Autonomous Logistics Technologies for Space Exploration: Experiment Results and Design Considerations

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The ability to autonomously track and manage assets in space or at a planetary exploration site holds the potential to greatly improve multiple aspects of space missions. At the International Space Station (ISS) everything from food and clothing to tools and experiments is currently managed manually or tracked using simple bar-coding techniques, often at the expense of time and accuracy. An autonomous system, based on radio-frequency identification (RFID) or related technologies, could save precious time, increase planning accuracy, increase safety, and even amplify science returns for extended exploration missions. However, these benefits must be weighed against overall system complexity, mass, and other issues such as ease-of-use and astronaut training. Such trades hinge on the requirements for the system in question: What technologies can and should be used? What kinds of applications should be included? At what level should assets be tracked? Suitable answers to these kinds of questions demand actual hardware/software development and field-testing.

This paper describes design and testing of tracking systems for remote base operations conducted during a field-season at the Haughton Mars Base on Devon Island in the summer of 2005. The goal for these experiments was to evaluate the benefits and limitations of RFID technology in the context of remote base operations and to identify potentially useful tracking applications. To accomplish these goals three experiments were run using two unique systems and informal observations were made of logistics needs and human behavior. These experiments included formal benchmarking of RFID verses Bar-Coding, "RFID gate" experiments for personnel and goods, and vehicle tracking and monitoring. Initial results have narrowed uncertainties on specific areas of concern, such as tracking accuracy and time savings, and have highlighted critical issues such as radio-frequency interference. The latter suggests that a tracking system should be integrated into the overall information architecture from the start, rather than being designed as an afterthought. Also, results and observations suggest some promising niche applications, such as the creation of "smart cabinets" that could provide significant benefits at less cost. These and other findings are currently being used to develop a next-generation integrated asset tracking and information architecture for implementation and testing at the Haughton Mars Base.

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I. Introduction

An important way of increasing the safety and efficiency of human space systems and missions involves removing the daily cognitive load on astronauts by simplifying and, where possible, automating habitation and exploration processes. The incorporation of automated tracking, monitoring, and telemetry technologies offers one such possibility with respect to basic micro-logistics tasks on the space station or at a lunar or planetary base. At a basic level, automating micro-logistics will greatly reduce the time it currently takes astronauts and ground operators to manage the thousands of tools, food items, cloths, science equipment, computers, and other items currently floating around the International Space Station. Successful implementation of automated logistics technologies at a space station or a planetary base also opens a whole new class of applications which, if linked to broader sensing and telemetry technologies, can have dramatic impact on mission safety, astronaut efficiency, and science return. For example, one can imagine combining multiple kinds of information such as asset-location, asset-type, asset-history, radiation-levels, and operational procedures, among others, in a rule-based system which autonomously issues alerts, operational suggestions, or other pieces of information necessary for a successful mission. Outside of a planetary base, specialized Geographical Information Systems (GIS) tools combined with the tagging of samples could autonomously associate multiple kinds of scientific information with EVA actions, greatly increasing EVA efficiency. While not quite "HAL", the automation of logistics and tracking and their merging with broader distributed sensing applications in a rule-based system is the first step in creating a "smart environment" to improve all manner of mission performance, cost, and risk.

This paper details experiments with Radio Frequency Identification (RFID) technology began in the summer of 2005 at the Haughton Mars Base in the Canadian Arctic as the first step in understanding design requirements and potential applications for autonomous logistics technologies at a remote scientific site. Before detailing these experiments, it will be useful to review the current state of asset tracking, as well as some background on RFID technology in general.

II. Current state-of-the-art for asset tracking on ISS

Currently, asset tracking on the International Space Station (ISS) relies on a barcode based system that interfaces to the Inventory Management System (IMS) database. The IMS database is a SQL Server 2000 database with a JAVA Graphical User Interface (GUI) that was jointly developed by NASA and the Russian Space Agency (RSA). All ISS inventory is tracked in the IMS database. Presently, over 20,000 items are tracked in IMS. All items that fly to the ISS are barcoded before launch. Critical information about each item, such as a part number, serial number, barcode, proper name, dimensions, owner, etc. is then entered into the IMS database buy U.S. or Russian flight controllers before the item arrives at the ISS. Once the item is on-orbit, the crew uses a handheld barcode reader to record movement of the item around the ISS.

Updates are made in IMS on a daily basis by either the ISS crew, the Inventory and Stowage Officer (in Houston) or the Russian Inventory and Stowage Specialist (in Moscow). The crew is allotted 20 minutes each day to update the IMS database either using the handheld barcode reader or manually entering changes on their laptop computers. IMS records a history for each item so that the crew or ground controllers always have the ability to see what has been changed on each item since it was initially entered into the database. On average 3% of the items in the IMS database are "lost", meaning that the item is not where the IMS shows it to be.

A. RFID Technology Overview

RFID is a generic term for technologies that use radio waves to automatically identify people or objects. There are several methods of identification, but the most common is to store a serial number that identifies a person or object, and perhaps other information, on a microchip that is attached to an antenna. The chip, which is about the size of a grain of sand, activates a signal when it approaches an electronic reader. Though RFID technology has been around since World War II, when it helped ground soldiers identify fighter planes as friend or foe, the cost of developing it has been prohibitive. Advances in the technology have lead to wide-spread pilot testing by industry. Business experts predict that RFID chips will be found in thousands of products by 2010, and that the technology will revolutionize supply chain, manufacturing, and retail efficiency.

Automatic identification (auto ID) technologies help machines or computers identify objects by using automatic data capture. RFID is one type of auto ID technology that uses radio waves to identify, monitor, and manage individual objects as they move between physical locations. Although there are a variety of methods for identifying objects with RFID, the most common method is by storing a serial number that identifies a product and its related information. RFID devices and software must be supported by an advanced software architecture that enables the collection and distribution of location-based information in real time.

B. System Components: Tags and Readers

An RFID system consists of tags and readers. RFID tags are small devices containing a chip and an antenna that store the information for object identification. Tags can be applied to containers, pallets, cases, or individual items. With no line-of-sight requirement, the tag transmits information to the reader, and the reader converts the incoming radio waves into a form that can be read by a computer system. An RFID tag can be active (with a battery) or passive (powered by the signal strength emitted by the reader).

Active Tags

- Can be read from a long-range distance of more than 100 feet.
- Are ideal for tracking high-value items over long ranges, such as tracking shipping containers in transit.
- Have high power and battery requirements, so they are heavier and can be costly.

Passive Tags

- Can only be read from a short-range distance of approximately 5–10 feet.
- Can be applied in high quantities to individual items and reused.
- Are smaller, lighter, and less expensive (and therefore more prevalent) than active tags.

Figure 1: How the RFID technology works

1. An interrogator emits RF waves, which are picked up by tags nearby
2. A tags modulates the signal and responds with its unique identifier
3. The interrogator filters the responses to identify events like tag arrivals and departures
4. These events are communicated to enterprise middleware software which understands the business process impact of this activity.

C. Using RFID

Although RFID is a proven technology that has existed since before World War II, it took several years for a large scale implementation to occur in the United States. The implementation eventually included freeway toll booths, parking areas, vehicle tracking, factory automation, and animal tagging.

The most common application of RFID technology today is for tracking goods in the supply chain, tracking assets, and tracking parts from a manufacturing production line. Another common application is for security—RFID is used to control building access and network security, and also for payment systems that let customers pay for items without using cash. As technological advancements in RFID lead to an even higher level of data transmission—in addition to an inevitably lower cost—RFID technology will become ubiquitous within the supply chain industry and other industries, increasing overall efficiencies and dramatically improving the return on investment (ROI).

III. Testing RFID at the Haughton Mars Base

How can RFID and its associated autonomous logistics technologies be in space missions? Because the application of RFID is relatively new, questions remain about both the technology itself and its potential uses. We conducted experiments at the Haughton Mars Analogue Research Base in the High Arctic to better understand the benefits and limitations of the technology as well as the opportunities for application to remote base operations.

The Haughton Mars Project (www.marsonearth.org) is an international interdisciplinary field research project sponsored by NASA and the Canadian Space Agency (CSA) and managed by the Mars Institute. The site was chosen both for its geological and scientific interest, and its similarity to Mars terrain. At 75 degrees North latitude, Devon Island is a high arctic desert and the largest uninhabited island on Earth. Science at the base is focused on the 38-million-year-old Haughton impact crater and surrounding terrain on Devon Island. While no climate on Earth is exactly like Mars, the unique combination of rocky polar desert, permafrost, and analogous geological formations, afford comparisons to the possible evolution of Mars – in particular the history of water and climates, the effects of meteor impacts, and the possibilities for life in extreme environments.

Figure 2: The High Canadian Artic, with Resolute on Cornwallis Island and Devon Island indicated. Researchers stopped in Resolute on the way to the HMP base on Devon Island (75° N 90°W)

Beyond basic science, the Haughton Mars Project functions as an analogue planetary base, supporting a diverse array of exploration technology and engineering test projects that also benefit from the Mars-analogue terrain, remoteness, and exploration-like activities undertaken by geologists and other scientists. For example, over the past several years, the Canadian Space Agency has supported the Arthur C. Clark Greenhouse project, to design, build, and test a greenhouse and autonomous plant-growth technologies in remote environments. Hamilton-Sundstrand, an aerospace engineering firm headquartered in Connecticut, uses the Haughton site to test advanced space suit designs. Also, this year a project on Drilling Automation for Mars Exploration (DAME), lead by the NASA Ames Research Center, tested autonomous fault diagnosis and artificial intelligence software on a prototype Mars drill. Many other exploration technologies and prototypes have been tested at the Haughton base since 1997.

Figure 3: Arial view of the Haughton Mars Base and surrounding terrain. The six core structures, including the newly erected MIT tent, can be seen on the left. Researchers sleep in the individual tents on the right.

The base itself now includes a main mess tent, a communication-systems tent, a large office and laboratory tent for general work, a greenhouse test bed, and an octagonal core module that will eventually unite the buildings into a single base-like structure. There are also roughly 20 all-terrain vehicles (ATVs), a Humvee outfitted for longer traverses, and a small airstrip to support Twin Otter airplane flights in and out of base. This year, an MIT tent was erected for the space logistics project and also in preparation for future MIT involvement at the site. As a whole, the base can currently accommodate about 40 to 50 people at a given time, with researchers sleeping in individual tents near the main structures. As a whole, the Haughton Mars Base provides an excellent site for testing the benefits and limitations of RFID technology for extreme environments and, by extension, Space Exploration.

IV. RFID Experiments and Results

Objectives at HMP included experiments to test the benefits and limitations of the technology, as well as less a formal effort to monitor base activity and understand how asset tracking might improve operations.

Our questions with respect to the former included: What are the actual benefits and costs of using an RFID system to track assets at a remote site in terms of time saved, accuracy, and system complexity? What additional requirements might be needed to make such a tracking system worthwhile? How can the accuracy of the system be improved in the field? What range is typical in the field and what kinds of tags are best to use? How should the architecture of the RFID system be designed? What are the main technical challenges to implementing such a system?

Our questions with respect to applications of the technology were of a different sort. They included: What items are most in need of tracking at a remote base? At what level should these items be tracked? Where should this information be presented? Can asset tracking be incorporated into other aspects of base-management? If so where?

In order to address these questions, we undertook a three-pronged strategy:

1. First, we established a formal experiment to compare the benefits and drawbacks of stowage using RFID to stowage using bar-code techniques.
2. Second, we developed two experiments, using different kinds of RFID technology, to track assets through parts of the base.
3. Finally, we made observations about how and when people looked for supplies, what kind of supplies they needed and, generally what kind of help they needed with managing base assets. The details of these experiments and results are below. Based the current available RFID technologies, we purchased 2 set of RFID equipments from Alien Technologies: ALR 9780 High Performance, 4-port UHF passive Reader with a reading range up to 30 feet; 2000 passive tags; ALR-2850 Long-Range, battery assisted passive reader, 30 Battery assisted tags with a reading range of 60 feet

A. Gate Experiment

The gate experiment compared the time savings and accuracy of RFID verses bar-coding systems in tracking assets. To do this, an RFID gate was set up at the entrance of the MIT tent, and volunteers were asked to walk through the gate and store objects in a specified way. The gate was composed of four one-watt, circularly polarized antennas, operating at 915mhz and arranged in a rectangle. The antennas were installed on tripods, bungeed to the tent roof, and placed in a zip-lock bag on the floor.

We asked a total of 10 volunteers to run through the following procedure six times:

1. Pick up a box filled with tagged items
2. Walk through the gate
3. Put the box down
4. Take the items out and order them from biggest to smallest on a table
5. *If using Bar-Code, scan items before laying them down

For each of the six runs we varied one of three parameters:

1. Tracking system: Barcode vs RFID
2. Active Antenna Number: 2 vs 4
3. Number of items: 10 v 20

For each run, we recorded both the total time taken and the accuracy of the system. In this way we hopped to compare system time-saving and system accuracy with respect to antenna number (radio power), item number, and tracking mechanism. The results of the experiment are discussed in the “results” section below.

Figure 4: LEFT: A volunteer carries out the formal benchmarking experiment. RIGHT: Items aligned in order on the shelf

B. Gate Experiment Results

As expected, the accuracy of the RFID system was below that of bar-coding, but the speed was much higher; fewer items were more accurately tracked than more items; and more antennas were, of course, better than fewer. Roughly, “time wasted” by bar-code does not scale linearly with the number of items—double the items means more than double the time.

More specifically, we recorded a total of 120 data points. Table 1 is a snapshot of some of this data. As indicated, for each run we recorded the number of items that the system recorded, the resulting accuracy, and the total time in seconds.

Table 1: Sample data for the formal RFID experiments.

Exp #	Name	Run #	RFID # rec.	RFID Acc.	RFID Time (sec)	BC # rec.	BC Acc.	BC Time (sec)
1	Richard L	1	14	70%	36	20	100%	95
1	Karin	2	16	80%	78	20	100%	232
1	Aginesh	3	15	75%	64	20	100%	154

Figure 5 shows the mean time and standard deviation for all the experiments. As can be seen, the bar-coding system took a bit more than twice the amount of time as the RFID system for ten items, and about three times the amount of time for twenty items. This trend suggests that as the number of items tracked increases, the time-savings for an RFID system become increasingly significant. This makes intuitive sense, since bar coding requires extra labor, and can become increasingly difficult as items numbers increase.

It should also be noted that the standard deviations vary significantly. The bar-code system on average had a greater variance than the RFID system, with a significant increase in SD when we increased to 20 items. This result also makes sense, since the time taken to record each item into the system depending somewhat on people's familiarity with bar-coding. It also suggests, however, that RFID systems may have additional benefits for accurately allocating time to logistics. If the time it takes to sort and store assets is known more accurately using RFID, it could help manage other aspects of camp life.

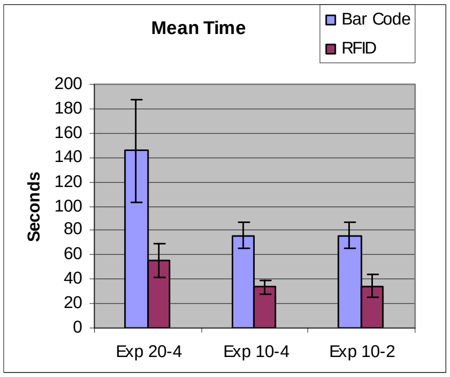


Figure 5: Average time and standard deviation for the six experiments conducted.

Figure 6 illustrates a similar plot of experiment type verses average accuracy, with standard deviation included. Again, the basic form of the results are as expected. The bar-code system was 100% accurate because participants continue to scan items until an indicator tells them that it has been recorded. For RFID, fewer items were recorded with better accuracy, and four antennas recorded items with more accuracy than two.

Again, the variance in the data-sets presents useful information. Although the mean accuracy of the 10-item/2-antenna experiment (10-2) and 20-item/4-antena experiments (20-4) were roughly the same, the former exhibited much higher variance. This suggests that if the number of items to be tracked is known beforehand, the worst-case accuracy increases significantly with number of antennas.

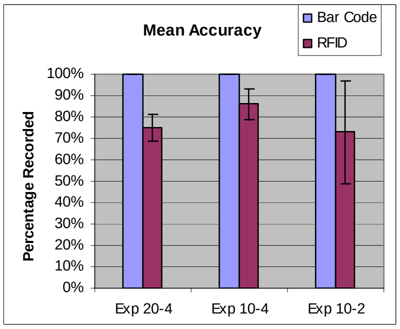


Figure 6: Average accuracy and standard deviation for the six experiments.

Some caveats with respect to the RFID experiments should be noted . First, we had each participant sort the objects after walking through the gate. We did this to ensure that the comparison between bar-code and RFID was fair. In reality, we assume, astronauts will read an object into the bar-code system before placing it in a specified storage location. This will involve sorting through the objects and placing them somewhere. An RFID system would eliminate the need to read the object into a system, but it would not get rid of the sorting task. Further, astronauts would probably scan an object with the bar-code reader after having selected it, but before storing it.

Second, the design of an RFID gate will of course be very different at an actual base. The important variable in our experiment with respect to gate-design, then, is not the exact configuration, but rather the kind of tags, the amount of RF power in the area, and the distance of the antenna's. In our case, each antenna produced one watt of power at 915mhz. While the exact system configuration will of course be different on a real planetary base, these studies will hopefully give some realism to assumptions made about their design.

Third, it should be noted, contrary to in an actual exploration situation, participants were in no way trained to use the systems. For this reason, the results of the experiment may also include some "learning" by the participants as the process of sorting and recording the objects was better understood. This may have had a particularly important affect on the Bar-Code part of the experiment, which necessitated understanding how to find and read each bar-code.

C. Inter-Module Transfer Experiment

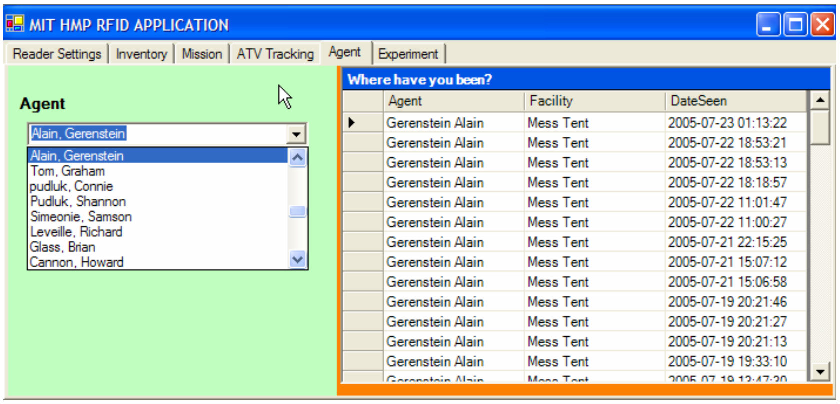
In addition to the RFID gate experiment, we set up a gate to monitor the flow of people past a given doorway, as a theoretical precursor to a base-wide tracking system. This system included four 1-watt antennas set up at the entrance to the Mess Tent, and multiple passive tags handed out to all HMP participants.

Figure 7: LEFT: Example passive tag handed out to each HMP participant for the RFID gate experiment. RIGHT: Setting up the system at the Mess tent entrance

The experiment was fairly straightforward: We asked participants to place tags in their pockets and the system recorded a hit when they passed the mess-tent door. We wrote a simple application to store this information in a data-base with which we could recreate the times when a given participant (or asset eventually) passed that location. We let this experiment run continuously for three days. **Error! Reference source not found.** shows Mike Li setting up the system at the entrance of the Mess tent.

D. Inter-Module Transfer Results and Discussion

The goal of the gate-tracking experiment was to let a tracking system run continuously and get an idea of the level of traffic past a given point. Figure 8: Inter-Module Human Tracking ApplicationFigure 8 shows an example of the personnel tracking experiment results.



Agent

Alain, Gerenstein

Alain, Gerenstein
Tom, Graham
pudluk, Connie
Pudluk, Shannon
Simeonie, Samson
Leveille, Richard
Glass, Brian
Cannon, Howard

Where have you been?

Agent	Facility	DateSeen
Gerenstein Alain	Mess Tent	2005-07-23 01:13:22
Gerenstein Alain	Mess Tent	2005-07-22 18:53:21
Gerenstein Alain	Mess Tent	2005-07-22 18:53:13
Gerenstein Alain	Mess Tent	2005-07-22 18:18:57
Gerenstein Alain	Mess Tent	2005-07-22 11:01:47
Gerenstein Alain	Mess Tent	2005-07-22 11:00:27
Gerenstein Alain	Mess Tent	2005-07-21 22:15:25
Gerenstein Alain	Mess Tent	2005-07-21 15:07:12
Gerenstein Alain	Mess Tent	2005-07-21 15:06:58
Gerenstein Alain	Mess Tent	2005-07-19 20:21:46
Gerenstein Alain	Mess Tent	2005-07-19 20:21:27
Gerenstein Alain	Mess Tent	2005-07-19 20:21:13
Gerenstein Alain	Mess Tent	2005-07-19 19:33:10

Figure 8: Inter-Module Human Tracking Application

Figure 9 provides a summary of the data retrieved during the experiment's operation, including "notional asset history" as an example of what such a system could eventually provide. The upper-right corner of the figure displays an example of the data retrieved. No logic was implemented on this data yet—as in the ATV experiment—so it only conveys when a person was near an antenna, and not whether they were entering or leaving the tent. Theoretically, this data could be used in any number of ways. The two graphs at the bottom of Figure 9 are histograms.

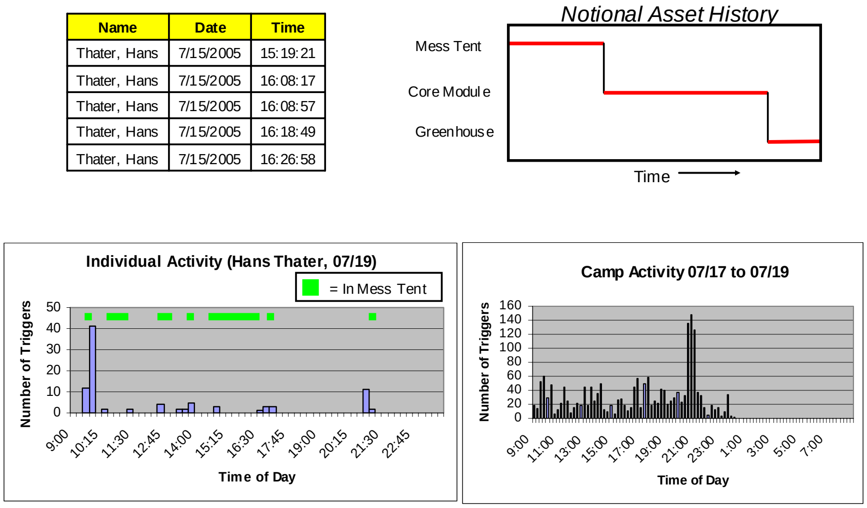

Name	Date	Time
Thater, Hans	7/15/2005	15:19:21
Thater, Hans	7/15/2005	16:08:17
Thater, Hans	7/15/2005	16:08:57
Thater, Hans	7/15/2005	16:18:49
Thater, Hans	7/15/2005	16:26:58

Figure 9: Summary of Mess-tent gate experiment

The graph on the bottom left is a histogram of the activity of one HMP participant during one day, partitioned into 15 second bins. It illustrates how many "counts" the antenna read from a tag in a given 15 minute period. It illustrates a spike of activity around 9:30am, in addition to activity around lunch and dinner. The green lines above this activity are notional logic-based conclusions from the counts. They show how the data could be used to infer when a participant or asset was entering or leaving a given area. Without additional information, however, such logic would be dependant on 100% read accuracy. As discussed below, it is not clear that such an implementation would be desirable, given other issues that arose with the experiment.

The graph on the bottom right of Figure 9 shows the total number of counts passed the antenna, also partitioned into 15 minute bins. If the assets were tools or items other than people, this kind of information could be used to better understand where an asset is most often moved/used. In this case, it demonstrates a clear increase in activity after dinner, around 9pm, with relatively constant activity during the day and no activity at night.

More than the data collected, the most useful part of the Mess-tent experiment involved understanding how the system, people, and tags, interacted and how this might inform future design. Our observations in this regard can be divided into two basic categories: HMP specific, and non-HMP specific.

HMP specific observations had to do with environmental issues at HMP itself, and are therefore less relevant to future exploration missions. Most significantly, the location of the antenna's caused some problems because it interfered with camp activity. We wanted to monitor traffic to the Mess tent because this was the one area where everyone passed at one time or another. However, either side of the mess tent entrance was filled with coats, chairs, drawers and other items. Further, this location became exceedingly dirty and was often quite moist due to the rain. These environmental factors undoubtedly affected the data, and also made the system difficult to manage.

Non-HMP issues include software and hardware issues. Most importantly, as the formal experiment demonstrated, passive tags are not 100% accurate at this distance. The goal for such a system would be to track assets as they move from module to module. In the absence of 100% accuracy, redundancy or other methods would need to be implemented to guarantee tracking. This might include location sensing, or setting up multiple antennas along a corridor to track movement. As later observations will discuss, however, it is not clear that such an effort is worthwhile. It may be far simpler and more useful, to create specific RFID sites, rather than create a base-wide tracking system.

Finally, the tags themselves were not extremely sturdy. We used standard passive tags provided by Alien Technology. When people put these in their pockets the often became bent or simply did not work due to interaction of the human body with RF waves (the moisture in the body absorbs RF). This issue, however, could be easily overcome by designing cases for the tags and/or identifying better locations for them. This should be addressed if we are to return to HMP to design a more comprehensive system.

E. ATV Tracking Experiment

The ATV tracking experiment was similar to the Mess-tent experiment, however in this case ATVs were tracked rather than people, and a different tag-type and system configuration was implemented. The system used battery-activated passive tags rather than strictly passive tags, and the antennas were placed outside along the airport road. The reader was connected to the camp intranet via a portable communications system provided by Steve Braham of Simon Frasier University.

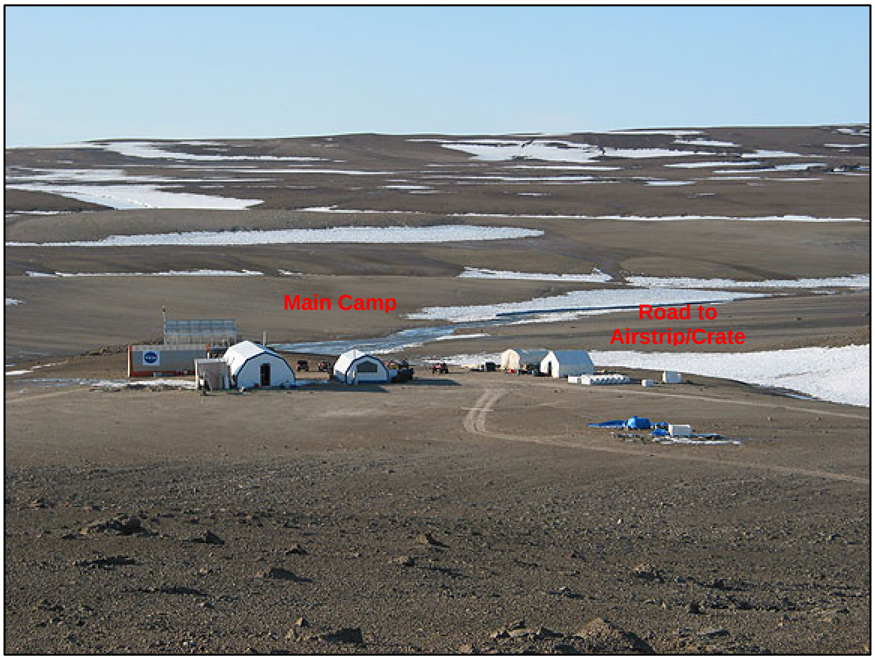
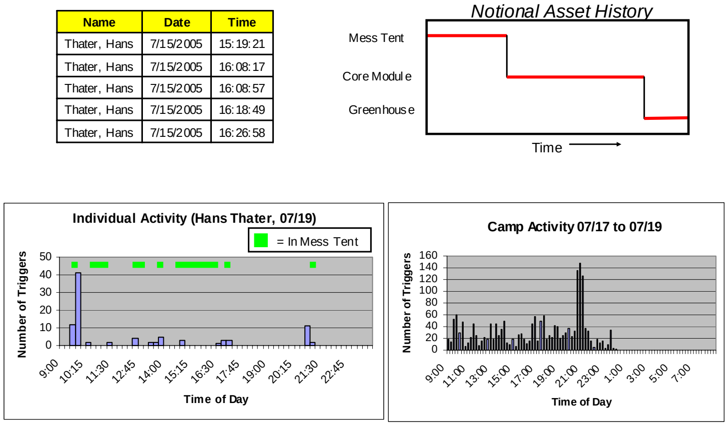


Figure 10: Main Camp with Airport Road

The main reason for the extra link was that the passive tags radiate at 2450mhz, which may have interfered with base communications. Even the 915mhz readers interfered with the safety radios when they passed nearby. These issues are fairly important, and will have to be worked around in the design of the communications infrastructure of a real planetary base. They are also part of the trade-off with developing tracking and logistics management systems that radiate RF although, as a previous post discussed, it is possible to insulate the signal for specific applications.

Once the system was set up on airport road, we tested multiple mounting locations for the tags on the ATVS. Figure 11 gives a summary of the experiment and provides a picture of this testing. Finding a suitable tagging location turned out to be more difficult than expected for two reasons. First, one of the antennas provided did not work, so we had less range than expected. Second, because ATVs were going in two directions it was hard to find a location that was close to the reader all the time. We ended up using two tags for each vehicle, mounted on either side of the wheel rim.



Name	Date	Time
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Thater, Hans	7/15/2005	16:08:57
Thater, Hans	7/15/2005	16:18:49
Thater, Hans	7/15/2005	16:26:58

Figure 11: Testing Tag Locations on the ATV

Once the system was set up, the tags were mounted, and each vehicle identified, we let the experiment run continuously for three days. The software application that we created allowed us to identify when a given vehicle was entering or leaving the base depending on whether the event was even or odd. This method was not 100% accurate however, but did give a better picture of ATV usage.

F. ATV Tracking Results and Discussion

The ATV experiment was essentially a technology demonstration for the battery activated passive tags and the potential to create a stand-alone system to regulate traffic in and out of camp. **Error! Reference source not found.** illustrates a snapshot of our raw results for the experiment.

The data generated proved the basic concept but was not 100% accurate. If a passage event was not logged at any time during the day, the program we created would thereafter attribute an entrance to an exit or vice-versa. Table 2 shows a snapshot of the reduced data. Further, as noted above, it turned out that one of the antennas used did not work, resulting in a reduced read-range.

Table 2: ATV Data

ATVID	dateLeftbase	Time Left Base	DateReturnBase	Time Return Base
1	7/26/2005	12:47:31	NULL	NULL
1	7/28/2005	23:11:35	7/29/2005	1:27:56
1	7/30/2005	14:28:24	7/30/2005	17:01:03

Still, some conclusions can be drawn from the experiment and basic results used for developing future systems. From a hardware perspective, it is clear that the battery-activated tags do not necessarily have the 30m range claimed for the specs. This suggests that, for HMP at least, future long-range applications should use active tags rather than battery-activated passive tags.

Active tags would radiate with more power than battery activated passive tags, making the need to avoid RF interference even more acute. As noted, we implementation the tracking system well outside of camp to avoid RF interference. This worked well, and the 5.6 Ghz relay antenna was reliable. However, a basic goal should be to reduce mass and complexity where possible, so future experiments using high-frequency radiation would be better off addressing the problem in less complicated ways.

These issues notwithstanding, the basic tracking data is useful and can have applications beyond real-time asset management. Figure 12, for example, uses the tracking data to estimate total usage rates for each vehicle. It demonstrates that some vehicles were used much more than others over the three-day period. This information could be fed back to base managers to optimize usage and minimize repair needs.

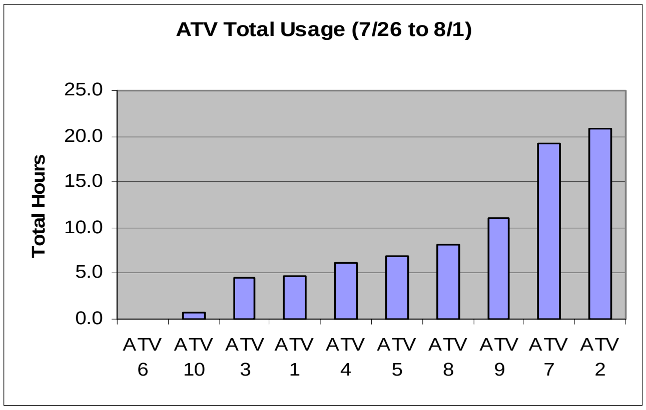

Figure 12: ATV Usage Rates

V. Conclusions and Recommendations

The basic ability to associate an object with information and then to autonomously track the location and state of assets, agents and vehicles, has the potential to help many aspects of surface operations. Most obviously, it could save researchers precious time by accurately and effortlessly tracking objects as they move about base, and reporting exact levels of supply. It could also enable more exotic applications, such as the rapid “check-out” of a vehicle for traverse using hand-held readers; by creating “smart shelves” that sense what items are on them, it could also save time locating and analyzing rock and soil samples that are obtained during field excursions.

Our studies suggest that while RFID technology will undoubtedly save time, basic improvements in accuracy and system design will be needed to justify their cost and mass. Most likely, special packaging would be needed to overcome basic problems of radio-wave reflection and attenuation. Further, it became clear that to avoid RF interference an RFID system needs to be designed together with the overall communications architecture of the base, rather than retrofitted as an afterthought.

Our experience at HMP has also revealed questions that need to be address before a comprehensive RFID solution for space exploration can be created:

- What read distance and field of view (FoV) is required?
- What amount and type of data will be stored?
- Will tags be moving and how fast?
- How can the new RFID solution integrate with legacy system software and solutions?
- How to build robustness solution with disparate information sources?
- What kind of Graphical User Interface (GUI) should be developed?
- What type of data formats must be supported?
- What communications protocols must be supported?

- What are the future needs of the system infrastructure (expandability)?
- Is an open system required?

Answering these questions will help us design better systems, both for testing at HMP, and for potential in-space applications.

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