A System for Airborne Measurement of Vertical Air Velocity

R. Paul Lawson

Colorado International Corporation, Boulder, CO 80303

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ABSTRACT

A system which measures vertical velocity of the air from an aircraft is discussed and evaluated. Basically, the vertical air velocity system (VAVS) utilizes an incidence vane, vertical accelerometer, and computer-directed high-accuracy vertical gyro to measure and display vertical air velocity in real time. This technique is found to have several advantages over computational techniques which use aircraft response to estimate vertical air velocity.

The VAVS is compared in a formation flight with the vertical air velocity output from a system employing an inertial navigation system (INS) mounted on an NCAR Queen Air. Spectral density plots for the VAVS and INS agreed well with each other for wavelengths from 2 km to 150 m. Also shown is a representative VAVS data output from penetrations of a cumulus cloud during the 1976 HIPLEX program.

1. Introduction

The measurement of vertical air velocity from an earth mounted platform is relatively straightforward (see, e.g., Wieringa, 1967). However, measuring the vertical air velocity W, with respect to the earth from an airborne platform is much more complex. The determination of W from an airborne platform requires knowledge of the atmosphere's motion with respect to the aircraft (W_a) and the aircraft's motion with respect to the earth (W_p). If all measurements are made at the same point,

$$W=W_a+W_p. \quad (1)$$

The measurement of both W_a and W_p from an aircraft is feasible. However, a substantial technical problem arises when one tries to accurately fix the aircraft's orientation with respect to the earth. This is necessary because the aircraft is free to rotate and accelerate with respect to the earth. Consequently, any vertical air motion system must either measure the aircraft's orientation directly or employ assumptions which simplify the problem.

A rigorous solution to this problem requires a complete set of measurements of the parameters in (1). One method is to use an inertial navigation system (INS) air motion system which accurately measures and compensates for changes in aircraft orientation and local accelerations. Lenschow (1972) has shown that angular deviations of the INS platform from the local vertical have a negligible effect on vertical air velocity. One may thereby accurately measure W_p with an integrated vertical accelerometer, pressure altimetry, radar altimetry, or combinations thereof. The vertical motion of the atmosphere relative to the aircraft (W_a) may be measured using an incidence vane plus measurement of true air speed and aircraft orientation outputs from the INS. Lenschow (1971) has addressed the subject of vanes for sensing incidence angles, as well as the calculation of W from an aircraft equipped with an INS air motion system (Lenschow, 1972).

An alternative approach which has been used is to measure the aircraft's vertical motion while minimizing the pilot-induced vertical motion (i.e., changes in pitch and thrust) by using aircraft performance parameters and changes in aircraft true air speed. This computational technique is generally employed where the aircraft is allowed to "float" with the atmospheric motion (such as in an updraft) while the pilot attempts to maintain constant aircraft orientation and thrust. Auer and Sand (1966) used this method to compute mean updraft velocities beneath the bases of cumulus and cumulonimbus clouds. More recently, Kyle *et al.* (1976) have applied the approach to estimate the vertical air velicity profiles during thunderstorm penetrations. This type of an approach suffers from a number of difficulties:

1) The aircraft's inertia limits its speed of response to air velocity changes.

2) It is impossible to maintain an absolutely constant aircraft orientation especially in a turbulent atmosphere.

3) The reference instruments used by the pilot to maintain constant aircraft orientation may be affected by aircraft accelerations and therefore drift relative to the earth's coordinate system.

4) The aircraft changes mass in flight as fuel burns off and from the accumulation of airframe icing which

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TABLE 1. Parameter threshold values, which when exceeded, trigger disengagement of the gravity erection mechanism.

Parameter	Threshold value
Rate of turn	1.5° s^{-1}
Angle of bank	10°
Pitch	2° s^{-1}
Air speed	2 m s^{-1} over 2 s
Turbulence*	5.5 $cm^{2/3}$ s^{-1}

* Meteorology Research Inc., universal indicated turbulence system.

also affects the coefficient of lift (C_L) and coefficient of drag (C_D).

5) Horizontal air velocity flucuations can cause vertical aircraft motions which may be indistinguishable from the aircraft's response to vertical gusts.

Lenschow (1976) investigated the error bands associated with some of these influences and found that the aircraft response may be utilized effectively under certain conditions. For example, in updrafts >8 m s^{-1} with a radius of 1500 m, where changes in C_L and C_D due to airframe icing are neglected, the aircraft response was felt to have sufficient fidelity to distinguish between a "top-hat" and "smooth" profile.

Kelly and Lenschow (1978) have recently compared the fidelity of another computational technique where angle of attack is computed and pitch is measured (using an INS), with the vertical air velocity output from the full INS air motion system. They agreed well for wavelengths from ~2 km to 200 m. Although this computational technique offers greatly improved fidelity, it is still susceptible to incloud airframe icing influences on C_L and C_D, and to errors due to the neglect of pitching rate terms in the computation of angle of attack.

In comparison with the computational techniques, the complete INS air motion system is highly accurate and nearly free of theoretical constraints; however, commercial INS systems are often prohibitively expensive and necessitate relatively large allocations of available aircraft electrical power, cabin space and payload. Due to the limitations associated with each of these techniques, a vertical air velocity system (VAVS) which utilizes some of the basic features of the INS air motion system, while costing a small fraction of a commercial INS, was developed in association with the involvement of Convergence Systems, Inc., in the High Plains Experiment (HIPLEX).[1] The VAVS is described in some detail in Section 3, although it is advantageous to first consider the equations governing the measurement of vertical air motion.

2. Theory of measurement

Lenschow (1972) has derived the three-dimensional velocity equations relevant to the measurement of vertical air velocity under all flight conditions. This was accomplished, in part, by rotating the three components of the vertical air velocity vector from an aircraft to an earth-based coordinate system. The vertical component of motion is expressed as

$$W = U_a(\cos\alpha \cos\beta \sin\theta - \sin\beta \cos\theta \sin\Phi - \sin\alpha \cos\theta \cos\Phi) + L\dot{\theta} \cos\theta + W_p, \quad (2)$$

where

U_a	true airspeed relative to the aircraft
α	aircraft angle of attack
β	aircraft angle of sideslip
θ	aircraft pitch angle
Φ	aircraft roll angle
L	distance between the measurement of vertical air velocity and W_p (the term $L\dot{\theta}\cos\theta$ compensates for the angular acceleration of the incidence vane about the aircraft's lateral axis).

Most cloud penetrations and airborne data runs are conducted in nearly straight and coordinated flight. One may then simplify (2) by using small-angle approximations $\Phi = \beta = 0$ and the trigonometric identity $\cos\alpha \sin\theta - \cos\theta \sin\alpha = -\sin(\alpha - \theta)$ to obtain

$$W = -U_a \sin(\alpha - \theta) + L\dot{\theta} \cos\theta + W_p. \quad (3)$$

The computational estimate of vertical air velocity measurement requires further simplification of (3) by assuming θ is constant [unless it is measured as in the case of Kelley and Lenschow (1978)] and that pilot-induced changes in W_a are negligible. The angle of attack α may then be computed from the aircraft lift equation, the measured aircraft vertical acceleration and the time-dependent aircraft mass. A critical assumption is that θ is constant. From (3), one can see that a change of only 1° in θ produces an error of 1.2 m s^{-1} at a true air speed of 70 m s^{-1}. It is impossible to consistently maintain pitch to better than a few degrees within the turbulent environment of a cumulus cloud. Also, C_L will change significantly with accumulation of air frame ice and since changes in α are approximately proportional to C_L, the computation of α is similarly influenced. Because both of these error factors are impossible to eliminate or quantify using the computational approach, the VAVS concept is introduced to accurately measure θ, α and W_p so that (3) may be used directly to calculate vertical air velocity.

3. Vertical air velocity system

Basically, the VAVS concept utilizes an incidence vane system (true air speed and angle of attack measurement), a high-accuracy, gravity-erected vertical gyroscope (pitch and roll outputs), and the integrated output of a vertical accelerometer corrected mathematically for pitch, roll, gravitational offset and centripetal accelerations. The system flown in 1976

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[1] HIPLEX is sponsored by the Bureau of Reclamation.

Table 2. Results of calm atmosphere initialization tests.

Flight maneuver	Heading (deg)	Average IAS (kt)	Average IROC (ft min^{-1})	Average duration (s)	Maximum departure from zero (m s^{-1})	Average departure (m s^{-1})	Standard deviation (m s^{-1})
Straight and level	0	140	0	300	1.8	0.2	0.6
Straight and level	0	120	0	300	1.6	0.2	0.6
Straight and level	0	100	0	300	2.0	0.3	0.7
Straight climb	0	120	500	240	2.9	0.5	0.9
Straight descent	0	140	1000	120	2.6	0.4	0.8

used an onboard mini computer to control disengagement of the vertical gyroscope gravity erection mechanism when the aircraft accelerated horizontally. It is necessary to isolate the gravity erection mechanism from accelerations other than the earth's gravity in order to continuously maintain verticality. Thus, a principle functional difference between the INS and VAVS is that the INS integrates the complete equations of motion to continually calculate a local vertical, while the VAVS uses gravity as the reference. This means that the INS is subject to long-term drift from true vertical which must be subsequently removed. The VAVS is updated by gravity reference so that its verticality is a function of the dynamic accuracy of the vertical gyro, i.e., the combined accuracy of the vertical gyro, gravity erection mechanism and the airborne measurement of horizontal acceleration.

As a normal function of the airborne data system used with the VAVS, the computer stores the aircraft angle of bank, air speed, longitudinal turbulence, pitch and heading. Table 1 lists these parameter threshold values which when exceeded would trigger disengagement of the gravity erection mechansim. Thus, the vertical gyroscope was allowed to free spin unless the computer ascertained that a valid signal was being provided by the gravity erection mechanism. The verticality of the gyroscope was then updated at a constant rate of 0.083° s^{-1}. The computer was able to isolate the vertical gyro from most effects of horizontal acceleration on a real-time basis, thereby permitting continuous measurement of aircraft pitch and roll. Since all parameters were recorded and processed by the computer in real time, W_a and W_p and their resultant W were read directly from a digital display in the cockpit of the airplane, which benefited both real-time evaluation and operations in the field. The VAVS used in 1976 was designed to achieve a relative accuracy of 0.5 m s^{-1} through most flight conditions, but not during flight maneuvers where significant aircraft-induced accelerations were produced. Since a controlled *in situ* evaluation of the entire system performance was impossible, a composite error analysis of component parts was utilized.

Alternatively, a free-spinning gyroscope as used by Telford and Warner (1962) may be employed. However, since all gyroscopes have some finite drift rate, it is necessary to correct the gyroscope's reference coordinate system when it exceeds the drift limits required to validate the design measurement accuracy. With Telford and Warner's system, it was necessary to initiate the gyroscope "vertically by hand" before each cloud pass "where setting up errors on the order of 0.1 m s^{-2} are undesirable."

Telford and Warner (1962) have cautioned against using an unstabilized accelerometer to measure vertical velocity from a turning aircraft. However, from (2) we may determine that the induced error is small when the aircraft angles of rotation are small. Using the manufacturer's published accuracy for our vertical gyro of 0.25° and a free drift rate of 0.0042° s^{-1}, 0.5 m s^{-1} accuracy in vertical velocity measurement may be maintained in an 18° bank for up to 60 s in the absence of large horizontal atmospheric accelerations. However, since cloud penetrations and most airborne data runs are conducted in nearly straight flight, the problem reduces to initialization of the measurement system prior to the data run. The initialization system utilized in the VAVS employed the continuous computer computation of W_p during all maneuvers with a third-order altimeter feedback algorithm (Blanchard, 1971) to correct the integrated vertical accelerometer for long-term drift. Since, in effect, the average velocity may be deduced to an accuracy determined by the time interval and accuracy with which altitude is measured (Telford and Warner, 1962), if altitude is measured to within 2 m, 4 s must elapse before an average velocity may be determined to 0.5 m s^{-1}. In this way, the doubly integrated accelerometer and altitude measurement systems provided high-frequency and low-frequency inputs, respectively, where each input was best suited to its respective bandwidth measurement.

4. Flight tests

Although it is difficult to simulate atmospheric effects on an aircraft in flight, certain boundary conditions may be approximated. An airborne vertical motion sensing system may be initiated where the atmosphere is assumed to have no effect on the sensing systems, i.e., $W=0$. Then from (1) we can see that $W_a=-W_p$. Early morning flight tests in a calm atmosphere ($W\approx 0$) were conducted for straight and level, and climbing

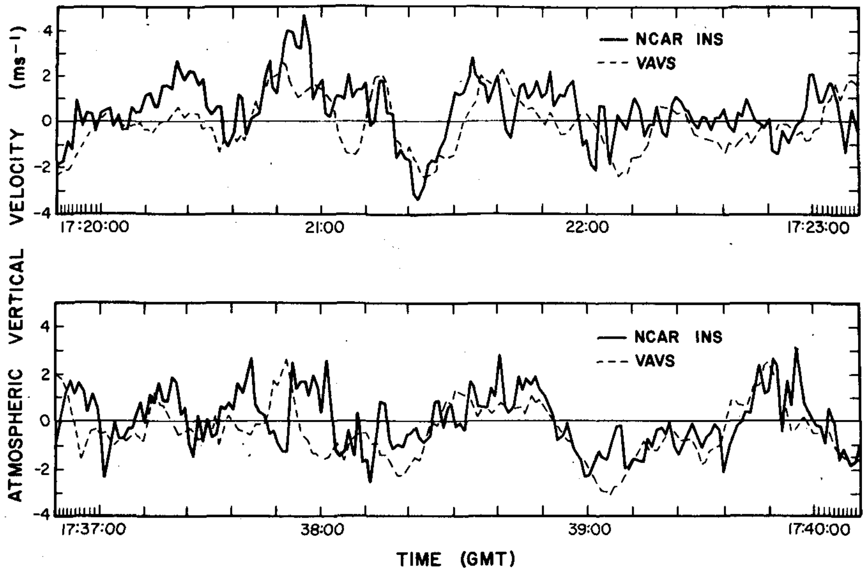

FIG. 1. Comparison of NCAR INS and VAVS atmospheric vertical air velocity outputs during a formation flight.

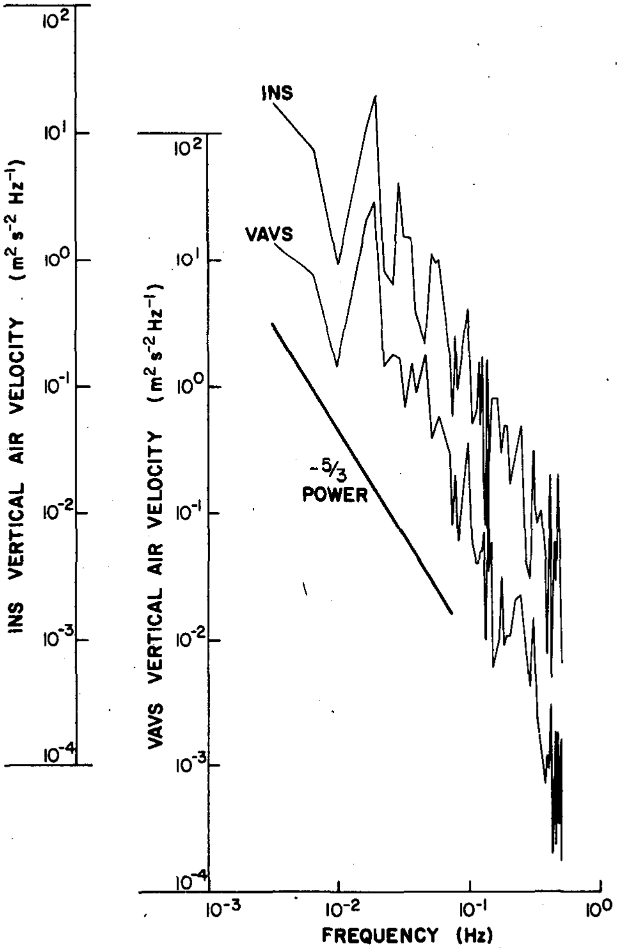

FIG. 2. Spectral density plots for the VAVS and INS for the period 1735:00–1740:00. The outputs and respective ordinates are displaced one cycle for sake of clarity.

and descending flight. This procedure was also used to zero the incidence vane. With the utilization of low-drift solid-state components, the incidence vane and vertical gyro initialization configurations were found to remain stable. The results of these early morning initialization tests are shown in Table 2. The VAVS used in 1976 was not designed to measure vertical air velocity during maneuvers. In particular, aliasing errors due to 1 s^{-1} sampling and phasing errors among the terms of (3) will degrade system accuracy if maneuvers of greater severity than those executed in Table 2 are conducted, i.e., in excess of aircraft accelerations generated from "normal" control pressure application. However, system recovery was rapid after completion of adverse maneuvers attributable chiefly to the disengagement of the erection mechanism during these maneuvers.

Further evaluation of the VAVS mounted in an Aero Commander was obtained from a formation flight with an NCAR Queen Air equipped with an INS air motion system. Some comparisons of the two systems include the following: 1) Sampling rate—the INS air motion system was sampled 16 times per second while the VAVS was sampled once per second. Thus, the INS air motion system resolved shorter wavelengths than the VAVS which aliased the shorter wavelengths. 2) Both systems utilize third-order altimeter feedback to compensate instrumentation drift; however, the feedback functions are somewhat different due to sampling resolutions and may affect overall response times. 3) Both systems use vertical velocity averaging to determine a mean atmospheric vertical velocity and consequently an absolute zero reference.

The aircraft were flown in formation under the bases of a scattered cumulus regime with the Aero Commander in the lead. Due to the different physical locations of the aircraft in the atmosphere (~50 m apart) and the higher sampling rate of the INS air motion system, it is inappropriate to compare phasing at the shorter wavelengths. However, we would expect both systems to measure vertical velocity of the same general magnitudes, and possibly show comparative traces in situations where differences in frequency thresholds and resolution times are minimized. Fig. 1 is a representative sample of the outputs of the systems for two 3 min periods. Relatively good comparison is seen in general wave form, especially for longer wavelengths (e.g., 1738:00–1740:00). Fig. 2 shows the respective spectral density plots of a continuous 5 min portion of the formation flight (1735:00–1740:00). The overall agreement is very good. The spectra agree well to about 0.5 Hz (150 m wavelength), which is the Nyquist frequency. The longer wavelengths showed good correlation in phase as well as amplitude.

Fig. 3 shows a representative sample of recorded data for 8 July 1976. Included in these data are the cloud water droplet concentration as determined from a Particle Measuring Systems' axially scattering spectrometer probe, and ice particle concentration determined from two instruments: 1) the PMS OAP-200X optical cloud particle probe (Knollenberg, 1975); and 2) the CSI cross-polarized optical ice particle probe which is a modification of the design by Turner and Radke (1973). Data from the cross-polarized ice particle probe are discussed in Holroyd *et al.* (1978) and Lawson (1978). These data were recorded in a developing cumulus which was seeded with dry ice pellets by a seeding aircraft in trail with the cloud physics aircraft after the latter had made two passes through the unseeded cloud.

5. Conclusions and recommendations

We have developed an airborne system which continuously measures and displays atmospheric vertical velocity with reasonable fidelity except with severe aircraft maneuvers (rapid pitching moments) or where the angle of bank exceeds about 18°. The maneuvering and banking restrictions are rarely a factor in practical application since data runs are generally conducted in reasonably straight flight. Sustained steep turns and violent maneuvers can generate discrepancies in the calculated and measured values of W_p, but are resolved through the altitude feedback algorithm shortly after recovery. These maneuvering restrictions are not in

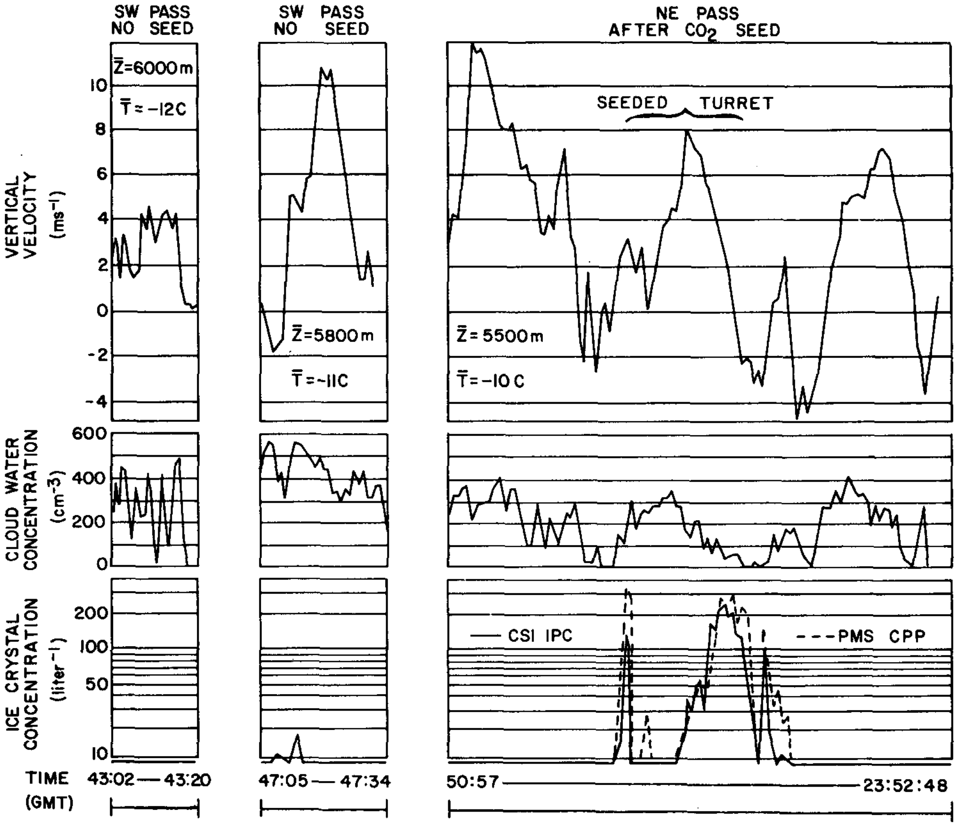

Fig. 3. Representative sample of HIPLEX data from cloud penetrations on 8 July 1976 showing the VAVS atmospheric vertical velocity output (top), cloud water concentration from the PMS ASSP (middle) and ice particle concentrations (lower) from the CSI ice particle counter (IPC) and PMS OAP-200X cloud particle probe (CPP).

herent to the system concept and could be removed by increasing sampling rate and upgrading the verticality reference. State-of-the-art attitude reference (two-gyro) systems are now available which have demonstrated dynamic verticality accuracy to within a few tenths of a degree RMS when flight tested with an INS (Lear Siegler, Inc., personnel communication).

The VAVS concept does not suffer the limitations encountered using a computational technique which assumes pitch is constant and estimates vertical air motion from aircraft response and performance parameters. The advantages are as follows:

1) The accurate measurement of pitch and angle of attack enables the calculation of W_a and limits the wavelength of measurement of the inertial limitations of the incidence vane and to the dynamic accuracy of the pitch measurement. This becomes specially significant when one considers the scale of wavelengths germane to mesoscale processes and particularly to eddy transfer of heat and momentum via entrainment where characteristic scales of influence are hundreds of meters.

2) The pilot need not maintain the aircraft attitude to within specified tolerances since pitch is accurately measured.

3) Since pitch reference comes from the high-accuracy vertical gyro and not the pilot's recognition of cockpit instruments, there are fewer limitations on maximum vertical velocity to updraft diameter ratio measurements.

4) There need be no compensation for variation in aircraft mass due to fuel consumption or airframe icing.

The VAVS was compared with an INS air motion system during a formation flight. The respective spectral densities showed good agreement from $\sim$2 km to 150 m. The high-frequency limitation was principally imposed by the 1 s^{-1} sampling frequency of the VAVS and the spatial difference separating the aircraft. The VAVS could be upgraded by increasing the sampling frequency and either 1) use of a state-of-the-art vertical reference system or 2) mounting lateral and longitudinal accelerometers to provide a direct measurement of horizontal accelerations enabling a more complete isolation of the vertical gyroscope gravity erection mechanism from influences other than the earth's gravity vector. Further upgrading could be accomplished by mounting the vertical accelerometer on a stable platform, thus enabling the system to measure vertical air velocity under all flight conditions.

The advantages of real-time data display capability are numerous (e.g., see Veal *et al.*, 1975; Telford *et al.*, 1977). Principally, they are found in the capacity to continuously monitor data quality and in the onboard direction of scientific experiments. With the evolution of microprocessors it is now possible to replace the onboard computer used in the VAVS with a small microprocessing unit which would control the vertical gyro gravity erection mechanism as well as output real-time data to a digital or graphic display.

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