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

Michael Woronowicz [a], Joshua Abel [b], David Autrey [c], Rebecca Blackmon [a], Tim Bond [d], Martin Brown [a], Jesse Buffington [d], Edward Cheng [e], Danielle DeLatte [f], Kelvin Garcia [g], Jodie Glenn [c], Doug Hawk [b], Jonathan Ma [e], Jelila Mohammed [g], Kristina Montt de Garcia [g], Radford Perry [g], Dino Rossetti [e], Kimathi Tull [h], Eric Warren [c]

[a] *Stinger Ghaffarian Technologies, Inc*

[b] *ATK*

[c] *Wyle STE Group*

[d] *NASA Johnson Space Flight Center*

[e] *Conceptual Analytics*

[f] *ASRC Federal Space & Defense*

[g] *NASA Goddard Space Flight Center*

[h] *Jackson and Tull*

presented by

Prof. Chunpei Cai

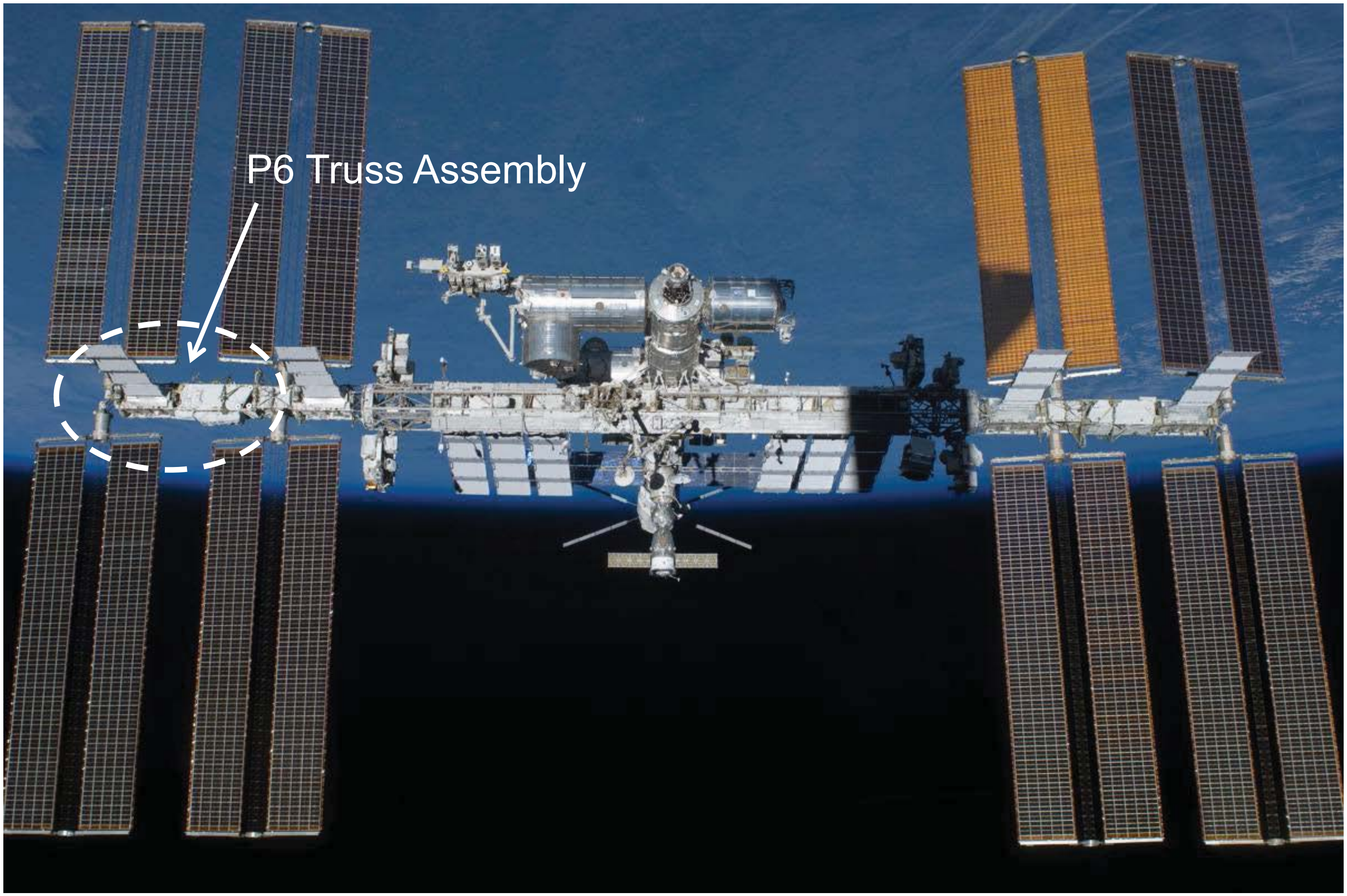
New Mexico State University

Outline

- Introduction
- Analytical Approach
- Instrument Features
- Discussion of Similar Spaceflight Applications
- Test Setup
  - Configuration
  - Types of leak sources
- Results
  - Selected case measurements
  - Model comparison

Introduction

- International Space Station (ISS) program officials have long been considering ways to locate external gaseous leaks from various sources
  - NH_3 from radiator assemblies
  - Air from crew compartments
- Crew members have performed two unplanned spacewalks since October 2012 to isolate NH_3 leaks from a Thermal Control System on the P6 Truss Assembly


P6 Truss Assembly

Introduction (3 of 3)

- ISS program is developing a robotically-operated leak locator tool featuring commercial off-the-shelf (COTS) units
  - Residual gas analyzer (RGA) for partial pressure measurements
    - Faint, distant, below ambient environment (10-10^3 lb_m/yr.)
  - Full range gauge (FRG) for total pressure measurements
    - Robust, proximal, above ambient environment (10-50 lb_m/day)
  - Called the Ammonia Leak Locator—ALL
- ALL would be positioned, oriented in various ways near suspect surfaces, use data to determine leak locations
- Test activity focus
  - Sensitivity (minimum detection level, directional influence)

Objective

- Compare RGA performance during ground testing to results from analytical plume model
  - Assess suitability for providing model predictions during on-orbit operations to assist with leak location

Source Behavior

- External neutral gas phase sources on ISS result from a number of different physical mechanisms
  - Supersonic expansion through thruster nozzles
  - Pressure-driven acceleration to sonic conditions across an orifice
  - Surface evaporation (may or may not have bulk velocity)
  - Effusion ($M = 0$)
- Effusion also often describes equilibrium gas conditions at rest
  - e.g. flux to a surface within a vacuum chamber
  - Mass flow rate $\dot{m}$ and pressure related by Hertz-Knudsen equation

$$\dot{m} = \rho A \sqrt{\frac{RT}{2\pi}} = \frac{pA}{\sqrt{2\pi RT}}$$

Plume Model Description

- Can consider modeling this regime using free molecule flow
  - Collision rates fall rapidly with distance from source
  - Majority of self-scattering collisions occur when faster molecules overtake slower ones on similar trajectories from source
  - Center-of-mass motion remains unchanged during collision
  - Existence of collisions may not substantially alter plume distribution from free-molecule description
- Have demonstrated considerable levels of success with such an approach over a wide range of applications

Plume Model Formulation—Source

- Find particular solution to collisionless Boltzmann equation for source Q_1:

$$\frac{\partial f}{\partial t} + \boldsymbol{v} \cdot \frac{\partial f}{\partial \boldsymbol{x}} + \boldsymbol{g} \cdot \frac{\partial f}{\partial \boldsymbol{v}} = Q_1$$

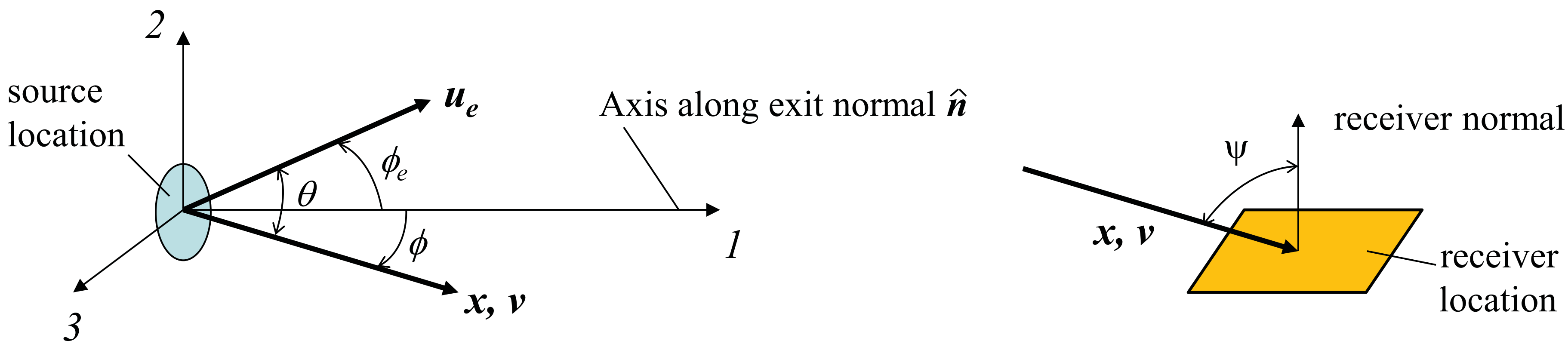
where Q_1 represents a Lambertian source superimposed on a bulk velocity

$$Q_1 \equiv \frac{2\beta^4}{A_1 \pi} \delta(\boldsymbol{x}) \dot{m}(t) |\boldsymbol{v} \cdot \hat{\boldsymbol{n}}| \exp\left(-\beta^2 (\boldsymbol{v} - \boldsymbol{u}_\mathrm{e})^2 \right)$$

and the normalization factor is given by

$$A_1 \equiv e^{-s^2 \cos^2 \phi_\mathrm{e}} + \sqrt{\pi}\, s \cos\phi_\mathrm{e} \left(1 + \operatorname{erf}\left(s \cos\phi_\mathrm{e}\right)\right)$$

Plume Model Formulation—Definitions



- Subscript *e* represents exit conditions from source
- Impingement angle with receiver surface given by ψ
- Simplifies for axisymmetric conditions
  - $\phi_e = 0$
  - $\phi = \theta$
- other definitions: $s \equiv \beta u_e = \dfrac{u_e}{\sqrt{2RT_e}}; \;\; w \equiv s \cos\theta$

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Plume Model—Steady Mass Flux

- Can compute many different types of local quantities at receiver position $\boldsymbol{x}$ relative to source
  - Steady mass flux given by

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

- RGA partial pressure measurements typically assume something akin to a vacuum chamber application where gas is at rest
  - Actually measures rate at which ions of a given mass/charge ratio successfully navigate quadrupole section after being ionized
    - This is a species-selected number flux, so mass flux equation is needed for the ALL device, not plume momentum flux
  - Mass flux converted to effective partial pressure using Hertz-Knudsen eqn.

ALL Device Sensitivity Considerations

- Expect ALL to distinguish leak constituents against backdrop of ambient environment
  - Atmospheric
    - Chiefly atomic oxygen (~10^{-8} Torr wake-oriented, > 10^{-6} Torr opposing ram direction)
  - Induced (less affected by ram vs. wake orientation)
    - Surface-desorbed, outgassed water vapor (typically < 10^{-8} Torr)
    - Outgassing of volatile condensable materials (polymerics, organics)
    - Discrete events like controlled venting and thruster firings
    - Strength depends on surface, source proximity, time on-orbit, *etc*.
- Review previous space flight mass spectrometer (MS), ion gauge applications
  - What issues do/did these instruments contend with?

Review of Previous Missions (1 of 3)

- Rosetta ROSINA Instrument Suite
  - Rosetta launched 2004, will rendezvous with comet mid-2014
  - ROSINA suite features sensitive mass spectrometers capable of high mass/charge ratio resolution
  - Capable of detecting species on the 10^{-11} mbar level or better
  - Suite location, orientation is fixed to the spacecraft
  - Attempted to measure interplanetary medium while on-route
    - Overwhelmed by spacecraft-induced atmosphere
  - Attempts to create direct flux and return flux mass transport models to reproduce measured effects have been unsuccessful

Review of Previous Missions (2 of 3)

- Mir Astra-2 Instrument Suite
  - Featured an experiment that used an ion gauge to measure the angular distribution of a small Ar cold gas thruster plume
  - Ion gauge mounted on arm ($r \sim 1$ m) that rotated on a pivot whose axis intersected the nozzle exit center, rotated through 135° arc
    - Always faced nozzle exit
  - At highest flow rate setting of about 1 g/s, could measure angular distribution over four orders of magnitude until surface outgassing effects obscured plume measurements beyond 90°
  - Broad plume core region not reproduced by various plume models or DSMC results; thought to have been the result of argon clustering

Review of Previous Missions (3 of 3)

- Materials Exposure & Degradation Experiment (MEDET)
  - Undertaken by a group of European research institutions
  - Exposed to ambient conditions external to the ISS Columbus module over 19 months
  - Ion gauge measured orbit-averaged impingement pressure levels of 10^{-7} to 5×10^{-6} mbar facing ram direction
  - Wake impingement levels were 100 – 1000× lower
  - Measurements made relative to free stream, not a point source

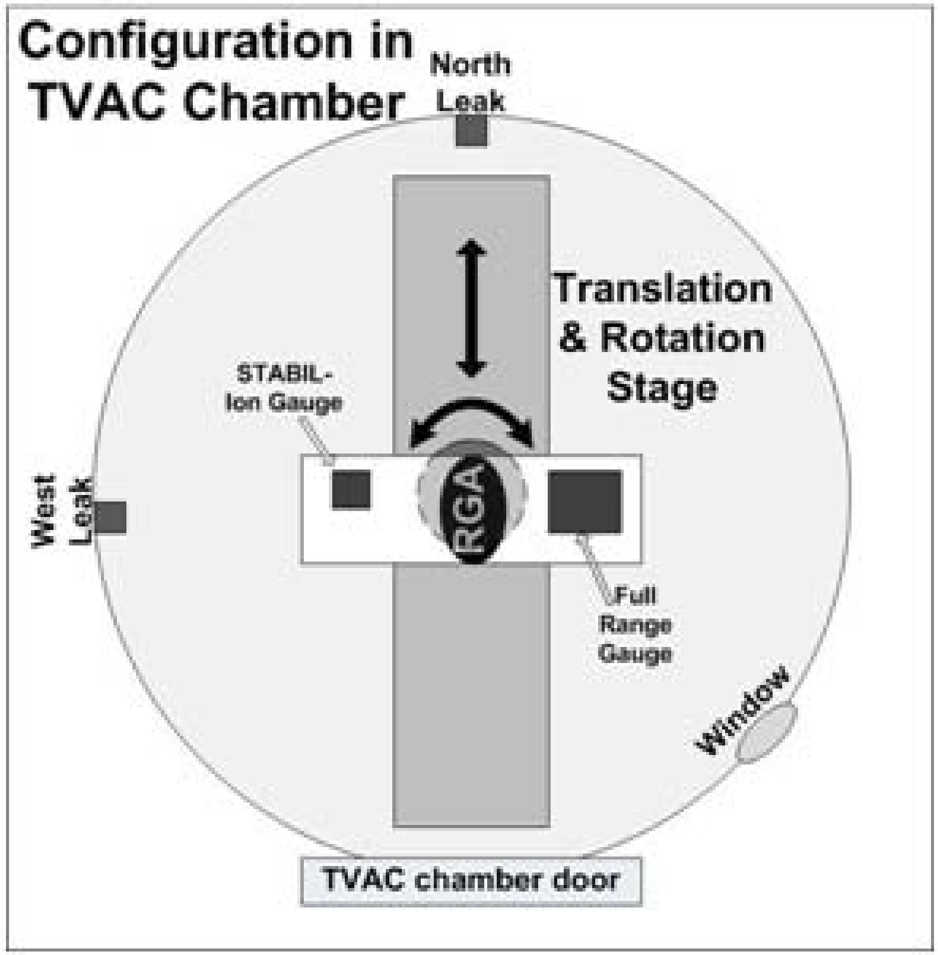
Leak Locator Configuration

- The ALL device operates without physical constraints of these example missions
  - Attached to robot arm, positions and orientations not fixed
  - Point source location not precisely known
    - *Raison d'être*—reason the device was created!
- Need plume model to understand measurements obtained
  - Make use of engineering test setup meant to demonstrate sensitivity of device concept for comparing results with plume model

Experimental Setup

- Conducted at NASA Goddard Space Flight Center
  - May 2013 and May 2014
- Used a large vertical thermal vacuum chamber featuring shrouds thermally controlled by gaseous or liquid N_2
  - Capable of reaching $T = 100$ K
- Special horizontally translating stage built with a platform that could rotate about the vertical axis
- A Stanford Research Systems Model 100 RGA was mounted with the ionizer tip passing through the stage's rotation axis
  - Canister enclosed electronics under atmospheric pressure
- To either side were mounted a STABIL-Ion gauge and a Pfeiffer Model PKR 251 full range gauge

TVAC Configuration



Experimental Setup (3 of 3)

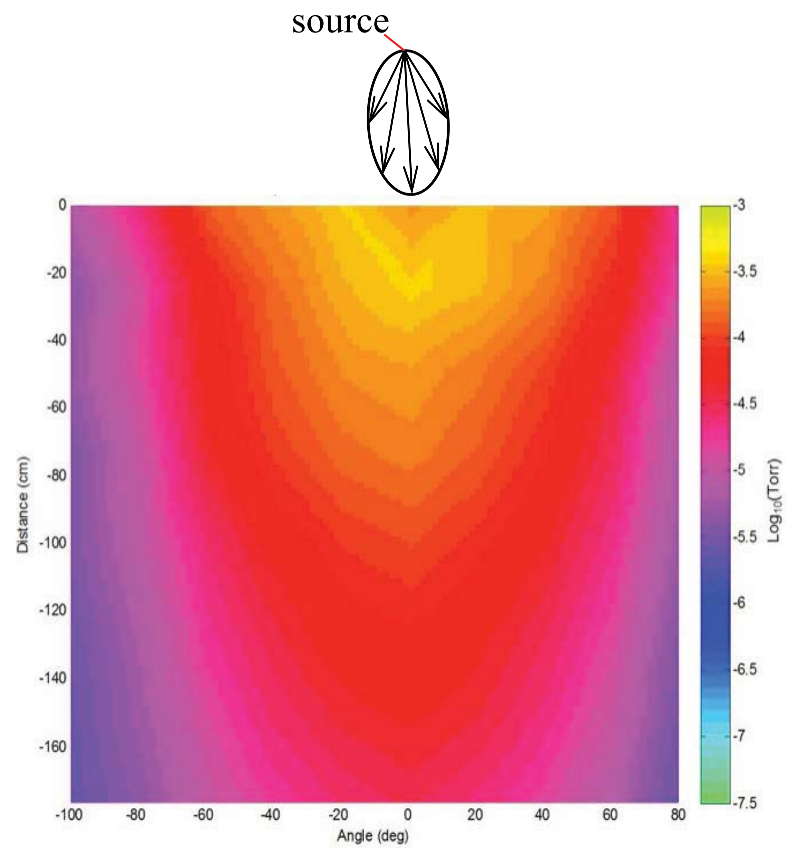
- A leak source manifold external to the TVAC chamber controlled introduction of gas to either of two orifices
  - North Leak (axial relative to translation stage)
  - West Leak (oriented transversely)
  - Leak tubing inside chamber insulated, thermally controlled with heaters
- Manifold valves were uncalibrated (engineering test consideration)
  - High leak rate test cases were measured by weight loss over time from source gas canisters
- Test gases included dry nitrogen, water vapor, and vapor from a strong ammonia solution
  - Vapor leaks driven by room temperature equilibrium pressure levels
  - N_2 used to observe level of agreement between test equipment and TVAC facility pressure measurements

Engineering Test Plan

- Leak source types and rates simulated a variety of scenarios
  - Ranged from approximately 10 lb_m/yr to 1 lb_m/day
- Stage translated to a series of set positions along translation axis
- At each position, platform was rotated through a set of angles
- Concentrated on observing RGA response in different modes
- Data reduction effort of most recent runs still underway

Results—Axial Source NH_3

- Early run contour map shows RGA partial pressure measurements on logarithmic scale based on
  - Stage location (vertical axis)
  - Rotation angle (horizontal)
- Source located ~35 cm "above" map
  - Not quite coincident with translation axis
- Mass flow rate ~ 1 lb_m/day
- Background pressure ~ 10^{-5} Torr



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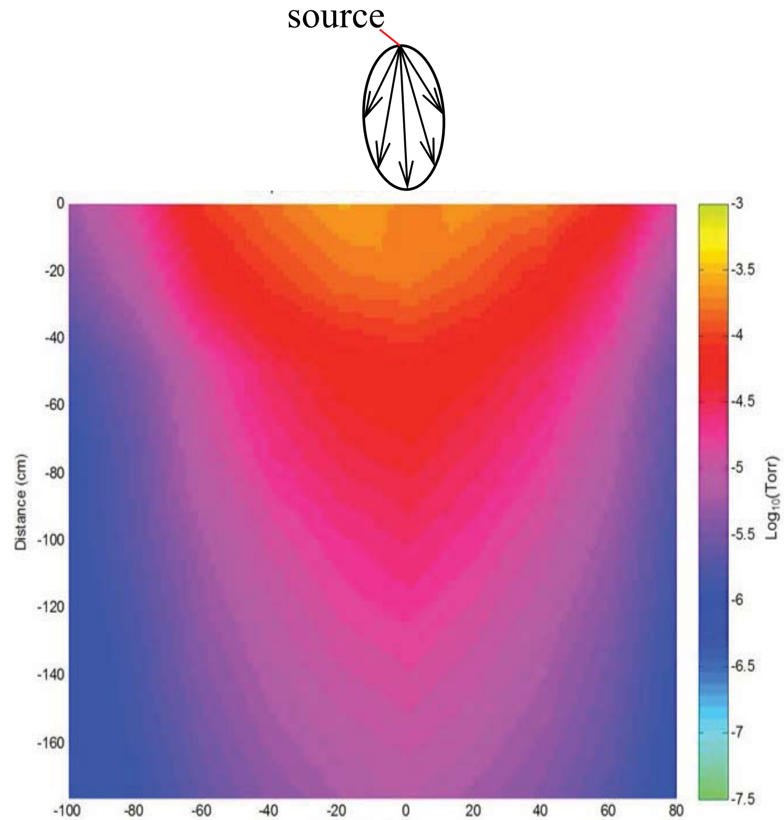
Results—Axial Source H_2O

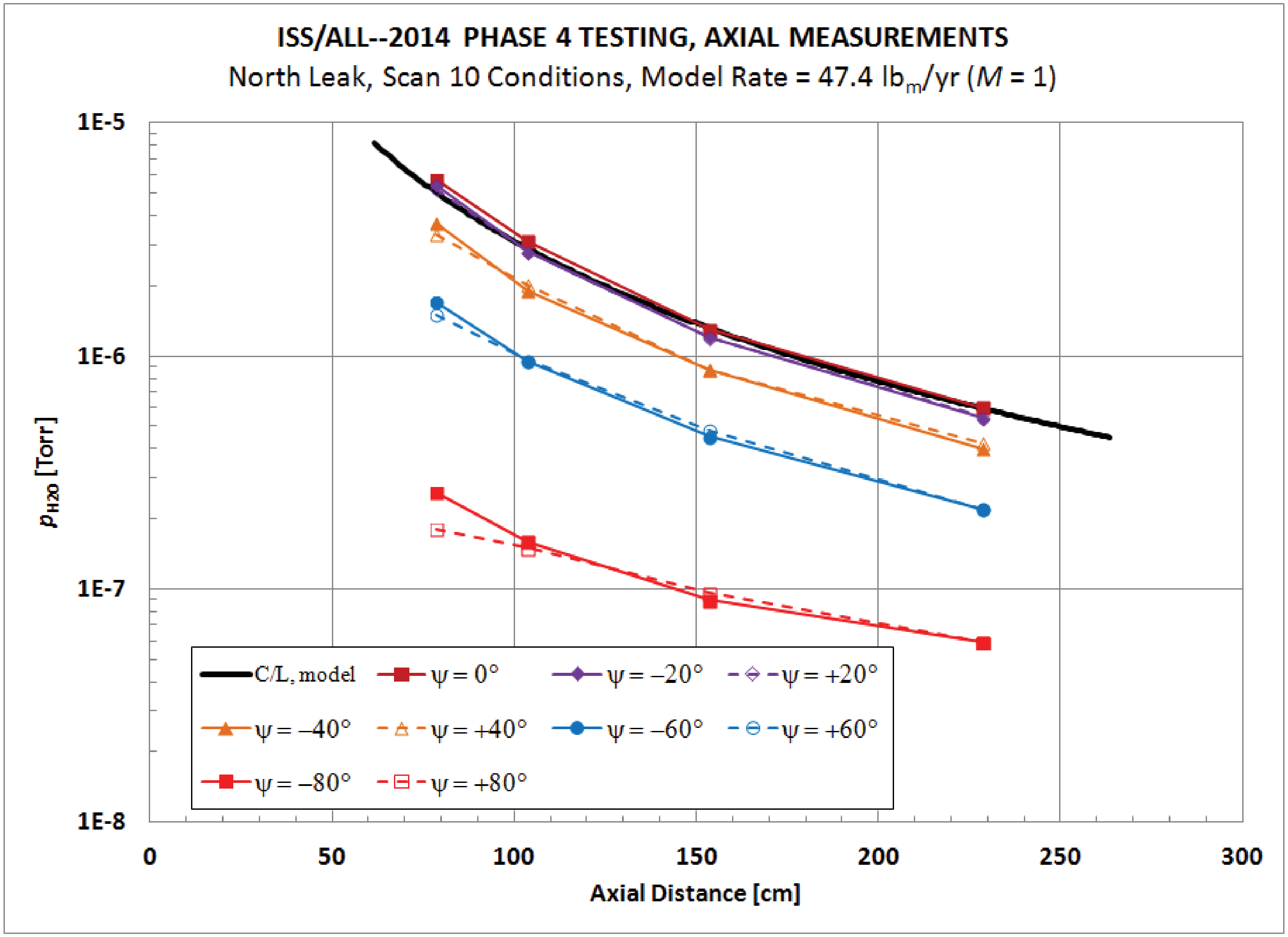
- Same ammonia solution leak source run of ~ 1 lb_m/day



Source Model Comparisons

- The following runs reflect a subset of data obtained during testing in May 2014
  - Better source alignment with translation stage axes than May 2013 testing
  - Worked with H_2O only due to NH_3 safety concerns
  - Data reduction effort ongoing
- In these runs, facility background pressure measured ~ 8×10^{-6} Torr
  - Chiefly air constituents with chamber shrouds operating around T = 100 K
    - Detected with facility RGA as well as by test unit
  - Model mass flow rate of ~ 47 lb_m/yr, Kn = 0.02 based on orifice diameter

Axial Source Model Comparison



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Axial Source Comparison Comments

- RGA intensity tends to drop off like $1/r^2$ as expected
  - Slightly steeper as source is approached
    - Could be a scattering effect from portion of platform ahead of instruments
- Dependence on capture angle ψ steeper than cosine
  - Assorted safety considerations led to physical features that scatter incident gas at entrance to RGA ionizer section
    - Scattering effect dependent on ψ as well as azimuth angle rotating about RGA axis
  - Effect needs to be compensated for when devising on-orbit test plan

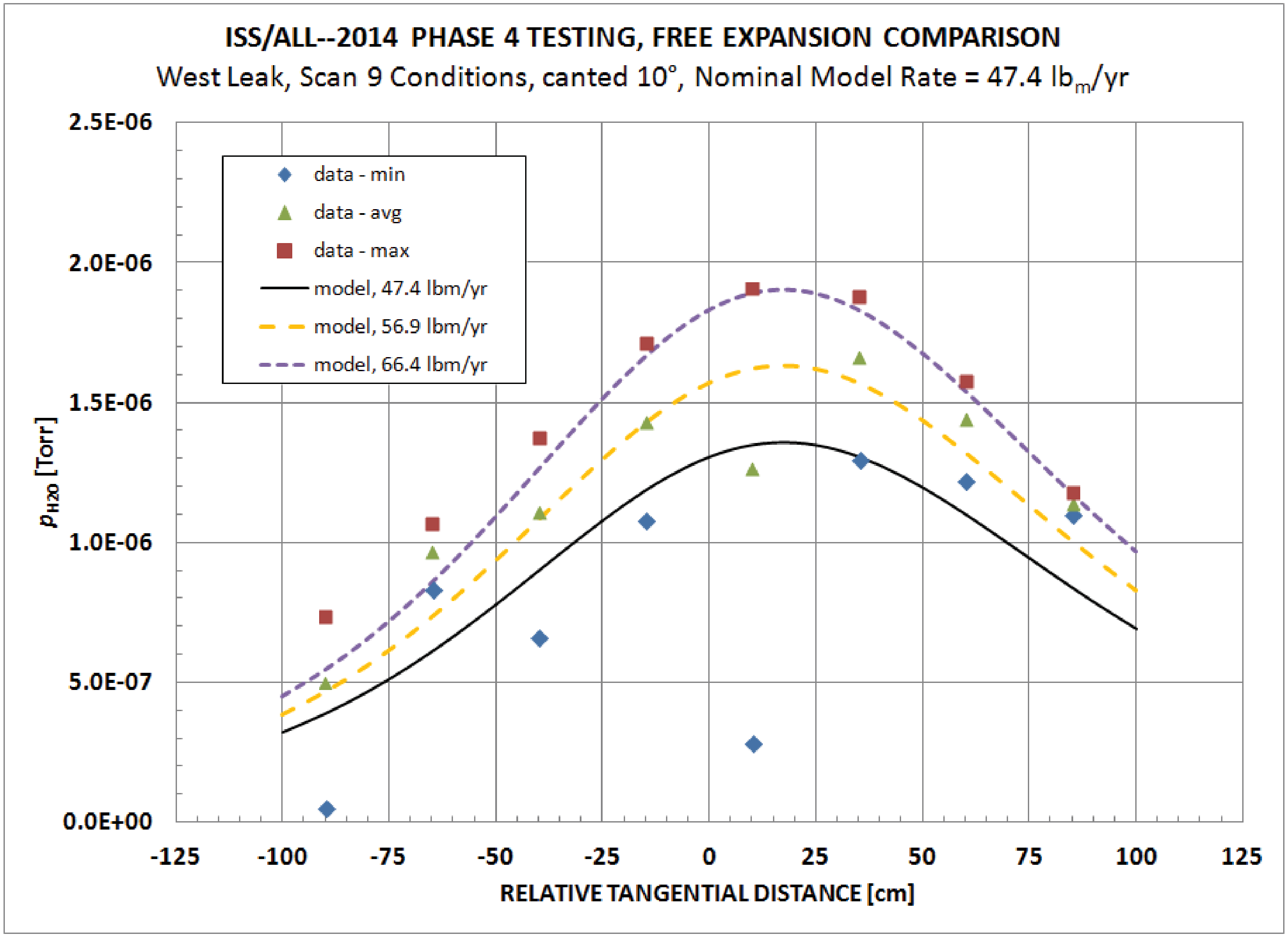
Transition Between Sources

- Leak manifold valves were manipulated to transfer the flow between source locations
  - Uncalibrated, so it is uncertain whether flow resistances and resulting rates should have been similar
    - Main test emphasis was to demonstrate source detection
- RGA then translated in 25 cm increments across range of motion
- At each stop, measurements were obtained at various platform rotation angles over a range of 100°
- Transverse source located ~1.5 m off of translation stage axis
- This setup emulates an operation where ALL is translated across a suspect surface in a plane containing a leak

Transverse Source Measurements

- Used axial run at same main valve setting to obtain ψ dependence
  - Measurements exhibit a fair amount of uncertainty not seen in axial run
  - Divide measurements to obtain estimates for free expansion of transverse plume
- Peak values apparently offset about 10° despite pre-test alignment
    - Thermally-induced mechanical stresses during cooldown?
    - Ice formed on orifice tip?
      - Less likely

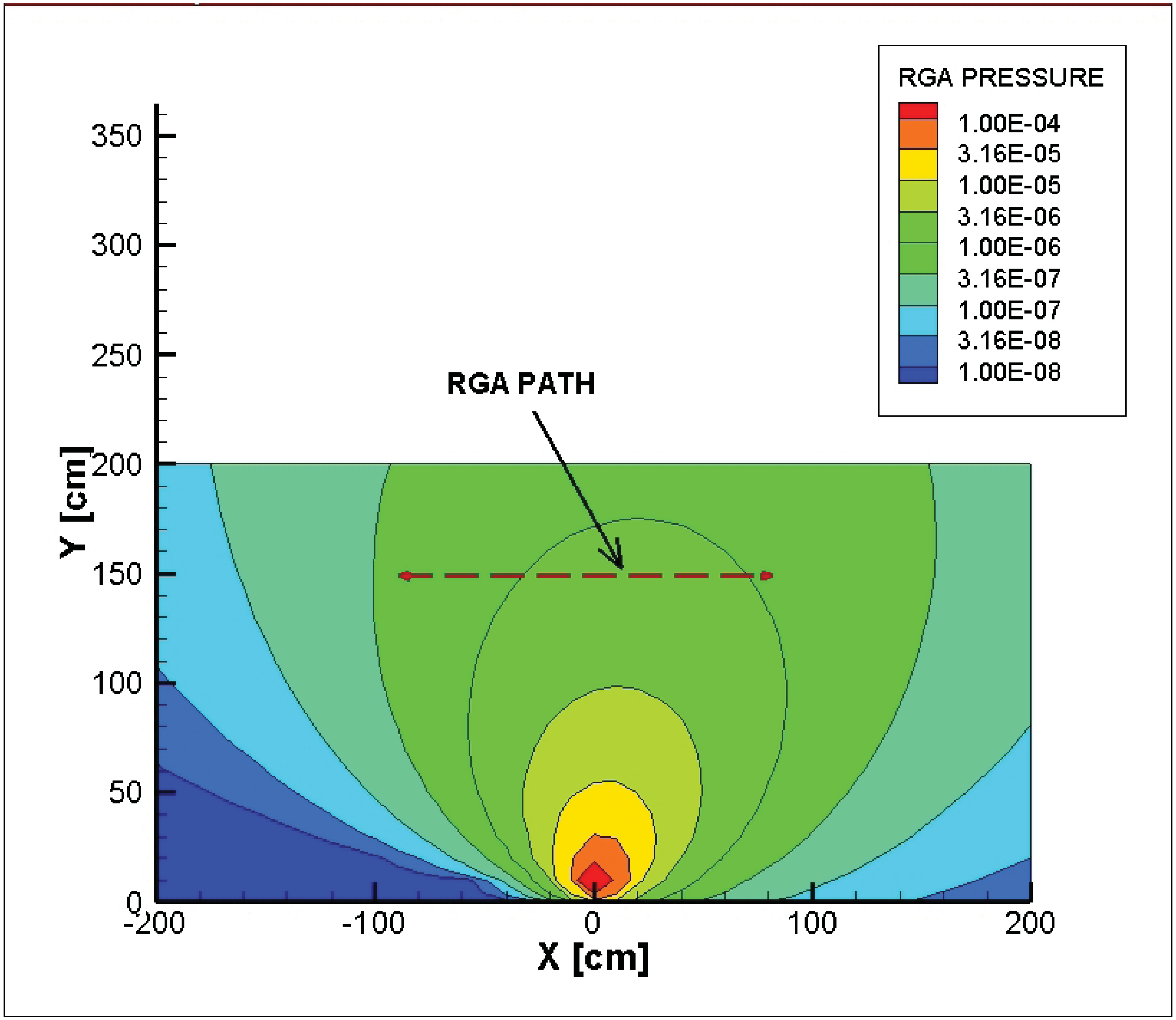
Transverse Source Comparison



Transverse Source Comparison Cmts.

- Model results calculated for same 47 lb_m/yr sonic orifice appear to fit lower range of measurements
  - Black solid line in both result figures
  - Same conditions but with 20% and 40% higher mass flow rates fit middle and upper ranges of RGA measurements
  - Model appears to capture curvature of source angle dependence also
- Can create model of approximate intersection of RGA path with transverse source plume

RGA Path, Plume Intersection Estimate



Concluding Remarks

- The COTS RGA unit performed well
  - Displayed desired levels of sensitivity to the intensity of faint leak sources
  - Demonstrated "directionality," or sensitivity to pointing angle
    - Non-cosine dependence will need to be accounted for when developing testing and operational plans at ISS
  - Sufficiently robust when adapted to high vacuum and extreme thermal environments
- Plume model did a reasonable job of reproducing test conditions for axially and transversely located sources
- The ALL device has been selected to demonstrate its capabilities at the ISS

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