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Leak Detection and Location Technology Assessment for Aerospace Applications

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September 2008

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Acronym List

AE	Acoustic Emission
COTS	Commercial Off-The-Shelf
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIDS	Distributed Impact Detection System
DSP	Digital Signal Processing
ESA	European Space Agency
EVA	Extra Vehicular Activity
FPGA	Field Programmable Gate Array
IR	Infrared Radiation
ISS	International Space Station
IVHM	Integrated Vehicle Health Management
MAC	Medium Access Control
MEMS	MicroElectroMechanical Systems
MMOD	MicroMeteoroid and Orbital Debris
RF	Radio Frequency
RFID	Radio Frequency Identification
RMS	Root Mean Squared
SAW	Surface Acoustic Wave
SBIR	Small Business Innovation Research
SHM	Structural Health Monitoring
SoC	System on a Chip
sps	samples per second
TRL	Technology Readiness Level
TSMP	Time Synchronized Mesh Protocol
ULD	Ultrasonic Leak Detection

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Abstract

Micro Meteoroid and Orbital Debris (MMOD) and other impacts can cause leaks in the International Space Station and other aerospace vehicles. The early detection and location of leaks is paramount to astronaut safety. Therefore this document surveys the state of the art in leak detection and location technology for aerospace vehicles.

1. Introduction

In “NASA’s Implementation Plan for International Space Station Continuing Flight,” Micrometeoroid and Orbital Debris (MMOD) are “recognized as a continuing concern for the ISS, the Shuttle, and other spacecraft [1].” The location of small leaks is difficult due to reflections from surrounding structures, audible noise from equipment, and normal atmospheric flows. For these reasons, the report identifies NASA’s ongoing research into improved leak detection.

On June 25, 1997, a cargo ship collided with the Mir space station, causing damage to the solar panels and creating a leak in the Spektr module [2]. The Mir began leaking again in November of 1997, due to a hatch malfunction on the Kvant-2 module [3]. In October of 1999, another leak occurred, in a hatch between the Spektr module and the Mir core [4]. The leak was not repaired until April of 2000 [5]. During the search for the leak and its repair, air continued to escape.

International Space Station (ISS) detected its first leak during initial assembly of an air lock, which began leaking shortly after its installation in July of 2001 [6]. The small leak did not cause concern. The leak was later traced to a faulty valve in an air circulation duct between the air lock and the rest of the station [7]. The valve was capped in order to prevent further leakage.

In 2004, a braided flex hose, which was part of the window in the U.S. Destiny module of the ISS, began to leak [8]. The probable cause for the leak was fatigue damage (from astronauts using the hose as a handhold while viewing out the window). The first attempt at finding the leak, by using a handheld ultrasonic leak detector, was unsuccessful due to the surrounding noise emanating from payload racks. The leak was found on the second attempt, when nearby instrumentation and payload racks were turned off.

Both Mir and ISS space stations have experienced problems with leaks. Any long duration space vehicle may face similar problems, as well. Currently, leak detection (not location) is being performed by monitoring the air pressure and setting off alarms when the pressure drops. After detection of a leak, leak location is performed using a variety of methods (listening for hissing, closing hatches, using handheld ultrasonic detectors, etc.). These methods are not 100% reliable. Also, significant time is needed to locate leaks, during which valuable resources are lost.

1.1. Background

Research work done in 1990 examined leaks from seals, leaks from impacts and cracks, and thermal techniques for leak detection [9]. The resulting report selected pressure measurements as the best way to detect leaks across seals, and acoustic emission as the best way to detect leaks from impacts, cracks and holes in the external shell. The thermal imaging techniques were determined to be technically feasible, but were removed from consideration because of programmatic constraints.

Another report from 2000 explored remote sensing technology for detection of H₂ and He leaks in air. The report assessed each technique for suitability (whether it could detect leaks), sensitivity, and NASA Technology Readiness Level (TRL) [10]. The report addressed technologies that are not present in this document. These technologies are not included here because they are primarily for detection of H₂ and He leaks in air, and are not suitable for detection of atmospheric leaks to the vacuum of space.

This document extends the previous work and attempts to catalog the current state of the art in leak detection methods for aerospace vehicles.

1.2. Purpose and Scope of this Study

Since leaks on the ISS are a high priority, this document will focus on technology that is suitable for retrofitting onto the space station. This focus is narrow; however, the proposed solution should be directly applicable to other space habitats and vehicles. Because mass, volume, power and costs are always a concern when developing space hardware, any solution must minimize these parameters to be successful. Adding wiring to existing space systems is extremely expensive; the use of wireless networks would avoid costly redesign to route network cables and the costs of performing safety recertification [11]. This will constrain the trade space to wireless solutions for communications, as well as the use of batteries or energy harvesting for power.

Although detection of leaks is paramount, current pressure gauges on the space station are sufficient for the detection of leaks. The use of pressure gauges is, however, not sufficient for discovering the location of leaks any more precisely than identifying the module that is leaking. Therefore, anything that can find leaks quickly, as well as detect leaks, is considered a better system than one that can *only* detect leaks. Although many different technologies will be presented for leak detection and location in this document, the scope of technologies considered for advocacy will be limited to those that can be retrofitted onto the space station.

Current leak detection/location methods can be divided into two broad categories: contact and noncontact methods (both of which are presented in Section 2). Section 3 will present the current processing and wireless node technology that is available for use in leak detection. Section 4 presents a survey of the currently available Commercial Off-The-Shelf (COTS) leak detection products applicable to ISS, and Section 5 presents recommendations for future development.

2. Leak Detection Methods

2.1. Contact

2.1.1. Ultrasonic Methods

Ultrasonic clamp-on flow meters, that use mass or volume balance techniques, can be attached to pipelines to detect small leaks. These devices use sonic profiles and accurate flow rate tracking to detect leaks. They are, however, not applicable to aerospace vehicles because they are slow. Furthermore, they do not identify the location of the small leaks [12].

Acoustic emission is capable of detecting ice and foam impacts on the leading edge of the space shuttle wing. Although an initial impact detector has been developed and flown on the space shuttle, there remains a need to improve bandwidth, communication reliability, radiation tolerance, and battery life [13]. Impact hammer tests provided acoustic emission data on the Shuttle Endeavour's wing leading edge and wing spar in the range of 10 to 150 KHz. The tests highlighted future upgrades to the existing wireless impact monitoring systems [14].

Acoustic emission was also explored as a method for detecting and locating atmospheric leaks onboard the ISS. A neural network system was developed and tested on representative panels with waffle grid construction similar to the space station structure [15, 16]. The system was also tested on a prototype of the common module at the Marshall Space Flight Center (Fig. 1.). Two drilled holes in the prototype provided data on two different leak rates for leak location tests. The results showed that RMS amplitude works for leak location on the space station modules.

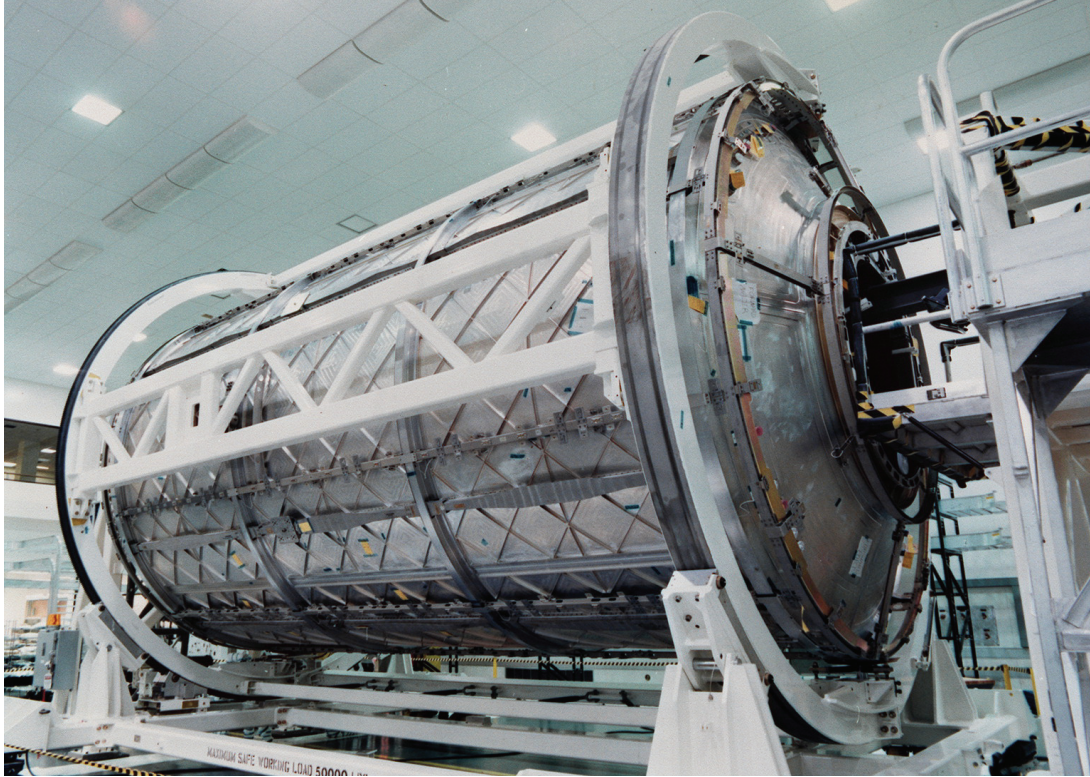


Figure 1. Ultrasonic testing has been performed on a common prototype module for the space station at Marshall Space Flight Center, similar to the module pictured here.

Structural borne ultrasonic waves are also being researched for the detection of leaks in spacecraft. The use of two cross correlated rotating sensors to find the relative phase delay as a method of detecting leaks has been investigated [17, 18]. The leak location is found using synthetic aperture analysis or from the variation of phase with angle. Another method involves the use of an array of micro sensors combined to form a single transducer to detect and find leaks [19, 20]. Sensors arranged in eight rows of eight columns comprise the 64 sensor array. The benefit of this system is that the sensors can remain stationary and do not need to be rotated. Cross correlation is still performed using multiple sensors; however, by selecting the sensors for their different spatial locations, movement of the sensors becomes unnecessary, and triangulation for leak detection becomes easier. This work has attracted NASA's attention for a Phase II SBIR grant [21]. If selected, the prototype would be integrated with a wireless telemetry unit and flight qualified, before delivery to NASA for installation on the space station.

2.1.2. Other Contact Methods

Checking for dropping pressure is the most common noncontact leak detection method. This method relies on the use of pressure gauges to act as sensors and detect leaks by the corresponding drop in pressure; but, this method has its problems. "Most of the conventional leak detection systems to date have, in general, failed to perform optimally within the criteria of response time, robustness, reliability, sensitivity, accuracy and cost. Furthermore, most of pipeline leak detection technologies are based on the continuous analysis of pipeline pressure, flow, temperature and density" [22]. To alleviate these issues, neural networks have been trained for improved leak detection using pressure drops in the presence of temperature changes when monitoring a dielectric fluid in power cables [23]. Some have used piezoelectric sensors to create dynamic pressure leak detectors in petroleum refineries [22]. A basic principle of piezoelectric pressure sensors is that they do not produce an output unless the pressure is changing. This effort relies on that principle for detecting leaks. Both of the methods are

tailored to systems with high-pressure and may be unsuitable for detecting the lower pressure differentials found in a spacecraft's atmosphere.

Leak detection of vacuum sealed micro electronic packages has led to the development of a MicroElectroMechanical System (MEMS) Pirani Gauge leak detector [24]. This technology has potential for space applications because it has little mass and uses little power. The micro gauge measures pressure from 10 mTorr to 760 Torr, but requires multiple devices with differing sensitivities to achieve the best resolution across the range of pressures. The devices were custom designed for packaging applications and may need costly redesigns before they are space qualified.

Wireless checking for leaks in water pipes by using accelerometers has been demonstrated [25]. The system is based on the Intel Mote platform and sampled data at a rate of 600 samples per second. The device could find leaks within 30 cm, and although the system could correctly classify 87% of the leaks, detecting small leaks remained problematic.

The "Worldwide Assessment of Industry Leak Detection Capabilities for Single & Multiphase Pipelines" suggests the range of leak sizes that can be detected is greatest when employing multiple leak detection methods [26]. Pressure methods quickly detect large leaks. Specialized hardware can detect small leaks but requires more time. Mass balance techniques detect medium flow leaks in a moderate amount of time. A combination of all three techniques would capture most, if not all leaks, in as timely a manner as possible.

2.2. NonContact

2.2.1. Optical Methods

Simple optical methods have been used in an attempt to visually detect and locate leaks from the MIR Spektr module. One technique employed astronauts and cameras on the STS-86 space shuttle mission to identify ice as it vented from the leaking Spektr module [27]. Although ice was seen and photographed, the technique did not lead to successful leak location.

As the Spektr module leaks persisted, another attempt to visually locate the leaks was performed in 1999. STS-91 carried 30 lbs of a gaseous mixture of nitrogen, Biacetyl, and acetone to the Mir space station. This gas mixture will fluoresce in the presence of sunlight. The gaseous mixture was released into the Spektr module during two separate tries to image the leaks. During the first try the space shuttle was docked, and during the second try the space shuttle was flying around the Mir (approximately 240 feet away). Unfortunately, both tries were unsuccessful, and fluorescing gas plumes were neither seen nor photographed during the attempts [28]. Glare from sunlight, the distance, and lack of sufficient quantities of the tracer gases were given as reasons for the unsuccessful outcome.

Other methods were considered before deciding on the use of fluorescing gases. One idea was to capture the IR signature of the escaping gases using a special IR camera. Another idea was to use a portable mass spectrometer to detect the escaping tracer gases during an EVA. Both of these ideas needed the development of expensive flight qualified hardware, and for that reason they were both dismissed in favor of the fluorescing gas method.

Active and passive IR imaging of the leaking gases has been explored terrestrially. For active systems, the gas plume is illuminated by a laser and imaged using a camera [29, 30, 31]. For passive mode systems, an IR camera with narrow spectral filters to detect the thermal emission of the gas plume is used for imaging [32]. Both of these methods have worked in laboratory settings, but each requires tailored hardware and configuration for each gas that it needs to detect. Also, it has not been proven that either method will work, in the case of a gas at atmospheric pressure escaping and dissipating into a vacuum.

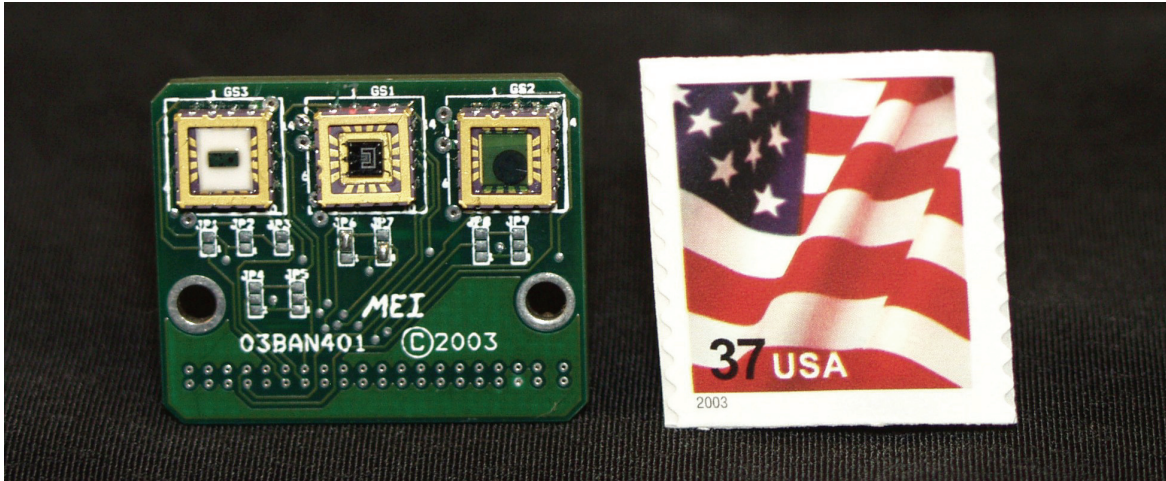


Figure 2. NASA Glenn Research Center's "Lick and Stick" leak sensor.

2.2.2. Chemical Detection

One method of performing leak detection is to detect escaping gases using chemical detection methods. NASA Glenn Research Center has developed a "Lick and Stick" technology (Fig. 2) that is small and wireless [33, 34]. These types of devices could be mounted externally to the structure or possibly placed on free flyers (autonomous spacecraft), and can be used to scan for leaks while flying around the aerospace vehicle.

This technique has the benefit of being wireless, and can be used to detect specific gases that may be escaping from any pressurized tanks as well as from escaping atmosphere. However, it works best when gases are not becoming more dilute, as is the case when the gases are dissipating into a vacuum. This device was designed for detection of specific hydrocarbons that are leaking within the spacecraft (not externally). Therefore, the sensor would have to be tailored to detect the constituents of the spacecraft atmosphere.

2.2.3. Gas Venting and Attitude Reaction

Aerospace vehicles need sensitive attitude sensing and control systems. These systems are highly sensitive, and it has been suggested that they can be used to detect and find leaks. Escaping gas from a vehicle creates reaction forces that act in the same manner as reaction forces created by thrusters. If the small amount of thrust can be detected and found using existing attitude control and rate systems, then a leak can also be identified and found [35, 36]. Using data from air lock depressurization for extravehicular activities has shown that the technique is feasible and capable of discovering the leak size and its location [37, 38].

One of the limitations of this method is that it relies on the inertia and mass component calculations that were performed on the ground before launching the units. The current configuration of the ISS is made up of complex shapes using the modules. The modules may have changes in the mass and inertia values due to changes in configuration and the addition or removal of mass during its lifetime. Another problem is that the vent of escaping gases may impinge on other surfaces of the space structure, making leak location difficult.

2.2.4. Ultrasonic Methods

Ultrasonic detection methods include the detection of high frequency sound waves produced by the escaping gases. For noncontact systems the sound waves are airborne. The basic premise involves detection of a high frequency sound signature that will indicate a leak. Normally, the background noise amplitude is less than the

leak noise amplitude at the monitored frequencies. Leak localization is performed by using spatial information from the sensors and using time, amplitude, and phase of the signals from each sensor.

The chaotic nature of acoustic sound has been examined in a petroleum refinery. The data was used with the chaos theory to discover the Lorenz attractors, which would enable detection of leaks using airborne ultrasonic waves [39]. Experiments were performed using a silencer nozzle near a high-pressure gas unit in a working refinery in Chiba. The results showed that it *is* possible to detect gas leaks using the chaos theory in a working refinery.

NASA has a history of working with companies to develop leak detection and location equipment. In 2001, a CTRL System's UL101 device was flight qualified and flown on STS-104 mission to the ISS. It was used to find the leak in the ISS air lock during the July mission [40]. The success from the first use of the device led NASA to manifest it on all Shuttle missions beginning in the third quarter of 2003 [41]. The device was used again on board the space station in 2004 with mixed results. The first try did not locate the leak; however, after turning off the equipment in the module, astronauts were able to find the leak. Although not space qualified, another device was developed for use at Kennedy Space Center to detect leaks from the Space Shuttle and launchpad equipment [42]. This device was specifically designed to reflect ultrasonic waves at the tip of the transducer to allow for smaller leaks to be detected.

An ultrasonic leak detection and location unit called UltraWIS has been developed by Invocon Inc. for the space station [13]. The unit has ten sensors: eight narrowband airborne ultrasonic transducers, one surface borne acoustic emission sensor, and one wideband ultrasonic microphone. The UltraWIS samples all of the sensors at 100 kHz before performing Digital Signal Processing (DSP) on the data. It was tested at Kennedy Space Center on Node 2 (Fig. 3.). The tests allowed the UltraWIS to monitor the background noise in the module while fully powered, but without any equipment racks installed. Although the background noise was determined to be low for the test, it did not include any noise from equipment which will be present in the final configuration of the module. The equipment noise has caused problems in the past when attempting ultrasonic leak detection. The system was developed through the NASA SBIR program, but must be certified for space before it can be flown or installed on the space station.

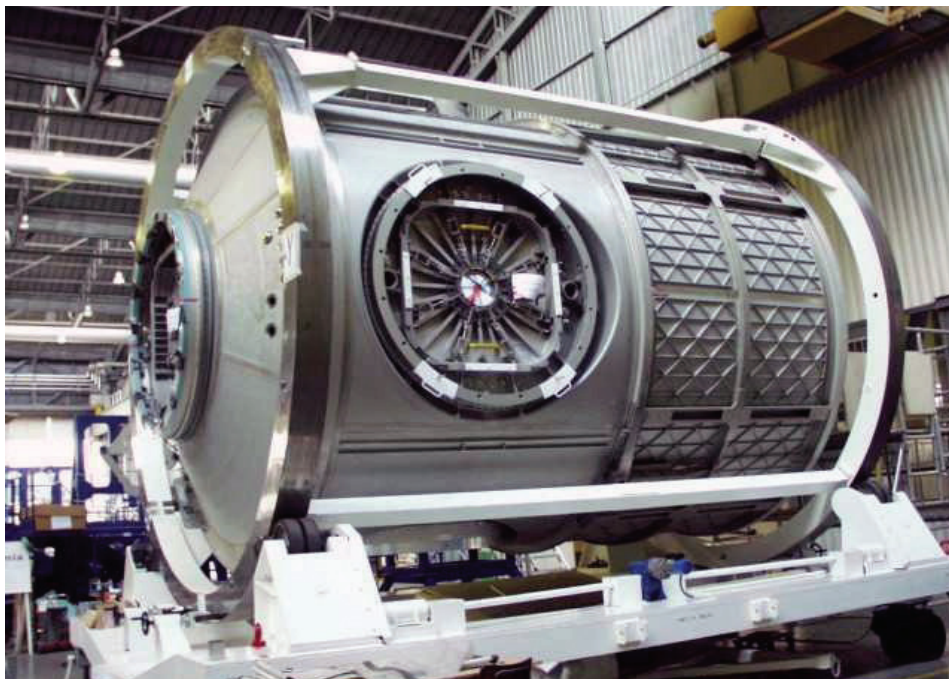


Figure 3. International Space Station Node 2.

3. Wireless Sensor Nodes

Wireless sensing is an outcome of research performed at Berkeley University on the Smart Dust program. Current commercial technology centers on the use of a processor with the addition of wireless transceivers. Other features that are sought in a wireless sensor are synchronization, reliability, processing power, DSP, self-diagnosis, and self-identification [43]. The standard term for a wireless node of this type is a “mote.” For a review of the evolution of motes, refer to Polastre [44]. Motes can be divided into three categories by the hardware implementation. The three divisions are microcontroller based motes, microprocessor based motes, and System-on-a-Chip (SoC) technology.

3.1. Microcontroller Based Motes

Although Berkeley and Dust Networks Inc. lead this research, several companies have capitalized on their work. Crossbow is one these companies that has risen to become the largest supplier of motes. Crossbow manufactures microcontroller based motes that are fairly small. They are roughly the size of a half dollar for their Mica2 products. Microcontroller based motes have been very successful in many applications. However, the applications can all be described as very low data rates systems, usually with extremely low duty cycles (since power is the biggest issue for all wireless devices). To make batteries last a reasonable amount of time, extremely low duty cycles must be used. Many NASA applications are found in inaccessible locations where batteries are not a good solution. Also, temperature extremes often exclude the use of batteries. Although energy harvesting has been successfully applied in some applications, the technology has not advanced as quickly as needed. Nor has battery technology advanced. Thus, power remains a major issue.

For most people, Crossbow Technology Inc. comes to mind when considering wireless sensing motes. Crossbow markets an extremely successful microcontroller line of products. They also manufacture a line of products for aircraft and UAVs, such as the inertial navigation systems [45]. Although these products are certified for aircraft, they do not include wireless functionality. However, the company’s experience in both wireless sensing nodes and aircraft avionics makes them a natural candidate for development of wireless sensor networks for aircraft applications.

Other groups have also developed microcontroller based sensor nodes. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia has developed hardware they call “Flecks.” These devices incorporate a microcontroller with long-range (500m) RF communications [46]. The Flecks have been used for various sensing applications in a wide variety of environments, from monitoring people in social situations to monitoring livestock in the field. Flecks have also been used to monitor greenhouses, or monitor underwater environments (by using the “Sea Fleck”).

One possible candidate for a wireless leak detection system is the low power, wireless, micro crack sensor, developed by GE global Research Center [47]. The micro crack sensor uses custom developed hardware to detect acoustic emission signals and “wake up” the microcontroller to take data. This allows the microcontroller to stay in a sleep mode for a longer period of time, thus prolonging the battery life. The system stores data at a high data rate for a very short time before sending the data wirelessly to the control node. Currently, it uses acoustic emission techniques to monitor micro cracks, but it could be modified for ultrasonic acoustic leak detection.

Another system that addresses the high data rates needed for Structural Health Monitoring (SHM) uses a Field Programmable Gate Array (FPGA) to conserve power while increasing the number of samples per second [48]. The system also uses a discrete analog to digital converter that is much faster than those found integrated into microcontrollers. The system was demonstrated by sampling a 220 kHz signal at 1 Msps, but it is capable of a maximum rate of 10 Msps. The data can then be transmitted to the base node at a rate of 14.4 kbps.

3.2. Microprocessor Based Motes

To address the needs of complex measurements, greater processing than what is currently available in microcontrollers needs developing. For that reason, microprocessors have been used to develop motes with a magnitude increase in processing, in comparison to microcontrollers. Microprocessor based motes are being developed for both medical applications *and* radiation tolerant versions for space applications.

Unfortunately, this processing power comes at the expense of greater power utilization. Power is the biggest issue that affects all forms of motes for wireless sensing. “For tiny, low power sensors, the most important issue is the power consumption. To make such sensor networks useful, power consumption issues must be addressed. In a word, all protocols and applications for sensor networks must consider the power consumption issue and try their best to minimize power consumption” [49].

The use of a microprocessor instead of a microcontroller increases the choices for operating systems on wireless sensing platforms. One example is the use of the Linux on Gumstix single board computers [50]. The Gumstix operating frequency runs in the hundreds of megahertz, far above the processing speed of a microcontroller, but at the expense of greater power drain and, consequently, shorter battery lifetimes.

Greenpeak claims to have developed a low power, batteryless, wireless module, that has three times the communication range of similar products [51]. The module has an interface for connecting energy harvesting power devices for batteryless operation. Like its counterparts, the data rate is 250 kbps. This technology may prove useful for current low data rate applications, and could provide the starting point for developing low power high data rate systems needed for leak detection, as well as other Integrated Vehicle Health Management (IVHM) applications. It should be noted that Greenpeak does not make the energy harvesting module and that others also have interfaces to the third party energy modules.

Even the processor giant, Intel, has entered the arena of wireless sensing by introducing the “Intel Mote platform” [52, 53]. These devices feature the Intel XScale CPU that includes DSP functionality, RAM, FLASH memory and an 802.15.4 compatible radio. The processor can run from 13 ~ 416 MHz, making it useful for a variety of sensing tasks. Of course, power consumption and clock speeds both increase together.

Very few are working on new hardware for wireless sensing applications; however, a hardware accelerated implementation of the IEEE 802.15.3 Medium Access Control (MAC) protocol has been developed [54]. This device offloads the computational requirements from the main processor. This allows a public domain processor like LEON-2 to be used for wireless sensor applications such as medical monitoring [55]. If pursued, this technology could be combined with work on a fault tolerant and radiation tolerant LEON-3 FT processor [56, 57]. This processor is being developed for the European Space Agency (ESA) for future space missions.

3.3. System-on-a-Chip (SoC) Based Motes

System-on-a-Chip (SoC) technology is the direct result of the constant trend towards higher integration in electronic circuits. Integration has several benefits. It reduces the power and increases the speed of operation while increasing the functionality. Custom SoC technology allows designers to tailor the hardware for specific applications. Dust Networks Inc. and Berkeley University have consistently used these techniques to develop the smallest, lowest power hardware as they strive to develop “Smart Dust.” They are targeting a 2mm² mote-on-a-chip that will include all the functionality of a conventional wireless sensing mote, but will be small enough to be deployed as throw away devices for military applications [58]. Besides miniaturizing hardware for wireless sensing, they have also developed a networking protocol called, “Time Synchronized Mesh Protocol” (TSMP) for their devices [59]. This is an ultralow-power, wireless sensing, network protocol, which is self-organizing, multihop and very reliable in harsh RF environments.

4. ISS Application

Many of the systems and methods discussed in Sections 2 and 3 are still experimental and are not ready for near term application. The following is a survey of commercially available leak detection and location devices currently being advertised. Thirty-eight companies were identified with a total of 76 products (Table 4.1.). Websites for these companies are listed in Appendix A. The survey was performed to determine the best candidates for solving the issue of leak location on board the ISS.

The survey began with criteria for web searches that produced over 30,000 hits. From this large number of potential sites, the search criteria were adjusted in order for the researchers to examine only a few hundred websites. Of these websites, 38 companies were identified, returning 76 products that needed to be evaluated in order to determine potential for the application.

In an effort to establish the top twelve candidates to be considered for development of flight certified hardware, the following scoring system was developed.

4.1. Scoring System

Each requirement is scored using a simple points system. The points are in Table 4-2

4.1.1. Evaluation Categories (Requirements)

Representative off-the-shelf products from various leak detection categories were evaluated based on a general set of minimal requirements. The following subsections describe the general requirements for each unit or system under evaluation.

4.1.2. Detect Leak and Provide its Location

The product line should detect leaks and provide the specific location of the leak source. In the evaluation, the detection and location requirements are separated and weighted to fairly represent the various methods of leak detection.

4.1.3. Complete System Available & Operational

This requirement category shows whether the product line is a complete operational package (Meets), in development (Possible), or a possible candidate to be incorporated into a package (Possible).

4.1.4. Autonomous Operation

Except for startup and routine maintenance, the product line must be capable of operating autonomously without human intervention.

4.1.5. Wireless Communications (Where applicable)

To reduce cabling, the product line should use wireless communications for control, networking, and data acquisition.

Leak detection/location units

Company	Number of Products
Accutech	1
Aerovac Systems Limited	1
American Gas & Chemical Co. Ltd.	1
Amprobe	2
Ansonics, Inc.	2
CTRL Systems, Inc.	1
Compressed Air Management Impact RM Inc.	2
CrossBow	1
CSIRO	3
Dust Networks	1
Enercheck Systems, Inc.	7
Exair Corp.	1
Fisher Labs	4
Gassonic	3
Gayle Technology In.	2
Greenpeak Technologies	1
Gumstix	1
HeatCon Composite Systems	1
Honeywell	1
Inficon	1
Institute for Scientific Research, Inc.	1
Intel	2
IntelliSensing	1
Invocon	2
JORC Industrial	1
Kernco Instruments	2
Logis-Tech Associates	6
MetroTech Corp.	1
Monarch Instrument	3
NDT International, Inc	1
Physical Acoustics Corp.	3
Pure Technologies LTD	1
Rogers Machinery Company, Inc.	1
Sonatest LTD	1
SPX Robinair	1
Superior Signal Company	3
Triple 5 Industries	4
UE Systems Inc.	5
Total	76

Table 4-1. Summary of Leak Detection/Location Units.

4.1.6. Low Power Operation

It is desired to have a unit or system that uses very little power and is capable of being powered for years, either by battery (i.e. requiring little or no maintenance) or no battery. This attribute should also extend the operation using the smallest battery possible.

Category Evaluation	Key	Points Value
Meets/Positive/Pro	Y	+3
Does Not Meet/Negative/Con	N	-1
Almost Meets or Possible	P	+1
Not Applicable	N/A	0

Table 4-2.

4.1.7. Low Impact Integration

The unit or system should require only minimum mechanical and electrical integration/retrofitting. This requirement also applies to stowing of the unit or system onboard the ISS. A simple “bolt-on” or “stick-on” installation is preferred with a majority of the systems being battery powered to reduce cabling. Any system communications will be by low-power wireless methods.

4.1.8. Installation, Operation & Maintenance Procedures for Astronauts

The installation and operation should be simple. Maintenance requirements should be extremely low. Where applicable, the installation should call for simple tools and “plug-and-play” interfaces. The operator interface should be minimal and its indicators should be informative and simple to interpret. Maintenance should only be proper stowage (where applicable) and infrequent battery changes (when required).

4.1.9. Flight Qualification for ISS Installation

The product line must be qualified for reliable installation onboard the ISS. If the product line is not already qualified from the manufacturer, consideration is extended to the possibility that the unit or system can be retrofitted to meet the requirements. In this evaluation, only the product’s apparent complexity and external enclosure were used to determine the possibility of being retrofitted.

4.1.10. Miniature Size

Each unit or system component should be small and lightweight enough to be installed anywhere space will allow, or easily carried in a tightly confined area.

4.2. Results

The survey results concerning the top twelve candidates for consideration for development of flight certified hardware are presented in Table 4-3. Companies not evaluated did not offer products that addressed ISS requirements. Many of the methods mentioned previously are not directly applicable to leak detection on the space station and therefore were not rated. Some do not detect and locate leaks. Others are too costly. The Technology Readiness Level (TRL) is too low, thus requiring more development time and costs to be developed. Some devices which involve external access incur extra costs for radiation hardening, environmental hardening, shuttle time or EVA time. These extra costs exclude the technology from consideration. Of the notes discussed previously, only those that can already detect leaks or where the company has flight experience have been included in the rating system. It is not the intent of this document to discourage anyone from further development; instead, it should provide insight for future partnerships that may lessen the development time and costs.

Manufacturer or Source	Invocon	Accutech	Crossbow	Invocon/ Iowa State Univ	UE Systems	Triple 5
Product (Line)	DIDS/ UltraWIS	WI-AM	MCS410 Cricket	PZT Array	Ultraprobe	50UBA
Stage	Prototype	Product	Platform	Concept/Research	Product	Product
Detection Method	Ultrasound-Air-AE	Ultrasonic	Ultrasound-Air	Ultrasonic-AE	Ultrasonic-Air	Ultrasonic
Additional Description	4-8 detectors/ node SBIR	Industrial system	1 detector/ node	64-element Array NAG-1-029098	Handheld	Benchtop
Detects Leak	Y	Y	Y	Y	Y	Y
Auto. Locates Leak	Y	N	N	Y	N	N
Complete System Autonomous Operation	P	N	N	N	N	N
Wireless System	P	N	P	P	N	N
Battery Powered Low Impact	Y	Y	Y	P	Y	Y
Integration Installation by Astronauts?	P	N	P	N	N/A	N/A
ISS Qualified Can it be Qualified for ISS?	P	N	P	N	N/A	N/A
Miniature Size	N	N	N	N	N	N
Score	19	3	13	9	1	1

Manufacturer or Source	JORCO	Intellisensing	Honeywell	PAC	PAC	Sonatest
Product (Line)	7900	Nothing	XYR5000	5110	5610	Soundscan
Stage	Product		Product	Product	Product	Product
Detection Method	Ultrasonic		Ultrasound	Ultrasonic	Ultrasonic	Ultrasonic
Additional Description	Handheld	Previous flight experience	Similar to Accutech	Handheld Mech. Contact	Rackmount Controller	Handheld
Detects Leak	Y	N/A	Y	Y	Y	Y
Auto. Locates Leak	N	N/A	N	N	N	N
Complete System Autonomous Operation	N	N/A	N	N	N	N
Wireless System	N	N/A	Y	N	N	N
Battery Powered Low Impact	Y	N/A	Y	Y	N	Y
Integration Installation by Astronauts?	N/A	N/A	N	N/A	N	N/A
ISS Qualified Can it be Qualified for ISS?	N/A	N/A	N	N/A	N	N/A
Miniature Size	N	N/A	P	P	N	P
Score	-1	0	11	1	-7	1

Table 4-3. ISS Leak Detection/Location Product Survey Results

4.2.1. Handheld Units

Handheld ultrasonic units were represented by UE Systems Ultraprobe, Jorco 7900, PAC 5110 and the Sonatest Soundscan. A handheld unit is onboard the ISS to aid in leak detection. Although portable, the handheld units do not address locating the leak source automatically, and each unit requires an operator. Also, airborne systems require a line-of-sight between the source and sensor.

4.2.2. Desktop and Rack-mount Units

Desktop/Rack-mount ultrasonic units were represented by PAC 5610 and the Triple-5 50UBA. These units are designed for a benign environment and only detect the presence of a leak. Similar to the handheld units, these types do not address pinpointing the location of the leak, and each unit requires an operator.

4.2.3. Industrial Monitoring Systems

The industrial monitoring systems are used to monitor process equipment in harsh environments. These systems utilize a separate master controller with a network of various sensor modules. Ultrasonic airborne leak detection sensors are available. These sensor modules are mainly designed to detect leaks in the general vicinity of the sensor installation. No specific leak source location capability is included. Another drawback is the sensor module's size and weight. Designed to withstand punishing industrial environments, the modules tend to be heavy, bulky, and require heavy duty mounting.

4.2.4. Other Platforms & Prototypes

The PZT Array from Invocon/Iowa State University [17-18] is a research prototype, which addresses detection and location. Its development is being supported by NASA under their STTR program. Because of the inherent complexity in integration, it falls short as a system ready for immediate application. A video demonstration of this promising system is available on line at:

http://home.eng.iastate.edu/~rreusser/leakdetection_h2641q.mov (for Macintosh) and

<http://home.eng.iastate.edu/~rreusser/leak3.mpg> (for Windows).

As for the Crossbow MCS410 Cricket product, the unit scores high in all but the important categories of detection/location. The Cricket was included in the evaluation to represent a product that could possibly be used as a baseline design for a leak detection/location module or system.

4.2.5. Leading Candidate System

As is often the case when performing trade-offs between existing systems, an optimal solution does not exist. The number one candidate was chosen primarily because it will have a shorter development time than its counterparts. The Distributed Impact Detection System (DIDS), from Invocon [13], is a more recently developed wireless system that is a next generation ultrasonic system after the UltraWIS. DIDS has advantages in its leak detecting/locating possibilities, small size, low integration resource requirements, and flexibility. Invocon also has experience in developing and building devices for NASA missions; hence, it is likely that the DIDS can be flight qualified.

As discussed earlier, DIDS will require additional development and refinement before being considered as foolproof. To operate reliably, the system will need to address background equipment noise and multiple receptions of the same leak source.

5. Future Directions

The Distributed Impact Detection System (DIDS) was developed under a NASA Phase 2 Small Business Innovation Research (SBIR) grant to create the DIDS [60]. This system is a wireless acoustic emission system for monitoring spacecraft for MMOD impacts. The system addresses some of the issues for structural borne acoustic emissions. Although the system does not address airborne signals, it could easily be adapted to mimic the configuration of the UltraWIS. The system will also need to be flight certified before it can be flown.

Currently, a drop in pressure gives the best indication of a leak on the space station. Handheld leak location hardware *is* presently aboard the space station; however, in the past, the hardware has had difficulty detecting small leaks while equipment was running. Closing hatches remains the best way to discover which module is leaking; developing new hardware will improve this situation.

The hardware developed in the future must be more sensitive. Increasing the data transmission rate permits more sensors and higher bandwidth (for those sensors). An increased sampling rate that covers a bandwidth of at least 400 KHz per sensor enables acoustic emission leak detection techniques. Better synchronization between channels allows for more accurate phase and time of flight measurements. There is always a trade off between specificity and sensitivity for leak detection systems. The hardware should be designed with this trade-off in mind, and at the same time, attempt to be flexible in order to handle either case, when required by a new situation. For keeping down the costs of retrofit devices on the space station, wireless systems are more appealing than their wired counterparts. Also, hardware standardization is preferable, because it makes the hardware useful in other applications.

Besides hardware, new algorithms that decrease the false positive and false negative rates are desired. Software that improves the accuracy of the leak detection (while reducing the time for leak detection) is also sought after. Naturally, the algorithms will need to be efficient in using the resources of both CPU cycles *and* memory usage. This will keep the weight and power at a minimum. Autonomous programming techniques are needed to lower the burden on astronauts, by reducing the complexity of the information that is presented to them. They will need answers, not raw data. Artificial intelligence techniques such as neural networks, fuzzy logic, and genetic algorithms may play a role in producing these answers. The new software should be able to detect small leaks, as well as assess the extent of the damage while locating the leak. The software systems should be flexible, reconfigurable, and reprogrammable. This will allow future algorithm developers to upgrade the software after it is in place. Due to the crew's high workload, they prefer to not have the extra responsibility of dealing with upgrades and computer software maintenance. The ground controllers should handle that task remotely. Of course, following best practices, standards, and developing reusable code are always encouraged.

As mentioned earlier, power is the biggest issue for these systems. Low power designs for each element will increase battery life. This includes the hardware, software, and RF systems. Each piece must do its part to keep the power consumption at a minimum. For applications like structure borne leak detection, it is preferable to have passive sensors attached to structure. These can use energy harvesting, scavenging, and RF techniques to power themselves rather than rely on astronaut time to change batteries. Passive RFID tags and Surface Acoustic Wave (SAW) sensors are both being investigated by NASA as potential solutions to the power problem for wireless sensor systems.

Conclusions

Various methods for leak detection and location have been examined. Also, the requirements have been presented for leak detection and leak location on board the ISS. Commercial leak detection devices have been surveyed and the candidate that currently best suits the requirements has been identified. Although the candidate is more developed than its counterparts, it will require flight certification before it can be flown.

Even though a candidate was chosen, future aerospace vehicles will still require the detection of smaller leaks, faster response, and more accurate leak location without false positives and false negatives. The hardware will need to have higher data rates and consume less power, while also fitting in a smaller volume. Therefore, opportunities still exist for new systems to be developed.

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Appendix A

Portable leak detection/location units

Aerovac Systems Limited
<http://www.aerovac.com>

American Gas & Chemical Co. Ltd.
<http://www.amgas.com/sonpage.htm>

Amprobe
<http://www.amprobe.com/>

Ansonics, Inc.
<http://www.ansonics.com/>

Compressed Air Management Impact RM Inc.
<http://www.impactrm.com/>

CTRL Systems, Inc.
<http://www.ctrlsys.com/>

Enercheck Systems, Inc.
<http://www.enerchecksystems.com>

Exair Corp.
<http://www.exair.com/>

Fisher Labs
<http://www.fisherlab.com/industrial/xlt30.htm>

Gayle Technology In.
<http://www.microphonics.com/>

HeatCon Composite Systems
<http://hcs.heatcon.com/>

Inficon
<http://www.inficonultrasonicleakdetectors.com/>
JORC Industrial
<http://jorc.thomasnet.com/>

Kernco Instruments
<http://www.kerncoinstr.com/>

Logis-Tech Associates
<http://www.logis-tech.co.uk/ultraset.htm>

Monarch Instrument
<http://www.monarchinstrument.com>

NDT International, Inc
<http://www.ndtint.com/corona.htm>

Rogers Machinery Company, Inc.
<http://www.rogers-machinery.com/>

Sonatest LTD
<http://www.sonatest.com/>

SPX Robinair
<http://robinair.com/>

Superior Signal Company
<http://www.superiorsignal.com/>

Triple 5 Industries
<http://www.triple5industries.com/portables.htm>

UE Systems Inc.
<http://www.davidson.com.au/products/ultrasonic/s/ue>

Wireless leak detection/location units

Accutech

<http://www.savewithaccutech.com/>

Honeywell

<http://hpsweb.honeywell.com/Cultures/en-US/Products/wireless/xyr5000/XYR5000Gateway/default.htm>

Institute for Scientific Research, Inc.

http://www.isr.us/NR12_19_05.asp

Invocon, Inc.

<http://www.invocon.com>

MetroTech Corp.

<http://www.metrotech.com>

Physical Acoustics Corp.

<http://www.pacndt.com>

Pure Technologies LTD

<http://www.puretechnologiesltd.com>

Wireless processing nodes with potential for leak detection:

CSIRO

<http://www.ict.csiro.au/page.php?cid=87>

CrossBow

<http://www.xbow.com/>

Dust Networks

<http://www.dust-inc.com/flash-index.shtml>

Greenpeak Technologies

<http://www.greenpeak.com/>

Gumstix Inc.

<http://gumstix.com/>

Intel

<http://www.intel.com/research/exploratory/motes.htm>

IntelliSensing

<http://www.intellisensing.com/>

Wired leak detection/location units

Gassonic

<http://www.gassonic.com/>

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