

# A Review of 0-G and Low-G Mass Gauging Technologies

Low-Gravity  
Slosh Workshop

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# A Review of 0-G and Low-G Mass Gauging Technologies

This review covers technologies that have been funded by NASA and are described in the public domain from the Apollo era onward\* to measure the mass of propellant in a flight tank under low to zero G conditions.

It does not represent a complete literature review, nor does it include proprietary material. Most of the technologies described include links to source material.

The emphasis will be on cryogenic fluids.

\*When looking for an aerospace solution to almost any problem, start with Apollo.

# A Review of 0-G and Low-G Mass Gauging Technologies

## Outline:

### Recent NASA funded low-G mass gauging activities:

1. Capacitive Mass Gauging
2. Radio Frequency Mass Gauging
3. Spectral Mass Gauging
4. Modal Propellant Gauging

### Older NASA funded low-G mass gauging approaches:

1. Resonant Infrasonic Gauging System (RIGS)
2. Volumetric Modulation
3. Pressure-Volume-Temperature
4. Thermal Gauging
5. Nucleonic

# A Review of 0-G and Low-G Mass Gauging Technologies



A long cylindrical capacitance liquid level gauge being installed.

Linear Capacitance Probe (not appropriate for low-G). Used on Saturn V, Centaur Upper Stage (1968-1990), Apollo LEM, Space Shuttle OMS tanks and Ariane 5 first and second stages.

Requires access to the inside of the tank and works well under significant acceleration. However, at low-G, capillary forces can cause fluid to climb up the cylinder, yielding an incorrect mass reading.

Some researchers have worked to extend the success of the cylindrical capacitor, by placing multiple electrodes inside of a tank to provide more measurements.

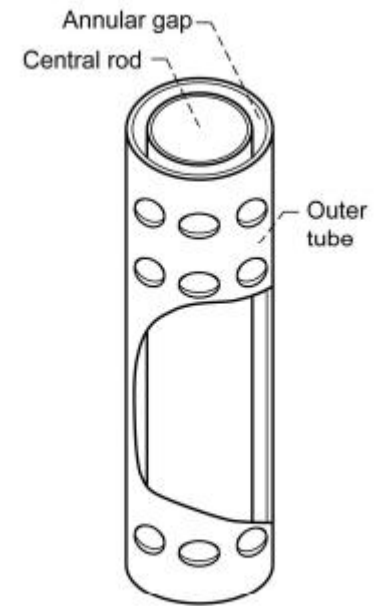


Figure 2.2 Schematic of cylindrical capacitance probe with perforations.

[Propellant Mass Gauging: Database of Vehicle Applications and Research and Development Studies - NASA Technical Reports Server \(NTRS\)](#)

# A Review of 0-G and Low-G Mass Gauging Technologies

## #2a. Multi-Element Capacitance Gauging (Tomography)

One approach is capacitance tomography, where multiple capacitance measurements can be used to yield an image of the 3-D mass distribution. Integrating this yields the mass.

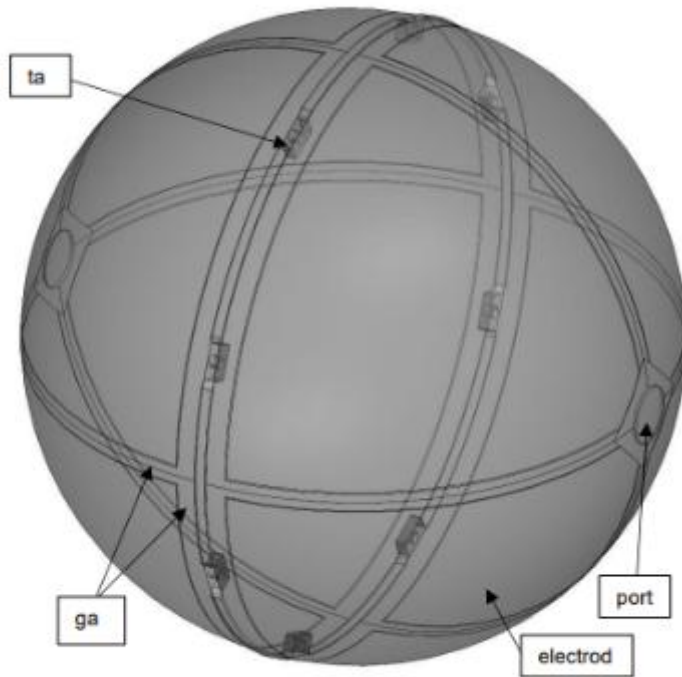


Figure 2 Tank Internal Volume CAD, translucent

Spherical Tank with 8 electrodes.

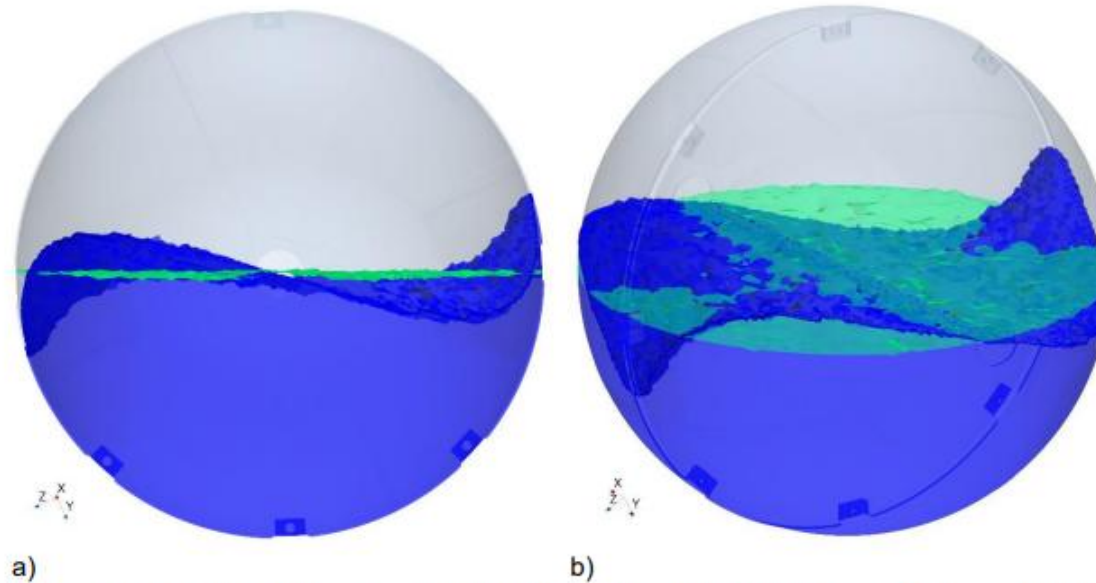


Figure 27 LBP Liquid Volume Reconstruction from 50% NVF Ground Test: a) View 1, b) View 2  
LBP reconstruction in blue, actual surface in green.

Zero-G parabolic flight tests using a surrogate fluid yielded maximum transient errors of 1.6% defined relative to a full tank.

[Propellant Mass Gauging in Microgravity with Electrical Capacitance Tomography - NASA Technical Reports Server \(NTRS\)](#)

Storey, Jedediah M.,  
Brandon S. Marsell,  
Michael T. Elmore,  
and Scott Clark.

"Propellant mass gauging in microgravity with electrical capacitance tomography." (2023).

# A Review of 0-G and Low-G Mass Gauging Technologies

## #2b. Multi-Element Capacitance Gauging (Without Imaging)

By placing multiple electrodes over the inside of a tank and then reading the capacitances between each capacitor, the total mass can be estimated directly without going through an imaging step.

A simplistic version was first demonstrated in 1967 for possible use on the Saturn V. Circuitry was developed and a small demo using RP-1 showed the concept, but the errors were large.

Lack of computer modeling and modern electronics limited the performance.

[19670025277.pdf](#)

Klopp, D. A., and J. C. Niehoff. "Capacitance propellant gaging study for orbiting spacecraft Final development report." *NASA Contractor Report* (1967): 25277.

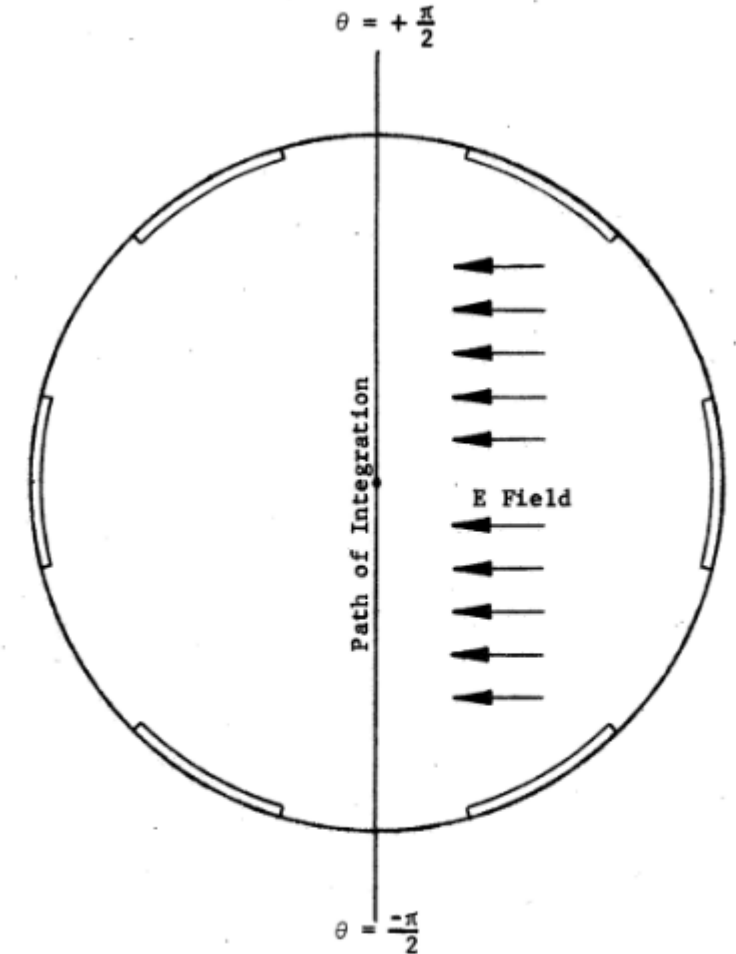
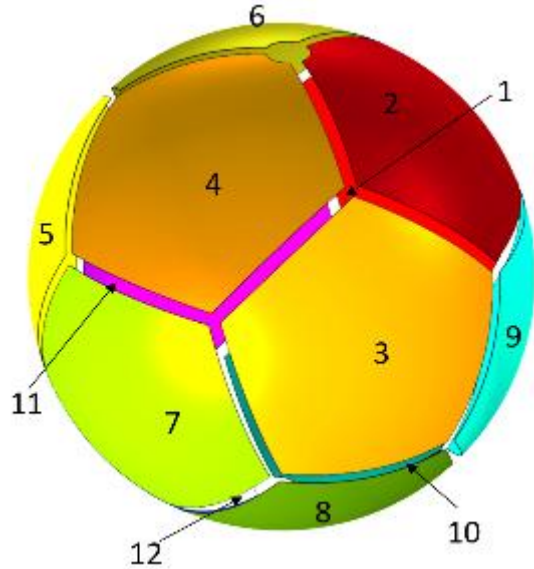
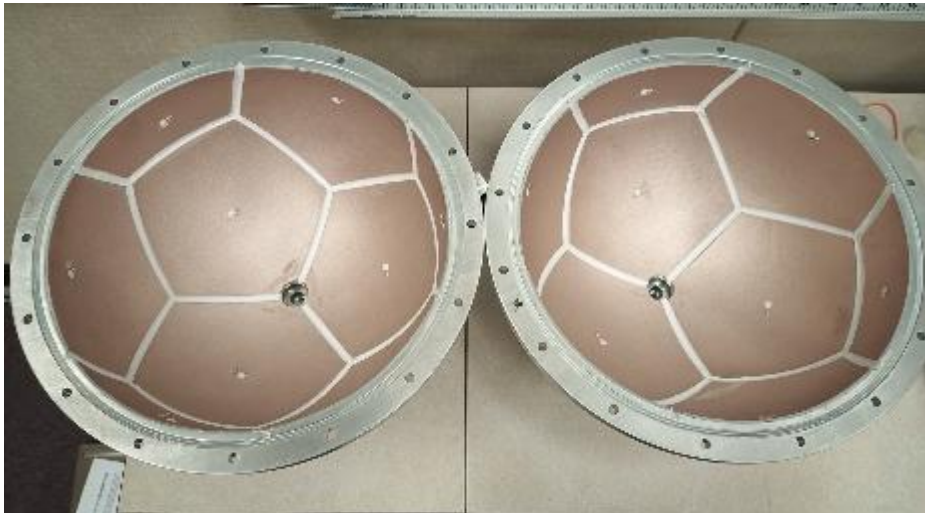


Figure III-1

Cross-Section of Tank Showing Path of Integration for the evaluation of Gauss' Integral.



12-electrode array on inner surface of 12" spherical tank (split into hemispheres)



## Concept of Operation

### 1) Measure all unique capacitances

$$C_{i,j} = \frac{Q_i}{V_j} \rightarrow \begin{array}{l} V_j \text{ is applied (i.e., fixed and known)} \\ Q_i \text{ is measured} \end{array}$$

$$\text{Number of unique capacitances} = \frac{n(n-1)}{2} \rightarrow 66 \text{ for 12 electrodes}$$

### 2) Combine unique capacitances to get mass fraction

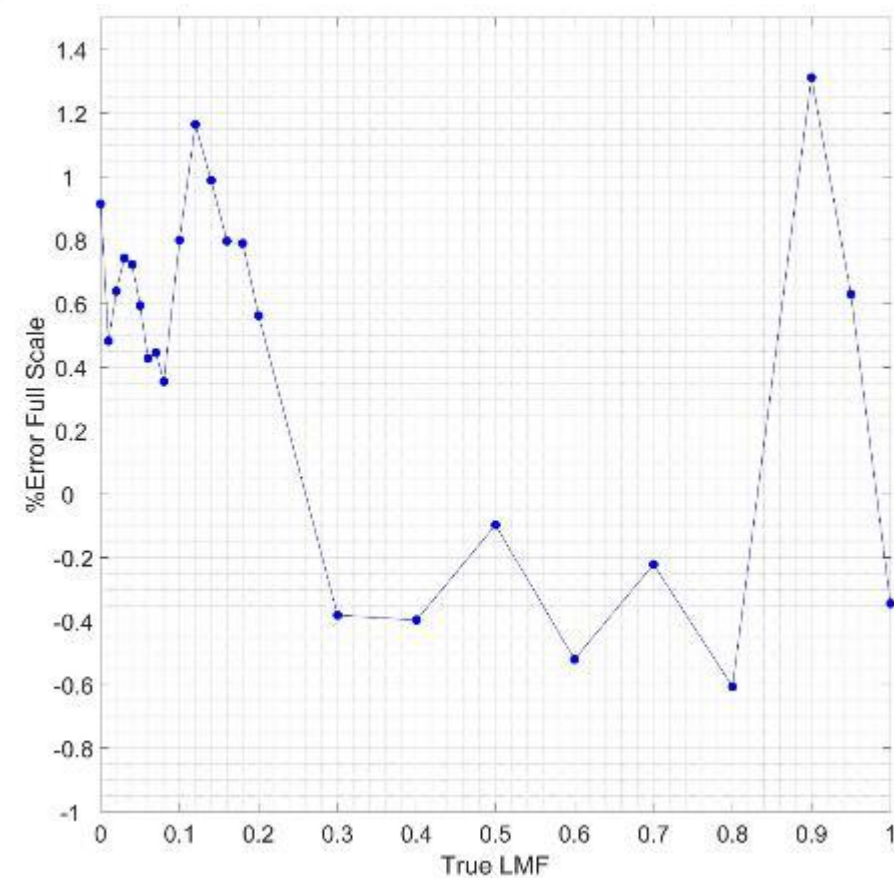
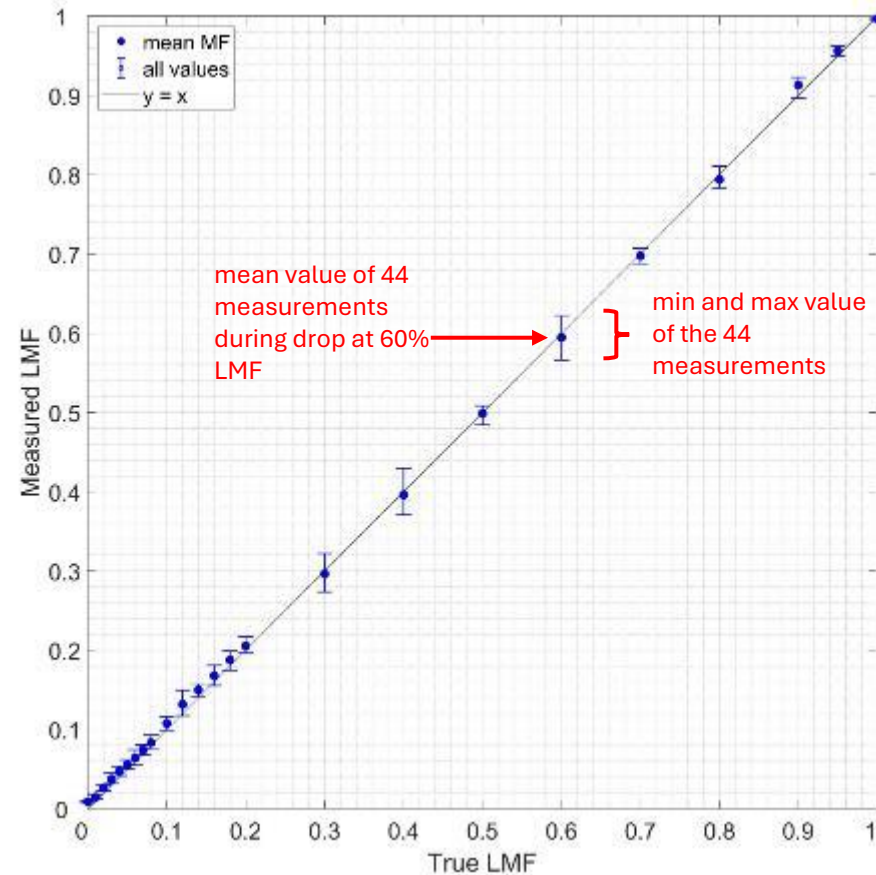
e.g., group capacitances by symmetry

$$F_p = \frac{W_a}{N_a} \sum_{i=1}^{N_a} C_{a,i}^{\alpha} + \frac{W_b}{N_b} \sum_{i=1}^{N_b} C_{b,i}^{\beta} + \frac{W_c}{N_c} \sum_{i=1}^{N_c} C_{c,i}^{\gamma}$$

e.g., deal with capacitances individually

$$F_p = \sum_{i=1}^N W_i C_i$$

weighting factors ( $W_a, W_b, W_c, W_i, \alpha, \beta, \gamma$ ) determined through optimization with test data set (either measured or modeled capacitances versus known fill fractions)

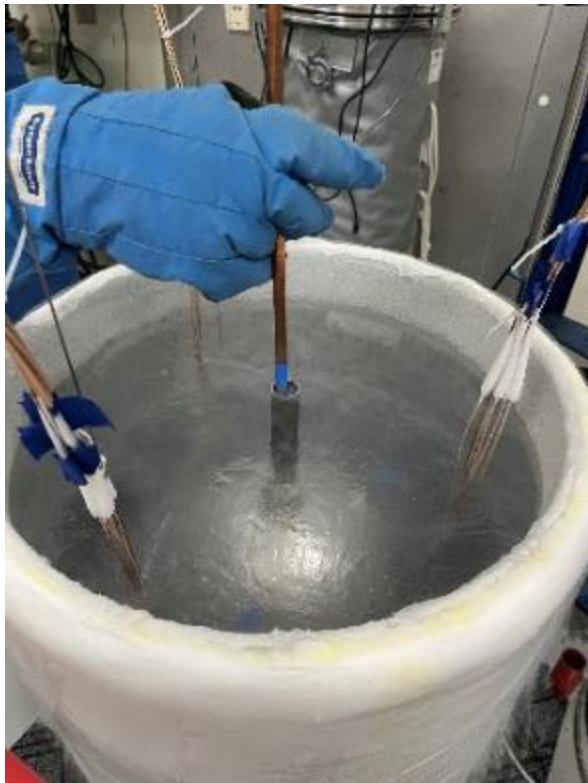
2.2-second drop experiments performed with mineral oil ( $\epsilon_r = 2.1$ )

- 2 drops for following liquid mass fractions (LMF): 0%, 2% to 20% in 2% increments, 10% to 90% in 10% increments, 95%, 100%.
- Each drop  $\rightarrow$  4.4 seconds of LMF measurements recorded at 10 Hz (44 measurements)
- Left plot: mean of 44 LMF measurements and range of individual measurements
- Right plot: Error of 4.4-second mean

## #2b. Multi-Element Capacitance Gauging (Without Imaging)

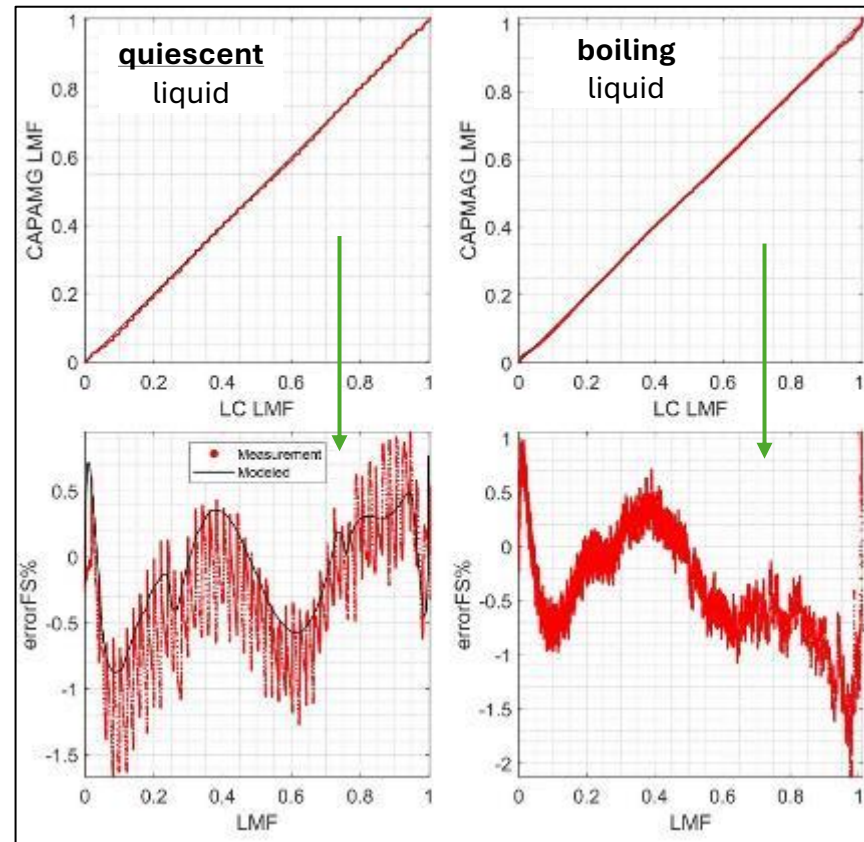
Slides from Dr. Biagi, KSC Applied Physics Lab.

Tank submerged in LN2 bath to attain **quiescent** fluid in tank. Tank is filled while submerged and chilled to 77K.



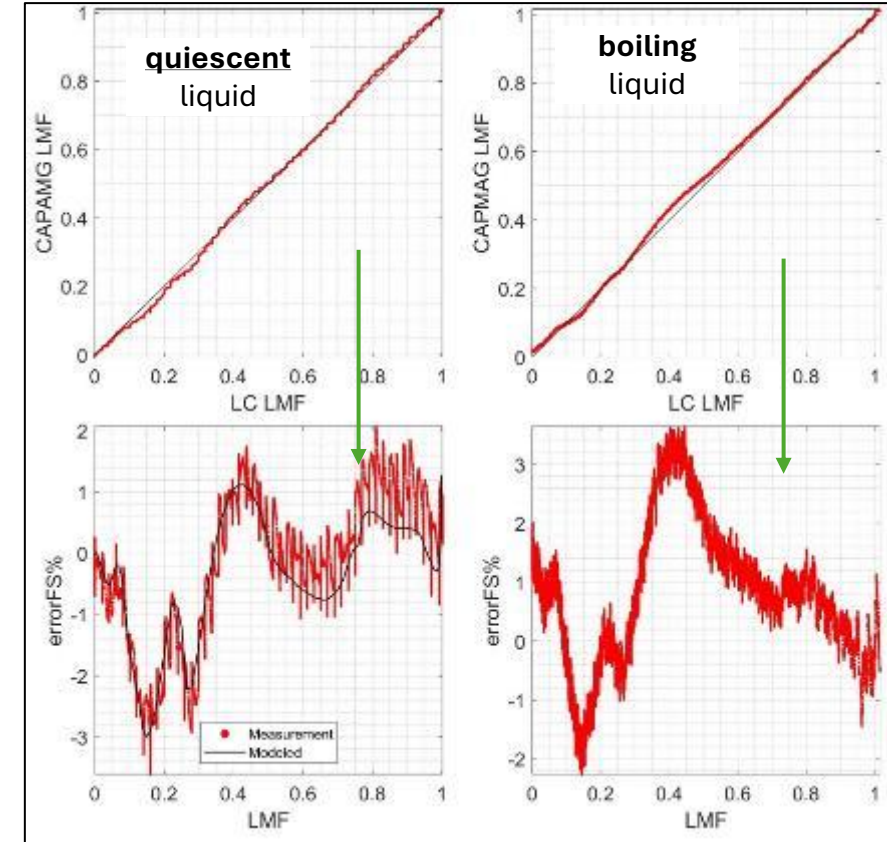
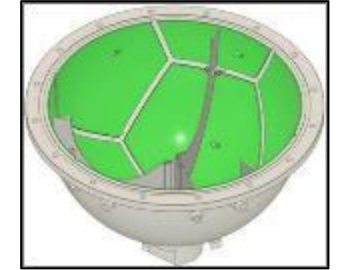
After it is full, it is lifted out of bath so that LN2 in tank vigorously **boils off**

Tank without vanes



**Top Row** CAPMAG versus Load Cell LMF ; **Bottom Row** Full-scale error in percent

Tank with metal vanes over bottom electrodes



# A Review of 0-G and Low-G Mass Gauging Technologies

## #2. Multi-Element Capacitance Gauging.

### Pros:

1. Current development indicates potential 0-G and cryogenic operation.
2. A direct measurement of material
3. Low Power,
4. Rapid results.
5. No moving parts.
6. Potential for 1% accuracy.

### Cons:

1. Requires electrodes covering the inside of the tank.
2. Not yet flight demonstrated.
3. May not perform well with LH2 due to its low permittivity.

# A Review of 0-G and Low-G Mass Gauging Technologies

In 1989 Ball Aerospace conducted a review of 0-G mass gauging concepts, ranking them based on potential accuracy, tank geometry restrictions, and development level. Six technologies survived elimination criteria.

| Concept                           | Score for Use in LOX | Score for Use in LH2 | Comments                                                                 |
|-----------------------------------|----------------------|----------------------|--------------------------------------------------------------------------|
| Radio Frequency Mass Gauging      | 575                  | 575                  | Highest score and developed further.                                     |
| Capacitance                       | 530                  | 530                  | Cylinders and plates. Multiple electrodes were not considered.           |
| Microwave                         | 505                  | 505                  | Linear density measurement but does not cover the full tank.             |
| Resonant Infrasonic Gauging       | 555                  |                      | Measure the resonant frequency of the ullage gas. Higher errors with H2. |
| PVT (Pressure Volume Temperature) | 540                  |                      |                                                                          |
| Gamma Radiation Attenuation       |                      | 510                  | Radiation hazard. (requires excessive energy for LOX).                   |

[19930003511.pdf](#)

Crook, Andrew J., and Robert A. Delaney. "Zero-gravity quantity gaging system." *NASA Contractor Report* (1989): 03511. Appendix B. Extensive literature search.

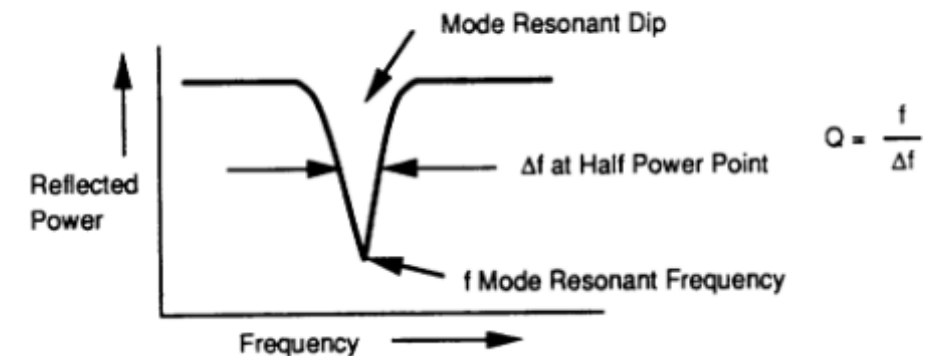
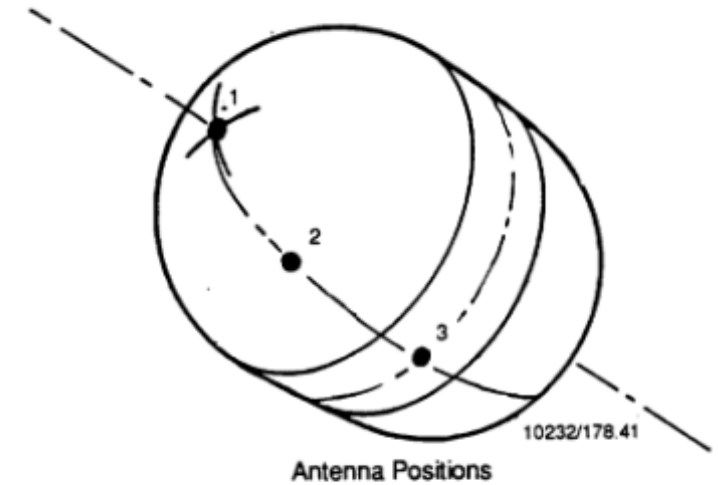
# A Review of 0-G and Low-G Mass Gauging Technologies

In the same report Ball Aerospace described a detailed study of Radio Frequency Mass Gauging (RFMG) (first demonstrated by Lockheed in 1966).

In their approach an antenna was placed into a tank and swept through the frequencies covering the four lowest transverse magnetic (TM) resonances.

They built demo tanks and tested with LN2, LOX, and LH2 (settled and random orientations). They tested with paraffin to simulate globules of liquid.

After developing algorithms, they achieved better than 2% mass measurement accuracy versus a full tank mass.

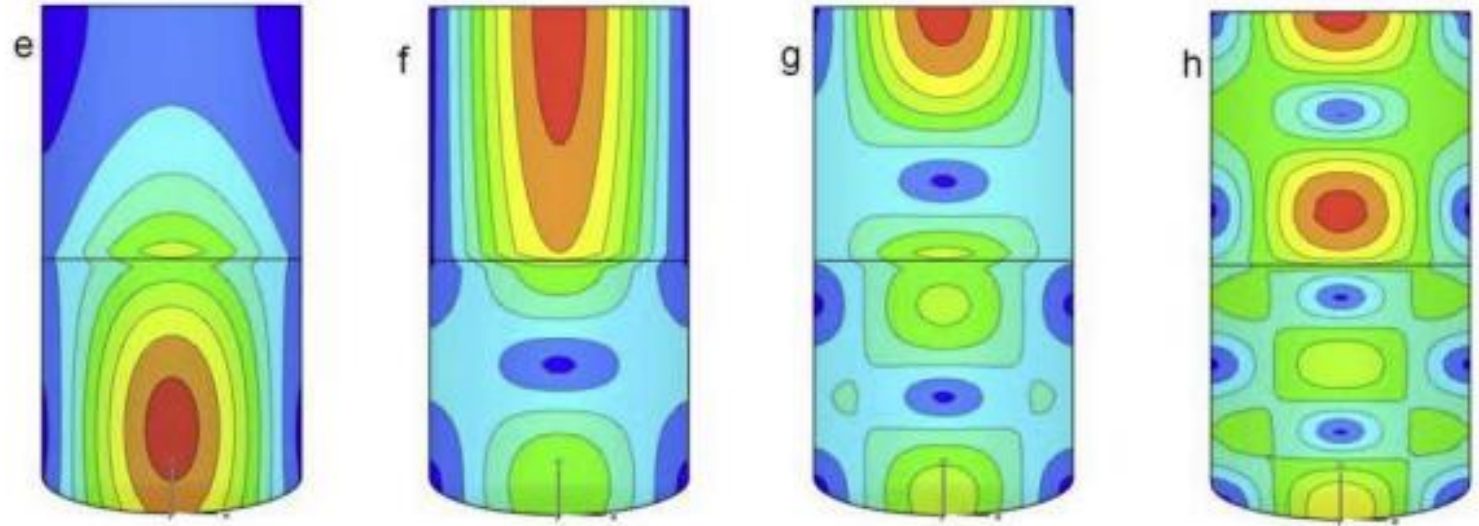


[19930003511.pdf](#)

Crook, Andrew J., and Robert A. Delaney. "Zero-gravity quantity gaging system." *NASA Contractor Report* (1989): 03511.

# A Review of 0-G and Low-G Mass Gauging Technologies

With the advent of computer modelling and advanced algorithmic analysis RFMG was advanced by a group at GRC (Zimmerli, et.al.)



Lowest four TM modes, 50% LOX in tank.

The GRC RFMG system was tested in parabolic flight in 2014, demonstrated on ISS Robotic Refueling Mission 3 in 2018, and scaled to large tanks in eCryo's SHIVER program in 2019/2020.

[19930003511.pdf](#)

Zimmerli, Gregory, Karl Vaden, Michael Herlacher, David Buchanan, and Neil Van Dresar. "Radio frequency mass gauging of propellants." In *45th AIAA Aerospace Sciences Meeting and Exhibit*, p. 1198. 2007.

# A Review of 0-G and Low-G Mass Gauging Technologies

An RFMG system was installed in the flight and flight-spare tanks of the Intuitive Machines lunar lander.

RF scanning occurred from 100 to 1300 MHz.

Over 10,000 antenna responses were generated and stored, acting as a database that the in-flight scans could be compared to determine the mass of propellant.

The system monitored LOX and liquid methane throughout the mission, including microgravity coast phases.



[2022 TDM Annual Review - RFMG for IM-CLPS 2022-03-02.pdf](#)

Hans Hansen and Greg Zimmerli, March 2022.

[E-20280 RFMG-IM Results.pdf](#)

Zimmerli, Gregory, David Fischer, Marius Asipauskas, Carol Kory, Scott Metzger, Andrew O'Connor, and Adam Rice. "Results From the Radio Frequency Mass Gauge Technology Demonstration on the Intuitive Machines Nova-C Lunar Lander." In *AIAA SCITECH 2025 Forum*, p. 0959. 2025.

# A Review of 0-G and Low-G Mass Gauging Technologies

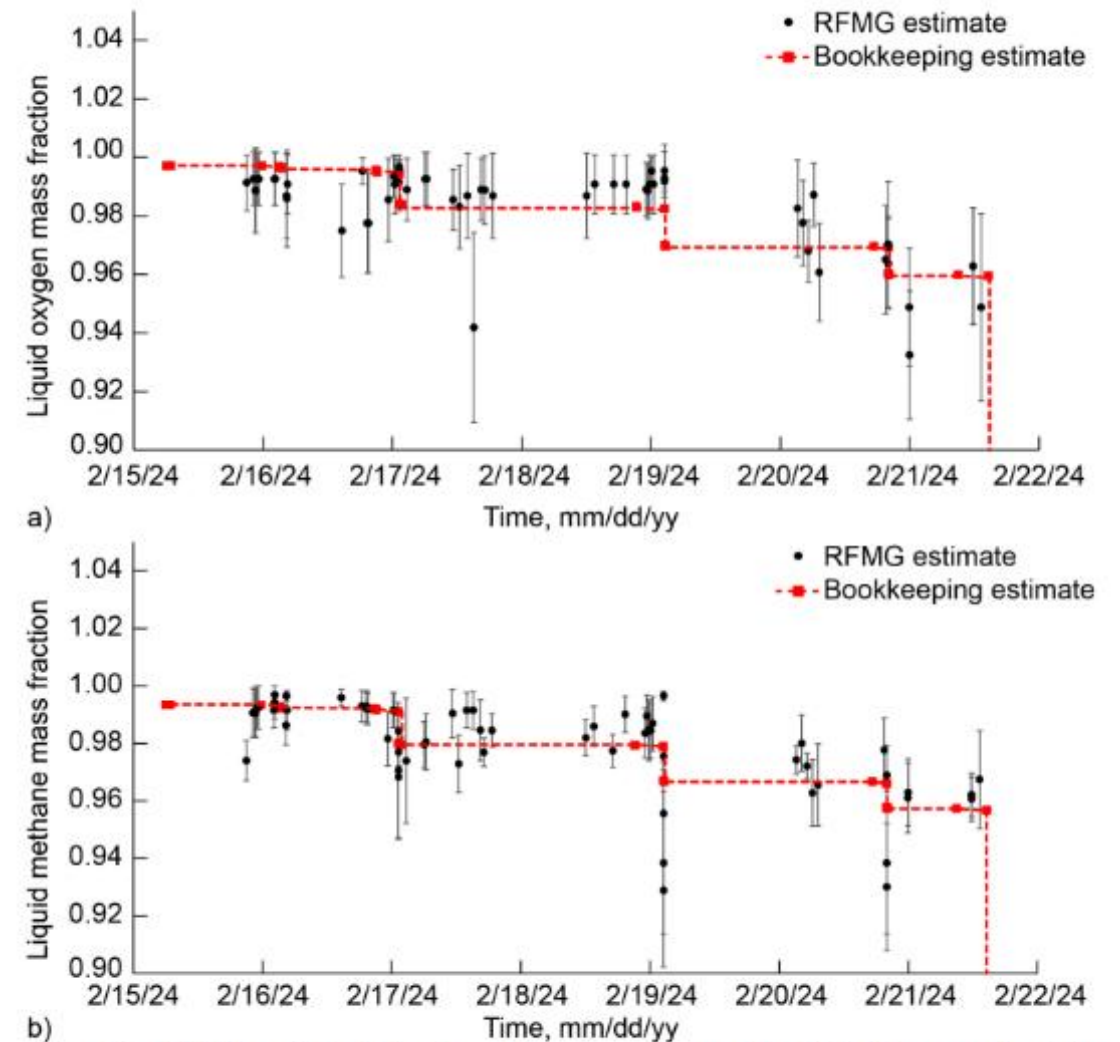
The RFMG system mass measurements on the Lunar Lander were within the bookkeeping estimates to about  $\pm 4\%$ .

Sources of error include:

1. Fidelity of the tank model.
2. Fidelity of the simulated tank spectra.
3. Insufficient fluid configurations modelled.
4. Resolution of the simulation libraries.

[E-20280 RFMG-IM Results.pdf](#)

Zimmerli, Gregory, David Fischer, Marius Asipauskas, Carol Kory, Scott Metzger, Andrew O'Connor, and Adam Rice. "Results From the Radio Frequency Mass Gauge Technology Demonstration on the Intuitive Machines Nova-C Lunar Lander." In *AIAA SCITECH 2025 Forum*, p. 0959. 2025.



**Fig. 11 RFMG and bookkeeping estimates of propellant liquid mass fraction during translunar coast. a) Liquid oxygen. b) Liquid methane.**

# A Review of 0-G and Low-G Mass Gauging Technologies

## #3: Radio Frequency Mass Gauging.

### Pros:

1. Demonstrated in-space and in cryogenic media.
2. Can operate in 0-G.
3. Lab demonstration in LH2.
4. Low Power.
5. Minimal tank intrusion.
6. No moving parts.
7. Light weight.

### Cons:

Requires an extensive library of high-fidelity fluid configurations and spectra. If an unplanned fluid configuration occurs, then incorrect readings may result.

The review article cited below posits the “dimensionality curse”, indicating that a 1-D spectral scan can not contain enough information to choose among 3-D fluid configurations.

[Mass Gauging for Sustained Presence in Outer Space: A Technology Review | AIAA SciTech Forum](#)

Parson, Jaelon, Keaton Roe, Jeffrey Feller, Michael Khasin, and Surendra P. Sharma. "Mass gauging for sustained presence in outer space: A technology review." In AIAA Scitech 2021 Forum, p. 0047. 2021.

# A Review of 0-G and Low-G Mass Gauging Technologies

## #4a: Resonant Approaches: RF Spectral Mass Gauging (SMG)

Weyl's Law (paraphrased):

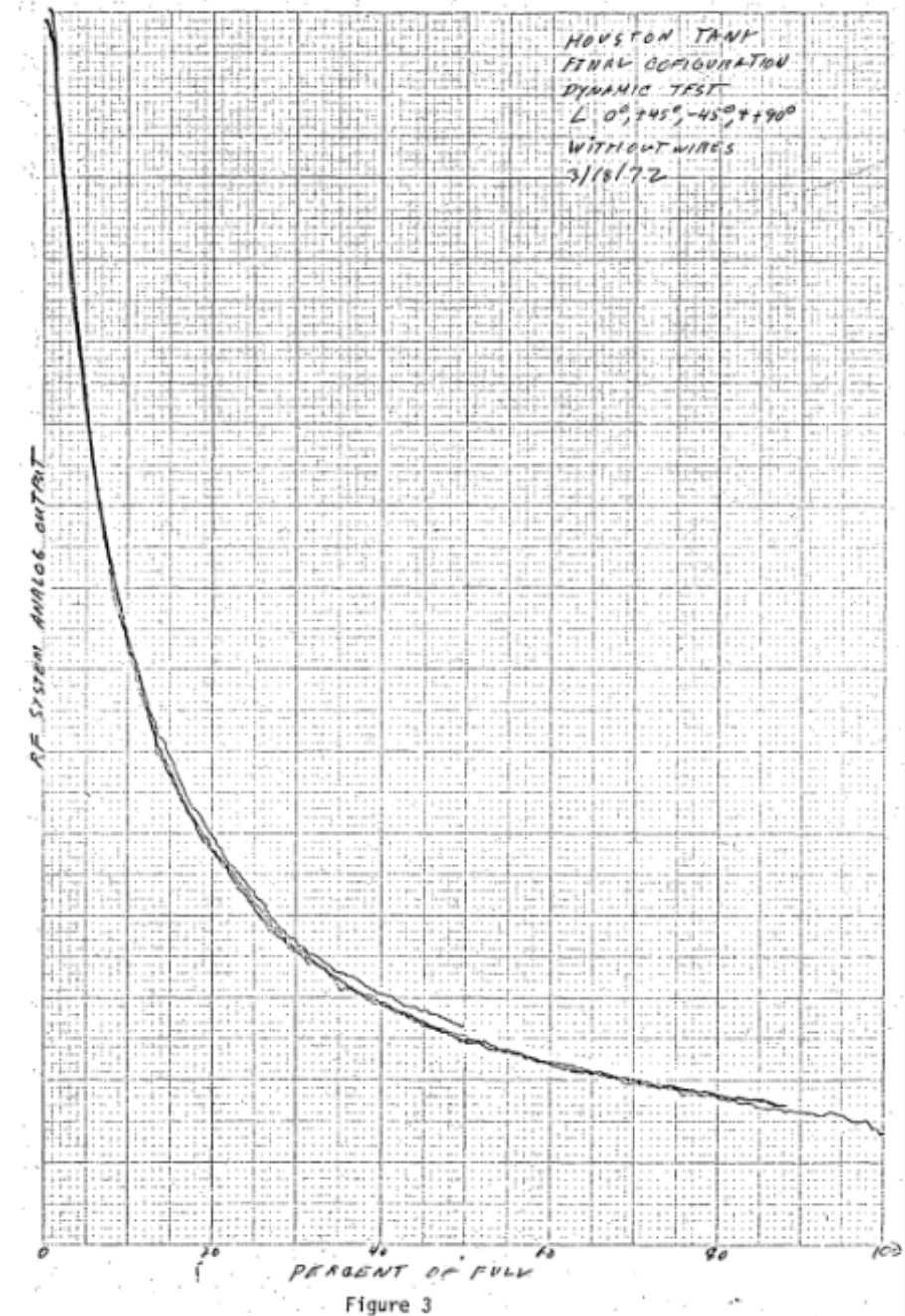
The number of modes in a volume, up to frequency,  $f$ , is proportional to the volume, regardless of its shape.

Bendix (1972) briefly explored a version of this by measuring the RF frequency response of a tank of RP-1 working between 1.875 GHz and 3.0 GHz.

The plot to the right shows the system performance while draining a tank at  $0^\circ$ ,  $+45^\circ$ ,  $-45^\circ$ , and  $+90^\circ$  and while gently sloshing the tank.

Ball Aerospace later stated that near 0-G flights occurred and that the errors increased to as much as 18%. I could not find a publication describing those flights.

[RF quantity gauging system - NASA Technical Reports Server \(NTRS\)](#) Hurley, H. S., and D. J. Kozakoff. "RF quantity gauging system." *NASA Contractor Report* (1972): 16670.



## #4b: Resonant Approaches: Acoustic Spectral Mass Gauging (SMG)

Weyl's law has been applied to mass gauging by counting acoustic modes.

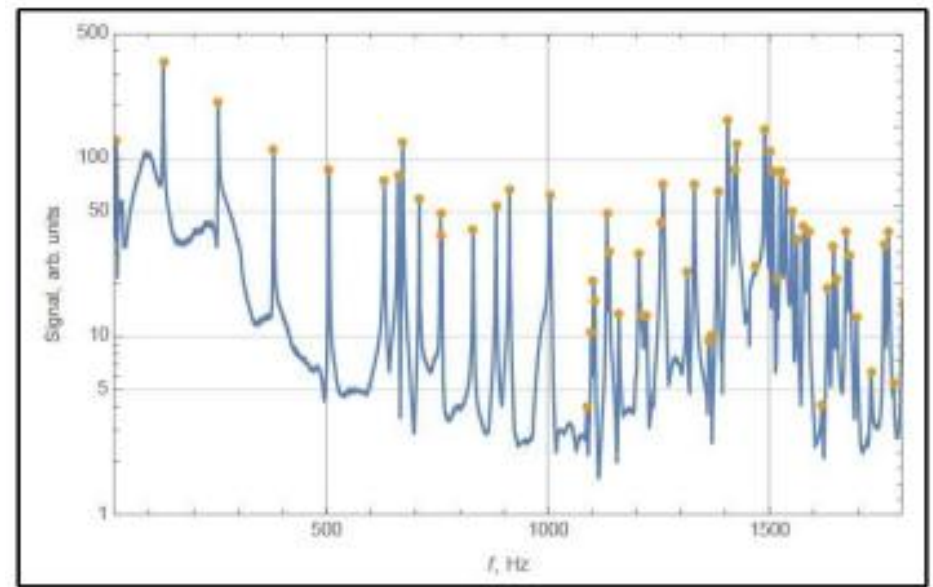
A group at ARC (Ames Research Center), Feller et.al. has been developing this concept.

The upper plot to the right show the acoustic modes excited in an air filled large dewar.

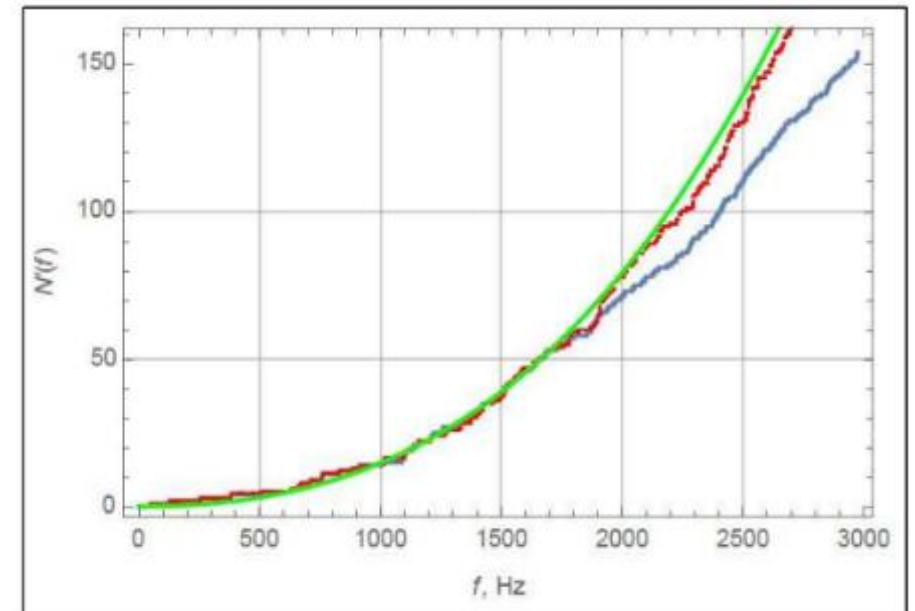
The lower plot shows the mode count versus frequency. The green is Weyl's theory, the red is theoretical counting of modes, and the blue is experimental data. Good fit until high frequency where it is difficult to resolve the modes.

[C:/Users/mkhasin/Documents/projects/nasa/mass-gauging/conference 2017/LaTeXTemplates/NASASMG3.dvi](C:/Users/mkhasin/Documents/projects/nasa/mass-gauging/conference%202017/LaTeXTemplates/NASASMG3.dvi)

Feller, Jeffrey, Ali Kashani, Michael Khasin, Cyrill Muratov, Viatcheslav Osipov, and Surendra Sharma. "Spectral mass gauging of unsettled liquid with acoustic waves." In *IOP Conference Series: Materials Science and Engineering*, vol. 278, no. 1, p. 012003. IOP Publishing, 2017.



The acoustic frequency spectrum from tapping a large tank.



Weyl's theory (green), versus mode theory (red), and versus experiment (blue).

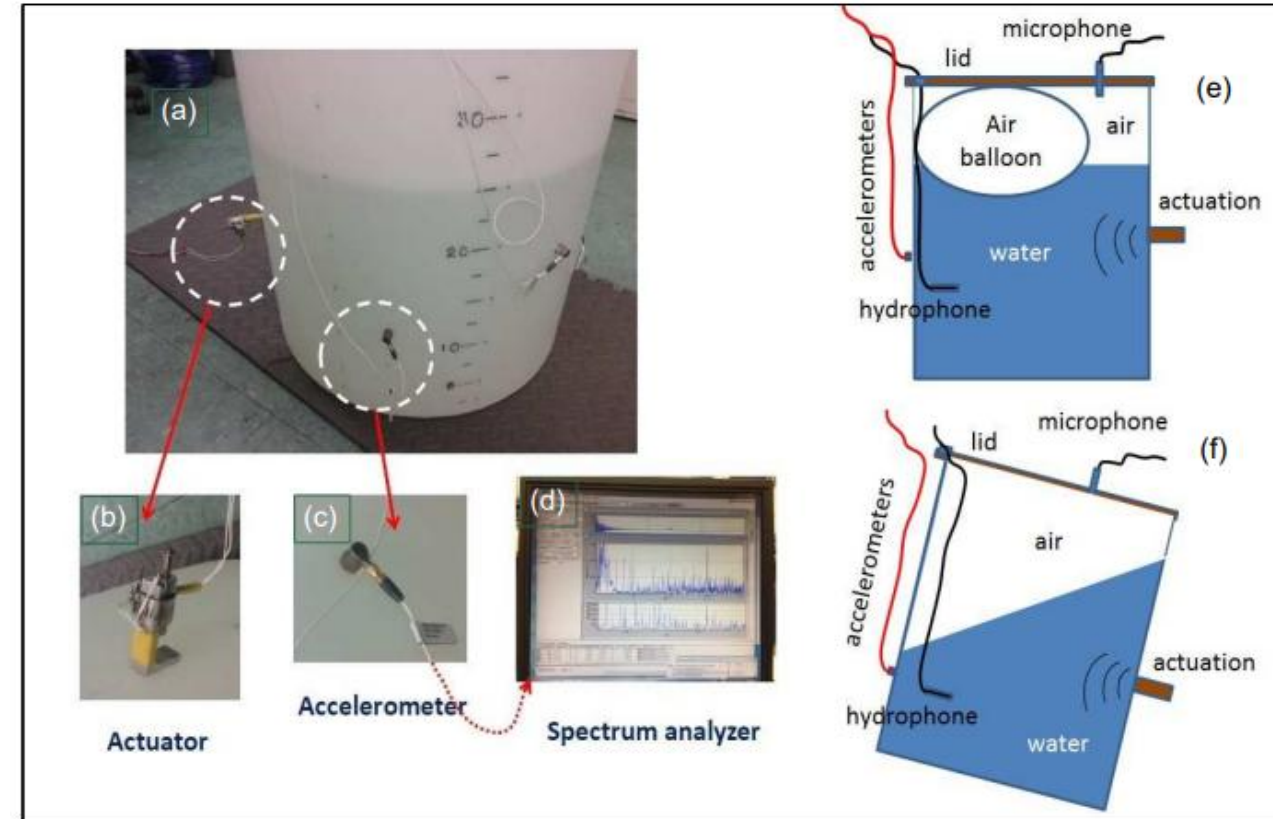
# A Review of 0-G and Low-G Mass Gauging Technologies

## #4b: Resonant Approaches: Acoustic Spectral Mass Gauging (SMG)

The Ames group then demonstrated SMG with a 200 liter water tank.

An external accelerometer pinged the tank from 10 different locations, exciting acoustic modes in the water, while 3 accelerometers and one hydrophone measured the response (the hydrophone was later dropped making this a non-intrusive measurement). From these the number of modes could be plotted versus frequency yielding the volume of the water.

Tests were performed at a 100 liter fill at 18 degrees and with an air balloon. The volume was determined to within 3% error.



<C:/Users/mkhasin/Documents/projects/nasa/mass-gauging/conference 2017/LaTeXTemplates/NASASMG3.dvi>

Feller, Jeffrey, Ali Kashani, Michael Khasin, Cyrill Muratov, Viatcheslav Osipov, and Surendra Sharma. "Spectral mass gauging of unsettled liquid with acoustic waves." In *IOP Conference Series: Materials Science and Engineering*, vol. 278, no. 1, p. 012003. IOP Publishing, 2017.

# A Review of 0-G and Low-G Mass Gauging Technologies

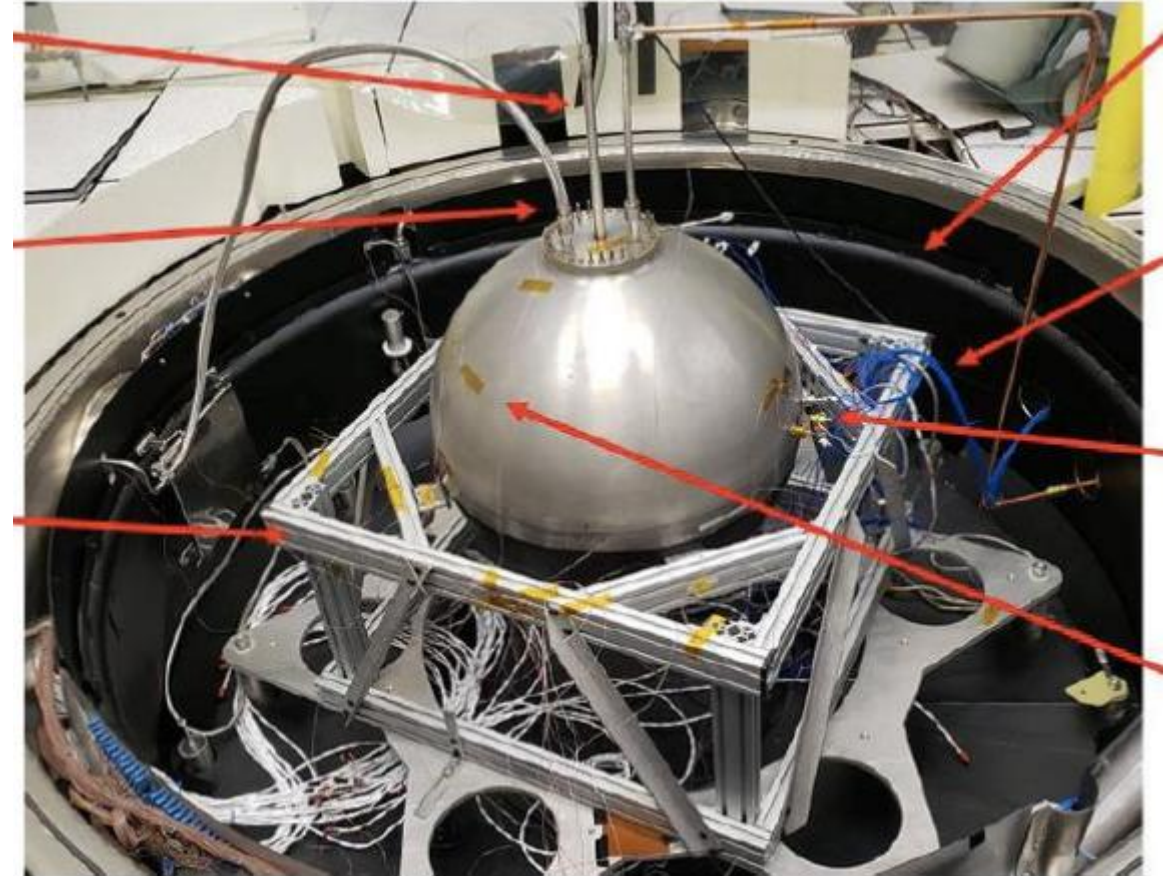
## #4b: Resonant Approaches: Acoustic Spectral Mass Gauging (SMG)

The Ames group performed liquid nitrogen tests, but the presentation does not state what mass accuracy was achieved.

This concept has been considered for use in monitoring water mass in low-G (see the reference below).

<https://ttu-ir.tdl.org/items/22534ace-02c5-4c5f-b197-447f889374e6>

Fili, Thomas, Guillem Quintana-Buil, and Ricard González-Cinca. "Spectral mass gauging in terrestrial gravity and microgravity conditions." *Acta Astronautica* 194 (2022): 174-184.



[Spectral Mass-Gauging of Propellant Tanks - NASA Technical Reports Server \(NTRS\)](#)

Khasin, M., J. Feller, M. Corbetta, J. Rogers, B. Helvensteijn, and A. Kashani. "Spectral Mass-Gauging of Propellant Tanks." In *NASA In-Space Chemical Propulsion TIM*. 2022.

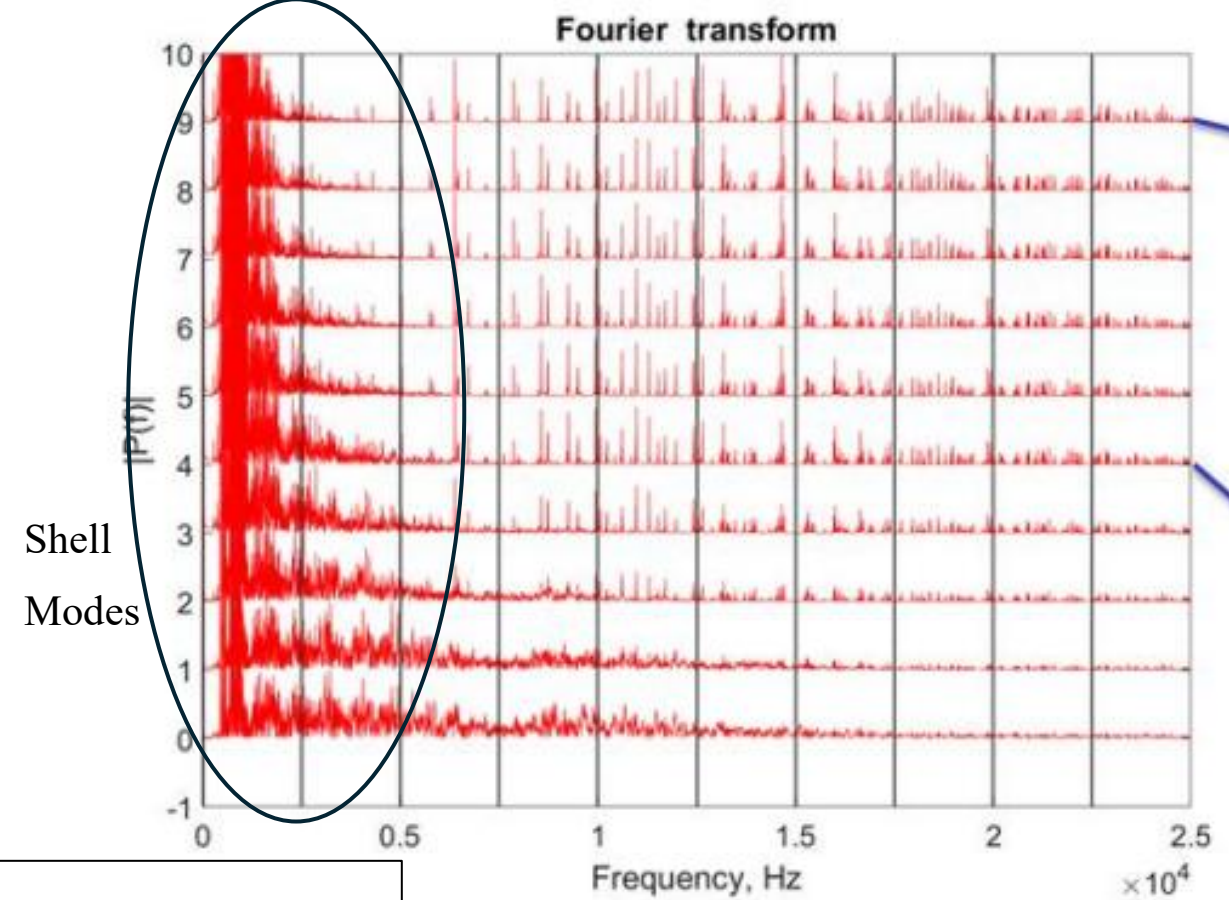
## #4b: Resonant Approaches: Acoustic Spectral Mass Gauging (SMG)

### Pros:

1. Non-intrusive.
2. A direct measurement of volume.
3. Low power
4. Demonstrated with cryogenics (?).

### Cons:

1. Relies on the liquid being in one mass and touching the inner wall of the tank at the location of the acoustic source.
2. Mode counting becomes difficult at higher frequency, limiting accuracy.
3. Dependent on the speed of sound and liquid density, both of which can vary due to temperature gradients in the tank.
4. Can be difficult to excite and detect all the modes and to resolve degenerate modes (modes having the same frequency).



SMG Data from LN2 Tank test.

Vibrating the tank wall excites both internal resonances in the water (desired by SMG), but also excites shell modes in the tank structure.

Shell modes decay more quickly than the water modes, allowing them to be separated.

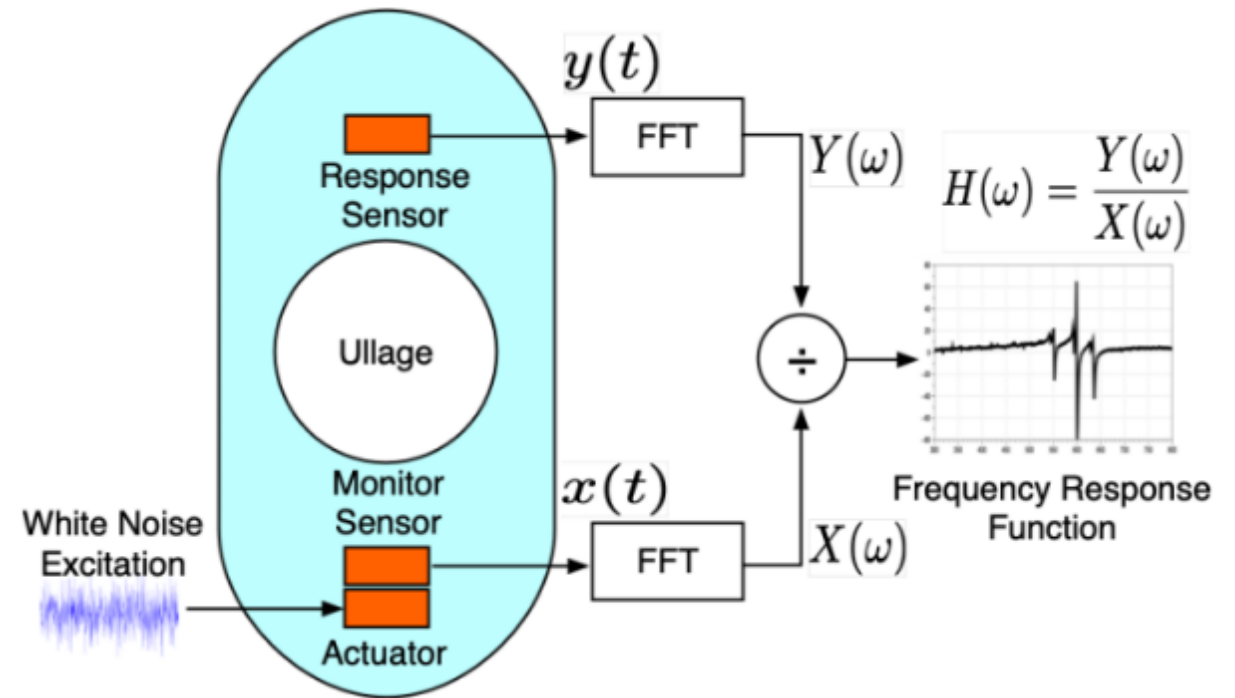
# A Review of 0-G and Low-G Mass Gauging Technologies

## #4c: Resonant Approaches: Modal Propellant Gauging (MPG)

The tank or shell modes have been used to measure the liquid in a tank, with the work led by Werlink et.al. (KSC/JSC) and Crosby at Carthage College.

The idea is that the tank modes will be shifted lower by the loading of liquid in contact with the inner wall of the tank.

This work has been in development for several years and followed a path similar to that of RFMG, until recently



The primary approach used in MPG is to excite the tank modes with white noise and monitor the source spectrum and response spectrum, Fourier Transform them and divide to obtain and frequency response function.

### Modal Propellant Gauging: Spectral Density Method

Crosby, Kevin M., Rudy Werlink, and Eric Hurlbert. "Modal propellant gauging: Spectral density method." In AIAA Scitech 2020 Forum, p. 1443. 2020.

### Modal Propellant Gauging in Low Gravity

Crosby, Kevin M., Tessa Rundle, Kevin LeCaptain, and Rudy Werlink. "Modal propellant gauging in low gravity." In AIAA SPACE 2016, p. 5533. 2016.

# A Review of 0-G and Low-G Mass Gauging Technologies

## #4c: Resonant Approaches: Modal Propellant Gauging (MPG)

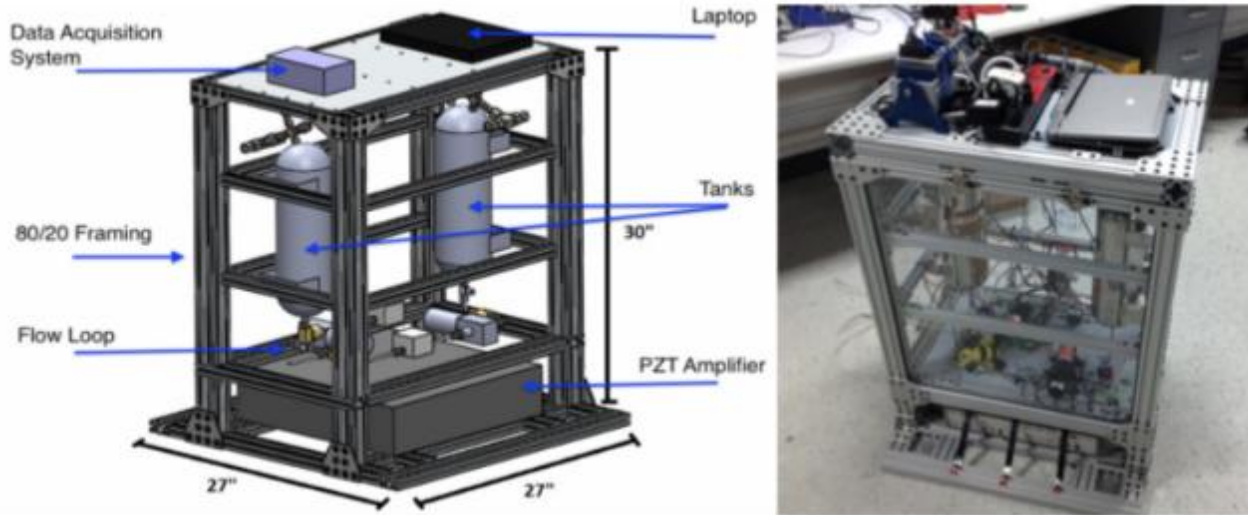
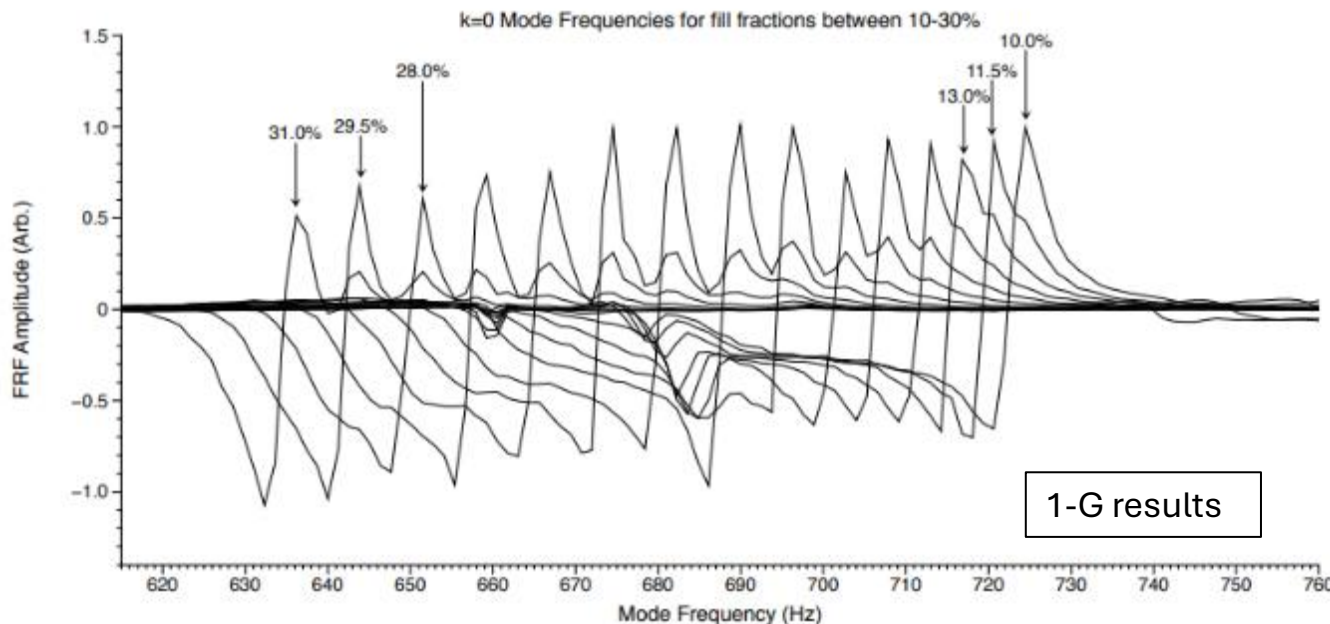


Figure 3. Flight rig for the MPG experiment.



Similar to the early RFMG work, MPG considered tracking lower order tank modes to make a mass measurement. The image to the left shows a test system allowing water to be moved from one tank to another. The plot below shows 1-G testing where the lowest order mode's frequency changes monotonically with mass (fill fraction).

However, in testing during 180 low-G parabolic flights (20 seconds of low-G per flight) the liquid did not have time to settle, resulting in sloshing "presenting a time-varying contact fraction between tank and liquid". This is believed responsible for peak broadening. In addition, small pressure changes can stiffen the tank shifting the frequencies.

Some limited data was gathered with fill fractions between 10% and 16%, but another algorithm was needed.

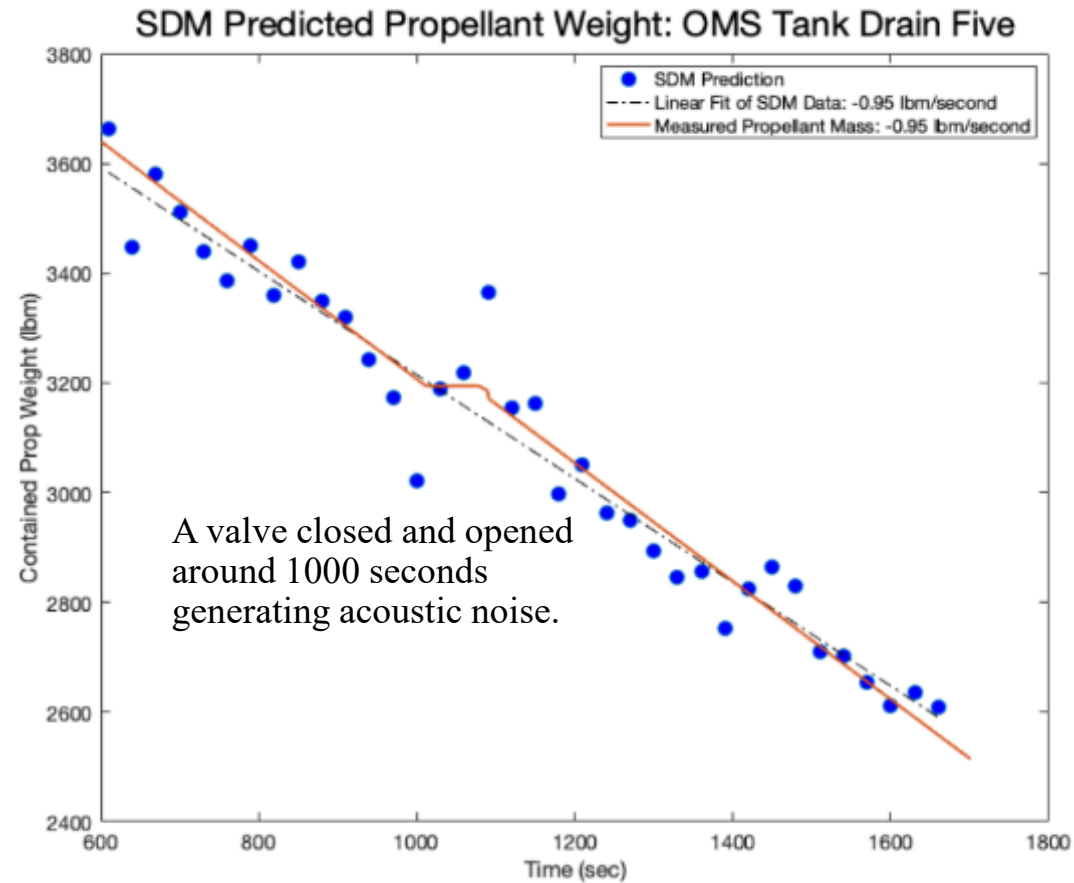
### [Modal Propellant Gauging in Low Gravity](#)

Crosby, Kevin M., Tessa Rundle, Kevin LeCaptain, and Rudy Werlink. "Modal propellant gauging in low gravity." In *AIAA SPACE 2016*, p. 5533. 2016.

# A Review of 0-G and Low-G Mass Gauging Technologies



A Space Shuttle Orbital Maneuvering System Propellant Tank with 8 sensors installed.



## #4c: Resonant Approaches: Modal Propellant Gauging (MPG)

### Modal Propellant Gauging: Spectral Density Method

Crosby, Kevin M., Rudy Werlink, and Eric Hurlbert. "Modal propellant gauging: Spectral density method." In AIAA Scitech 2020 Forum, p. 1443. 2020.

The team shifted to a cross-correlation approach, where a database using multiple sensors monitoring fill level during a typical drain could be used to determine fill level at differing pressures and drain rates, but 0-G modes do not correlate well with 1-G modes. So this approach, without substantial modeling like RFMG, was dropped.

The team then adopted a Spectral Density Method (SDM), developing an algorithm dependent on looking at the power spectrum frequency response and had some limited success doing that. But recently they have returned to mode tracking.

# A Review of 0-G and Low-G Mass Gauging Technologies

## #4c: Resonant Approaches: Modal Propellant Gauging (MPG)

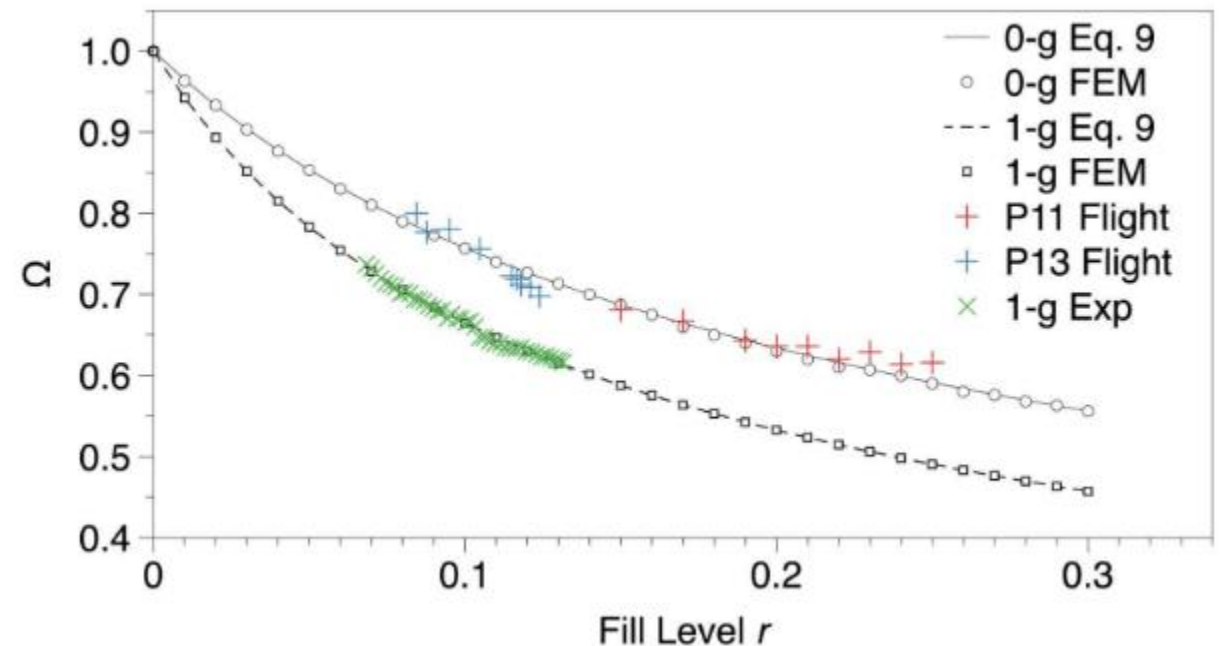
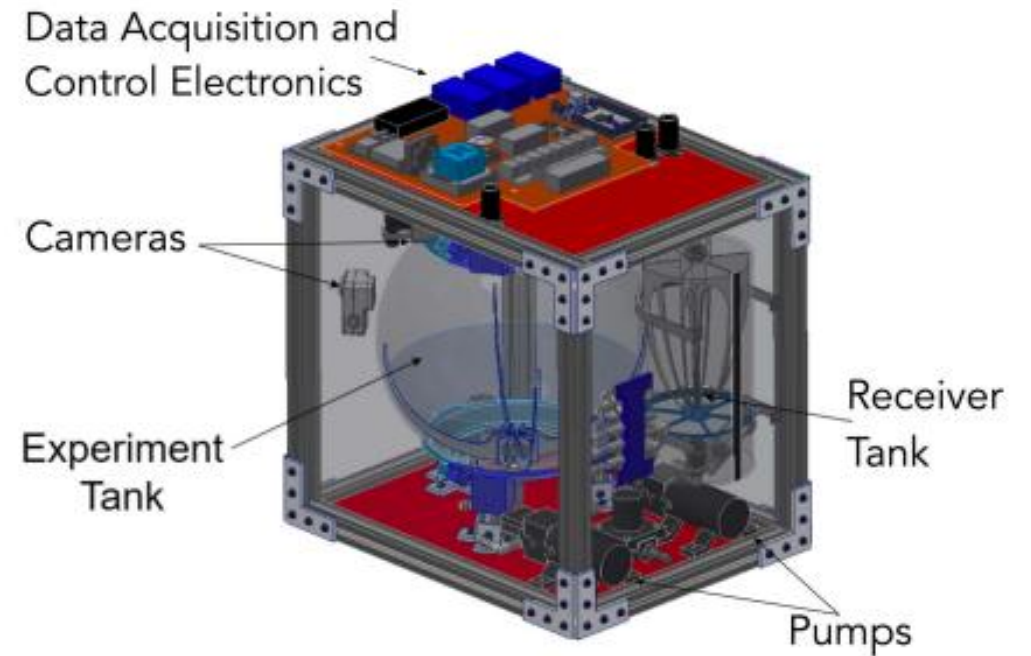
In recent work, the MPG team has returned to mode tracking. The flew a jig on a New Shepard flight where sufficient time allowed some liquid settling in low-G. Liquid could be transferred from one tank to another. They also put substantially more effort into finite element modeling and theoretical analysis.

Even so, there was only one receiving sensor on the tank and the lowest order modes sometimes vanished, limiting the fill level range that could be sensed.

The results, for two zero-0 flights, P11 and P13 are shown to the right (fill level versus normalized frequency), compared to the numerical and analytical models. Comparing to their equation 9, the maximum fractional error is 1.2%.

[Liquid mass gauging during propellant transfer in microgravity – ScienceDirect](#)

Crosby, Kevin, Eric A. Hurlbert, and Rudolph J. Werlink. "Liquid mass gauging during propellant transfer in microgravity." *Acta Astronautica* 220 (2024): 283-296.



# A Review of 0-G and Low-G Mass Gauging Technologies

## #4c: Resonant Approaches: Modal Propellant Gauging (MPG)

### Pros:

1. Extrinsic, no access to the fluid.
2. Demonstrated in 0-G.
3. Latest version detects mass directly, rather than through a cross correlation to a data base of frequencies.
4. When it works the accuracy is good.
5. Moderately light weight.

### Cons:

1. Moderately high power
2. Only demonstrated for fluid settled in 0-G touching the tank walls.
3. Pressure sensitivity is unclear.
4. Cryogenic demonstration? Could only find water demonstrations.

# A Review of 0-G and Low-G Mass Gauging Technologies

## #4d: Resonant Approaches: Resonant Infrasonic Gauging System (RIGS)

The idea is that the acoustic resonant frequency of the tank varies with propellant mass. RIGS shifts this frequency into an isothermal range with an external mass and then measures the resulting frequency.

Developed for Apollo and Shuttle and showed good performance with water and a rubber diaphragm. Material and electrical limitations made cryogenic use difficult (1970s).

Not appropriate for LH2 due to the compressibility of LH2.

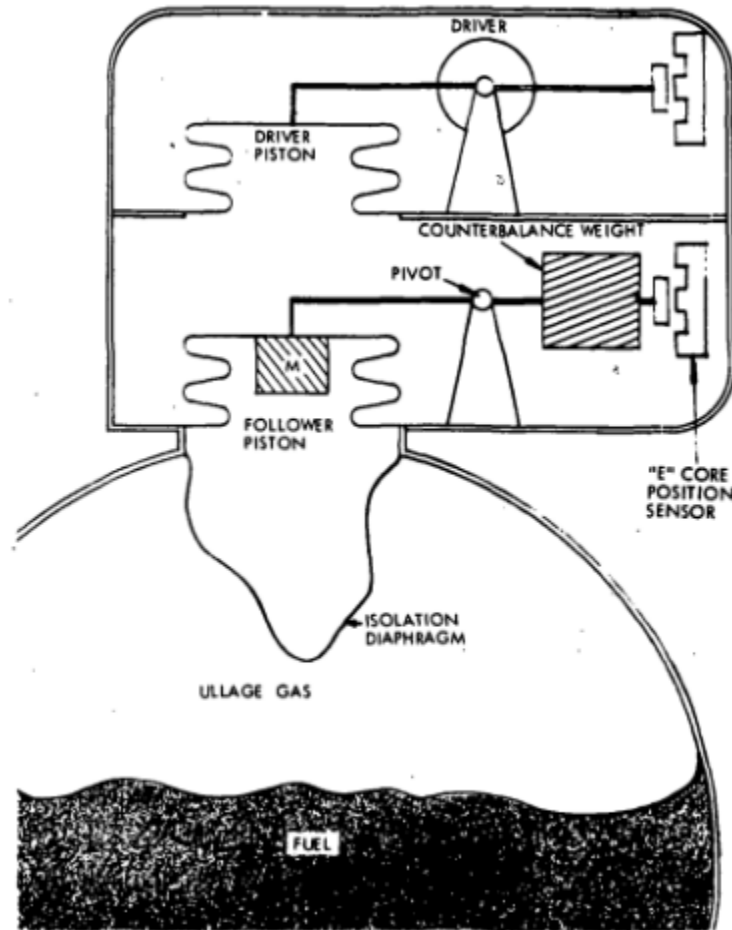


Figure 2-1. RIGS Sensor Schematic Diagram



<https://ntrs.nasa.gov/api/citations/19710026628/downloads/19710026628.pdf>  
Propellant Quantity Gauging System Under 0-G, 1971. TRW. Contains further information on RIGS and recommends it for LOX.

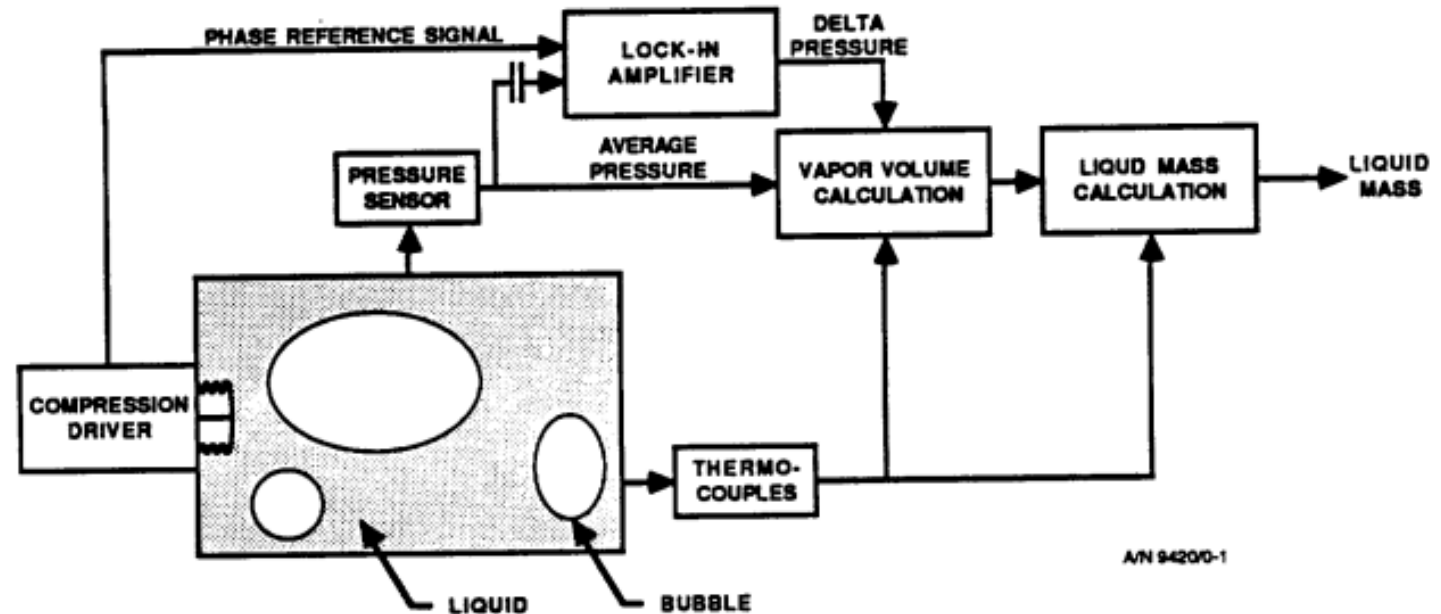
Development of isothermal rigs - NASA Technical Reports Server (NTRS)  
Kaminskas, R. A., and D. J. Malone. *Development of isothermal rigs*. No. NASA-CR-124314. 1973.

# A Review of 0-G and Low-G Mass Gauging Technologies

## #5: PVT (pressure-volume-temperature)-volumetric modulation.

In this approach, a piston oscillates, changing the tank's volume (about 0.01%) at about 1 Hz, while measuring the tank pressure and temperature. 1 Hz is claimed to allow pressure stabilization without causing temperature changes.

Accuracy shown to be 0.2 % in water. No evidence it was developed further.



1988 system developed by Ball Aerospace.

[Fluid quantity gaging - NASA Technical Reports Server \(NTRS\)](#)

Mord, A.J., Snyder, H.A., Kilpatrick, K.A., Hermanson, L.A., Hopkins, R.A. and Vangundy, D.A., 1988. *Fluid quantity gaging* (No. NASA-CR-185516).

# A Review of 0-G and Low-G Mass Gauging Technologies

#5: PVT-Pressure-Volume-Temperature, used in some satellites, e.g., HS601 Geosynchronous (hypers)

Monitor the pressure of the ullage and pressurizing tank to determine the ullage volume.

Requires a pressuring gas that is non-condensable and is conserved (no venting).

Requires accurate modeling and temperature measurements.

VanDresar and Zimmerli achieved 2% LOX quantity errors by modeling Helium solubility, correcting for plumbing issues, and use of a spray system to ensure the liquid was isothermal.

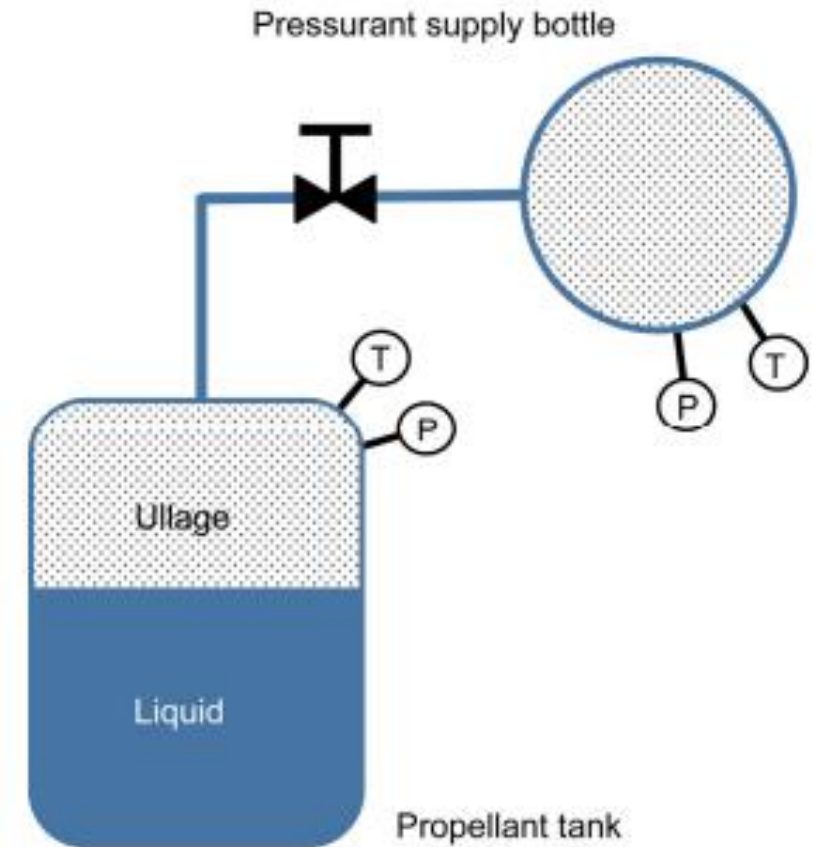


Figure 1.—Simplified pressure-volume-temperature schematic showing locations of pressure,  $P$ , and temperature,  $T$ , gauges.

[Mass Gauging for Sustained Presence in Outer Space: A Technology Review | AIAA SciTech Forum](#)

Parson, Jaelon, Keaton Roe, Jeffrey Feller, Michael Khasin, and Surendra P. Sharma. "Mass gauging for sustained presence in outer space: A technology review." In AIAA Scitech 2021 Forum, p. 0047. 2021.

[Pressure-Volume-Temperature \(PVT\) Gauging of an Isothermal Cryogenic Propellant Tank Pressurized with Gaseous Helium - NASA Technical Reports Server \(NTRS\)](#) VanDresar, Neil T., and Gregory A. Zimmerli. *Pressure-volume-temperature (PVT) gauging of an isothermal cryogenic propellant tank pressurized With gaseous helium*. No. E-18769. 2014.

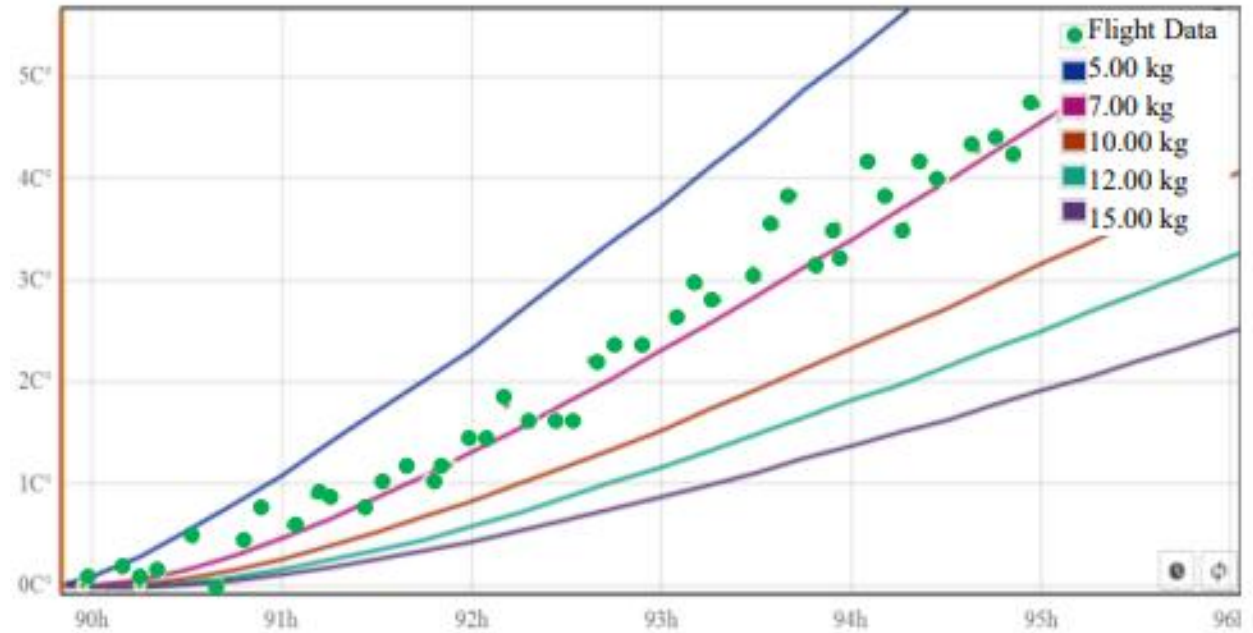
# A Review of 0-G and Low-G Mass Gauging Technologies

## #6: Thermal Gauging Method (TGM) used on some geosynchronous satellites.

Given an accurate tank model, adding a known amount of heat and measuring the resultant temperature change can yield the mass of propellant.

This method becomes more sensitive as the propellant mass lessens.

It can take several days to obtain a mass measurement.



**Figure 4. Simulation results and flight data for fuel tank.** *Markers- temperature sensor reading; curves - simulations for different tank loads. The heater turned ON at 89 hr.*

### [Implementation of Thermal Gauging Method for Orbital STARBus™ Satellite](#)

Yendler, Boris S., Sergey Chernikov, Jason Molinsky, and Daniel Guadagnoli. "Implementation of Thermal Gauging Method for Orbital STARBus™ Satellite." In *AIAA SPACE 2013 Conference and Exposition*, p. 5452. 2013.

Yendler, Boris. "Implementation of thermal gauging method for SpaceBus 3000A (ArabSat 2B)." In *SpaceOps 2012*, p. 1269441. 2012.

# A Review of 0-G and Low-G Mass Gauging Technologies

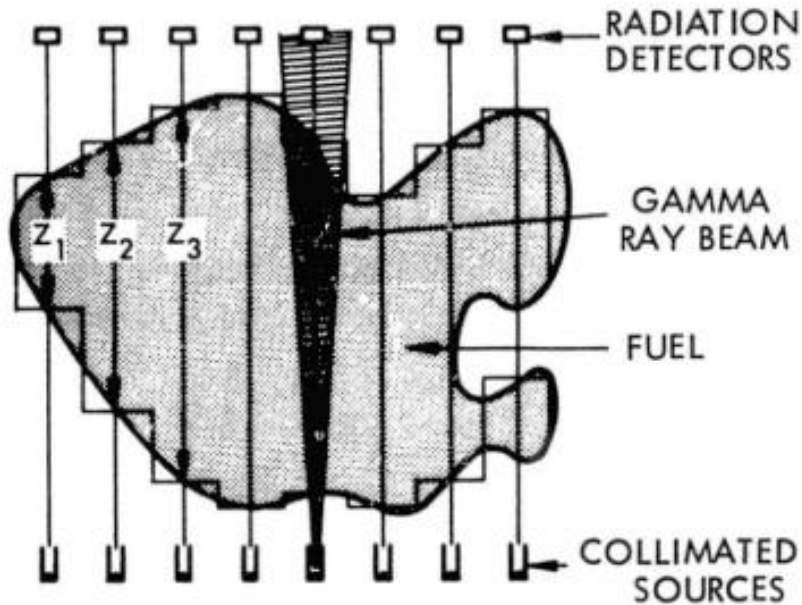
## #6: Thermal Gauging Method (TGM).

A thought:

Adding heat to a cryogenic tank is not advisable, but perhaps chilling a cryogenic commodity while monitoring the temperature can provide insight into the amount of remaining liquid.



A Northrop Grumman  
space-rated cryocooler

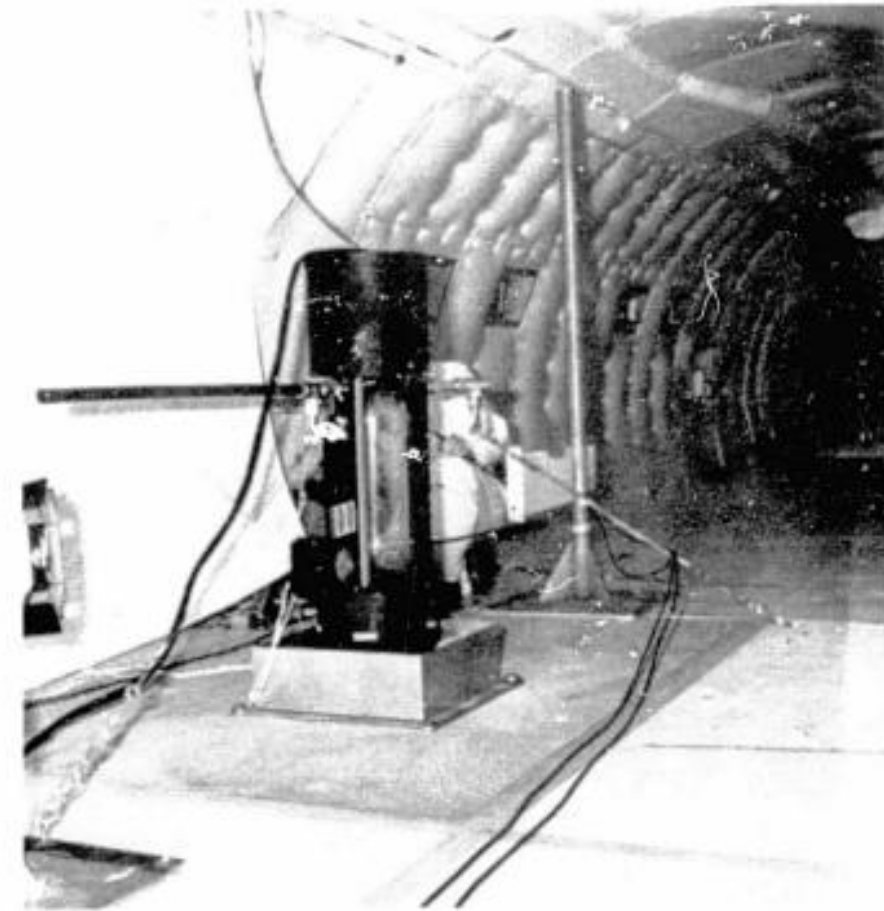


<https://ntrs.nasa.gov/api/citations/19710026628/downloads/19710026628.pdf>

Dumbauld, R. K., and J. R. Bjorklund. "Propellant quantity gauging system under zero g." NASA Contractor Report (1971): 26628.

In 1971 TRW demonstrated gamma ray attenuation could measure liquid mass (brine) to better than 1 % in ground tests. The ultimate goal was a LH2 gauging system, but the early work was directed towards the Shuttle OMS tank.

0-G flight tests were conducted with a water tank using collimated Cesium-137 sources to inspect the tank. 3% mass gauging accuracy was reported. Radiation dosages for all personnel were monitored with dosimeter badges with none showing dangerous levels.



[Zero-G flight test of a gauging system. Volume 1: Summary - NASA Technical Reports Server \(NTRS\)](#)  
CENTER, LYNDON B. JOHNSON SPACE. "ZERO-G FLIGHT TEST OF A GAUGING SYSTEM." (1976).

# A Review of 0-G and Low-G Mass Gauging Technologies

## #6: Nucleonic

### Pros:

1. External to the Tank,
2. No moving parts,
3. Rapid measurements (typ.1 second),
4. Measures mass directly,
5. Appropriate for LH2, but may require higher energy sources for LOX.
6. Demonstrated in 0-G with water to better than 3% accuracy with 4 sources.
7. Independent of internal structures such as baffles or propellant management devices-claimed.

### Cons:

1. Uses radioactive sources. During development, personnel wore radiation detectors and no excessive exposures were seen.
2. Might be heavy due to shielding.

# A Review of 0-G and Low-G Mass Gauging Technologies

That's it.

Some thoughts in closing:

1. If a nonconductive tank were used, then capacitive measurements could be made with electrodes outside the tank.
2. Adding windows to a tank would allow imaging of the liquid. This might provide a means to determine mass or at least information on the liquid distribution.
3. Consider the requirement. Bookkeeping might be adequate until liquid levels are low. Measuring mass during a burn when the liquid is at a low level could simplify the approach. A few point sensors might be adequate.

# A Review of 0-G and Low-G Mass Gauging Technologies

Backup

Table A.1. Methods for propellant gauging between thruster firings.

| Method                  | Used for        | Measurement Principle                                                                                                                                                                                   | Advantages and Disadvantages                                                                                                                                            | Heritage / Development Status                                                                                                                                                                                                                                      |
|-------------------------|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>pVT</i>              | 3axis + spinner | Measurement of the tank temperature and pressure and calculation of the tank ullage volume and thereby the remaining propellant mass by applying the gas law.                                           | + no additional equipment and lowest costs<br>- decreasing accuracy towards EOL, low accuracy with conventional pressure transducer                                     | used on many spacecrafts                                                                                                                                                                                                                                           |
| <i>Thermal Knocking</i> | 3axis + spinner | Heating of the propellant tank and measurement of its thermal response which is related to the propellant load.                                                                                         | + no additional equipment<br>- low accuracy, high calibration efforts and long operational gauging times                                                                | used on<br>• OLYMPUS<br>• EUROSTAR                                                                                                                                                                                                                                 |
| <i>Gas Injection</i>    | 3axis           | Transfer of a known amount of pressurant gas into the propellant tank and measurement of the pressure and temperature increase to determine the ullage volume and thereby the remaining propellant mass | + good accuracy at EOL<br>- complex system, modification of propulsion system required, needs high accuracy pressure transducer, high calibration effort and high costs | • ground qualification of an Engineering Model Gauging Device <sup>1)</sup><br>• operational use of Hughes Propellant Gauging System <sup>2)</sup><br>• in-flight demonstration of Foreign Mass Injection Method and Periodic Volume Stimulus Method <sup>3)</sup> |
| <i>Liquid Leveling</i>  | spinner         | Measurement of liquid level in tanks of satellites where propellants are settled due to spin acceleration.                                                                                              | + simple system with very high accuracy<br>- limited to spinning satellites                                                                                             | used on :<br>• MSG (capacitive measurement)<br>• Hughes ( $\Delta p$ measurement)                                                                                                                                                                                  |

Table A.2. Methods for propellant gauging during thruster operation.

| Method                 | Used for        | Measurement Principle                                                                                                                                                                                                                                   | Advantages/<br>Disadvantages                                                                                                         | Heritage / Development Status                                                                                                                                                                                   |
|------------------------|-----------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Bookkeeping</i>     | 3axis + spinner | Calculation of propellant consumption during each maneuver by on-ground recording of all maneuver data (e.g. pulse duration, pulse mode, thruster temperature). making additionally use data of individual thruster calibration test firings on ground. | + simple system with no additional equipment needed<br>- inflight calibration required, operational effort on ground                 | used on many spacecraft                                                                                                                                                                                         |
| <i>Flowmeter</i>       | 3axis           | Integration of thruster mass flowrate measurements during operation.                                                                                                                                                                                    | + high accuracy<br>- sensor still to be developed, low accuracy for pulse firings                                                    | CNES funded spatialisation of a thermal flowmeter failed in 1990 due to sensitivity to gravity vector, thermal environment and small gas bubbles in flow.<br>ESA/ESTEC development of an ultrasonic flowmeters. |
| <i>Liquid Leveling</i> | 3axis           | Measurement of liquid level in tank during thruster operation.                                                                                                                                                                                          | + accuracy improvement feasible<br>- low achieved accuray, works only during thruster firings of a minimum thrust level and duration | used on <ul style="list-style-type: none"> <li>• Apollo</li> <li>• Shuttle OMS</li> </ul>                                                                                                                       |

Hufenbach, Bernhard, Rolf Brandt, Gerard Andre, Raoul Voeten, Patrick van Put, Berry Sanders, Andeas Schwer, Ad Delil, Olaf Mastenbroek, and Aswin Pauw. "Comparative assessment of gauging systems and description of a liquid level gauging concept for a spin stabilized spacecraft." In *European Spacecraft Propulsion Conference*, vol. 398, p. 561. 1997.

Table A.3. Realization alternatives of the liquid leveling method.

| Method                | Principle                                                                                                                           | Advantages                                                                                                                           | Disadvantages                                                                                                                                                                                                                                                                                                        |
|-----------------------|-------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Ultrasonic            | measurement of the time delay of an ultrasonic signal reflected by the liquid-vapour interface                                      | <ul style="list-style-type: none"> <li>• non intrusive</li> <li>• existing sensor</li> <li>• high accuracy</li> </ul>                | <ul style="list-style-type: none"> <li>• heavy</li> <li>• high recurring costs</li> <li>• low reliability</li> </ul>                                                                                                                                                                                                 |
| Thermal Transient     | measurement of the thermal capacity                                                                                                 | <ul style="list-style-type: none"> <li>• non intrusive</li> <li>• low recurring costs</li> </ul>                                     | <ul style="list-style-type: none"> <li>• high power consumption</li> <li>• pipe conductivity disturbs measurement: low accuracy</li> </ul>                                                                                                                                                                           |
| Electrical Resistance | measurement of the electrical resistance of a circuit inside fluid                                                                  | <ul style="list-style-type: none"> <li>• low mass</li> <li>• demonstrated performance</li> </ul>                                     | <ul style="list-style-type: none"> <li>• intrusive</li> <li>• compatibility problems</li> </ul>                                                                                                                                                                                                                      |
| Differential Pressure | measurement of the differential pressure between the liquid at the tank outlet and the vapor of the tank ullage volume              | <ul style="list-style-type: none"> <li>• existing sensor</li> <li>• good accuracy potential</li> <li>• low recurring cost</li> </ul> | <ul style="list-style-type: none"> <li>• difficult to implement: measurement may be disturbed by trapped liquids</li> </ul>                                                                                                                                                                                          |
| Natural Frequency     | measurement of the natural frequency of a pipe inside the fluid                                                                     | <ul style="list-style-type: none"> <li>• demonstrated performance</li> </ul>                                                         | <ul style="list-style-type: none"> <li>• heavy</li> <li>• power consumption</li> <li>• moving parts</li> <li>• high recurring costs</li> <li>• low reliability</li> <li>• intrusive</li> </ul>                                                                                                                       |
| Capacitive            | measurement of the time delay to load capacitors which depends on the dielectric constant of the fluid between the capacitor plates | <ul style="list-style-type: none"> <li>• existing sensor</li> <li>• high accuracy</li> <li>• low mass and recurring costs</li> </ul> | <ul style="list-style-type: none"> <li>• effect of surface tension forces</li> <li>• unknown dielectric behavior propellants</li> <li>• different sensor designs and/or electronics may be required for different fuels</li> <li>• sensitivity to electric properties of environment</li> <li>• intrusive</li> </ul> |