Propellant Mass Gauging: Database of Vehicle Applications and Research and Development Studies

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1.   INTRODUCTION

NASA is currently developing propulsion system concepts for the exploration of the solar system, including the return of humans to the lunar surface and eventually, it is expected, to Mars. These concepts are considering the use of cryogenic propellants. During some parts of the mission, the propellants will be exposed to weightless conditions (i.e., effective low gravity) such as during the unpowered flight of the vehicle stages used for earth insertion orbit and earth departure. The engines of these stages will have to be re-started at least once and perhaps more than once. For that reason, and to assure that there is an adequate mass of onboard propellant before beginning the human exploration part of the mission, an accurate, robust, reliable method is needed to gauge the mass of propellants in their tanks in low gravity. Gauging the mass of propellants in a tank in low gravity is not a straightforward task because of the uncertainty of the liquid configuration in the tank and the possibility of there being more than one ullage bubble. Several concepts for such a low-gravity gauging system have been proposed, and breadboard or flight-like versions have been tested in normal gravity or even in low gravity, but at present, a flight-proven reliable gauging system is not available.

NASA has, therefore, initiated a technology program to develop one or more low-gravity gauging systems to a Technology Readiness Level (TRL) of Six. As part of this development, NASA desired a database of the gauging techniques used in current and past vehicles during ascent or under "settled" conditions, and during short coasting (unpowered) periods, for both cryogenic and storable propellants. Past and current research and development efforts on gauging systems that are believed to be applicable in low-gravity conditions were also desired. This report documents the results of that survey.

The sensors, instrumentation, and electronics used by current gauging systems are not described in detail in this report, since the emphasis is on the gauging methods themselves. In addition, the detailed operation of some of the sensors and instrumentation is proprietary. It was thought worthwhile, however, to provide generic descriptions of the common types of sensors, and this is done in Section 2 of this report. When appropriate, any special or unique sensors required for a specific research and development gauging program are described as part of that gauging system.

The database/survey is organized in two sections in this report. Section 3 and Appendix A summarize the gauging systems actually used in past and current space vehicles. Section 4 and Appendix B describe past and current research and development efforts on gauging systems that show promise for low-gravity applications, but have not yet been used in an actual vehicle. These descriptions focus on the essential features and principles of the gauging methods. In many cases, the methods are proprietary, so it was not feasible to review the methods in more detail. Some further details are given in the references cited for each gauging system.

2.   GAUGING SYSTEM SENSORS

A wide range of propellant gauging systems has been used in space vehicles or proposed for future applications. All of them require sensors to measure the quantities of interest that can be related to the mass or volume of liquid in a tank. This section describes a representative selection of such sensors. The cited references are listed on the relevant pages.

2.1   Sensors to Detect the Presence of Liquid or Gas at a Point

Sensors to detect the presence of liquid or gas at a point (i.e., at the sensor location) are usually called *wet-dry* sensors or *point* sensors. Common forms include a hot wire[1] or an electrical resistor[2] or some other kind of electrical impedance element[3,4] through which a small current is passed. These sensors in general determine the presence of liquid or gas at their location by determining the change in their electrical impedance as a function of whether they are immersed in liquid or in gas. The value of the sensor impedance depends on its temperature, which in turn depends on the heat transfer from the sensor that dissipates the ohmic heating of the element caused by the electric current; the heat transfer is greater when the sensor is in liquid. Thus, monitoring the change in the current for a constant applied voltage (or the change in voltage required to maintain a constant current) indicates the change in impedance (i.e., whether the sensor is in liquid or gas). An alternative to an electrical impedance sensor is an optical point sensor. In one form of this sensor, see Figure 2.1, a laser light source is incorporated in a prism-like capsule whose index of refraction is matched to the index of refraction of the liquid in the tank.[5,6] When the sensor is immersed in gas, the light is reflected off the end of the prism back to a photocell at the light source; when the sensor is immersed in liquid, the light is transmitted into the liquid without reflection off the prism. The reflection thus provides a wet or dry indication.

All of these kinds of wet-dry sensors are applicable in principle to storable propellants as well as cryogens. They all have the limitation that liquid may adhere to the sensor in low gravity, even when the sensor is nominally in gas, as a result of surface tension and the absence of any force to drain the liquid off the sensor; thus, their wet-dry indication may be false. For that reason, other kinds of wet-dry sensors have also been investigated, such as, for example, small vibrating reeds or torsionally vibrating rods.[7] The natural frequency, or the amplitude of forced vibrations, of the reed or rod is different in liquid than it is in gas and, thus, the presence of liquid

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[1] Olsen, W. A., Jr., *An Integrated Hot Wire – Stillwell Liquid Level Sensor System for Liquid Hydrogen and Other Cryogenic Fluids*, NASA TN D-2074, 1963.
[2] Muhlenhaupt, R., and Smelser, P., *Carbon Resistors for Cryogenic Liquid Level Measurement*, NBS Technical Note 200, 1963.
[3] Burgeson, D. A., Pestalozzi, W. G., and Richards, R. J., *The Performance of Point Level Sensors in Liquid Hydrogen, Preprint G-5*, 1963 Cryogenic Engineering Conference, 1963.
[4] O'Neill, J. A., and Mills, E. D., *Differential Temperature Cryogenic Liquid Sensing Sensor*, Final Report, Cryonetics Corp. 42-002, Contract NAS8-11734, 1965.
[5] Lenker, P., Resh, R., Dray, W., Hosforth, N., and Shearer, R., *Development of Optical Liquid Level Sensor for Use in Liquid Hydrogen*, Bendix Corporation Report 3464-1-66, Contract NAS 8-11644, 1966.
[6] Duffell, A., *Optical Cryogenic Tank Level Sensor*, NASA-MSFC Faculty Fellowship Program Report, 2004.
[7] Franklin, R., *Feasibility Study of Liquid Hydrogen Level Detector for Zero G*, General Dynamics/Astronautics Report 55B1039-1, 1968.

or gas can be determined by monitoring the vibrations. These sensors can be used in low-gravity applications since the vibrations tend to shake off any liquid adhering to the sensor.
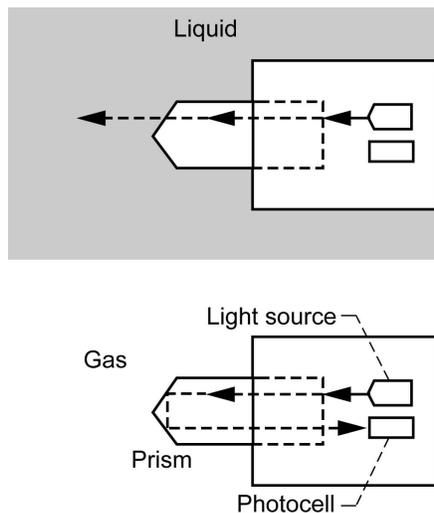
Figure 2.1 Schematic of wet-dry optical sensor.

2.2   Sensors to Detect the Location of the Liquid-Gas Interface

Sensors that can detect the location of the liquid surface (or the depth of liquid above the sensor) are usually called *level* sensors; some of them are adaptations of wet-dry or other kinds of point sensors. Level sensors have a long history of use, dating back to at least the 1960s.[8] Common forms of level sensors are pressure transducers and ultrasonic probes. (Capacitance probes can also be used as level sensors, but because of their widespread use in many vehicles, they will be discussed separately below.)

Pressure sensors require that the liquid is not in a weightless condition since they measure the pressure head, or weight, of the liquid above the location of the sensor. Commonly, a pressure transducer is inserted at the bottom of a gauge line that extends from the bottom of the tank to the top. The pressure sensor thus detects the difference in pressure between the gas at the top of the tank and the liquid at the bottom of the tank; this difference can be related to the depth of the liquid when the state (i.e., pressure and temperature) of the liquid and gas are known.

Ultrasonic level sensors transmit an ultrasonic pulse through the liquid.[9,10] The mismatch in acoustic impedance at the liquid-gas interface generates an echo that is transmitted back through the liquid to an ultrasonic receiver at the transducer location. The time between the first pulse and the echo is related to the depth of liquid above the transducer by the sonic velocity in the liquid. Since this type of sensor does not depend on the weight of the liquid, it is, in principle, applicable to low-gravity conditions; however, the liquid would have to be maintained in a

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[8] Ring, E., **Rocket Propellant and Pressurization Systems**, Prentice-Hall Book Co., 1964.

[9] Orazietti, A. J., Orton, G. F., and Schreib, R., *Propellant Gaging for Geostationary Satellites*, AIAA Paper 86-1716, 1986.

[10] Jacobson, S. A., Korba, J. M., Lynnworth, L. C., Nguyen, T. H., Orton, G. F., and Orazietti, A. J., *Low-Gravity Sensing of Liquid/Vapor Interface and Transient Liquid Flow*, **IEEE Trans., Ultrasonics, Ferroelectrics, and Frequency Control, UUFC-34**, No. 2, pp. 212-224, 1987.

known configuration above the sensor by a capillary-based propellant management device. An alternative form of ultrasonic level sensor is a torsional wave guide.[9] The principle of this sensor is that the speed of a torsional wave along the wave guide (e.g., a rod) depends on whether the wave guide is in liquid or gas. The impedance mismatch at the liquid-gas interface generates an echo that is detected and interpreted in terms of the length of the wave guide that is immersed in liquid. In proof-of-concept tests conducted during zero-g flights of a KC-135 airplane, it was found, however, that liquid adhered to the nominally dry portions of the wave guide and seriously degraded the accuracy of the gauging.

2.3   Bookkeeping and Other Propellant Consumption Sensors

In the absence of a specific gauging system, the quantity of propellants remaining in a tank can be estimated by determining the consumption of the propellants that have already been used, compared to the quantity initially loaded in the tank; this system is commonly called *bookkeeping*. A variety of methods and sensors are used to implement the bookkeeping method, sometimes separately, but more commonly in conjunction. These include:

- Flow meters or venturis in the lines between the tanks and engines (or gas generators) to measure propellant flowrates.

- Flowrate determination by measuring pump pressure in conjunction with pump performance curves.

- Calibrations of engine thrust versus propellant flowrate and tank pressure.

Various kinds of flow meters, turbine meters, accelerometers, and pressure sensors are required for the bookkeeping method. The method can only be implemented during periods of engine thrusting. Its main disadvantage is that errors made in estimating the propellant consumption accumulate over time, and it is, therefore, of limited accuracy, especially, near the point of propellant depletion. Moreover, the method is not able to detect leaks.

Other propellant consumption methods include:

- Vehicle acceleration compared to engine thrust, to determine vehicle mass at a given time compared to the empty weight of the vehicle.

- Ullage pressure decay (for tanks that are initially pressurized) as the liquid is drained from the tank and the ullage volume increases.

2.4   Cylindrical Capacitance Probes

Capacitance probes for propellant gauging have a long history of use[11]. They can provide a continuous indication of the propellant liquid level in a tank during engine burns. A typical

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[11] Szabo, S. V., Jr., Berns, J. A., and Stofan, A. J., *CENTAUR Launch Vehicle Propellant Utilization System*, NASA TN D-4848, 1968.

capacitance probe is a cylindrical tube containing a central wire or rod, which extends over all or most of the tank length, see Figure 2.2. The probe is open to the tank contents, either by being open at each end of the tube or by drilling an array of holes in the tube wall. In either case, when the liquid is in a settled condition, the level of liquid in the tube coincides with the level in the tank. An electric field is established between the central wire or rod and the wall of the cylindrical tube, and the total electrical capacitance of the annular space between the central rod or wire and the tube is measured. Since the dielectric constant of a liquid is substantially different from the dielectric constant of a gas, the total capacitance of the probe depends on the proportion of it that is filled with liquid. Thus, the measured capacitance can be interpreted in terms of the liquid quantity in the tank. With suitable electronics, the measurements can be made in real time. This type of probe clearly depends on the liquid being settled, and can, therefore, only be used for gauging during periods of thrusting. In principle, a capacitance probe might be applicable to low gravity if the liquid configuration is controlled by propellant management devices. In low gravity, however, capillary forces in the annular gap between the central rod/wire and the cylinder wall would cause the liquid meniscus location to differ from the liquid level in the tank and, thus, cause an inaccurate reading (which may be small and could be compensated for). Depending on the design, the probe can also be sensitive to liquid motions such as occurred with the first landing of the Lunar Excursion Module on the moon, for which nonlinear sloshing lowered the effective level of the liquid within the gauge to the point that a premature low liquid level warning was given.[12]
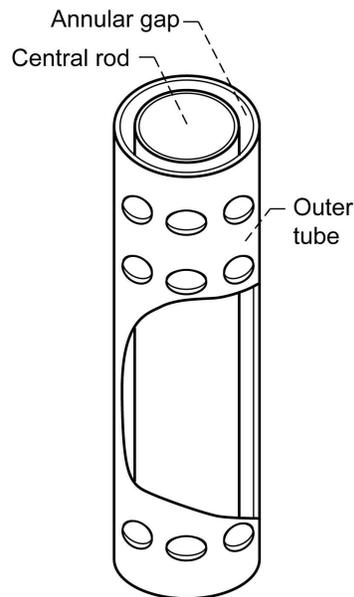
Figure 2.2 Schematic of cylindrical
capacitance probe with perforations.

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[12] Rimer, M., and Stephens, D. G., *The Effect of Liquid Oscillations on the LM Propellant Quantity Gauge System,* **Shock and Vibration Bulletin,** 41, Pat 7, pp. 181-194, 1970.

3. GAUGING SYSTEMS OF PAST AND CURRENT VEHICLES AND SPACECRAFT

3.1 Vehicle Data Listings

This section describes the gauging systems used in a variety of vehicles and spacecraft, from about the 1960s to the present, to the extent that such information is available and relevant. These systems are summarized in Appendix A and they are presently roughly in the chronological order of their first use.

The data provided for each vehicle includes:

- Dates of use

- Gauging method

- Low-G mission and Bond Number

- Propellants and their states

- Tank capacity, size, or mass of contained propellants

- Gauging frequency

- Gauging uncertainty of the method

- Reliability of the gauging method

- Comments or descriptions of the gauging method

- References for the cited data and information

It should be noted that many of the vehicles in the listings have a tank configuration that employs a common bulkhead between the fuel and the oxidizer tanks. The "upper" tank is generally in the shape of a cylinder with ellipsoidal or spherical domes; the lower dome of this tank forms the common bulkhead between the tanks and is generally concave with respect to the upper tank, as shown in Figure 3.1. For conciseness, this kind of tank configuration is generally described in the vehicle listings as a *two-tank domed cylinder*.

In some cases, information on the gauging systems used by specific vehicles was not available, at least not in the open literature. In particular, this lack of information included the Japanese H-5 vehicle and all of the Russian vehicles. It is known, however, that some Russian vehicles employ bookkeeping as the gauging method. NASA contacts indicated that the propulsion system for the International Space Station is also a Russian-managed system, and little or no information concerning its gauging method is available.
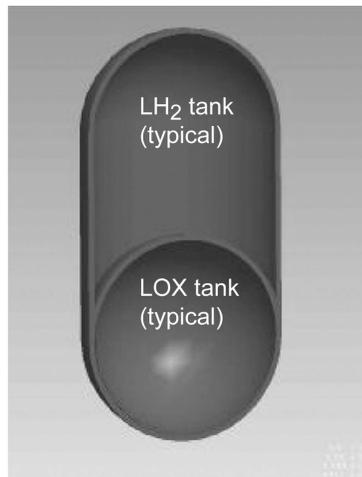
Figure 3.1 Cutaway view of generic
domed tank with common bulkhead.

3.2 Propellant Abbreviations

The following abbreviations are used for propellant names in the vehicle listings:

- Aerozine 50 – mixture of 50% hydrazine and 50% UMDH by weight

- LH2 – liquid hydrogen

- LOX – liquid oxygen

- MMH – monomethyl hydrazine

- N_2O_4 – nitrogen tetraoxide

- RFNA – red fuming nitric acid

- RP1 – Rocket Propellant One (essentially kerosene)

- UMDH – unsymmetrical dimethyl hydrazine

3.3 Significance and Importance of the Bond Number

As was discussed in Section 2, some gauging systems use level sensors to determine the position of the liquid free surface and thereby to infer the amount of liquid in the tank. These sensors depend on the liquid having a flat free surface with a known orientation relative to the axis of the sensor. Whether or not the free surface of a liquid is flat in a low-gravity environment depends primarily on the contact angle of the liquid at the tank wall and the value of a dimensionless parameter named the Bond Number N_{Bo}, which is the physical criterion that

delineates whether the environment of a liquid should be considered as being "low gravity" or not. The Bond Number compares the importance of the weight of the liquid relative to capillary forces at the liquid surface in determining the liquid configuration. It is defined as:

$$N_{Bo} = \frac{rgD^2}{s}$$

In this relation, ρ is the liquid density, g is the effective gravity level, D is a characteristic tank dimension such as diameter, and σ is the liquid surface tension. When $N_{Bo} < 1$, the environment is low gravity and the liquid configuration is dominated by capillary or surface tension effects, rather than the weight of the liquid. The value of the effective gravity for a vehicle in near earth orbit is about 10^{-6} to 10^{-7} of standard gravity (depending on the vehicle size and configuration), and the value of σ/ρ for liquid hydrogen under standard conditions is about 26.7 cm^3/sec^2 and about 11.6 cm^3/sec^2 for liquid oxygen. Consequently, for a vehicle in earth orbit, the value of $N_{Bo} \approx 1$ or less for cryogenic liquids, even for tanks with a diameter as large as 10 m. This conclusion is also valid for storable propellants because of their approximately similar values of σ/ρ. Because of these low values of N_{Bo}, the liquid configuration in a tank in low gravity is generally uncertain and the free surface is not flat. When coupled with the extremely slow response of liquid in low gravity to a disturbance, it can be concluded that conventional gauging systems that rely on "settled" liquids, or a flat free surface oriented in a known direction relative to the axis of the gauge, cannot be used reliably in low gravity.

4. RESEARCH AND DEVELOPMENT PROGRAMS ON ZERO-GRAVITY GAUGING SYSTEMS

Many kinds of gauging systems have been proposed as being applicable to zero-gravity conditions, which is generally taken to mean that the liquid does not have to be settled or its configuration specified. All of the systems discussed here have been investigated at least in a breadboard form in ground tests. A few have been tested in zero gravity to some extent. The uncertainty levels found for these gauging methods in breadboard and ground tests are difficult to extrapolate to flight tanks and arbitrary liquid configurations; at this point the true uncertainty is still to be determined.

As with the previous section on vehicle gauging systems, one or more representative examples of each proposed system is described individually. Information on these gauging systems can be found in Appendix B.

APPENDIX A

GAUGING SYSTEMS OF PAST AND CURRENT VEHICLES
AND SPACECRAFT

VEHICLE: AGENA-D (target vehicle for the GEMINI program).

DATES: Early to mid 1960s.

GAUGING METHOD: Augmented bookkeeping.

LOW-G MISSION: Coasting between burns; gauging only during burns (settled liquids).

BOND NO.: $N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during coasting.

PROPELLANTS: Inhibited RFNA and UDMH.

PROPELLANT STATE: Liquid (pressurized).

QUANTITY: Fuel tank volume ≈ 7.3 ft^3 (sphere with diameter ≈ 5.2 ft); oxidizer tank volume ≈ 98.4 ft^3 (domed cylinder with diameter ≈ 5.2 ft, length ≈ 4.6 ft).

GAUGING FREQUENCY: During engine burns (once or twice during the flight).

UNCERTAINTY: Not specified, but on the order of $\pm 5\%$ of full tank capacity.

RELIABILITY: Not specified, but no problems noted.

COMMENTS: Propellant consumption is needed only to determine flight performance parameters. "Start" tanks are used to supply the engine to settle the propellants before a burn. The propellant pump pressures are used to determine flowrates with the aid of pump head vs. flow curves, in conjunction with the gas generator ΔP, turbine speed, and augmented with PVT computations of the ullage pressurizing gas (nitrogen).

REFERENCES: Anon., *Propulsion Subsystem: Engineering Analysis Report: GEMINI-AGENA Target Vehicle,* NASA CR-96963, 1964.

VEHICLE: S-IVB Stage of SATURN V.

DATES: ~ 1965 to 1972.

GAUGING METHOD: Cylindrical capacitance probes with wet-dry (resistor) sensors.

LOW-G MISSION: Coasting between burns; gauging only during burns (settled liquids).

BOND NO.: $N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during coasting.

PROPELLANTS: LH2 and LOX.

PROPELLANT STATE: Liquid (pressurized above saturation).

GAUGING FREQUENCY: During engine burns (once or twice during the flight).

QUANTITY: LH2 tank volume ≈ 13,000 ft^3 (diameter ≈ 21.7 ft; length ≈ 36.4 ft); LOX tank volume ≈ 3,600 ft^3 (diameter ≈ 21.7 ft; length ≈ 14.8 ft).

UNCERTAINTY: ≈ ±0.5 inch of settled non-sloshing liquid level (≈ 0.3% of LOX tank length, ≈ 0.1% of LH2 tank length).

RELIABILITY: Not specified, but no problems noted over many flights.

COMMENTS: The capacitance probes (called the Propellant Utilization Probes) extend over the entire length of the tanks. Solid propellant ullage motors are used to settle the propellants before burns and for engine chilldown, supplemented by venting of the LH2 and LOX. An array of wet-dry sensors was added for an orbital experiment of liquid dynamics in zero gravity that used the S-IVB LH2 tank as a test bed.
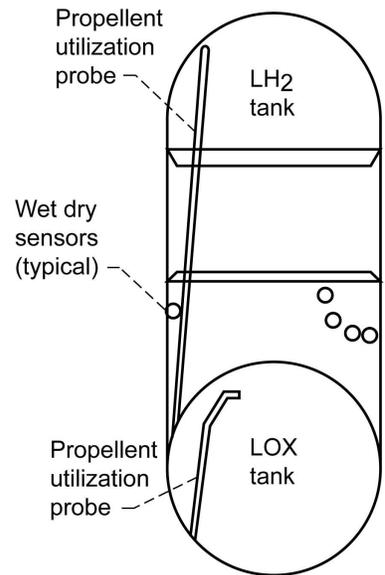
Schematic of S-IVB stage in orbital experiment configuration.

REFERENCES: Buchanan, H. J., and Bugg, F. M., *Orbital Investigation of Propellant Dynamics in a Large Rocket Booster*, NASA TN D-3968, 1967.

Swalley, F., Platt, G., and Hastings, L., *SATURN V Low-Gravity Fluid Mechanics Problems and Their Investigation by Full Scale Orbital Experiment*, **Proc. Symposium on Fluid Mechanics and Heat Transfer Under Low Gravity**, Palo Alto, Ca., pp. 1-1 through 1-25, 1965.

VEHICLE:	CENTAUR upper stage (prior to upgrade in 1990s).
DATES:	1968 to time of upgrade for ATLAS.
GAUGING METHOD:	Cylindrical capacitance probes.
LOW-G MISSION:	Coasting between burns; gauging only during burns (settled liquids).
BOND NO.:	$N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during coasting.
PROPELLANTS:	LH2 and LOX.
PROPELLANT STATE:	Liquid (pressurized above saturation).
GAUGING FREQUENCY:	Continuous during engine burns (once or twice during the flight).
QUANTITY:	LH2 tank volume $\approx 1{,}150$ ft^3 (diameter ≈ 10 ft; length ≈ 14.8 ft); LOX tank volume ≈ 320 ft^3 (diameter ≈ 10 ft; length ≈ 6.1 ft).
UNCERTAINTY:	Not stated, but predicted to have less than 20 kg of LH2 remaining at the instant of LH2-LOX depletion, for an initial propellant mass of 13,600 kg.
RELIABILITY:	Not specified, but no problems noted over many flights.
COMMENTS:	The tank configuration is a two-tank domed cylinder. The capacitance probes extend along most of the length of each tank. The cross-section area of the central tube of the probe has a variable diameter along its length to compensate for the variable diameters of the tanks, so that the capacitance measurement directly indicates liquid mass.
REFERENCES:	Szabo, S. V., Jr., Burns, J. A., and Stofan, A. J., *CENTAUR Launch Vehicle Propellant Utilization System*, NASA TN D-4848, 1968.
	Stubblefield, W. O., *Control Dynamics Analysis of the CENTAUR Stage Propellant Utilization System*, General Dynamics Convair Report GD/C DDE65-007, 1965.
	Magrini, O. J., *Analysis of CENTAUR Propellant Utilization Difference Bridge*, NASA TM X-1440, 1967.

VEHICLE:	APOLLO Service Propulsion System.
DATES:	~ 1969 – 1972.
GAUGING METHOD:	Cylindrical capacitance probes with wet-dry point sensors and flow integrator.
LOW-G MISSION:	Gauging only during burns (settled liquids).
BOND NO.:	$N_{Bo} \gg 1$ during gauging; $N_{Bo} < 1$ coasting.
PROPELLANTS:	N_2O_4 and UMDH.
PROPELLANT STATE:	Liquid (pressurized by helium).
GAUGING FREQUENCY:	Continuous during engine burns.
QUANTITY:	Fuel tanks (two) contain 30,000 lbs of usable propellant; oxidizer tanks (two) contain 15,000 lbs of usable propellant.
UNCERTAINTY:	Unknown.
RELIABILITY:	Described as extremely reliable.
COMMENTS:	The capacitance probes are located centrally and extended along most of the length of each tank. Four wet-dry (impedance) sensors positioned along the probe and a flow integrator are used as an auxiliary backup.
REFERENCES:	Gibson, C. R., and Wood, J. A., *APOLLO Experience Report: Service Propulsion System*, NASA TN D-7375, 1973.

VEHICLE:	APOLLO Lunar Excursion Module.
DATES:	~ 1969 – 1972.
GAUGING METHOD:	Cylindrical capacitance probes and one low-level alarm (a wet-dry impedance sensor).
LOW-G MISSION:	Gauging only during burns (settled liquids).
BOND NO.:	$N_{Bo} >> 1$ during gauging.
PROPELLANTS:	N_2O_4 and Aerozine 50.
PROPELLANT STATE:	Liquid (pressurized by helium).
GAUGING FREQUENCY:	Continuous during engine burn.
QUANTITY	Two fuel and two oxidizer domed cylindrical tanks (all identical); diameter ≈ 4.17 ft; total fuel load ≈ 7,057 lbs; total oxidizer load ≈ 11,190 lbs.
UNCERTAINTY:	Depended on fill level: ±0.5% of liquid volumes of 95% to 25% fill; ±0.25% for 25% to 8% fill.
RELIABILITY:	Sloshing during the landing of the first flight caused a false low level cutoff indication when the liquid levels were actually still above the low level indicator; later flights incorporated a slosh baffle to suppress the sloshing and no further problems were noted.
COMMENTS:	The capacitance probe for each tank is a two-inch diameter cylinder containing a central wire. The low level indicator is inside the tube at the 5.6% fill level; it issues an alarm when there is only 90 seconds of burn time remaining.
REFERENCES:	Hammock, W. R., Currie, E. C., and Fisher, A. E., *APOLLO Experience Report: Descent Propulsion System*, NASA TN D-7143, 1973.
	Rimer, M., and Stephens, D. G., *The Effect of Liquid Oscillations on the LM Propellant Quantity Gauging System*, **Shock and Vibration Bulletin,** 41, 7, pp. 181-194, 1970.
	Classen, K. P., *Calibration of the Descent Propulsion System Propellant Tanks and Propellant Quantity Gauging System – Case 310*, Bellcomm Report, NASA CR-112743, 1970.

VEHICLE: APOLLO Ascent Propulsion System.

DATES: ~ 1969 – 1972.

GAUGING METHOD: Wet-dry resistor sensor.

LOW-G MISSION: Gauging only during burns (settled liquids).

BOND NO.: $N_{Bo} \gg 1$ during gauging.

PROPELLANTS: N_2O_4 and Aerozine 50.

PROPELLANT STATE: Liquid (pressurized).

GAUGING FREQUENCY: Used only as low level alarm.

QUANTITY: Two identical tanks with a total propellant load of $\approx$ 5,210 lbs; the oxidizer/fuel ratio was 1.6 to 1.

UNCERTAINTY: ~ ±0.5 inch of settled, non-sloshing liquid level.

RELIABILITY: Not specified, but no problems noted over many flights.

COMMENTS: There are multiple burns. RCS engines are used to settle the propellants for burns.

REFERENCES: Humphries, C. E., and Taylor, R. E., *APOLLO Experience Report: Ascent Propulsion System*, NASA TN D-7082, 1973.

VEHICLE:	ARIANE 1/2/3/4 First and Second Stage.
DATES:	~ 1979 – 1997.
GAUGING METHOD:	Ultrasonic liquid level sensor.
LOW-G MISSION:	First stage only during burn; second stage coasting (zero gravity), but gauging only during burns (settled liquids).
BOND NO.:	$N_{Bo} >> 1$ during burns; $N_{Bo} < 1$ during coasting.
PROPELLANTS:	N_2O_4 and UDMH.
PROPELLANT STATE:	Liquid (pressurized).
GAUGING FREQUENCY:	On demand during engine burns.
QUANTITY	Second stage fuel tank diameter $\approx$ 4.2 m; height $\approx$ 3.0 m; second stage oxidizer tank diameter $\approx$ 4.2 m, length $\approx$ 4.0 m.
UNCERTAINTY:	$\approx \pm 5$ mm (minimum) of settled, non-sloshing liquid level ($\approx$ 0.17% of fuel tank length, 0.12% of oxidizer tank length).
RELIABILITY:	Not specified, but no problems noted over many flights.
COMMENTS:	The tank configuration is a two-tank domed cylinder. Liquid interface levels are measured from 0.25 m to 3.0 m above the tank bottom (where the ultrasonic transducer and receiver were located). The method uses an ultrasonic pulse from the transducer to create an echo off the liquid-gas interface that is sensed by the receiver. The time delay is interpreted in terms of the depth of the settled liquid. An ultrasonic reflector at a known height above the tank bottom is used to generate an echo as a reference to correct for liquid temperature and pressure effects on the ultrasonic velocity.
REFERENCES:	Demarais, J. C., and Déom, A., *Ultrasonic Level-Meter for Measuring Propellant Levels in the Tanks of ARIANE First and Second Stages*, **La Rech. Aerospatiale**, No. 1980-1, 1980. pp. 13-30, 1980,
	Orazetti, A. J, Orton, G. F., and Schreib, R., *Propellant Gaging for Geostationary Satellites*, AIAA Paper 86-1716, 1986.

VEHICLE:	STS (Space Shuttle) External Tank.
DATES:	1981 to present.
GAUGING METHOD:	Wet-dry impedance sensors.
LOW-G MISSION:	None: gauging occurs only during ground loading and engine burns (settled liquids); there are no periods of coasting.
BOND NO.:	$N_{Bo} \gg 1$.
PROPELLANTS:	LH2 and LOX.
PROPELLANT STATE:	Liquid (pressurized by helium).
GAUGING FREQUENCY:	Primarily only during the eight- to 12-second period before SSME cutoff, and during ground loading.
QUANTITY:	LOX tank volume $\approx$ 19,560 ft^3 (diameter $\approx$ 27.6 ft, length $\approx$ 49.3 ft); LH2 tank volume $\approx$ 53,500 ft^3 (diameter $\approx$ 27.6 ft, length $\approx$ 96.7 ft).
UNCERTAINTY:	Not specified; at least two of the four sensors for each tank must indicate "dry" to initiate a premature engine shutdown; because of the sensor locations, the LOX dry indication occurs first.
RELIABILITY:	Sensors have failed or given erratic indications periodically for unknown reasons related to either the sensors or the electronics, or the polling method.
COMMENTS:	The tank configuration is a two-tank domed cylinder. The sensors are platinum resistors and are called Engine Cutoff Sensors (ECO sensors). The LH2 tank contains four sensors at the bottom of the tank. The four LOX sensors are in the feedline between the LOX tank and the engine. Similar sensors in the tanks at the 5%, 98%, 100%, and 102% percent fill levels are used for loading the tanks on the ground.
REFERENCES:	Rumpf, K. S., personal communication, NASA-KSC, 2006.
	Anon., *NASA Engineering and Safety Center Technical Consultation Report*, NASA RP-05-125, 2005.
	http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/et.html

VEHICLE:	STS (Space Shuttle) Reaction Control System (RCS) Tanks.
DATES:	1981 to present.
GAUGING METHOD:	"Burn Time Integration" with post-flight tank check.
LOW-G MISSION:	Gauging only during burns (settled liquids); PMDs used to orient propellants during coasting periods.
BOND NO.:	$N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during coasting.
PROPELLANTS:	N_2O_4 and MMH.
PROPELLANT STATE:	Liquid (pressurized).
GAUGING FREQUENCY:	After each burn and post-flight.
QUANTITY:	Two identical spherical tanks (diameter $\approx$ 3.25 ft); Oxidizer load $\approx$ 1,460 lbs; fuel load $\approx$ 920 lbs.
UNCERTAINTY:	$\approx \pm 3.9\%$ (maximum) of capacity for MMH tank; $\approx \pm 5.4\%$ for N_2O_4 tank.
RELIABILITY:	Not specified, but no problems noted over many flights.
COMMENTS:	Propellant usage is computed in flight by integrating the engine thrusting periods with curves of thrust vs. flowrate. The propellant usage is checked after the flight by comparing the pre-launch and post-flight propellant masses. Filling on the ground is gauged by a combination of turbine meters and Coriolis meters in the fill lines, and PVT calculations of the ullage pressure after the tanks are loaded.
REFERENCES:	Koci, F. D., personal communication, NASA-KSC, 2006.
	Duhon, D., *Error Analysis of the Shuttle RCS Propellant Gauging Models*, McDonnell-Douglas Report, 1975.
	http://science.ksc.nasa.gov/shuttle/technology/sts-rcs.html#sts-rcs

VEHICLE:	STS (Space Shuttle) Orbital Maneuvering System (OMS) Tanks.
DATES:	1981 to present.
GAUGING METHOD:	Cylindrical capacitance probes.
LOW-G MISSION:	Gauging only during burns (settled liquids); propellants oriented during coasting by PMDs.
BOND NO.:	$N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during coasting.
PROPELLANTS:	N_2O_4 and MMH.
PROPELLANT STATE:	Liquid (pressurized).
GAUGING FREQUENCY:	During any of the OMS engine burns.
QUANTITY	Two tanks; volume of each tank ≈ 89.9 ft^3; diameter ≈ 4.1 ft, length ≈ 8.0 ft.
UNCERTAINTY:	Specified as better than 0.5% of tank volume.
RELIABILITY:	Not specified, but there is a history of partial failures during flight.
COMMENTS:	Each tank contains a forward and an aft capacitance probe. The probe is an axial cylinder with a central rod. There is an ungaugeable region between the upper surface of the bulkhead screen and the bottom of the forward probe, which includes tank fill levels from 30% to 45%. Flowrate and burn-time calculations are used to compute the liquid mass for these liquid fill levels.

Schematic of an OMS tank.

REFERENCES:	Lunney, B. C., *OMS Gauging System*, NASA-JSC Report OMS/RCS/JSC-18958, Rev.B, 1980.
	http://science.ksc.nasa.gov/shuttle/technology/sts-oms.html#sts-oms-propellant
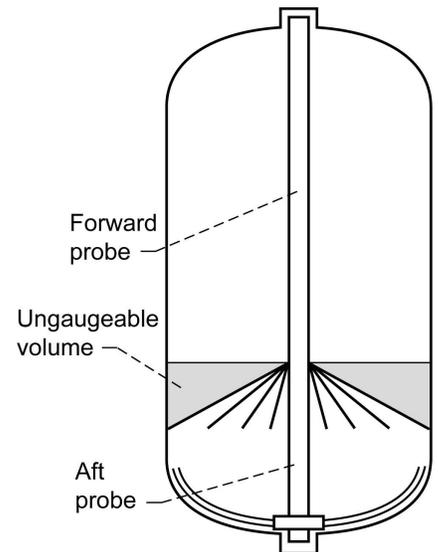
VEHICLE: HS601 Geosynchronous 3-Axis Stabilized Satellite (stationkeeping propellant tanks).

DATES: 1991 to present.

GAUGING METHOD: Isothermal Pressure-Volume-Temperature (PVT).

LOW-G MISSION: Zero gravity with liquid oriented by PMDs.

BOND NO.: $N_{Bo} \approx 0$.

PROPELLANTS: N_2O_4 and MMH.

PROPELLANT STATE: Liquid (pressurized by helium).

GAUGING FREQUENCY: During tank re-pressurization after each engine burn.

QUANTITY: Four identical cylindrical tanks with a diameter of 2.9 ft and spherical domes; volume of each tank ≈ 5.9 ft^3.

UNCERTAINTY: 0.22% of tank volume at midlife, which satisfies the requirement for two-month notification before the end of life.

RELIABILITY: Not specified, but no problems noted.

COMMENTS: Because the satellite uses an integrated bipropellant system for both orbit insertion and on-orbit stationkeeping, there is a substantial uncertainty in the propellant masses in the tanks at the start of stationkeeping activities; this ruled out the bookkeeping methods used for previous geosynchronous satellites. The PVT method for this application is based on isothermal calculations, because thermal and pressure transients prevent an adiabatic calculation. Each of the four tanks is gauged separately and each gauging instance requires several hours to achieve isothermal equilibrium in both the high-pressure helium tank and the gauged propellant tank. During this time, external thermal effects perturb the system, so the three tanks not being gauged are used as reference thermometers to correct for the thermal effects on the ΔP measured in the gauged tank.

REFERENCES: Tam, W. H., Jaekle, D. E., and Farokhi, S. A., *Design, and Manufacture of the HS 601 Block II Propellant Tank Assembly*, AIAA Paper 98-3199, 1998.

Chobotov, M. V., and Purohit, G. P., *Low Gravity Propellant Gauging System for Accurate Predictions of Spacecraft End-of-Life*, **AIAA J. Spacecraft & Rockets,** 30, pp. 92-101, 1993.

Chobotov, M. V., *Propellant Measurement System*, U. S. Patent Application 07/252740, 1988.

VEHICLE:	ANIK E Geosynchronous 3-Axis Stabilized Satellite (stationkeeping propellant tanks).
DATES:	1991 to present.
GAUGING METHOD:	Thermal Pulse Pressure-Volume-Temperature (PVT).
LOW-G MISSION:	Zero gravity with liquid oriented by PMDs.
BOND NO.:	$N_{Bo} \approx 0$.
PROPELLANTS:	Hydrazine.
PROPELLANT STATE:	Liquid (pressurized).
GAUGING FREQUENCY:	On demand and after each engine burn.
QUANTITY	Four identical spherical tanks; diameter ≈ 1.25 ft.
UNCERTAINTY:	Within 1.5 kg for each tank at the time when the tank has only 10 kg of fuel remaining; this result compares well with bookkeeping and is sufficient for end-of-life estimations.
RELIABILITY:	Not specified, but no problems noted.
COMMENTS:	A heater in the tank wall imparts a thermal pulse to the tank contents. An array of thermocouples is used to measure the small temperature rise of the propellants. With the temperature data and the heating pulse, a thermal model is used to compute the liquid mass in the tank. The accuracy of the method increases as the tanks become near-empty. A very detailed thermal model is used offline to check the online simplified thermal model. Early in the mission, the pressure-volume-temperature method is used for gauging. A modification of the thermal pulse method was used in a superfluid helium experiment (SHOOT) during the flight of STS 57 to gauge the mass of superfluid helium in low gravity.
REFERENCES:	Yip, A., Yendler, B., Martin, T. A., and Collicott, S. H., *ANIK E Spacecraft Life Extension*, 8th International Conference on Space Operations, Montreal, 2004.
	Ambrose, J., Yendler, B., and Collicott, S. H., *Modeling to Evaluate a Spacecraft Propellant Gauging System*, **AIAA J. Spacecraft & Rockets,** 37, pp. 833-834, 2000.
	Yendler, B., *Review of Propellant Gauging Methods*, AIAA Paper 2006-939, 2006.
	http://cryowwweber.gsfc.nasa.gov/XRS/Mass_gauge.html

VEHICLE:　　　　　　ARIANE 5 First and Second (ESC-A) Stages.

DATES:　　　　　　　1997 to present.

GAUGING METHOD:　Cylindrical capacitance probes for both stages.

LOW-G MISSION:　　Second stage can have several periods of coasting and engine restarts.

BOND NO.:　　　　　$N_{Bo} >> 1$ during burns; $N_{Bo} < 1$ during second stage coasting.

PROPELLANTS:　　　LH2 and LOX (both stages).

PROPELLANT STATE:　Liquid (pressurized by helium).

QUANTITY:　　　　　Second stage contains 12 tonnes of LOX in a domed cylindrical LOX tank (diameter = 2.6 m and length = 2.8 m) and 2.7 tonnes of LH2 in the LH2 tank (diameter = 5.4 m and a length =3.0 m).

GAUGING FREQUENCY: First stage: continuous; second stage: during engine burns.

UNCERTAINTY:　　　Not specified, but estimated as ± 5 mm for settled, non-sloshing liquid (≈ 0.18% of LOX tank length; 0.17% of LH2 tank length).

RELIABILITY:　　　Not specified, but no problems noted.

COMMENTS:　　　　The tank configuration is a modification of a two-tank domed cylinder. The LOX and LH2 tanks share a common bulkhead, but the LOX tank is the upper tank and the LH2 tank is the lower tank. The common bulkhead between the tanks is concave relative to the wider LH2 tank.

REFERENCES:　　　http://www.dta.airliquide.com/space/space_1.1.1.html

　　　　　　　　　　http://www.dta.airliquide.com/space/space_1.1.7.html

VEHICLE:	DELTA IV First and Second Stages.
DATES:	2002 to present.
GAUGING METHOD:	First stage: wet-dry resistance sensors; second stage: ΔP liquid level sensors.
LOW-G MISSION:	Gauging only during engine burns; second stage can have several periods of coasting and engine restarts.
BOND NO.:	$N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during second stage coasting.
PROPELLANTS:	LH2 and LOX (both stages).
PROPELLANT STATE:	Liquid (pressurized by helium).
GAUGING FREQUENCY:	First stage: continuous; second stage: during engine burns.
QUANTITY:	For the 4.0 m second stage (diameter = 4.0 m), propellant mass $\approx$ 20.4 tons (maximum); for the 5.0 m second stage (diameter = 5.1 m), propellant mass $\approx$ 27.2 tons (maximum).
UNCERTAINTY:	$\approx \pm 0.5$ inch of settled, non-sloshing liquid level.
RELIABILITY:	First stage gauge reliability is similar to the gauges used in STS external tank; reliability is not critical for the second stage (for reasons explained below).
COMMENTS:	The first stage wet-dry sensors are located at the ~ 0% fill level and at the 20% fill level; similar sensors are used to monitor the tank filling on the ground where reliability is critical. The second stage tank configuration is a two-tank domed cylinder. The second stage tanks use a gauge line from the bottom of the tank to the top to determine the ΔP of the liquid relative to the ullage pressure, from which the liquid depth is inferred. The ΔP sensors are used only to acquire data for reconstruction post-flight of fuel consumption vs. flight profile; this data is augmented by the vehicle acceleration data. The propellants are settled before an engine burn by LOX boiloff flow and the attitude control thrusters. The earlier DELTA III vehicle used a 16-inch long cylindrical capacitance probe for its first stage.
REFERENCES:	Olsen, A. and Petrilla, S., personal communication, Boeing Integrated Defense Systems, 2006.
	http://www.geocities.com/launchreport/delta4.html#config

VEHICLE:	ATLAS 3/4/5 First and Second Stage (upgraded CENTAUR).
DATES:	2002 to present.
GAUGING METHOD:	ΔP liquid level sensor for both stages.
LOW-G MISSION:	Gauging only during engine burns; second stage can have several periods of coasting and engine restarts.
BOND NO.:	$N_{Bo} \gg 1$ during burns; $N_{Bo} < 1$ during second stage coasting.
PROPELLANTS:	First stage: LOX and RP1; Second stage: LH2 and LOX.
PROPELLANT STATE:	Liquid (pressurized).
GAUGING FREQUENCY:	25 times per second during burns.
QUANTITY:	First stage propellant mass $\approx$ 6,500,000 lbs (maximum). Second stage propellant mass $\approx$ 46,000 lbs (maximum); second stage oxidizer tank volume $\approx$ 550 ft^3 (diameter $\approx$ 10.0 ft, length $\approx$ 5.25 ft); second stage fuel tank volume $\approx$ 1,970 ft^3 (diameter $\approx$ 10.0 ft, length $\approx$ 25.1 ft).
UNCERTAINTY:	$\approx \pm 0.5$ inch of settled, non-sloshing liquid level ($\approx$ 0.8% of second stage LOX tank length; 0.2% of LH2 tank length).
RELIABILITY:	Not specified, but no problems noted.
COMMENTS:	Second stage tank configuration is a two-tank domed cylinder. The ΔP gauge lines run from the bottom of each tank to the top to measure the liquid head, from which the depth of the liquid is inferred, in conjunction with data about the vehicle acceleration and the ullage and liquid densities. These sensors replaced the capacitance probes used previously in order to obtain better reliability and lower cost. Post-flight modeling and measured residual propellants are used to check the ΔP sensors. An optical low level sensor in the first stage LOX tank is used with the ΔP sensor when the liquid level nears depletion.
REFERENCES:	Kutter, B., personal communication, Lockheed Martin Corporation, 2006. http://www.astronautix.com/lvs/atlasv.htm

APPENDIX B

RESEARCH AND DEVELOPMENT PROGRAMS ON ZERO-GRAVITY GAUGING SYSTEMS

TECHNIQUE: Pressure-Volume-Temperature (PVT).

DATES: ~ 1960 to present.

PROPELLANTS: Storable and cryogenic propellants; for storable propellants, the method is already in use for communication satellites with good results.

ZERO-G TESTS: Version (a): Space Shuttle GAS Can experiment (1994) (similar technique used for communication satellites).
Version (b): Breadboard apparatus (2006).
Version (c): U. S. Patent (~ 1960).

GROUND TESTS: Version (a): Simulated storable propellant.
Version (b): Liquid nitrogen.
Version (c): Water.

UNCERTAINTY: Version (a): ±2% of tank volume for GAS Can experiment.
Version (b): Variable with fill volume and tank conditions.
Version (c): Not specified.

DESCRIPTION: All versions perturb the static pressure of the ullage gas. For Versions (a) and (b), a small amount of pressurizing gas (usually helium) is injected into the ullage from a separate high-pressure tank; for Version (c), gas is extracted from the ullage and compressed separately before being re-injected into the ullage. With Versions (a) and (b), the pressure and temperature change of the high-pressure tank is measured, from which the mass of gas injected into the ullage is determined; the pressure and temperature changes of the ullage are also measured and, since the change in the mass of ullage gas is known, these measurements are used to determine the ullage volume. With Version (c), the pressure and temperature changes of the ullage are measured. The temperature and pressure change of the gas extracted from the ullage (for a known amount of volume compression of the extracted gas) are also measured to determine the mass of gas extracted from the ullage. These measurements allow the volume of the ullage gas to be determined.

REFERENCES: (a) Monti, R. and Berry, W., *Liquid Gauging in Space: The G-22 Experiment*, **ESA J.,** 18, pp. 51-61, 1994.

Chobotov, M. V., and Purohit, G. P., *Low Gravity Propellant Gauging System for Accurate Predictions of Spacecraft End-of-Life*, **AIAA J. Spacecraft & Rockets,** 30, pp. 92-101, 1993.

(b) Van Dresar, N. T., *An Uncertainty Analysis of the PVT Gauging Method Applied to Sub-Critical Cryogenic Propellant Tanks*, **Cryogenics**, 44, pp 515-523, 2004.

Van Dresar, N. T., *PVT Gauging with Liquid Nitrogen*, **Cryogenics**, 46, pp 118-125, 2006.

(c) Morris, B. G., *Tank Gauging Apparatus and Method*, U. S. Patent 4,956,996, 1960.
Downey, M. G., and Trevathan, J. T., *Zero Gravity Vortex Vent and PVT Gaging System*, Proc. 1989 JANNAF Propulsion Meeting, Cleveland, Ohio, 1989.

TECHNIQUE: Radio Frequency (RF).

DATES: Early versions in 1960s and late 1980s; research is continuing at NASA-GRC.

PROPELLANTS: Applicable to storable and cryogenic propellants; may not be applicable to liquids with significant dissipation at radio frequencies.

ZERO-G TESTS: Low- g aircraft tests using liquid nitrogen in an 18-inch diameter tank.

GROUND TESTS: Breadboard tests using RP-1, LH2, LOX, liquid nitrogen, water and shaped volumes of paraffin wax.

UNCERTAINTY: Still to be determined for arbitrary liquid configurations; some tests suggest 3% uncertainty can be achieved; recent tests (2006) have demonstrated 1% uncertainty when comparing computer models with settled-liquid tests.

DESCRIPTION: An antenna inside the tank "fills" the tank with radio frequency waves, and the power reflected back through the antenna is measured. A swept frequency signal is used to identify the resonant frequencies of the tank, at which the reflected power is minimized. The resonant frequencies depend on the tank shape, and the location, quantity and dielectric constant of the liquid. The resonant frequencies and mode shapes of the waves depend on the dielectric constant of the liquid, the tank shape, and the liquid mass. Various methods can be used to relate the resonant frequencies to the liquid mass, including "mode counting" and "modal analysis." Most of the past work has used modal analysis of four to six modes. In any case, heavy data reduction analyses are required. Some ground tests have used shaped paraffin wax volumes in a tank to simulate zero-g liquid configurations.

REFERENCES: Lockhart, James D., *RF Liquid Level Sensing Techniques* (Lockheed Missiles and Space Co.), NASA CR-74204, 1966.

Anon., *RF Quantity Gauging System*, Bendix Corporation, NASA CR-115584, 1972.

Collier, R., Ellerbruch, D., Cruz, J., Stokes, R., Luft, P., Petersson, R., Heister, A., *Mass Quantity Gauging by RF Mode Analysis*, NBS Interim Report NBSIR 73-318, 1973.

Bahr, A. J., Karp, A., *Study of Zero-G Propellant Gauging Based on Tank Electromagnetic Resonances*, Stanford Research Institute, NASA CR-150270, 1975.

Van Leuven, K., *Zero Gravity Quantity Gauging System Bench-Top Tests*, Ball Aerospace Report # ZG-011, 1988.

Van Leuven, K., *RF Modal Quantity Gauging*, Proc. 1989 JANNAF Propulsion Meeting, Cleveland, Ohio, 1989.

Zimmerli, G., Vaden, K., Herlacher, M., Buchanan, D., and Van Dresar, N., *Radio Frequency Mass Gauging*, High Energy Space Systems In-Space Cryogenic Depot Project (NASA report), 2006.

TECHNIQUE: "Whole Tank" Capacitance Gauge.

DATES: ~ 1967.

PROPELLANTS: Tested with water; applicable to storable and cryogenic propellants.

ZERO-G TESTS: None.

GROUND TESTS: Breadboard tests were conducted on a small cylindrical tank with ellipsoidal domes containing water.

UNCERTAINTY: Depends on the number of electrodes. Ground tests used 12 electrodes and the expected value was ±2% of the full tank.

DESCRIPTION: Electrodes that extend over the entire outside length of the tank are distributed around the circumference of the tank; one-half are held at a + voltage and one-half at a − voltage. The capacitance of the array of electrodes is a function of the mass of liquid in the tank. The tank and electrodes have to be calibrated as a function of fill level. The ground test program was not completed because it was found that the electrode configuration was faulty in theory; a corrected configuration was developed but not tested before the end of the program.
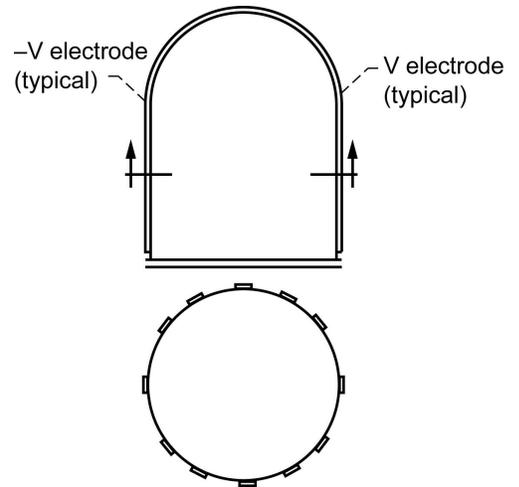
Schematic of "whole tank" capacitance probe.

REFERENCES: Anon., *Capacitance Propellant Gauging Study for Orbiting Spacecraft – Final Development Report*, Trans-Sonics Report (N67-34606), 1967.

TECHNIQUE: Nucleonic Gauge ("X-Raying Tank").

DATES: Two versions: (a) ~ 1966 and (b) ~ 1986.

PROPELLANTS: Developed for storable propellants, but should be applicable to cryogens.

ZERO-G TESTS: Version (a): None.
Version (b): Used in three-axis stabilized geostationary satellites with PMDs for liquid configuration control.

GROUND TESTS: Version (a): Tested with water in a mockup OMS tank.

UNCERTAINTY: Version (a): ≤0.35% of full tank.
Version (b): Unknown (end of life prediction within ± several months).

DESCRIPTION: Version (a): The tank contents are "X-Rayed" by Cesium-137 sources and receiver (four of each, the sources on a plane outside the bottom of the tank, and the receivers on a plane outside the top of the tank). The total attenuation of the gamma rays between the sources and the receivers is proportional to the liquid mass. The tank must be calibrated for various liquid levels.

Version (b): Similar to (a) but Krypton-85 gas is used for the sources.

REFERENCES: (a) Dyes, O., and Bupp, F. E., *Nucleonic Zero-G Propellant Gaging System*, **ISA Trans.,** 15, pp. 42-56, 1976.

Bupp, F. E., *Development of a Zero-G Gaging System*, Report AFRPL-TR-74-5, 1974.

(b) Orazietti, A. J., Orton, G. F., and Schreib, R., *Propellant Gaging for Geostationary Satellites*, AIAA Paper 86-1716, 1986.
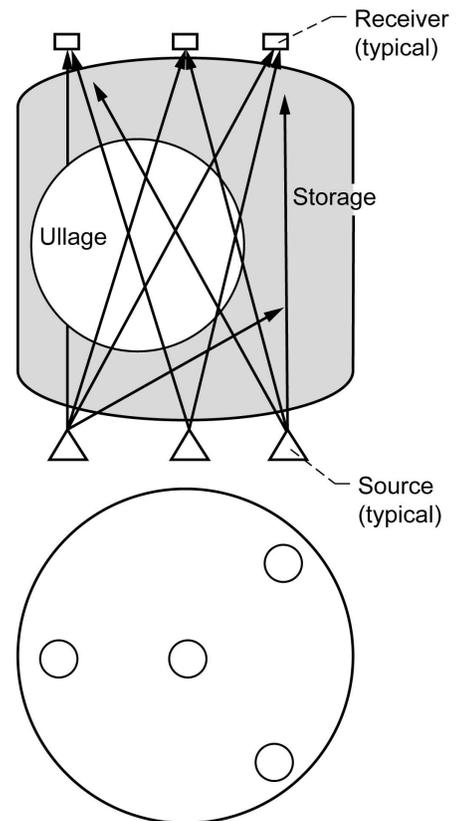
Schematic of nucleonic gauge.

TECHNIQUE: Resonant Infrasonic Gauging System (RIGS).

DATES: ~ 1971.

PROPELLANTS: Developed for storable propellants, but should be applicable to cryogens.

ZERO-G TESTS: None.

GROUND TESTS: Breadboard tests using a tank filled with water.

UNCERTAINTY: Claimed to be good for settled liquids; unknown for non-settled liquids.

DESCRIPTION: A variable-frequency bellows or pulsar is used to set up acoustic waves in the ullage space, and the resonant acoustic frequency of the space is determined by pressure measurements. The resonant frequency depends strongly on the ullage volume and less strongly on the ullage configuration. The ullage volume is determined by analyzing the resonant acoustic frequencies, and the liquid volume is determined as the difference between the tank volume and the ullage volume. This system is a modification of the volume perturbation (compression) method described later.

REFERENCES: Anon., *Propellant Quantity Gauging System Under Zero-G*, TRW Report, NASA CR-119935, 1971.

TECHNIQUE: Ullage Volume Perturbation (Compression Mass Gauge).

DATES: Three versions: (a) ~1988; (b) ~ 1994; and (c) ~ 1995 – 2004.

PROPELLANTS: Applicable to storable and cryogenic propellants.

ZERO-G TESTS: Version (a): 1994 Space Shuttle GAS Can experiment (with PMDs and simulated storable propellant).
Version (b): None.
Version (c): None, although flight hardware was planned and designed for the zero-g environment of the Solar Orbital Thermal Vehicle Space Experiment (SOTVSE) but not conducted.

GROUND TESTS: Version (b): Breadboard ground tests using water in a barrel-size tank.
Version (c): Breadboard tests using water, alcohol, liquid nitrogen, and LH2 in tanks of various sizes; flight-like hardware version tested in liquid nitrogen.

UNCERTAINTY: Versions (a), (b), and (c) all claim uncertainties of ±2% of tank volume.

DESCRIPTION: A bellows varies the ullage volume V_G by a small amount ΔV, typically 0.01% of tank volume V_T, although Version (a) used a much larger value. A pressure transducer determines the tank pressure change ΔP and static pressure P. To determine V_G, Version (a) uses the relation $V_G/V_T = 1 - (P/P_o)(\Delta P_o/\Delta P)$ where the subscript o indicates a value measured with the tank filled with vapor only. The other versions use $V_G = \gamma P(\Delta V/\Delta P)$ where γ is the adiabatic gas constant for the vapor. Liquid volume is determined from the difference between V_T and V_G. Version (a) should have its best accuracy for nearly empty tanks, and the other versions should have their best accuracy for nearly full tanks. A combination of the two methods might be best to cover the range of tank fills although no method did this.
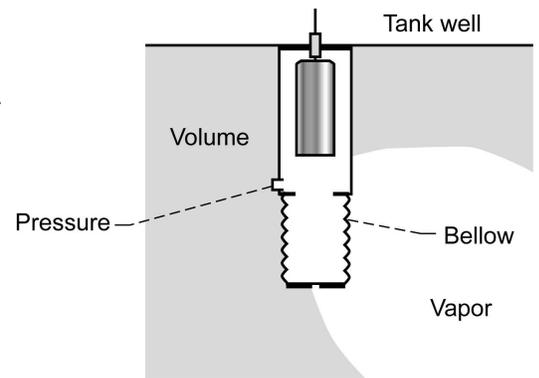
Schematic of a generic ullage volume perturbation gauge.

REFERENCES:

(a) Monti, R. and Berry, W., *Liquid Gauging in Space: The G-22 Experiment*, **ESA J.,** 18, pp. 51-61, 1994.

(b) Mord, A. J., Snyder, H. A., Kilpatrick, K. A., Hermanson, L. A., Hopkins, R. A., and Van Gundy, D. A., *Fluid Quantity Gaging*, Ball Aerospace Report DRL-5, DRD MA-183T, F88-06, 1988.

(c) Dodge, F. T., Green, S. T., Petullo, S. P., and Van Dresar, N. T., *Development and Design of Zero-G Liquid Quantity Gauge for Solar Thermal Vehicle*, NASA/TP-2002-211595, 2002.

Deffenbaugh, D. M., Dodge, F. T., Green, S. T., Walter, D. B., and Siebenaler, S. P., *Microgravity Advanced Upper –Stage Gauging Experiment (µGauge)*, SwRI Final Report 18.02799, Contract NAS3-99152, 2004.

TECHNIQUE: Optical Absorption.

DATES: 2000 to present.

PROPELLANTS: Applicable to storable and cryogenic propellants (if a suitable absorption band can be used).

ZERO-G TESTS: None.

GROUND TESTS: Breadboard tests using LH2 in a large tank, and water and LOX in smaller tanks.

UNCERTAINTY: Still to be determined for arbitrary liquid configurations; $\approx \pm 1\%$ of tank volume claimed for preliminary tests with settled liquids.

DESCRIPTION: A laser light source is "flashed" into the tank, and a photo detector is used to measure the light intensity at a point on the inside tank wall. Ideally, the laser light would reflect many times off the tank walls and is partially absorbed by the liquid. This process would then produce a uniform light intensity over the entire tank wall, so the photo detector can be located anywhere on the wall. The intensity at the photo detector, normalized by the empty tank intensity, is a measure of the liquid quantity, since the fraction of light absorbed depends on the mass of fluid in the tank.
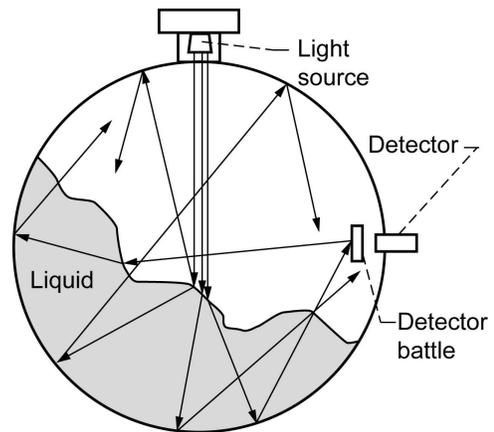
Schematic of whole tank optical gauge.

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Justak, J. F., Caimi, F. M., Bryant, C. B., and Hastings, L., *An Optical Mass Gauge Sensor for Zero-G Environments*, **AIP Conference Proceedings,** 210, No. 1, pp. 451-467, 2004.

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14. ABSTRACT
Gauging the mass of propellants in a tank in low gravity is not a straightforward task because of the uncertainty of the liquid configuration in the tank and the possibility of there being more than one ullage bubble. Several concepts for such a low-gravity gauging system have been proposed, and breadboard or flight-like versions have been tested in normal gravity or even in low gravity, but at present, a flight-proven reliable gauging system is not available. NASA desired a database of the gauging techniques used in current and past vehicles during ascent or under settled conditions, and during short coasting (unpowered) periods, for both cryogenic and storable propellants. Past and current research and development efforts on gauging systems that are believed to be applicable in low-gravity conditions were also desired. This report documents the results of that survey.

15. SUBJECT TERMS
Propellants; Gauging; Sensors; Low-gravity

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