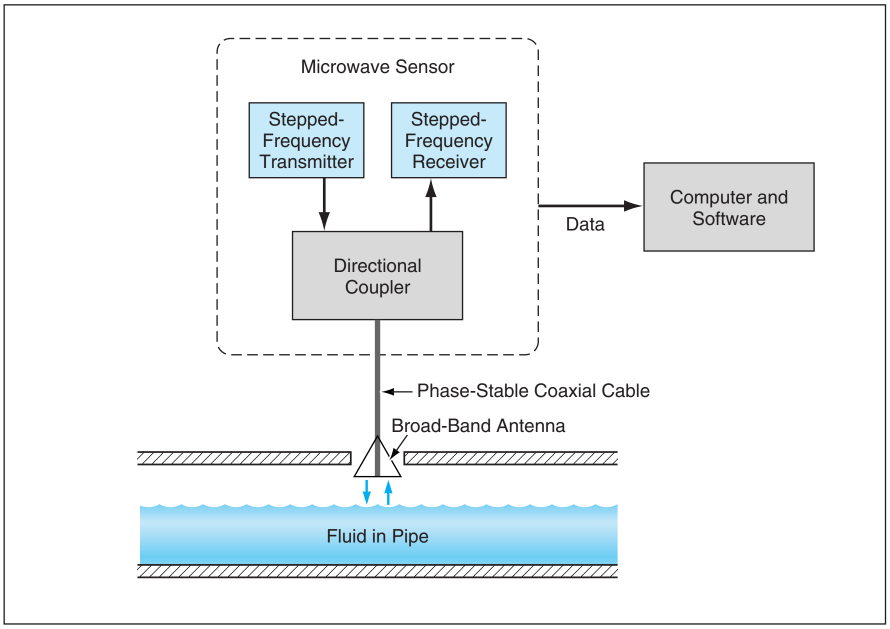

The **Height of the Fluid** relative to the antenna is determined from differences between the phases of stepped-frequency microwave signals transmitted to, and reflected from, the top surface of the fluid.

of pipe is located immediately upstream of the point of discharge of the flow to be monitored. The special section of pipe must be large enough that the pipe can accommodate the entire flow of interest (in contradistinction to a small diverted sample flow), that the flow remains laminar at all times, and that the pipe is never entirely full, even at the maximum flow rate.

In another configuration, the apparatus does not measure the rate of flow or the density directly: Instead, it (a) measures the height of the fluid in the special section of pipe and computes the flow rate as a predetermined function of the height and (b) measures the speed of sound in the fluid and computes the density of the fluid as a predetermined function of the speed of sound in the fluid. To enable the apparatus to perform these computations, one must calibrate the apparatus, prior to operation, by measuring the flow rate as a function of height and the mass density as a function of the speed of sound for the drilling mud or other fluid of interest.

In the second configuration, the velocity of the fluid can be measured subsurface using a set of one transmitter and two receivers to measure differential phase shifts. This second configuration can be used within a filled or unfilled closed pipe to measure volume flow. The microwave portion of the apparatus (see figure) includes a broadband swept-frequency (more precisely, stepped-frequency) transmitter/receiver pair connected, via a directional coupler, to an antenna aimed downward at the liquid. Transmitted- and received-signal data are processed by an algorithm that uses a modified Fourier transform to compute the round-trip propagation time of the signal reflected from top of the fluid. The height of the fluid is then computed from the round-trip travel time and the known height of the antenna. A sonic sensor that operates alongside the microwave sensor gives an approximate height reading that makes it possible to resolve the integer-multiple-of-2π phase ambiguity of the microwave sensor, while the microwave sensor makes it possible to refine the height measurement to within 0.1 in. (≈2.5 mm).

Ultrasonic sensors on the walls near the bottom of the special section of pipe are used to measure the speed of sound needed to compute the density of the fluid. More specifically, what is measured is the difference between the phase of a signal of known frequency at a transmitting transducer and the phase of the same signal at a receiving transducer a known distance away. It may also be necessary to resolve an integer-multiple-of-2π phase ambiguity. This can be done by using two sonic frequencies chosen according to a well-established technique. Alternatively, one could use a single sonic frequency low enough not to be subject to the phase ambiguity, albeit with some loss of density resolution. Simulations indicate that a density accuracy measurement of 0.25 percent (0.0025) can be attained with a single-tone system.

This work was done by G. D. Arndt and Phong Ngo of **Johnson Space Center** *and J. R. Carl and Kent A. Byerly, independent consultants.*

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Johnson Space Center, (281) 483-0837. Refer to MSC-23311.

Reducing Errors by Use of Redundancy in Gravity Measurements

Mathematical identities are exploited to suppress noise or reduce numbers of measurements.

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A methodology for improving gravity-gradient measurement data exploits the constraints imposed upon the components of the gravity-gradient tensor by the conditions of integrability needed for reconstruction of the gravitational potential. These constraints are derived from the basic equation for the gravitational potential and from mathematical identities that apply to the gravitational potential and its partial derivatives with respect to spatial coordinates.

Consider the gravitational potential ϕ in a Cartesian coordinate system $\{x_1,x_2,x_3\}$. The ith component of gravitational acceleration is given by

$$g_i = -\frac{\partial \phi}{\partial x_i}$$

(where i = 1, 2, or 3) and the (α,β) component of the gravity-gradient tensor is given by

$$\Gamma_{\alpha\beta} \equiv \frac{-\partial g_\alpha}{\partial x_\beta} = \frac{\partial^2 \phi}{\partial x_\beta \partial x_\alpha}$$

where $\alpha = 1, 2,$ or 3 and $\beta = 1, 2,$ or 3. The aforementioned constraints are such that the components of the gravity-gradient tensor are not independent of each other. In particular, it is easily shown that the gravity-gradient tensor is symmetrical and has a zero trace; that is,

$$\Gamma_{\alpha\beta} = \Gamma_{\beta\alpha} \text{ and } \Gamma_{11} + \Gamma_{22} + \Gamma_{33} = 0.$$

Hence, if one measures all the components of the gravity-gradient tensor at all points of interest within a region of space in which one seeks to characterize the gravitational field, one obtains redundant information. One could utilize the constraints to select a minimum (that is, nonredundant) set of measurements from which the gravitational potential could be reconstructed. Alternatively, one could exploit the redundancy to reduce errors from noisy measurements.

A convenient example is that of the selection of a minimum set of measurements to characterize the gravitational field at n^3 points (where n is an integer) in a cube. Without the benefit of such a selection, it would be necessary to make $9n^3$ measurements because the gravity-gradient tensor has 9 components at each point. It has been shown that when the constraints are applied to the measurement points in an appropriately chosen sequence, the number of measurements needed to compute all $9n^3$ components is only n^3+n^2+3n.

The problem of utilizing the redundancy to reduce errors in noisy measurements is an optimization problem: Given a set of noisy values of the components of the gravity-gradient tensor at the measurement points, one seeks a set of corrected values — a set that is optimum in that it minimizes some measure of error (e.g., the sum of squares of the differences between the corrected and noisy measurement values) while taking account of the fact that the constraints must apply to the exact values. The problem as thus posed leads to a vector equation that can be solved to obtain the corrected values.

This work was done by Igor Kulikov and Michail Zak of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*
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