# Analytical and Experimental Studies of Leak Location and Environment Characterization for the International Space Station

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**Abstract**. The International Space Station program is developing a robotically-operated leak locator tool to be used externally. The tool would consist of a Residual Gas Analyzer for partial pressure measurements and a full range pressure gauge for total pressure measurements. The primary application is to detect $NH_3$ coolant leaks in the ISS thermal control system.

An analytical model of leak plume physics is presented that can account for effusive flow as well as plumes produced by sonic orifices and thruster operations. This model is used along with knowledge of typical RGA and full range gauge performance to analyze the expected instrument sensitivity to ISS leaks of various sizes and relative locations ("directionality").

The paper also presents experimental results of leak simulation testing in a large thermal vacuum chamber at NASA Goddard Space Flight Center. This test characterized instrument sensitivity as a function of leak rates ranging from 1 $lb_{m}$/yr. to about 1 $lb_m$/day. This data may represent the first measurements collected by an RGA or ion gauge system monitoring off-axis point sources as a function of location and orientation.

Test results are compared to the analytical model and used to propose strategies for on-orbit leak location and environment characterization using the proposed instrument while taking into account local ISS conditions and the effects of ram/wake flows and structural shadowing within low Earth orbit.

**Keywords:** plume flows, residual gas analyzer, International Space Station
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## INTRODUCTION

The NASA Goddard Space Flight Center (GSFC) and Johnson Space Center (JSC) are developing a robotically-operated leak locator tool or device for external use on the International Space Station (ISS) called the Ammonia Leak Locator (ALL). The tool will consist of a Residual Gas Analyzer (RGA) for detecting small leaks on the order of 10-100 $lb_m$/yr, and a full range pressure gauge (FRG) for larger leaks on the order of 10-50 $lb_m$/day. Potential leak sources on ISS include ammonia coolant used in the thermal control system and crew compartment air. All instruments incorporated into the ALL are commercially available.

Detecting and locating leaks will require an understanding of the physics associated with the leak plume and the mechanisms by which the leak is sensed. Thermal vacuum (TVAC) testing served as a precursor to the flight development program and was intended to inform future testing and instrument development. Although this testing was designed to demonstrate the functionality of an engineering device, the data obtained also proved useful in making comparisons with model predictions which will be used to help inform on-orbit test program and operational procedures.

This paper presents an analytical model of leak plume physics and uses this model and knowledge of typical RGA & FRG performance to analyze expected instrument sensitivity to ISS leaks of various sizes and locations (i.e. directionality). The paper also presents experimental results using a large thermal vacuum chamber at GSFC to characterize instrument sensitivity as a function of leak size, location, and direction. Finally, although the data reduction effort is still currently underway, comparisons are made with model behavior for a test case having a flow rate of about 50 $lb_m$/yr.

# ANALYTICAL APPROACH

## Source Behavior

A source characterized by gas leaking under pressure into the high vacuum of space is often described by acceleration to sonic conditions at the downstream end of its path outside, neglecting frictional losses along that path. For sonic flow issuing from a thin orifice with area $A$, the local Mach number $M$ = 1, and the mass flow rate $\dot{m}$ is given by1

$$\dot{m} = p_0 A \sqrt{\frac{\gamma}{RT_0}} \left( \frac{\gamma + 1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} . \qquad (1)$$

In Eq. (1), rest conditions for pressure $p$ and temperature $T$ are denoted by subscript 0. Parameter $\gamma$ is the ratio of specific heats for the gas, and $R$ is a species-dependent gas constant.

In contrast, for conditions associated with an ammonia leak from the ISS thermal control system, it is possible that the fluid emanates from somewhere within a radiator panel and evaporates on its surface. Evaporation is generally a subsonic process, often similar to molecular effusion in the limit of $M$ = 0. For molecular effusion in an equilibrium gas,

$$\dot{m} = \rho \sqrt{\frac{RT}{2\pi}} A = \frac{pA}{\sqrt{2\pi RT}} . \qquad (2)$$

Equation 2 is sometimes referred to as the Hertz-Knudsen equation.[2,3]

## Plume Model

As a plume expands into vacuum either effusively or via sonic orifices, density levels, and hence collision rates, decrease rapidly by many orders of magnitude. Even near the source where significant intermolecular collision rates may occur, effectively little thermal scattering occurs normal to mainly radial streamlines. Due to these features, plume expansion models based upon free molecule theory have proved to be quite successful.[4,5]

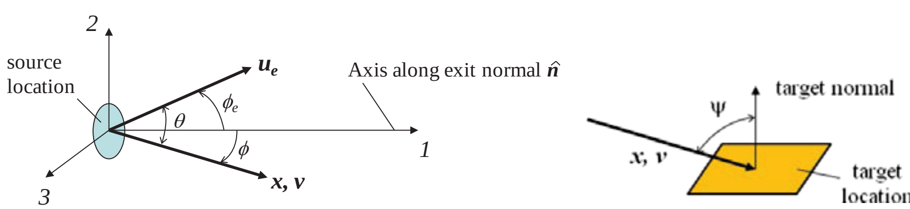


**FIGURE 1.** Schematic representation of various quantities and angles used in source flow model.

In this plume model, the collisionless Boltzmann equation has been solved for flow from a point source meant to describe directed flow over $2\pi$ steradians centered about the source normal.[4] Using Fig. FIGURE 1, directed flow with velocity $\boldsymbol{u}_{\mathbf{e}}$, temperature $T$, and mass flow rate $\dot{m}$ issues from the source. We introduce parameter $\beta \equiv 1/\sqrt{2RT}$ to define speed ratio $s \equiv \beta u_{\mathrm{e}}$. Normal $\hat{\boldsymbol{n}}$ represents the orientation of a local starting surface element, and $\boldsymbol{v} \cdot \hat{\boldsymbol{n}}$ emphasizes the imposed directional constraint. Generally $\boldsymbol{u}_{\mathbf{e}}$ is not aligned with $\hat{\boldsymbol{n}}$, the angle between the two being defined by $\phi_{\mathrm{e}}$. Local angle $\phi$ is measured between variable position $\boldsymbol{x}$ (distance $r$, experiencing local velocity $\boldsymbol{v}$) and $\hat{\boldsymbol{n}}$, and angle $\theta$ is measured between $\boldsymbol{u}_{\mathbf{e}}$ and $\boldsymbol{x}$.

The distribution of various flowfield quantities is found by integrating successive velocity moments of the resulting distribution function. In particular, the steady-state mass flux $\dot{\Phi}$ is given by

$$\dot{\Phi}\left(\boldsymbol{x},t\right) = \frac{\dot{m}\cos\phi\cos\psi}{A_1\,\pi\,r^2}\,e^{w^2-s^2}\left\{\left(w^2+1\right)e^{-w^2}+\left(\frac{3}{2}+w^2\right)\sqrt{\pi}\,w\left(1+\operatorname{erf}\,w\right)\right\} \tag{3}$$

where

$$A_1 \equiv e^{-y^2}+\sqrt{\pi}\,y\left(1+\operatorname{erf}\,y\right) \tag{4}$$

In these equations, $w \equiv s\cos\theta$ and $y \equiv s\cos\phi_{\mathrm{e}}$. As depicted in Fig. 1, angle $\psi$ is defined between $\boldsymbol{x}$ and the target surface normal.

## INSTRUMENT SENSITIVITY

### Pressure Sensor Measurement

In the case of an RGA, the measurement is presented in terms of pressure, but what is actually being measured is the transient flux of typically singly-charged ions successfully navigating the RGA quadrupole mass filter passage from the ionizer to a Faraday cup or electron multiplier unit. The rate of ion production is proportional to the rate at which gas molecules reach the ionizer upstream, so the source species mass flux intercepted by the RGA across its ionizer surface envelope is the important quantity to compute.

For a typical RGA installation in a thermal vacuum chamber, the relationship between mass flux and pressure reaching the ionizer is given by Eq. 2. In the ISS leak locator application, it is the mass flux of leak plume molecules, Eq. 3, which is converted by the Hertz-Knudsen equation to produce an anticipated “pressure” measurement.

### On-Orbit Sensitivity Considerations

Instrument sensitivity will depend on detection of the leak constituent against the background gases. Plume model results, anticipated ISS background conditions as described in the literature (see next section), and experimental measurements of sensor non-repeatability are used to generate predictions of instrument sensitivity (signal-to-noise ratio) as a function of leak rate, distance, and direction. In this project, the ALL is comprised of commercial off-the-shelf (COTS) units with repackaged electronics to handle the space environment, and a number of safety concerns led to a need to baffle the ionizer volume. These changes will affect device sensitivity beyond the instruments’ intended functions for monitoring TVAC environments.

### Review of Previous Missions

A number of space flight mass spectrometer (MS) instruments have been built, particularly for scientific missions to obtain measurements of other celestial bodies (e.g. Cassini—Ion & Neutral MS, Giotto—Neutral MS, Ion MS, Lunar Atmosphere and Dust Environment Explorer—Neutral MS). 7, 8[8] Although the main purpose of the

ISS leak locator device differs from the scientific objectives of those spacecraft missions, some aspects bear degrees of similarity to the present application.

*Rosetta ROSINA Instrument Suite*

The European Space Agency's (ESA's) Rosetta observatory was launched in 2004 and will rendezvous with comet 67P/Churyumov-Gerasimenko to make detailed studies in mid-2014.[9] The spacecraft hosts a number of instrument systems, including the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA), which includes pairs of mass spectrometers and pressure sensors. [10,10] This suite has the ability to resolve mass/charge variations between species of similar molecular weights, such as CO and $N_2$.[7] These units have been operating throughout the majority of Rosetta's decade-long transit phase, and based on their fixed locations and orientations on the spacecraft bus have captured a variety of remarkable transient data associated with outgassing and thruster firings.[9] However even with some level of confidence in observatory material outgassing behavior with time and local thermal conditions, and accounting for direct and reflected surface impingement as well as self-scattering of outgassed molecules, project personnel were unable to reproduce measured pressure profiles through geometric mass transport modeling.[11]

*Mir Astra-2 Instrument Suite*

The Astra-2 instrument suite, containing a variety of pressure measurement devices, resided external to Space Station Mir's Spektr module from 1995-1997. It was designed in part to measure ambient atmospheric parameters.[12] In addition, a notable experiment was conducted to measure the angular distribution of a small Ar cold gas thruster plume.[13] An ion gauge directly facing the nozzle exit was mounted to a boom whose pivot axis intersected the nozzle exit center and was able to rotate from the plume axis well into the backflow regime through a 135° arc. At the highest flow rate setting, this gauge was able to distinguish plume variations over four orders of magnitude. A variety of point source plume models and a carefully developed direct simulation Monte Carlo (DSMC) study failed to reproduce the breadth of the core region exhibited by experimental data, a feature attributed to the effects of Ar clustering. The relatively flat profile at angles observed above 90° was thought to be caused by the influence of outgassing from nearby structures.[13]

*MEDET Observations*

The Materials Exposure and Degradation Experiment (MEDET), undertaken by a group of European research institutions, was exposed to ambient conditions external to the International Space Station (ISS) Columbus module for nineteen months of operations, usually facing the ram direction. [14,15] It contained an ion gauge that measured orbit-averaged impingement pressure levels (relative momentum flux) of $10^{-7}$ to $5\times10^{-6}$ mbar in this orientation, and recorded $10^2$-$10^3$ lower levels when exposed to the ISS wake. These measurements provide an expectation of the environment in which the ALL must be capable of discriminating individual species in the presence of ambient gases such as atomic oxygen, outgassing from nearby surfaces, and the ability to handle discrete events such as local venting.

## EXPERIMENT

### Setup

Experiments were conducted at NASA GSFC using one of their large TVAC chambers in May 2013 and May 2014. The cylindrical chamber is vertically oriented and contained a large translation/rotation stage (TRS), lights, and a camera to verify motion. The TRS provided movement over 175 cm of test length and 190 degrees of rotation (Fig. 2). Leak source introduction tubes were set up at north (axial) and west (transverse) points within the chamber. Source flow rates were controlled by a manifold using non-calibrated valves. A window allowed the position to be verified with a laser range finder. TVAC chamber shrouds were cooled with liquid nitrogen to condense certain source leak gases.

Instruments tested in the chamber included a Stanford Research System Model 100 RGA, a Granville Phillips STABIL-Ion Gauge (SIG), and a Pfeiffer Model PKR251 FRG. Each device is a COTS unit. The TRS has a pedestal and platform where the instruments were mounted side by side. The RGA was located at the center of the table and the SIG and FRG were off to either side as shown in FIGURE 2 below. The platform rotated about an axis that intersected the RGA aperture center to remove parallax effects.

The SIG and FRG can be used in vacuum environments and were installed unmodified. The RGA was installed in a large aluminum canister that allowed its electronics to remain at atmospheric pressure. Heaters applied to the outside kept the units at favorable temperatures as the chamber went cold. Electrical feedthroughs through the chamber wall supplied power and data links for the instruments, TRS, lights, and camera. Both original and commercial software were used to command instruments and collect data.

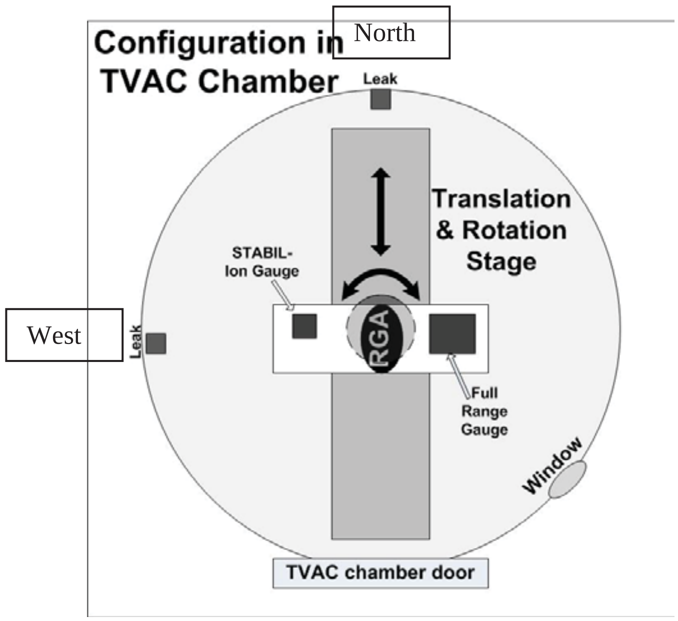


**FIGURE 2.** Configuration of instruments and ground support equipment in the thermal vacuum chamber.

A source manifold external to the TVAC chamber controlled the introduction of gas into the chamber for the ALL components to sense. Manifold valves were uncalibrated, so higher leak rates were measured approximately by weight loss over time.

Tests were performed with dry nitrogen, water vapor, and vapor from a strong $NH_3$ solution. Facility lines provided the dry nitrogen, and aluminum canisters supplied vapor from either liquid water or ammonia solution based on room temperature equilibrium vapor pressure levels (~20 °C). Each was piped individually through the leak source manifold and chamber feedthroughs to either the north or west source for various runs.

Since the TVAC chamber shrouds could only be cooled to 100 K using the facility's $LN_2$ cooling system, only the water vapor and $NH_3$ solution gases could be condensed effectively. Introduction of noncondensable molecular nitrogen sources were used to demonstrate a level of agreement between test equipment and facility pressure measurements.

## Tests Performed

Leak source types and rates simulated a variety of scenarios ranging from approximately 10 $lb_m$ per year to 1 $lb_m$/day. Discussion will be somewhat condensed and abridged, due to project exigencies in providing the flight hardware and due to the fact that the data reduction effort is still currently underway.

# RESULTS

## Axial Source Measurements (2013)

Figures 3 & 4 demonstrate the ability of the RGA to distinguish a wide range of pressure variations spanning many orders of magnitude against a facility chamber background pressure measurement of approximately $1.0\times10^{-5}$ Torr dominated by air constituents. The contour maps depicted in these figures relate experimental RGA measurements of $NH_3$ and $H_2O$ from an overall source rate of approximately 1 $lb_m$/day in a single run using the north leak source in May 2013. These maps were created by moving the TRS to each of the angles and distances indicated in increments of 20° and 25 cm, respectively, from -100° to 80° and 0 to 175 cm along the TRS axes.

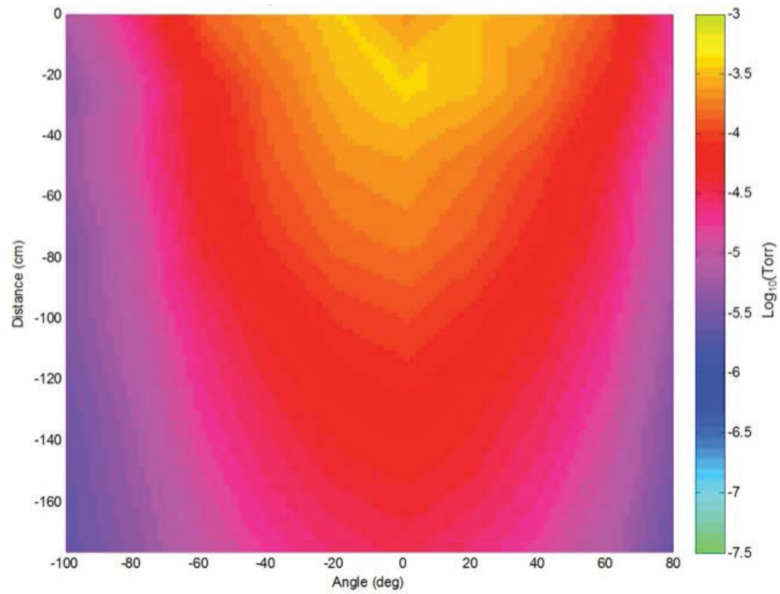


**FIGURE 3.** RGA measurements, axial source measurement, $NH_3$ @ 1 $lb_m$/day.

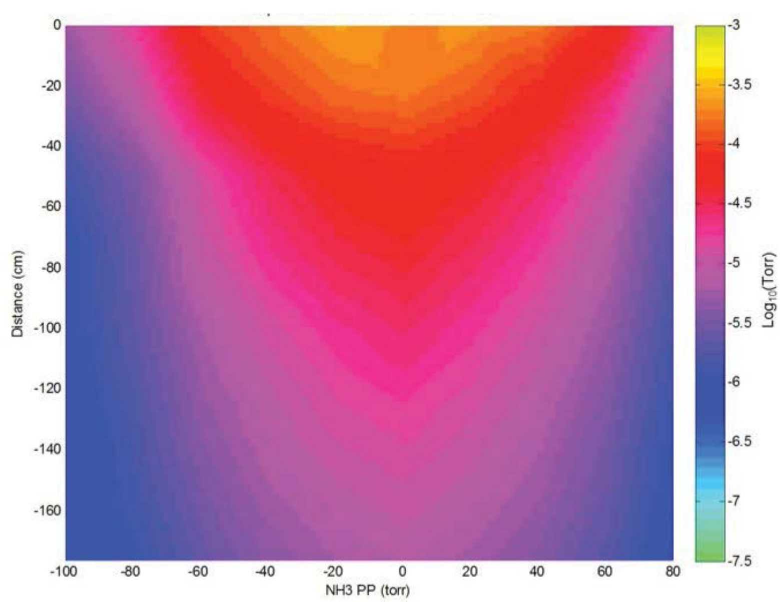


**FIGURE 4.** RGA measurements, axial source measurement, $H_2O$ @ 1 $lb_m$/day.

The source was located approximately 35 cm ahead of the stage's forward translation limit and about 3 cm east of that axis. It was also located about 8 cm above the RGA aperture center. In addition, its orientation was about 5° above the horizon and 5° eastward. These points of detail help explain slight asymmetries observable in the figures. It is also evident in these figures that the variation of intensity with angle at a given position is steeper than cos$\psi$.

## Axial Source Comparison (2014)

During the May 2104 test setup, a series of measurements were obtained with better alignment of the north and west sources with the TRS translation and RGA centerline, using water vapor alone. One particular test run using the north source was compared to the plume model, which gave good agreement with a model rate of about 47 $lb_m$/yr assuming sonic conditions, given that the hard sphere Knudsen number $Kn$ = 0.02 based upon the source orifice diameter (Fig. 5). Facility chamber pressure was approximately $8\times10^{-6}$ Torr and again chiefly consisted of air constituents.

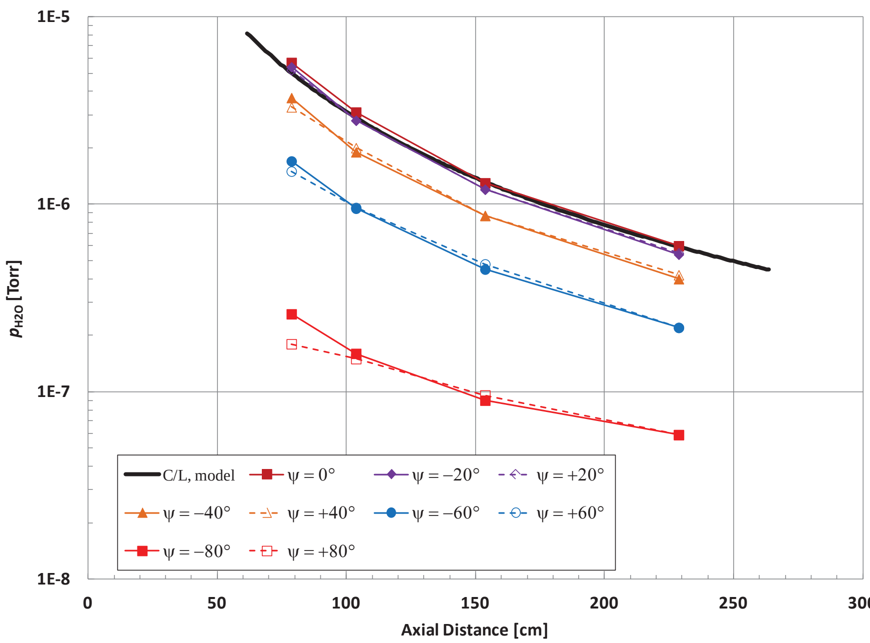


FIGURE 5. Comparison of model centerline pressure variation with water vapor test data, $\dot{m}$ = 47 $lb_m$/yr.

RGA measurements tend to a dependence more sensitive than $1/r^2$ as the north source is approached, but this may be a scattering effect. A portion of the instrument platform extended ahead of the instruments. This section was covered with insulating blankets in an attempt to make it a condensing surface, but ionizing filaments may have produced local heating effects that allowed some platform surface scattering to occur.

One development observed during this and other RGA measurements using the axial source was that necessary safety features of the device's ionizer section geometry led to a steep dependence on capture angle $\psi$ that deviated from cosine behavior. This effect will need to be compensated for when the ALL device is used on orbit.

## Transverse Source Comparison (2014)

The leak manifold transferred the gas from the axial north source to the transverse west source at the same flow rate setting. The RGA then took measurements at similar locations along the TRS translation axis with rotations ranging from -90° to +10° off this axis, where negative angles tended to face the RGA aperture towards the transverse source. The setup emulates an operation where the ALL is translated across a suspect surface in a plane containing a leak.

Attempting to divide out the non-cosine dependence on capture angle $\psi$ produces measurements of the free expansion of such a source (see Eq. 3). Data reduction efforts are still in their early stages at this time, but results for various RGA pointing angles and locations along the translation axis produced the data presented in Fig. 6 below.

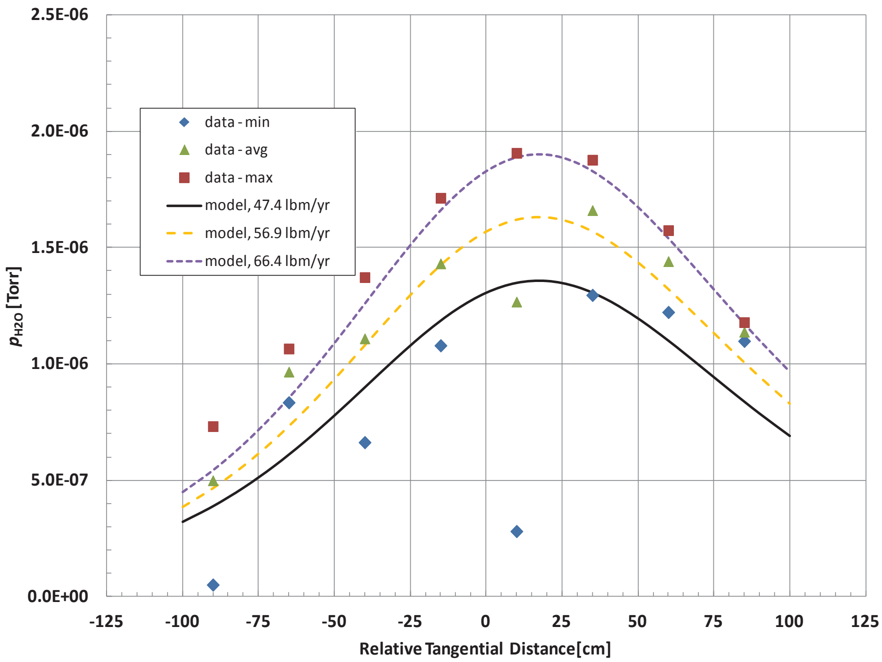


**FIGURE 6.** Plume model comparison against adjusted measurements of a water vapor free expansion.

Assuming the same strength point source sonic plume of water vapor at 47 $lb_m$/yr facing the side of the translation stage from 1.5 m away, but canted at a clockwise angle of 10° in the figure, led to the curve represented by the solid line. Increasing the model source rate by 20% & 40% leads to the dashed lines in the figure. All of these seem to provide a fair level of agreement with the range of measured values. Also, they appear to capture the curvature exhibited by the data. The model indicates sensitivity in this curvature based on relative distance from the source location as well as the assumed speed ratio *s*.

At this time it is not clear why higher mass flow rates fit this data better, unless the uncalibrated leak manifold produced lower levels of flow resistance when the water vapor was directed from the axial source to the transverse one. Also, it is not clear why the data exhibit a 10° cant angle not apparent in test setup measurements. It may be that some water vapor froze at the west source exit, changing the orifice geometry to produce this effect. It is also possible that the bracket and stand supporting the transverse leak experienced thermally-induced mechanical stresses when subjected to the 100 K TVAC shroud.In any case, a plume model contour map was produced to show the approximate intersection of the RGA path with water vapor flowing from this source through a sonic orifice (Fig. 7).

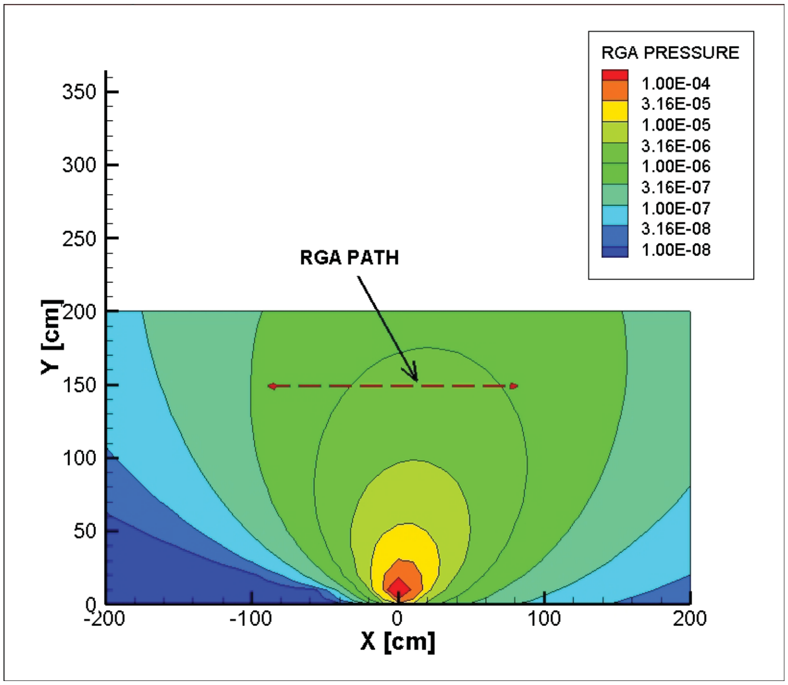


**FIGURE 7.** Approximate intersection of RGA path with the west leak based on plume model.

## CONCLUDING REMARKS/FUTURE WORK

The COTS RGA unit performed well and displayed both sensitivity and directionality to leak sources in the TVAC chamber.Sources of water vapor and ammonia were measured with partial pressures orders of magnitude below the overall chamber pressure. The variation of measurement sensitivity with capture angle $\psi$ did not exhibit cosine dependence, and this effect will need to be compensated for when developing testing and operational plans once at the ISS. Compensated data using the transverse source produced free expansion estimates that were easily fairly well reproduced using the plume model advocated by this group.

Test results helped prove the viability and usefulness of such an instrument configuration for on-orbit leak detection at ISS. After these tests, the Ammonia Leak Locator was selected to be a flight project jointly developed by NASA GSFC and NASA JSC. The flight instrument combines the SRS RGA and a Pfeiffer FRG, and is currently undergoing further environmental testing at GSFC in preparation for a handoff to the ISS office at JSC. Another effort is underway to devise a detailed on-orbit test plan for demonstrations once the ALL has been delivered to the ISS.

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