads, each servicing a specific sensor. This feature is quite useful in that ArcTech members can work separately on independent threads, increasing implementation efficiency. The resulting modularity greatly simplifies testing and integration as the functionality of one thread does not affect that of another thread. Each sensor is serviced by a discrete thread which communicates with a central control thread. The central control thread is tasked with consolidating all acquired measurements, sending them to the Iridum modem and handling power management of the entire system. This design parallels that of the physical system itself and is quite intuitive.

The various sensors communicate with the microcontroller using one of the following communication protocols: synchronous peripheral interface (SPI), inter-integrated circuit (I^2C) and universal asynchronous receiver/transmitter (UART). One of the major factors in deciding to use FreeRTOS was its driver support for all of these protocols.

The process in which the data is acquired and sent over the Iridium network is outlined below:

1. The microcontroller awakens from deep sleep every hour
2. The central control thread powers on all of the sensors
3. The central control thread resumes all sensor threads and instructs them to begin measurement acquisition
4. Each sensor thread acquires measurement data multiple times, averages the data in order to obtain more accurate results and sends it to the central control thread; the sensor thread is then suspended
5. Once the central control thread has received data from each of the sensor threads, it parses an intermediary data message together containing the results obtained during the current cycle and
    - if the last message sent was four hours ago, the four most recent intermediary data messages are parsed into one resulting message that is sent to the Iridum modem, otherwise
    - the intermediary data message is stored into non-volatile memory for future use as specified above
6. The central control task powers off all of the sensors
7. The microcontroller puts itself back into deep sleep (return to step 1)

Note: the energy consumption of the Iridum modem is quite large. Battery life can be extended substantially by minimizing the frequency of outgoing messages over the Iridum network, thus we can choose to send longer messages at a less frequent rate. This is limited by the maximum character number of an Iridium message which was described in Section 7.4 to be 340 characters.

10 System Testing

Our system has two main functional requirements, that it determine and communicate its position and that it withstand and provide information about an arctic marine environment. These requirements will govern our test plan as they can be tested both separately and together after integration.

10.1 Temperature Measurement and Range Test

We will use a variable freezer from the SFU Physics Department to test the temperature measurement accuracy and sensitivity and the unit's performance at lower temperatures. These freezers are available down to -80° Celsius which will be more than adequate to test the ICE system in its required range.

10.2 Barometric Pressure Test

This test involves extracting the barometric pressure determined by the unit on the microcontroller development software and comparing it to a known value from a number of reliable sources such as a barometer.

10.3 Humidity Test

A simple method we plan to use for testing the humidity sensor is placing it in an insulated area with a hot water source, for example a shower stall or steam room with a humidity measuring device for comparison.

10.4 Heave and Environmental Conditions Test

As our client has access to a vessel and another device which can measure heave, we will test our product against this reliable source for comparison. We can also expose our unit to a marine environment with incident water, wind and humidity to test its resistance to such factors. While we cannot fully test the performance of our unit after eight months of exposure to such an environment, we can observe the effects of several hours or days and extrapolate an estimate of its long-term performance.

10.5 Flotation Test

To test flotation, the ICE unit will simply be placed in water to see if it meets this requirement. If it does not, a flotation collar will be added as previously described. This test can be integrated with the environmental conditions and heave test.

11 Conclusion

The ArcTech Integrated Climate Evaluator will prove to be an invaluable tool for researchers in the arctic. It will be functional for an excess of eight months with no energy harvesting or recharging available. The variety of sensors provided on the ICE and ICE Cap will allow researchers to monitor numerous parameters on ice floes in Canada's far North. The architecture of the ICE system allows for modification and deployment in other scenarios as well, which increases the value of the Intellectual Property.

The ICE system is easy to deploy alongside existing research operations and surpasses previous monitoring solutions in reliability and feature set. The messages are delivered via email, allowing for easy development of an end-user application. Data gathered by the ArcTech ICE system will be used to set future policies regarding the sensitivity of the arctic environment. The development of this Intellectual Property has the potential to give Canadians a better understanding of our far North.

This document has addressed the functional requirements outlined in ArcTech's document *Functional Specification for a GPS Ice Tracking System* with specific design solutions. Construction and testing should be completed by the end of March with a prototype delivery and demonstration expected at the beginning of April 2011.

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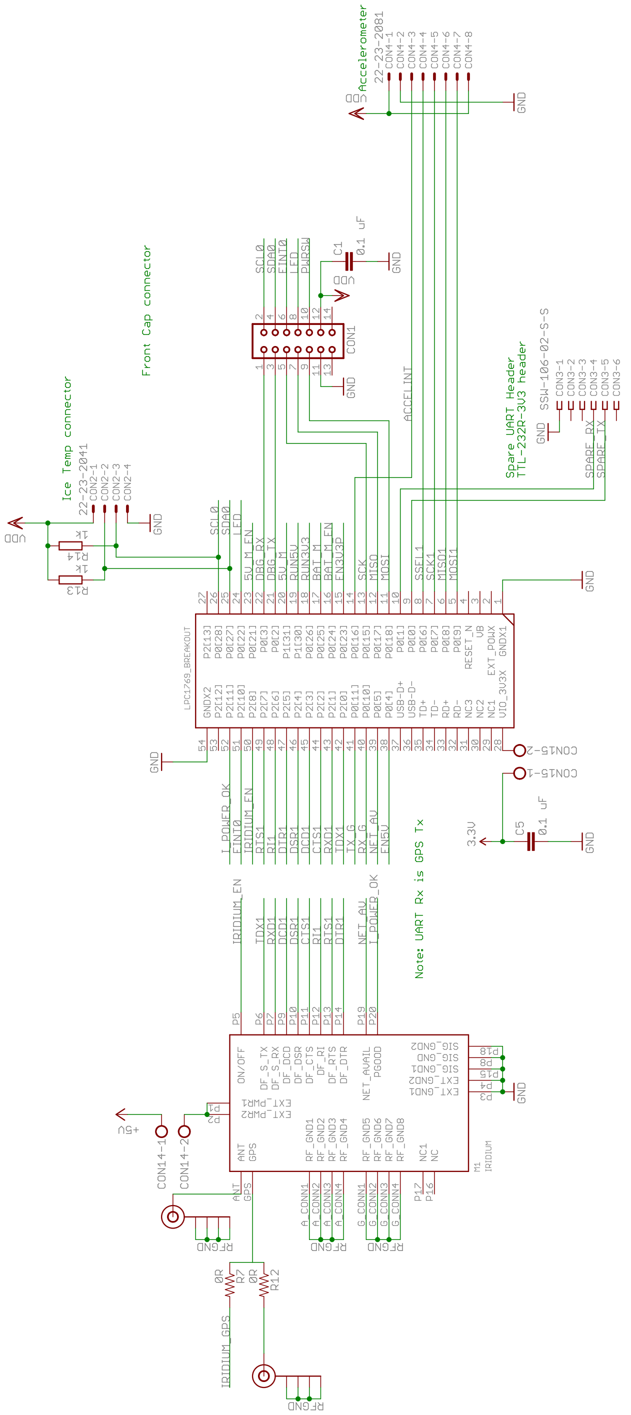
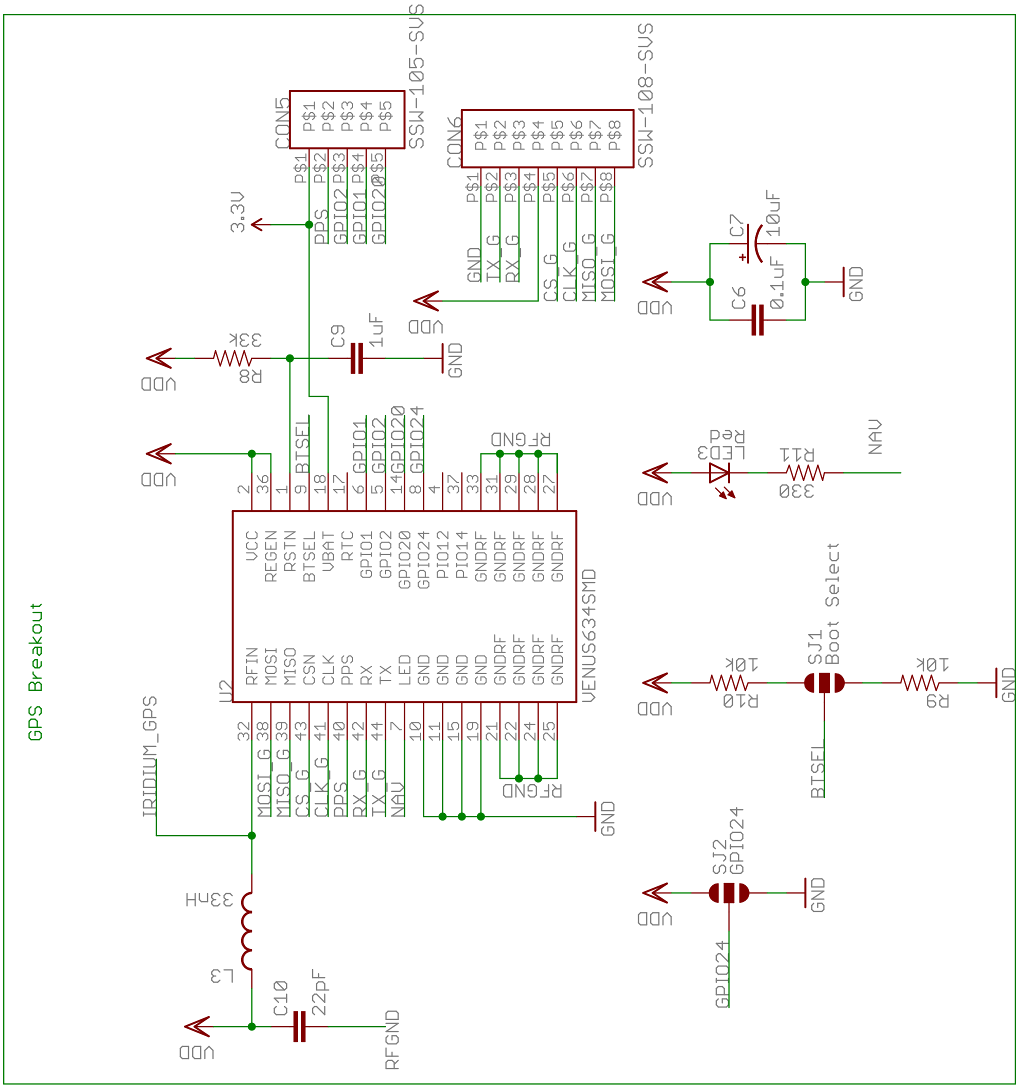
A Internal PCB Schematic

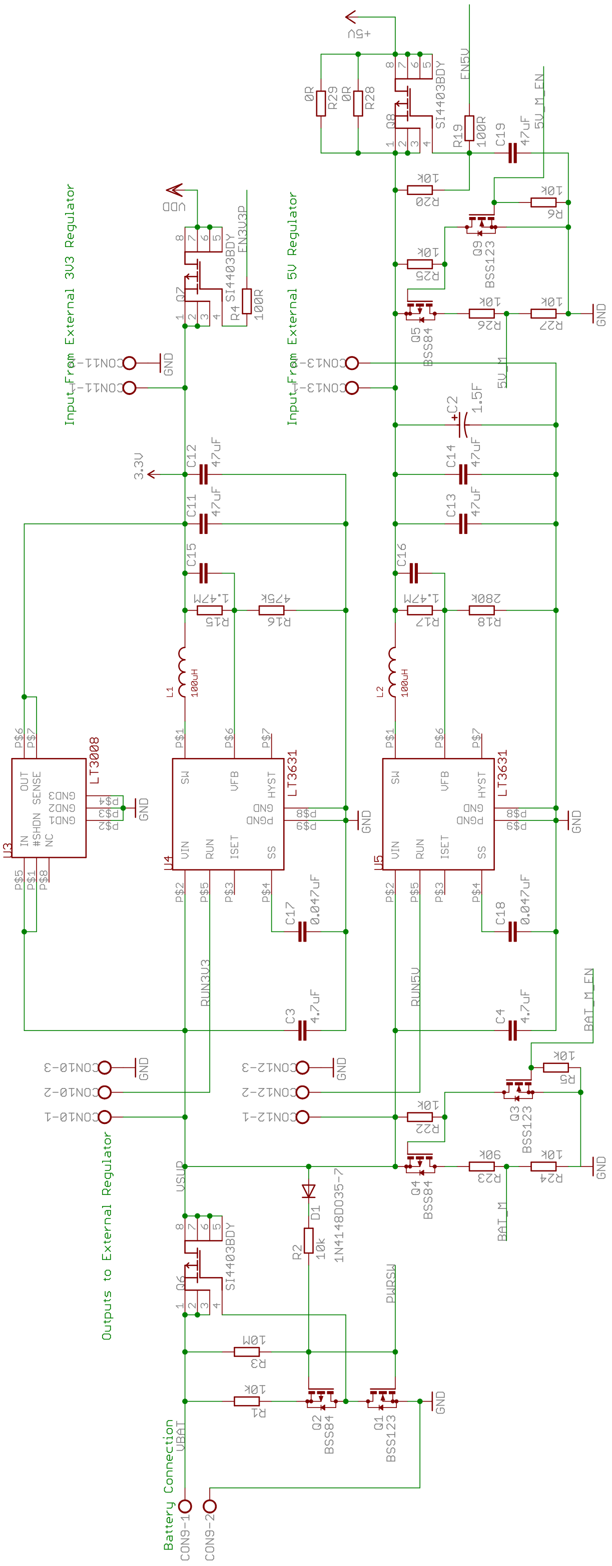
Page 1/3: Microcontroller, accelerometer and external connections



Page 2/3: GPS module



Page 3/3: Power control



B External PCB Schematic

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