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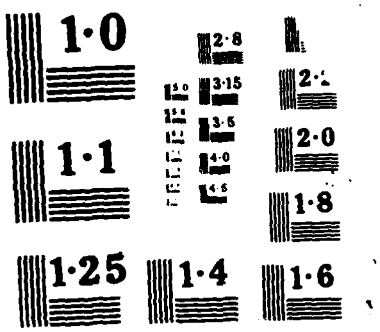
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Laser Gyro Attitude Control System Feasibility Study

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24 April 1987

AEROSPACE ENGINEERING DIVISION PROJECT 7659

AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MA 01731

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This report briefly reviews the principles and properties of optical rate sensors. It then further describes some existing ring laser gyro systems and considers how their utilization would affect performance, cost and reliability of attitude control systems currently used or proposed for use in sounding rocket applications at the Air Force Geophysics Laboratory (AFGL).

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1. INTRODUCTION

Two separate, but overlapping concerns in the selection of attitude control systems for AFGL sounding rocket and shuttle payloads motivate this report. First, some missions that AFGL has supported recently and will continue to support in the future have pointing accuracy and stability requirements that tax the limits of our traditional pointing control systems. Since these requirements can be expected to increase with time, it is necessary to look to new technologies to maintain adequate capability at AFGL. Second, for those missions that do not tax the limits of our traditional systems, it is still advisable to keep abreast of new technology; there is considerable potential for cost savings, as well as increased reliability, decreased environmental susceptibility, and a reduction in the complexity and time spent on procedures for maintenance and calibration, both in testing and during countdown.

Within the last decade, the ring laser gyroscope (RLG) has emerged as an important device for state-of-the-art inertial reference systems. The availability of a number of models from several manufacturers and the increasing use of RLGs for commercial as well as military applications show that a fair degree of maturity has been attained by this technology. The ring laser gyro is part of a wider class of optical rate sensors, a family that also includes the fiber-optic gyroscope.

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Fiber optic technology has not yet achieved the maturity of the RLG but it holds such promise, particularly for lower costs, that it too should be examined for a possible future system.

Section 2 of this report reviews the family tree of Inertial Reference Systems. Section 3 discusses some common mechanical rate sensors. Section 4 addresses the most important topics in this report, the principles and properties of optical rate sensors. Section 5 then describes the requirements for present and possible future AFGL missions, both in general and for specific missions. Section 6 describes the characteristics of some existing RLG systems and contains suggestions about how their use would affect performance, cost, and reliability, as compared to the Attitude Control Systems presently used or proposed for use at AFGL. Section 7 discusses promising, but not yet available, technology and how it could benefit attitude control systems. Finally, Section 8 presents suggestions for research needed if laser gyroscopes are to become feasible for AFGL attitude control systems.

2. INERTIAL REFERENCE SYSTEMS

This section describes the physical principles applied in many mechanical inertial reference systems. The "tree" shown in Figure 1 is structured to emphasize laser gyroscopes, but the wider family is addressed to show the similarities and differences of laser gyros and more conventional systems. Some engineering considerations will be addressed in Sections 3 and 4 but most will be saved for the sections discussing specific systems and requirements in Sections 5 and 6.

Any navigation or pointing system can measure position or attitude only by relating its measurement to some other quantity that is assumed to be invariant despite the motions of the measuring system. For celestial navigation it is the position of the "fixed" stars that provides the invariant. For electronic navigation, the position of navigation aids or beacons serves the same role. Inertial reference systems, which measure no quantity outside themselves, use the invariance of certain physical properties. This approach is both more subtle and more difficult to employ successfully. For gyroscopic systems, the angular momentum vector of a spinning mass (free from torque) provides that invariant. For optical rate sensors, including laser gyroscopes, the invariant is the speed of light, which special relativity tells us is invariant in any frame of reference.

It should be made clear that although this study addresses attitude sensors exclusively, a full-fledged inertial reference system (as opposed to an attitude reference or control system) must measure acceleration in all three axes in addition to attitude to determine its position and orientation in space.

INERTIAL REFERENCE SYSTEMS

STRAP-DOWN SYSTEMS

GIMBALLED SYSTEMS

DYNAMICALLY TUNED FREE-ROTOR GYRO (DTG)

OPTICAL RATE SENSORS (all derived from simple Sagnac Interferometer)

PASSIVE SYSTEMS (rate-sensing)

MULTI-TURN SAGNAC INTERFEROMETER (fiberoptic gyro)

PASSIVE RING-RESONATOR

ACTIVE SYSTEMS (rate-integrating) - RING LASER GYROS

(Distinguishable by method used to circumvent lock-in phenomenon)

- MECHANICAL DITHER
- MAGNETIC MIRROR
- DILAG (MULTI-OSCILLATOR)

Figure 1. Inertial Reference Systems Family Tree

3. MECHANICAL SYSTEMS

Mechanical inertial reference systems are divided into two types: those that preserve an attitude reference mechanically (gimballed systems) and those that preserve the reference computationally (strapdown systems).

3.1 Gimballed Systems

This was the first type of inertial reference unit developed and it continues to have many applications. A platform is kept stable in inertial space through gyroscopic inertia, and rotation of the vehicle around the platform can be measured by a number of means to determine vehicle orientation. With accelerometers oriented in each of three orthogonal axes and mounted to the inertial platform, it becomes relatively straightforward to determine the vehicle's motion because each accelerometer maintains its orientation in inertial space. Since the sensitive elements are located within the gimballing system, their repair and calibration are difficult and time-consuming. It is also more difficult to control drift in such a multi-axis system. However, in applications such as AFGL's spin-stabilized rockets where a high-spin rate is necessary to stabilize the rocket during ascent before the low-spin-rate mission begins, the fact that the gimballed system maintains a physical inertial reference rather than requiring a computer to keep track of it computationally, may still make it the better choice. A good example of a gimballed system is the MIDAS class of platforms made by Space Vector Corporation, and used extensively by AFGL.

3.2 Strapdown Inertial Reference Systems

In contrast to the gimballed systems, where the sensor platform is free to maintain its attitude in inertial space while the vehicle rotates around it, the sensors in a strapdown system are fixed to the vehicle's frame of reference (as the name implies) and are thus subjected to the same full range of angular motion as the vehicle. Advantages of this configuration include the elimination of the mechanically complex and bulky gimballing system. However, this relative mechanical simplicity comes at the cost of a vastly increased computational workload. This increase has two sources. First, angular sensors must detect very large angular rates as well as the low threshold values that gimballed systems must detect, thus increasing their dynamic range requirement by many orders of magnitude. Second, the rotations and accelerations are measured in the constantly changing vehicle frame of reference. Not only must the measurements be translated to the inertial frame of reference; the system is not capable of mechanically "remembering" where the inertial frame is, and therefore must computationally update the orientation of the inertial frame relative to the vehicle frame continuously. Thus, a powerful digital computer is required for any strapdown inertial reference system. Recent advances in computer technology have made strapdown systems practical, and because electronics continues to improve at a much faster rate than the technology of electromechanical devices, strapdown systems may supersede gimballed systems in a wide variety of applications.

The mechanical strapdown system that seems to dominate the market is the Dynamically Tuned Gyro (DTG) or Tuned Rotor Gyro (TRG). It gives the best performance for most applications, and will therefore be used as the example of a mechanical strapdown system.

The rotor or flywheel of a DTG is attached to its spin motor through a gimbal system that allows the rotor limited angular movement in both axes perpendicular to the rotor spin axis. It is in these two axes that the device senses rotation rate. The rotor is "tuned" because only at a certain motor rotation rate does the gimbal system compliance go to zero, letting the rotor keep its spin axis fixed in inertial space as the rest of the device rotates with the vehicle. In these respects, the DTG is no different than an ordinary gimballed system. However, in each axis of rotation, there is a torquer coil and pickoff (motion-sensing) assembly employed in a feedback loop that senses rotor motion and applies electromagnetic torque to keep the rotor spin axis aligned with the spin motor axis. Since the torquer coil current required to keep the rotor centered is proportional to the rotation rate around that axis, the torquer current for the two axes is the sensor output and measures rotation rate in those axes. Since each device measures rotation in two axes, only two are needed to completely specify orientation, and since only a limited degree of rotational freedom is needed in the axes perpendicular to the spin motor, the devices can be compact, self-contained units. Like gimballed systems, and unlike ring laser gyros, there are some acceleration-dependent error terms. Also, unlike RLGs, which are very insensitive to rotation about axes other than the sensitive one, there are some error cross terms between the two sensitive axes of the DTG.

Mechanical inertial reference systems are now being replaced in many applications by the newer optical rate sensors that are the subject of the next section.

4. OPTICAL RATE SENSORS

4.1 Basic Principles

The basic principle on which all optical rate sensors are based is the Sagnac effect. This effect causes a difference in the optical path length between two light beams traveling in opposite directions within a closed rotating path. The path length difference is a function of the instrument's rotation rate (as well as the length and geometry of the path) and manifests itself as a phase difference between the two light beams that is measurable by interferometry.

The easiest way to derive the Sagnac effect is to assume that a circular light path of radius R is rotated about an axis perpendicular to its area with the constant angular rate ω clockwise (see Figure 2). Two counter-rotating beams are assumed to start from a beam splitter at point C in the path of the rotating arrangement. The counterclockwise light beam (b) hits this point again at the point C' of a reference system that is assumed to be stationary; the distance between C and C' is ΔS_b. Likewise, the clockwise beam (a) hits its entering point at C'' which is ΔS_a apart from C.

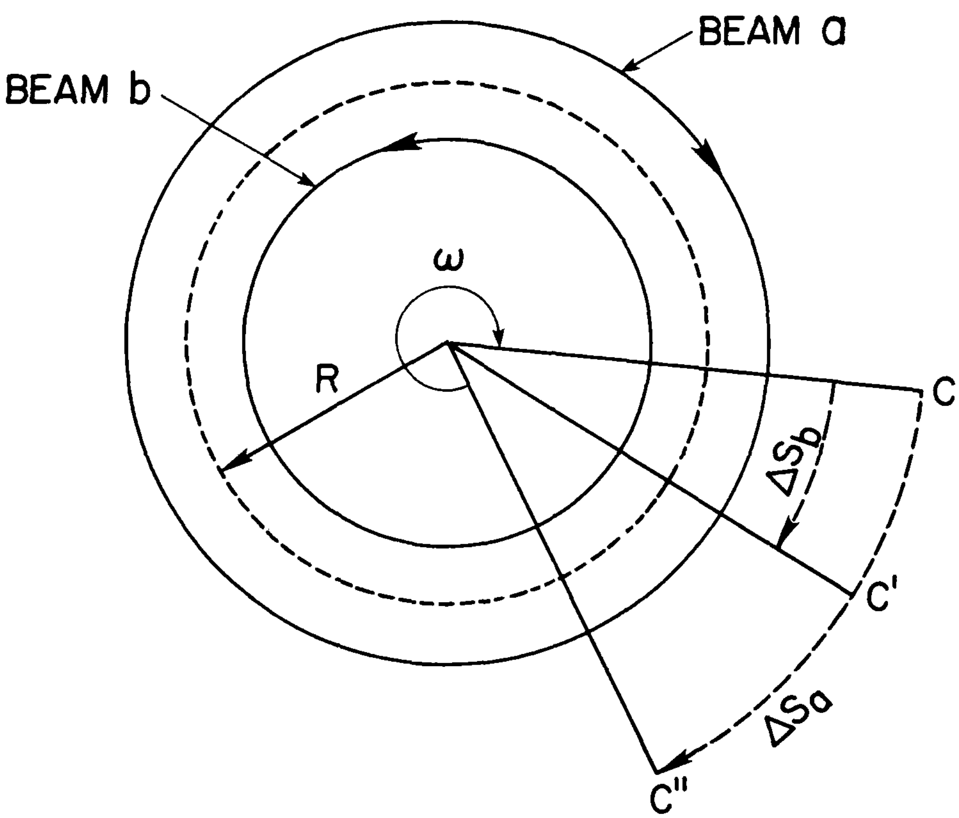

Figure 2. Sagnac Effect

The length traveled by beam b in the stationary frame of reference is $(2\pi R - \Delta S_b)$. The velocity of light in the stationary frame, as in any frame of reference, is c. Thus the time required in the stationary frame for beam b to travel this path is $\tau_b = (2\pi R - \Delta S_b)/c$. In the same time the point C has rotated with the apparatus to C' so that $\tau_b = \Delta S_b | R\omega$. For beam a in the stationary frame the length traveled is $(2\pi R + \Delta S_a)$, so that by similar process the closed-path propagation times for both beams for a stationary observer are:

$$\tau_b = \frac{2\pi R - \Delta S_b}{c} = \frac{\Delta S_b}{R\omega}$$

$$\tau_a = \frac{2\pi R + \Delta S_a}{c} = \frac{\Delta S_a}{R\omega} .$$

The time difference (in the stationary frame) between the two beams is $\Delta\tau_N = \tau_a - \tau_b$, which with the elimination of ΔS_b and ΔS_a in the above equation leads to

$$\Delta\tau_N = \frac{4\,A\,\omega}{c^2 - (R\,\omega)^2} \; ; \quad A = \pi R^2$$

Because the speed of light is constant in any frame of reference (the invariant property governing optical rate gyros) τ_b is clearly unequal to τ_a. If light behaved instead like macroscopic particles we would find that τ_b exactly equals τ_a and $\Delta\tau_N = 0$ for any rotation rate; the device would not sense rotation.

Since the time difference is measured in the rotating (sensor) frame rather than the stationary frame of reference, theoretically it is necessary to translate $\Delta\tau_N$ to $\Delta\tau_R$ in the rotating frame. That there is a difference is due to time dilation; an effect that (along with space contraction) arises from holding the speed of light constant in all frames of reference. The transformation can be written:

$$\Delta\tau_R = \frac{\Delta\tau_N}{\gamma} = \frac{4\,A\,\omega}{\gamma(c^2 - (R\,\omega)^2)}$$

$$\gamma = \left[1 - \left(\frac{R\,\omega}{c}\right)^2\right]^{-1/2} .$$

However, for any realistic rotation rate, the time difference is negligible. The expression for $\Delta\tau_N$ simplifies to an expression independent of frame of reference.

$$\Delta\tau = \frac{4\,A\,\omega}{c^2} .$$

This time difference can be expressed as an optical path length difference $\Delta L = c\,\Delta\tau$. If we superimpose the counter-rotating beams in an interferometer, the resulting light at the observing position will have low intensity when the two beams are out of phase, and greatest intensity when in phase. If the beam path lengths differ by one wavelength then the interference pattern will go from high intensity to low intensity and back to high; an interference "fringe" is said to have passed. For a path length difference ΔL the number of interference fringes counted would be $\Delta Z = \Delta L/\lambda$, where λ is the wavelength of the light used in the two beams. We can also express this as: $\Delta Z = 4\,A\,\omega/c\lambda$. We see that the interference fringe shift is directly proportional to the rotation rate, and the area enclosed by the light path serves as a scaling factor.

Unfortunately, the resolution of such a device, if of practical size, is rather poor. For example, in 1925 Michelson and Gale set up a 340 × 610 m interferometer ring (207,400 m^2) on the University of Chicago campus. The 10 deg/hr vertical component of the earth's rotation at that latitude caused a shift of 0.23 fringe. Krogmann[1] (pp. 4-27) has shown that for devices of more practical size, say 0.01 to 1 m^2, the fringe shift resolution becomes exceedingly small, even at fairly high rotation rates (Table 1).

Table 1. Measurement Resolution of Sagnac Effect

A [m^2]	Ω [°/h]	ΔL [Å]	$\Delta\tau$ [sec]	$\Delta Z = \Delta L/\lambda$
	10^{-2}	$6 \cdot 10^{-8}$	$2 \cdot 10^{-26}$	10^{-11}
10^{-2}	10^{6}	6	$2 \cdot 10^{-18}$	10^{-3}
	10^{-2}	$6 \cdot 10^{-6}$	$2 \cdot 10^{-24}$	10^{-9}
1	10^{6}	600	$2 \cdot 10^{-16}$	10^{-1}

$\lambda = 0.6\ \mu m$, 10^{6}°/h = 278°/sec

For A = 1 m^2, Ω = 278°/sec $\longrightarrow \Delta Z = {}^{1}/10$ of a fringe

For A = 10^{-2} m^2, Ω = 0.01°/h $\longrightarrow \Delta Z = {}^{1}/100{,}000$ million of a fringe

The technology of optical rate sensors hinges on ways to increase the resolution of the Sagnac effect. The methods used to date fall into two basic categories, termed passive sensors and active sensors. Passive sensors have the light source outside the optical path, and increase their resolution by increasing the effective area of the sensor. This can be done by sending the light beams through many coils of optical fiber to increase the path length (fiber-optic gyro), or by multiply reflecting a light beam within a single optical path (passive ring resonator). Active sensors increase their resolution by incorporating a laser medium into all or part of the optical path (ring laser gyro). Since the resonant frequency of a laser is a sensitive function of the path length of its cavity, the path length difference induced by the Sagnac effect serves to slightly shift the frequencies of the counter-rotating beams in opposite sense from their center (non-rotating) frequency. Thus for any given rotation rate of the sensor there will be a beat frequency between the beams

1. Krogmann, U.K. (1983) Introduction to optical rate sensors, in AGARDograph No. 272 Advances in Sensors and Their Integration Into Aircraft Guidance and Control Systems, NATO, Neuilly.

that results in a certain fringe counting rate at the point where the beams are brought together by interferometry. Note that for passive sensors a certain rotation rate induces passage, or shift, of a certain number of fringes (or fraction of a fringe), while for active sensors that same rotation rate induces a certain fringe passage rate. Alternatively, we could say that rotation of an active sensor through x degrees induces the passage of y fringes. From this we see that passive sensors are rate-sensing devices while active sensors are rate-integrating devices. The following sub-sections will describe each type in more detail.

4.2 Passive Systems

4.2.1 MULTI-TURN SAGNAC INTERFEROMETERS (FIBER-OPTIC GYROS)

If we take our Sagnac Interferometer of area A and make the counter-rotating light beams encircle this area N times instead of just once before combining them at the output, then the fringe shift we would measure is:

$$\Delta Z = N \frac{4 A \omega}{c \lambda} .$$

This is exactly what is done in the fiber-optic gyro by sending the beams through a coil of optical fiber. If the coil employs a thousand turns of optical fiber (a typical number) then the sensitivity of the device has been multiplied a thousand-fold, yielding phase shifts that are quite measurable for most rotation rates of interest. A beam-splitter can be used to divide the light from a source into the counter-rotating beams and then to recombine them for interference at a photo-detector[2] (Figure 3).

Considering its simplicity, one wonders why fiber-optic gyros haven't appeared on the market along with the rather more complex ring laser-gyro. The answer is that a number of practical problems have stood in the way; problems that only now are being addressed successfully. Among these is loss of intensity through long fiber length—now being solved by improved optical fiber. More difficult problems are large scale-factor errors associated with photodetector scale-factor uncertainties, light-source intensity variations, loss of rate sensitivity around zero input rate due to the $\cos^2\theta$ shape of the interference fringe, and phase angle variations due to mechanical movement between the beam splitter and fiber. The discrete component beam-splitter has been replaced by fiber-optic couplers (or junctions). The laser has been replaced by a narrow frequency bandwidth

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2. Savage, P. (1984) Advances in strapdown sensors, in AGARD Lecture Series No. 133 Advances in Strapdown Inertial Systems, NATO, Neuilly.

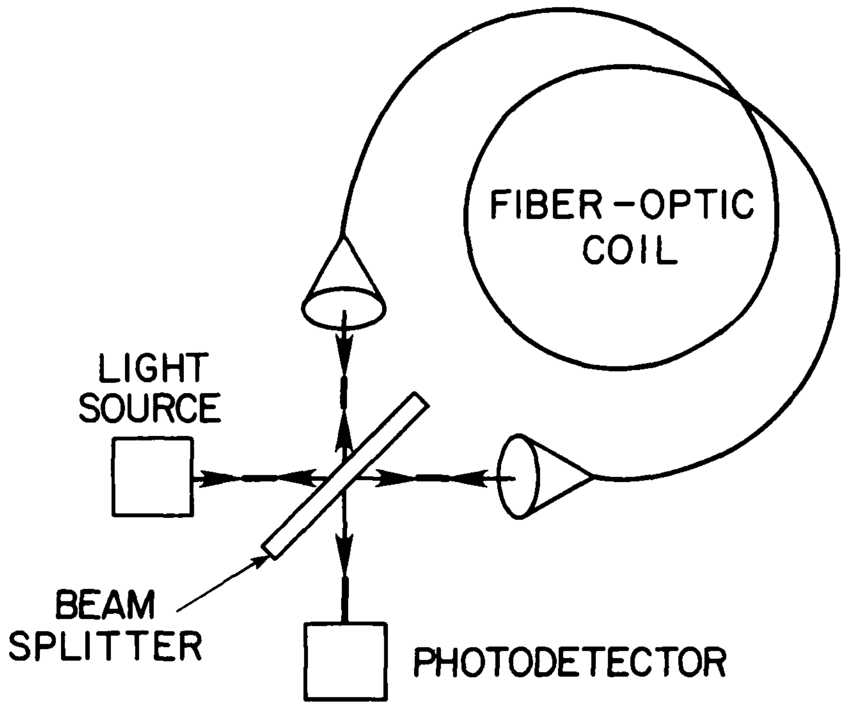

Figure 3. Basic Fiber-optic Rotation Rate Sensor Concept

source such as a gallium-arsenide diode that reduces non-reciprocal beam/fiber interaction error mechanisms due to the shorter correlation distance for the non-lasing source. (This would also seem to offer significant cost/size reliability benefits due to elimination of the laser.) A number of electro-optic devices have been inserted into the optical path at both ends of the fiber-optic coil. These include Bragg cells that frequency-shift the passing light by an amount equal to the frequency of an applied signal, and controllable electro-optic phase shifters. Suitable control and feedback circuitry will either eliminate or control the problems of zero-phase angle sensitivity, scale-factor errors associated with light-source intensity variations, and photodetector scale-factor uncertainties.

4.2.2 PASSIVE RING RESONATOR

The sensitivity of the Sagnac interferometer can be increased by a multiple transit of a light beam within a closed optical cavity (a three-mirror system). The beam traverses the cavity continuously; after each circulation a small fraction of the beam intensity is output at one of the mirrors. Each transit incurs a phase shift due to the Sagnac effect, and the combined interference pattern from many passages is directly analogous to that of a Fabry-Perot interferometer. The steepness or sharpness of the fringe is much greater than for interference of just two beams (that is, a much higher "Q" is achieved, if you prefer). A small change in rotation rate yields a much greater change in output intensity and thus a much greater sensitivity than for the basic Sagnac interferometer.

4.3 Active Systems (Ring Laser Gyros)

4.3.1 RLG PERFORMANCE

We have seen that for a rate sensor based on the basic Sagnac effect we get a fringe shift output ΔZ proportional to the rotation rate and scaled as:

$$\Delta Z = \frac{\Delta L}{\lambda} = \frac{4 A \omega}{c \lambda} \ .$$

However, by incorporating a laser medium into the optical path we get a frequency difference (beat frequency) Δf between the counterrotating beams that is proportional to the path difference ΔL, or:

$$\frac{\Delta f}{f_o} = \frac{\Delta L}{L} \ ; \ \Delta f = f_o \frac{\Delta L}{L} \ .$$

Since f_o is on the order of 10^{14} Hz we have amplified the scaling factor of the original Sagnac effect enormously with corresponding improvement in the measurement resolution.[1]

With the above expressions, and using $f_o = c/\lambda$,

$$\Delta f = \frac{4 A \omega}{L \lambda} \ .$$

For ω = 1 deg/sec, $\lambda = 0.6 \times 10^{-6}$ m, $A = 0.01$ m^2 and $L = 0.4$ m we find Δf = 3 kHz. We see that a modest rotation rate yields a fairly high beat frequency with a practically sized device. It is this sort of scaling magnitude that makes it clear that the ring laser gyro lends itself handily to digital techniques for its basic measurement. One needs only to count the passage of a large number of interference fringes to get good angular resolution, whereas for a passive optical rate sensor one must by analog means determine the shifting of a single fringe (or small number of them). Likewise for any rotor device, whether in a strapdown or gimballed system, the basic measurement is analog, and must then be translated to a digital signal before being handed to a computer.

We can get a measure of the angular resolution of the RLG by integrating over time:

$$N = \int_0^t \Delta f \, dt; \quad \Delta\theta = \int_0^t \omega \, dt \, .$$

Where N is the number of fringes counted over a period of time t, and $\Delta\theta$ is the corresponding angular rotation of the sensor. Then:

$$N = \frac{4A}{L\lambda}\Delta\theta \, .$$

Using the above-mentioned geometry, $N = 1.7 \times 10^5 \, \Delta\theta$. For the passage of a single fringe the corresponding sensor rotation is 1.2 arc seconds. If we take one fringe passage to be the smallest measurement unit of the device (though finer measurement is possible) then these nicely small angles represent the theoretical angular resolution for a ring laser gyro of this geometry.

It should be noted that, besides geometry, the scale factor of the RLG is a function of the wavelength of light used. That the light source should be as monochromatic as possible should be apparent from the need to get sharply defined interference fringes. The helium-neon laser has been used for all practical devices, for many reasons including high spectral purity, continuous wave output, sufficient gain, good stability, high reliability, and a long lifetime. It requires relatively low input power, and it can be made both rugged and compact. For this type of laser the lower gain 0.633 μm and 1.15 μm transitions are acceptable. Between these two the 0.633 μm transition is preferred because it yields the higher scale factor and thus better angular resolution.

Most ring laser gyros have been constructed with an equilateral triangle geometry, though apparently some have been produced with square geometry. Pros and cons can be offered for either geometry (Savage,[2] pp 2-9 and 2-10) but triangles dominate. Triangles provide the minimum mirror count to form an enclosed laser ring. This reduces mirror costs per gyro and reduces the number of light scatterers (mirrors) in the beam path. This latter point is important because backscattering of light from one beam into the counterrotating beam causes the phenomenon of "lock-in synchronization" at low rotation rates, a major source of drift in laser gyros (to be discussed later in this report). Proponents of square gyros point to reduced back-scatter per mirror due to lower angle of incidence (45° vs 60°) which more than compensates for the added mirror. Triangles are simpler to align; squares offer more flexibility to optimize performance in the adjustment of beam/cavity positioning. There are also various manufacturing considerations that favor one geometry or the other. The square geometry has a higher area-to-perimeter ratio (A/L) than a triangle of the same size: this means a greater scale factor $4A/L\lambda$ and thus a better angular resolution. The following discussion deals with stability and drift in ring laser gyros and how it affects their design.

4.3.2 RLG DRIFT AND STABILITY

Although a ring laser gyro has no moving parts there are still a number of mechanisms that can cause drift and stability problems. Among these are vibration and thermal variations. Either of these conditions can cause the optical path length of the gyro to vary by many multiples of the laser wavelength, with obvious implications for stability and accuracy. The first solution is to require the counter-rotating beams to travel in the same optical path so that both beams experience the same path-length variations. It would be desirable not to impose this requirement since we could side-step the lock-in sychronization problem already alluded to if we allowed adjacent rather than coincident paths. However, the worse problem is solved using coincident paths because the sensitive measurement of the instrument, the frequency difference of the two beams, subtracts out the center frequency (and its variations) as long as that frequency is the same for both beams. In addition to this necessary step, performance is optimized by further measures to keep the path length constant, since the scaling factor $(4A/L\lambda)$ is directly related to the wavelength. Typically, a ceramic glass material with low coefficient of thermal expansion, such as Zerodur or Cervit, is used to construct the optical cavity. Beyond this, residual path-length variations may be compensated for by mounting a piezoelectric transducer on one of the laser gyro mirror substrates. Actuation of the transducer by a control voltage flexes the mirror substrate to change the path length. This forms part of a feedback loop designed to maintain peak average power in the lasing beams. Maintaining peak lasing power implicitly keeps the average path length constant. The action of this piezoelectric path-length control is instantaneous in practical terms.

Other drift and stability problems arise from properties of the gas lasing medium, or from light scatter in the mirrors. There are three types of errors critical in the design of the laser gyro: null-shift, mode-pulling, and lock-in synchronization.[3]

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3. Aronowitz, F. (1971) The laser gyro, in Laser Applications, Vol. I, M. Ross, Ed., Academic Press, New York.

A null-shift error arises when the cavity is anisotropic with respect to radiation traveling in the two directions, that is, the index of refraction of the lasing gas is different in the two directions. This results in the optical paths being different for radiation traveling in opposite directions and hence the two waves oscillate at different frequencies. A non-zero rotation rate could thus be indicated even with the gyro at rest. Unless the gyro is properly designed, null-shift errors can be orders of magnitude greater than input rate. The effect is largely caused by bulk motion of the lasing gas, or by flow of gas or ion components. [There can also be effects from magnetic fields. This effect doesn't seem to drive the overall design of modern gyros, but it may still be a fundamental limiter of the stability and low drift rate attainable by modern laser gyros.]

Mode-pulling errors are changes in the effective scale factor (counts per radian) due to dispersion effects in the gas lasing medium. Changes in the dispersive effects of the medium can result in a lack of stability and reproducibility of the scale factor, which can be critical for navigation and attitude reference applications. Scale factor linearity (variation of the scale factor as a function of rotation rate) is not considered to be among the most critical problem areas in the laser gyro. However, it is well to note that to keep within a given drift rate, the scale factor must be known with increasing accuracy for higher rotation rates. Thus, to keep a system accuracy of 0.1 deg/hr, the scale factor must be known and kept constant to one part in 10^5 for a rotation rate of 10^4 deg/hr (2.8 deg/sec), but the scale factor must be kept constant to one part in 10^7 for a rotation rate of 10^6 deg/hr (0.77 rev/sec). As an illustration, for the 0.633 μm He-Ne ring laser with an equi-lateral triangle resonator 13.2 cm on a side, the scale factor is 0.58 when ω is expressed in deg/hr. Then $\Delta f = 0.58$ (ω deg/hr) or N fringe counts = $N = 0.58$ (θ arc-sec). For an arbitrary counting time of 100 sec the number of counts is given by $N = 58$ (ω deg/hr). For a system accuracy of 0.1 deg/hr the count uncertainty thus cannot exceed six counts per 100 sec, whatever the rotation rates experienced by the sensor.

The third source of error to be considered is lock-in synchronization. This phenomenon continues to be the most prominent error source in the laser gyro and the most difficult to handle. The various means used by different manufacturers for compensating lock-in have been a principal factor determing the overall configuration and performance of laser gyros.*

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*Lock-in is a well-known phenomenon common to all coupled oscillator systems. A good example is found in electronic oscillator tank circuits. In these coupled systems there is transfer of energy between the two oscillators such that when operating at sufficiently close frequencies the oscillators lock to a common frequency.

In laser gyros the counter-rotating laser beams act as two oscillators that are coupled by mutual scattering of energy from each of the beams into the direction of the other wherever the beams are reflected at a mirror surface.

The effect can be seen in Figure 4.* Below a certain threshold of input rotation rate the counter-rotating beam frequencies are close enough that they lock to a common frequency, thus indicating the zero rotation rate as an output. The implications on accuracy and drift are obvious, especially in applications where measurement of very low rotation rates is essential. The magnitude of the lock-in effect depends primarily on the quality of the mirrors, and mirror quality has improved greatly since the first laser gyros were developed. However, even with improved mirrors, lock-in rates on the order of 0.01 to 0.1 deg/sec are the lowest levels achievable with today's laser gyros using a 0.63 μm laser wavelength.

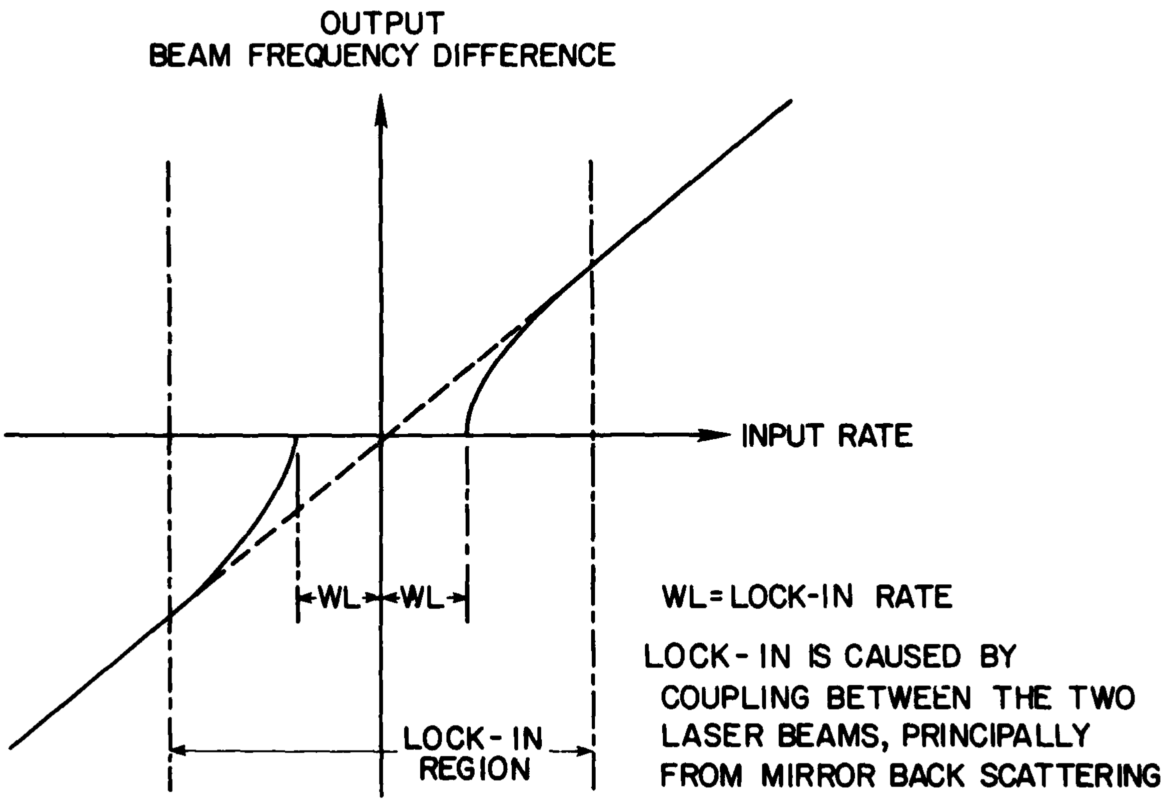

Figure 4. Laser Gyro Lock-in

*The following discussion of lock-in and methods for its compensation is taken from Savage, Reference 2, pp 2-10, 2-12.

This is not nearly good enough for most navigation applications (let alone the more stringent applications) and some question whether mirror technology will ever improve to the point where laser gyros can be used without employing additional means for lock-in compensation. These means can be divided into two general areas that will be discussed in the next two subsections. The first, mechanical dither, is the most commonly applied and yields the best accuracies at this time. It involves physically oscillating the gyro at high frequency on its sensitive axis to minimize the time spend in the lock-in region, and then subtracting the oscillatory (or dither) motion from the total motion. The second involves various electro-optic methods to achieve similar ends but without imparting physical motion to the laser gyro.

4.3.3 LOCK-IN COMPENSATION: MECHANICAL DITHER APPROACH

Under dynamic input rates that rapidly pass through the lock-in region, the effect of lock-in is to introduce a small angle error in the gyro output as the lock-in zone is traversed, but still retain sensitivity to input rate while in the lock-in region, that is, no hard dead-zone develops as in Figure 4. This effect underlies the basic principle behind adding cyclic high rate bias to the laser gyro as a means for circumventing the lock-in dead-zone effect, and converting it into a random angle error added to the gyro output each time the biased gyro input cycles through the lock-in regions. With mechanical dither, the oscillating bias into the laser gyro is achieved by vibrating the gyro block at high frequency about its input axis through a stiff dither flexure suspension built into the gyro assembly. The flexure suspension consists of spoke-like flexible metal reeds connecting metal rings attached to the laser block on the outside and to the gyro case/mount on the inside (Figure 5). Piezoelectric transducers attached to the reeds provide the dither drive mechanism to vibrate the gyro block at its resonant frequency about the input axis. One transducer is mechanized as a dither-angle readout detector and used as a control signal to sustain a specified dither amplitude. The resulting gyro random noise coefficient, a measure of the angle error accumulated from repeated traverses of the lock-in region, may be expressed ideally as:

$$\sigma_R = \Omega_L/(\Omega_o k)^{1/2}$$

where

σ_R = gyro random noise (or "random walk") coefficient (deg/hr$^{1/2}$),

Ω_L = lock-in rate (deg/sec) ,

Ω_o = dither rate amplitude (deg/sec), and

k = *gyro output scale factor expressed in fringes per input revolution.*

For typical values of σ_R = 0.002 deg/hr$^{1/2}$, Ω_L = 0.03 deg/sec, and k = 648,000 (that is, 2 arc sec per pulse), the above equation yields Ω_o = 72 deg/sec. For sufficient lateral stiffness the dither spring is designed so that the frequency of dither motion is on the order of 400 Hz. At that frequency the dither cycle amplitude corresponding to the (maximum) 72 deg/sec dither rate is 0.0289 deg or 103 arc sec (206 arc sec peak-to-peak). In practice somewhat larger dither amplitudes are required than predicted by this formula but this gives typical mechanical dither requirements.

Once mechanical dither is incorporated for lock-in compensation, some means to remove the oscillating bias signal from the gyro output must be provided. There are two general ways to do this: a "case mounted readout" method for optical cancellation of dither, or a "block-mounted readout" method for cancellation by computational methods. The first method is more elegant; the prism and photodiodes for fringe measurement are mounted on the gyro case rather than the laser block (see Figure 5) and will thus see fringe motion caused by the relative motion due to dither between case and laser block. This geometric fringe shift can be made to exactly cancel the dither signal in the gyro output through proper selection of the rotational center for the mechanical dither mount. The result is a photodiode output signal responding only to rotation of the gyro case. If, instead, the prism and photodiodes are mounted to the laser block (second general method) then the photodiode output will contain the dither signal. Filtering the output signal for frequencies near and above the dither frequency can work if the real rotation rate signals have frequency content well below the dither frequency. Otherwise, the dither motion must be measured, digitized, and subtracted from the gyro pulse output for dither motion compensation.

One practical disadvantage of the mechanical dither method is that three physically separate laser gyros are required in a three-axis system because each must be dithered about its own sensitive axis. In contrast, the cavities for three orthogonal gyros employing non-mechanical means for lock-in compensation can be interleaved into a single block of ceramic for considerable savings in size, weight and cost. Another problem that arises for three-axis dithered systems is that dither has been found to be the source of several mechanical coupling error mechanisms that must be considered at the three-gyro system level for solution. These produce both "pseudo-coning" effects due to "fooling" of the computation process, and real coning effects due to reaction torque of the gyro dither drives into the sensor assembly, and to mechanical coupling between axes. These problems can largely be handled with proper design but it should be noted that their effects are directly proportional to the magnitude of dither motion required for lock-in compensation. As lock-in rates are reduced, so can dither amplitudes be reduced, as seen from the formula for the gyro random noise coefficient. Since lock-in rates are dependent on mirror quality we see the need to use the highest quality mirrors even though mechanical dither provides a means for lock-in compensation.

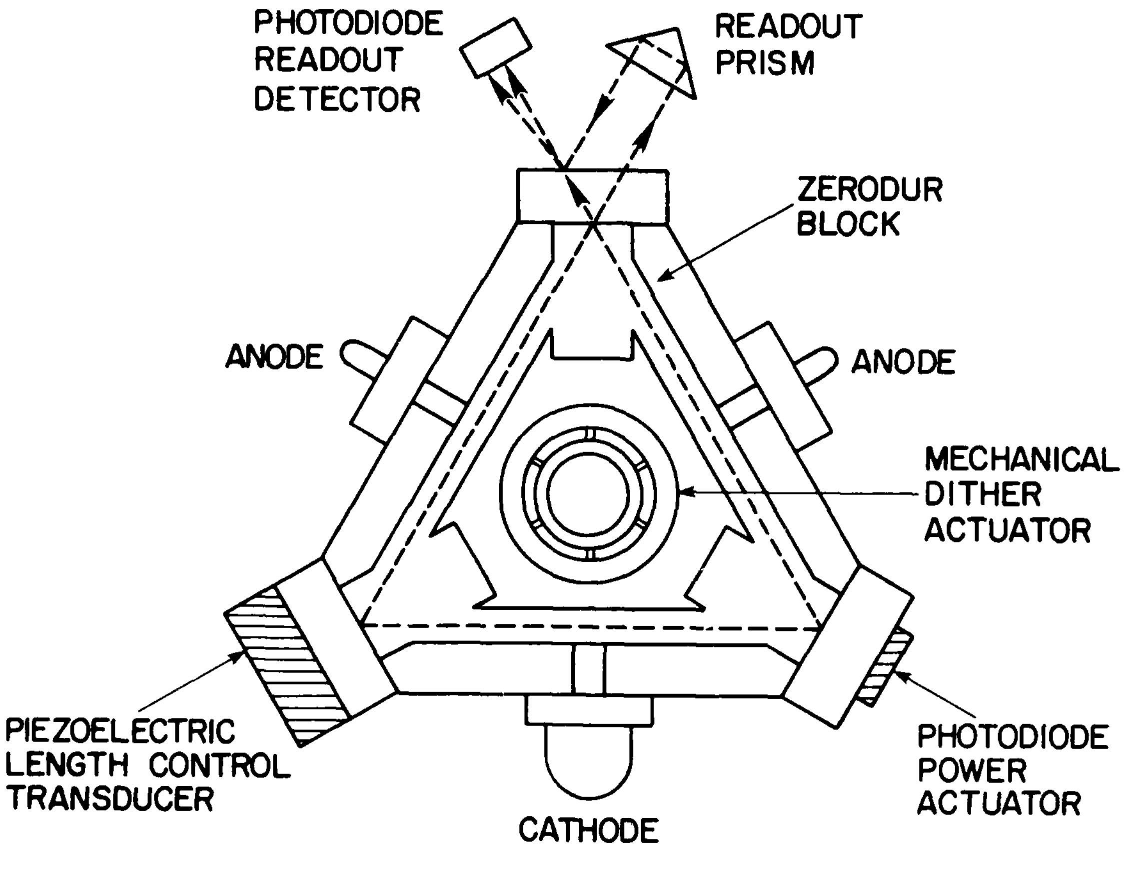

Figure 5. Laser Gyro Block Assembly

4.3.4 LOCK-IN COMPENSATION: ELECTRO-OPTIC METHODS

There are two techniques under this heading. The first is called the "magnetic-mirror" bias technique, which is based on the transverse magneto-optic Kerr effect. A special inner coating of ferromagnetic metal is applied to one of the laser gyro mirrors which, when magnetized normal to the plane of incidence by an applied magnetic field, imparts a non-reciprocal (opposite) phase shift between the counter-rotating laser beams. Thus the gyro can be biased out of the lock-in region in a way controllable by the applied magnetic field. The magnetic field intensity is set high enough to saturate the magnetic mirror; this minimizes bias shifts that could be generated by stray magnetic fields. By using alternating bias control (or square-wave dithering of the applied magnetic field) the error that would accumulate if the gyro were always biased in one direction is removed.

The advantage of the magnetic mirror technique is the elimination of the need for mechanical dither with its associated design complications and size/weight penalties, as discussed in the last subsection. A problem area has been the difficulty in generating a large enough bias due to low reflectance of the ferromagnetic coating. The resulting loss in beam intensity must be compensated by higher gain in the laser discharge, which cannot easily be tolerated for the 0.633 μm transition (though it works for the seldom used 1.15 μm transition). The alternative is to improve the reflectance of the magnetic mirror by layering of dielectric coatings. Recent work has concentrated on development of a garnet magnetic mirror with dielectric layer coatings of transparent garnet film to address the reflectance problem and some other problems.

The second technique, used for the Dilag or Multioscillator gyro, is similar to the first in that a frequency shift is induced between the clockwise and counter clockwise traveling laser beams to bias the gyro out of the lock-in region. However, the effective element is a Faraday rotator controlled by a magnetic field, in the beam path, acting on the laser beams, which are circularly polarized. This technique bypasses the problem of low mirror reflectance encountered in the magnetic mirror approach, but it seems no longer a major area for current development.

5. AFGL MISSION REQUIREMENTS

For the on-going types of missions that AFGL supports, as well as for the new types of programs that are likely to be supported in coming years, the attitude control requirements can be divided into two general areas where the new gyro technologies could be beneficial. These areas can be differentiated as having high vs medium level accuracy/stability requirements. The medium level requirements have for a long time been met by the Space Vector MIDAS gimballed inertial reference platform in its various configurations. The high level requirements are currently being met by Tuned Roto Gyro Systems and/or by Star Trackers. In this section, I will discuss several AFGL missions, past and present, with view to determining whether a change in the attitude control system is desirable for that type of mission.

5.1 High-Accuracy Requirements

High-level requirements, for purpose of this study, are defined as those that cannot be met by a MIDAS-class platform (to be described in Section 5.2). The pointing/stability requirements may be too high and/or mission duration too long (shuttle) so that drift becomes a problem. A sampling of past and present AFGL mission descriptions follows to illustrate some of the different types of requirements.

5.1.1 SPICE

For this mission in which a large portion of the sky was mapped by infrared telescope, a star tracker was used as the primary attitude sensor during the data-taking phase. The payload was rolled at a constant rate around the star tracker axis; at the completion of each rotation, the telescope was mechanically stepped through a specified angle around an axis perpendicular to the star tracker axis. In this way the telescope would map a different circle of sky with each rotation, and, over a number of rotations, would map a large portion of the celestial hemisphere. The star tracker had an $8 \times 8°$ field-of-view while in its search mode, and would acquire the brightest star within this area. Then in its track mode, the tracker's signal would be coupled to the attitude control system to keep that star within 16 arc min of the boresight. An inertial reference unit (IRU) was required to control the payload up to star acquisition and then to control the payload's roll rate around the star tracker axis. Also, in the event that the tracker failed to acquire a star, the IRU then became the primary pointing controller for the mission. An obvious candidate for the IRU, and the one chosen, was the MIDAS gimballed inertial platform, since it was the primary boost control system for the Aries vehicle and its use would not necessitate additional hardware. Though only of medium-level accuracy the MIDAS platform was more than adequate for payload control up to star acquisition because of the wide field-of-view of the tracker during its search mode. However, its use in roll control during the mission phase would seem to place an overall constraint on pointing accuracy, and so a more accurate system seems desirable, if it were otherwise competitive with the MIDAS. Likewise, the role as backup pointing controller indicates the desirability of a more accurate IRU. As with a roll control though, this desirability for more accuracy may be low enough in priority in this type of mission that other considerations, such as a clear economic advantage, might have to be demonstrated before a replacement to the MIDAS system is dictated.

5.1.2 IRBS

The IRBS payloads, like SPICE, used an infrared telescope for background measurements. However the mission geometry was much more complex and the pointing control requirements much tighter. The mission profile consisted of pointing the telescope at a number of zodiacal targets with a high degree of pointing control (± 1°, 3 sigma), combined with very low-rate scanning measurements (3.4 arc min of motion over 100 sec, or about 2 arc sec/sec ± 0.5). This specification did not lend itself to utilization of a star tracker, as in SPICE, so an inertial reference system that was capable of this level of pointing control had to be selected. It is interesting to note that the integrating contractor considered laser gyros during the selection process but decided that laser gyro technology, though promising, had not at that time (1977) matured adequately to be relied upon. The MIDAS A platform came close to the 1° pointing requirement but was eliminated on the basis that its threshold sensing limitation did not meet the low-rate scanning requirement. However, the MIDAS platform used for the Aries booster control system was proposed as a secondary data source. In the event of a temporary loss of TM data, the MIDAS platform could be used to re-initialize the integration process for the primary strapdown system. This concern just underscores the "volatility" of the reference point in strapdown relative to gimballed systems due to its computation-intensive nature, as discussed earlier. Tuned rotor gyros were chosen over other gyro candidates that met the specifications because they dominated the precision gyro market at the time and because only two tuned rotor gyros are required to specify orientation (see Section 3.2).

There were other specification requirements that candidate systems for IRBS had to meet. The acceleration-sensitive drift due to mass imbalance of the gyro rotor could not exceed 1.5°/hr g (3 sigma). Also, non-repeatability due to g-insensitive drift could not exceed 0.25°/hr (3 sigma). For tuned rotor gyros g-insensitive drift is affected by scale factor changes related to torquer temperature. Space Vector Corporation proposed the use of a heater to maintain the gyro at a nearly constant temperature (165° F, ± 1° F) and thus eliminate this source of drift. It should be noted that laser gyros have no g-sensitive drift because they do not employ spinning masses, and though they do have sources of g-insensitive drift, they are relatively insensitive to variations in temperature. If an IRBS-type mission were proposed today, laser gyros could be a viable contender for the ACS (see Section 6).

Besides an accurate attitude sensor, an accurate and finely-controlled actuator system was equally important to achieve the level of pointing control required by IRBS. Space Vector employed a dual pneumatic system for this purpose: a coarse system and a fine-control system. The coarse control system was virtually identical to the two-level system used in SPICE and the MSMP sensor Module. The fine-control system developed for IRBS achieved very low thrust by utilizing a much lower nozzle inlet pressure and a set of miniature nozzles. The nozzle arm was also significantly reduced to decrease the torque. This system provided the control needed for the low scanning rate requirements of the mission. (The focus of this study is on attitude sensors rather than the full control system but I mention this to identify an actuator system that could possibly be used in conjunction with laser gyros as well as conventional gyros.)

5.1.3 IMPS/SPAS

The Interaction Measurements Payload for Shuttle (IMPS) is an AFGL payload designed to be carried by the Shuttle Pallet Satellite (SPAS) free-flyer platform. The standard SPAS platform provides an Inertial Reference Unit (IRU) consisting of a three-axis strapdown conventional gyro system and a cold gas assembly for attitude control. There is concern that the IMPS mission requirements, which involve studying the shuttle/space plasma interactions at varying distances from the shuttle, may not be adequately met by the SPAS ACS capabilities. The SPAS can provide pointing accuracy with 1 deg deadband in all axes, and a drift rate of ± 1 deg/hr per axis (3 sigma) for a nominal flight profile. However, some of the IMPS science requires post-mission knowledge of carrier orientation, if not active attitude control, to ±0.5 deg over the duration of a several-hour sortie. It has been suggested that a more stable gyro system be incorporated to provide this improved attitude knowledge, though the problem of flight qualification might preclude actually replacing the gyros in the SPAS attitude control system. Laser gyros suggest themselves as candidates, though the very low drift rates implied may be pushing their state-of-the-art. This shuttle-oriented type of mission indicates different type requirements compared to sounding rockets since high pointing accuracies must be maintained over periods of hours on the shuttle instead of mere minutes on rockets.

5.1.4 EXCEDE III

This is a mother-daughter payload currently in the planning stage, to be launched by a booster with capabilities similar to the Aries. Two attitude control systems are required, one for each payload section. The "Gun" Module has a relatively modest requirement of being pre-programmable for pointing acquisition, with a system pointing accuracy ± 2.0 deg and ± 2.0 deg deadband. This can be met with the MIDAS gimballed platform. The sensor module has more stringent requirements: a pre-programmable ACS for pointing acquisition, with a system pointing accuracy of ± 0.5 deg and ± 0.2 deg deadband. In addition, one of the two ACS', will have to serve as the Vehicle Booster Control System (BCS). It has been proposed that the Sensor Module fill the BCS role, using what amounts to a full-fledged inertial reference system, since the proposed system employs three accelerometers as well as two tuned rotor gyros. This additional capability allows the Booster Control System to compensate for high altitude cross winds, predicted or unpredicted, and achieve much better trajectory accuracy than is possible with a system that senses and controls attitude alone, such as the MIDAS platform. Since most laser gyro systems are offered as inertial reference systems, they too would have the capability for this improved vehicle control.

5.2 Medium-Accuracy Requirements

Medium-level requirements, for purpose of this study, could be defined as those that can be met by a MIDAS-class platform. These include missions that do not have specific pointing requirements but still need a relatively controlled and stable mission environment. Included too are missions with specific pointing requirements that are not unduly restrictive, or for which flight duration is short enough so that drift is not likely to cause an unacceptable level of error. Use of a MIDAS-class platform is desirable wherever permissible because of its relative cost effectiveness. Expected drift of the MIDAS-class A platform is tabulated for comparison purposes. The data was taken from a sample of 25 units by Space Vector Corporation.

Drift Coefficients	Roll	Pitch	Yaw
Random (deg/hr)	2.58	1.74	3.96
Bias (deg/hr)	2.34	0.84	0.78
Z-Axis Accel. (deg/hr g)	1.92	2.58	1.68

6. EXISTING SYSTEMS

This section will discuss some of the ring laser gyro systems that have been produced by a number of manufacturers, and suggest where they might find application in light of the AFGL needs discussed in Section 5. The manufacturers are grouped according to the approach they use for lock-in compensation since, as discussed earlier, this so strongly affects the design and capabilities of the gyro. This list, which is probably not complete, is as follows:

- Mechanical Dither - Honeywell, Litton, GE, Rockwell, Sfena
- Magnetic Mirror - Sperry
- Dilag (or Multioscillator) - Hamilton Standard, Raytheon.

Systems employing mechanical dither are probably the only ones to date to be produced widely for commercial and military applications, although the other approaches continue to hold promise. The efforts of several manufacturers can be divided by their application: navigation systems for aircraft, and small missile guidance systems. Only one manufacturer has produced a system for applications similar to some of AFGL's needs: Sfena,[4,5] has produced a laser gyro inertial reference system that will be used as the secondary guidance system for the Ariane 4. While there are no existing systems that can be bolted into a sounding rocket off-the-shelf, several may be usable with some modification to hardware and software. The rest of this section discusses systems from some specific manufacturers.

6.1 Honeywell

Honeywell was a pioneer in the ring laser gyro field and now enjoys the largest share of the market. Though they have experimented with electro-optic methods for lock-in compensation, Honeywell has settled on mechanical dither for all its current systems. These current major systems employ two different models of the ring laser block; the GG-1328 and the GG-1342. The GG-1328 is the smaller of the two with a path length of 2.8 in. per leg (× 3 legs). This corresponds to a scale factor of 3.15 arc-sec per pulse, and a maximum input rate of 800 deg/sec is claimed. The GG-1342 has a path length of 4.2 in. per leg (×3 legs). This corresponds to a scale factor of 2.0 arc-sec per pulse, and a maximum input rate of 400 deg/sec is claimed.

The GG-1328 has been applied mainly to missile guidance. Used in the H-700-2 guidance system it saw numerous successful flights in the Simplified Inertial Guidance Demonstration (SIG-D), ATIGS-2, and Assault Breaker missile test

4. Lenorovitz, J., Sfena to start production of laser gyro, Aviation Week & Space Technology, 4/23/84.
5. Sfena qualifies Ariane 4 laser gyro reference system. Aviation Week & Space Technology, 2/3/86.

programs at White Sands Missile Range. The SIG-D was tested in the Vought T-22 missile. The GG-1328 is currently incorporated in the H-700-3 guidance system designed for high volume production. For this system the three gyros plus electronics are packaged in a box measuring 16.25 × 11.25 × 5.9 in., weighing 42 lbs., and drawing 28 Vdc, 70 Watts. This box is bulkier than the H-700-2 system, which had a missile-shaped geometry. It is nearly as bulky and weighty as systems employing the larger GG-1342, though drawing less power. Performance characteristics include bias stability of 0.1 deg/hr, random walk coefficient of 0.01 deg/hr$^{1/2}$, and scale factor stability of 10 parts/10^{6}. No specific pointing or navigation accuracy was given, but a test flight (using the H-700-2) of 138 sec covering 58.5 km and missing its target by less than 30 m gives some indication. A Honeywell representative suggested that a GG-1328 based system may be appropriate for AFGL-sounding rocket applications, citing the RLG characteristics that are valuable in a high dynamic environment. Addressing our smaller spin-stabilized rockets, he suggested that the high spin rates could be accommodated with changes to their readout electronics, which are presently designed to handle 1 MHz rates or only 800 deg/sec. I suspect, though, as discussed in Section 4.3.2, that increasing the rotation rate capability might decrease the drift stability to unacceptable levels, because the scale factor is only 10 ppm. The H-700-3 uses a pressurized air system for cooling; it is not clear how amenable to sounding rocket applications this is. However, since its main application is for missile guidance it might be accommodated. A sealed compartment is probably necessary unless the rocket flight is short enough to avoid heating problems.

The GG-1342 has been applied mainly to aircraft navigation. It has been incorporated in inertial navigation units for use in the Boeing 757/767/737 and in "Lasernav" for business-aviation aircraft such as the Gulfstream III. In the H-726 Laser Inertial Navigation System (LINS) it serves a number of indirect fire control applications. Incorporated in the H-423 LINS, it is designed to meet the specifications for the Air Force Standard Navigation System. The H-423 LINS is packaged in a box measuring 18.1 × 7.6 × 7.89 in. (0.63 cubic ft), weighs 48 lb, and draws 144 W dc (ac 140 Va). For cooling it requires 0.5 to 3.6 lb/min of air. Performance characteristics of the GG-1342 gyro include bias stability of 0.01 deg/hr and a random walk coefficient of 0.003 deg/hr$^{1/2}$. Performance characteristics of the H-423 LINS are tabulated as follows:

<u>Positioning Accuracy (CEP)</u>	
Full Performance	$\leqq$ 0.8 nmi/hr
Degraded Performance	$\leqq$ 1.5 nmi/hr
<u>Attitude Accuracy (rms)</u>	
Pitch or Roll	0.02 deg (72 arc sec)
True Heading	$\leqq$ 0.05 deg
Magnetic Heading	0.20 deg
<u>Velocity Accuracy (rms)</u>	
Full Performance	$\leqq$ 2.5 fps
Degraded Performance	$\leqq$ 3.0 fps
<u>Alignment Time (MAX)</u>	
Full Performance	8 min
Degraded Performance	2 min

The H-423 LINS offers a number of selectable functions:

- Present position lat/long navigation,
- Waypoint/Markpoint lat/long navigation,
- Self-test,
- Attitude mode,
- Selectable align: normal and degraded gyrocompass, stored heading, best available true heading.

The existence of an attitude mode offers hope that this system could be utilized for AFGL applications without major software modifications. A hardware concern that would have to be addressed, though, is cooling, since the circulation of air its design requires is probably impractical in AFGL applications. Radiative or conductive cooling may or may not be practical.

The 1986 price for a H-700-3 system (employing the GG-1328 RLG) is $125,000, and for a H-423 LINS (employing the GG-1342 RLG), is $90,000. Variations in the price of either system depend on the sub-model and options chosen. Though the H-423 LINS is the higher performance system its lower price reflects its greater level of production and sales. This pricing picture could change with time, and it should be noted that the systems detailed here are not the only ones to utilize the GG-1328 and GG-1342. It is possible that the H-423 LINS would be the more expensive system after modifications since more modifications might be needed to make an aircraft system suitable for sounding rockets than would be required to adapt a missile system. It also may be true that no practical modifications could make the H-423 LINS suitable for sounding rocket application. However, it would appear that the H-700-3 is too expensive (for now) since the H-423 LINS buys greater performance for lower price and for similar size and weight. Only the greater power consumption of the H-423 LINS might tip the balance the other way.

For the purpose of this study it might be better to compare GG-1328 type systems with GG-1342 type systems rather than comparing developed systems (even though Honeywell sells only systems, not discrete RLG's). The fact that one has developed around missiles and the other, aircraft, is an accident of supply and demand that need not reflect upon the inherent merits of the ring laser gyros themselves. Therefore, sounding rocket- and shuttle-compatible attitude control systems built around each of these gyros that would complement each other in the type of mission they satisfy can be envisioned. A GG-1328-based ACS could satisfy medium-level requirements and some higher-level requirements like SPICE and EXCEDE III; a GG-1342-based ACS could then satisfy the higher-level requirements like IRBS and IMPS. Developed to meet similar requirements, the GG-1328 based system should naturally be smaller, lighter and less costly than a GG-1342 based system, and if either or both systems are close enough economically to their conventional gyro counterparts, then other attributes of the RLG systems might pull business in their favor. These attributes include RLG "fit and forget" qualities: they need no periodic calibration or maintenance, they have demonstrated very high mean time between failure (MFBF), and they are amenable to rapid replacement and repair (unlike gimballed systems that require intricate disassembly to get to the essential parts). Low power-on-to-alignment times and suitability for dynamic environment (due to rugged construction and lack of moving parts) also favor RLG's.

6.2 Sperry Rand

Two-ring laser gyro models produced by Sperry in the late 1970's underwent extensive testing by the U.S. Air Force. Though these models never went into full-scale production they are presented here because they utilized the magnetic mirror approach for lock-in compensation rather than the "mainstream" mechanical dither approach. The resulting size and weight reduction, and potential for low cost, make this a technology worth watching, even though it is not currently dominant.

The SLIC-7 (Sperry Laser Inertial Cluster) has a 7-in. laser path length. It was a miniaturized version of the earlier and more accurate SLIC-15, with a 15-in. path length. Both models had their three gyros machined into a single

Cervit block. The packaged SLIC-7 sensor measured 4.5 in. in diameter, 4.5 in. long and weighed 4 lb. Combined with accelerometers and computer it was housed in a cylindrical container measuring 6 in. in diameter by 9 in. long weighing 14 lb. Sperry estimated that the SLIC-7 inertial guidance system could be built in quantity for $18,500 (1977 dollars) with $10,000 attainable. No performance figures were given but it would seem to be a candidate for some medium-level requirements with size, weight and cost considerations making it especially attractive. Some performance characteristics of the SLIC-15 are given in Table 2.[6] The SLIC-15 would seem to be a candidate for medium-level requirements and some higher-level requirements like SPICE and EXCEDE III.

Table 2. SLIC-15 Laser Gyro Characteristics (1σ)

g-Insensitive Drift (Turn-on Repeatability)	1.0	°/h
White-Noise Random Drift	0.03	$°/\sqrt{h}$
Markovian Random Drift (> 1 hr correlation time)	0.1	°/h
g-Sensitive Drift	NIL	
Anisoelastic Drift	NIL	
Scale-Factor Nominal Value	3.3	$\overset{\frown}{\text{sec}}$/pulse
Scale-Factor Stability	0.01	%
Scale-Factor Linearity	0.01	%
Sensitive-Axis Alignment Stability	6	$\overset{\frown}{\text{sec}}$

7. FUTURE DEVELOPMENTS

Passive optical rate sensors offer much potential; look for inertial reference systems employing them to appear within the next five to ten years. Besides their potential for lower cost than the ring laser gyro, they may ultimately achieve greater sensitivity than the RLG is capable of (see Figure 6). Work on the fiber-optic gyro is being pursued at McDonnel Douglas, Litton Inertial Systems, and Lear Siegler as well as research institutions such as C.S. Draper Laboratory and MIT.

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6. Levinson, E. (1978) Laser-gyro strapdown inertial system applications, in AGARD Lecture Series No. 95, Strap-down Inertial Systems, NATO, Neuilly.

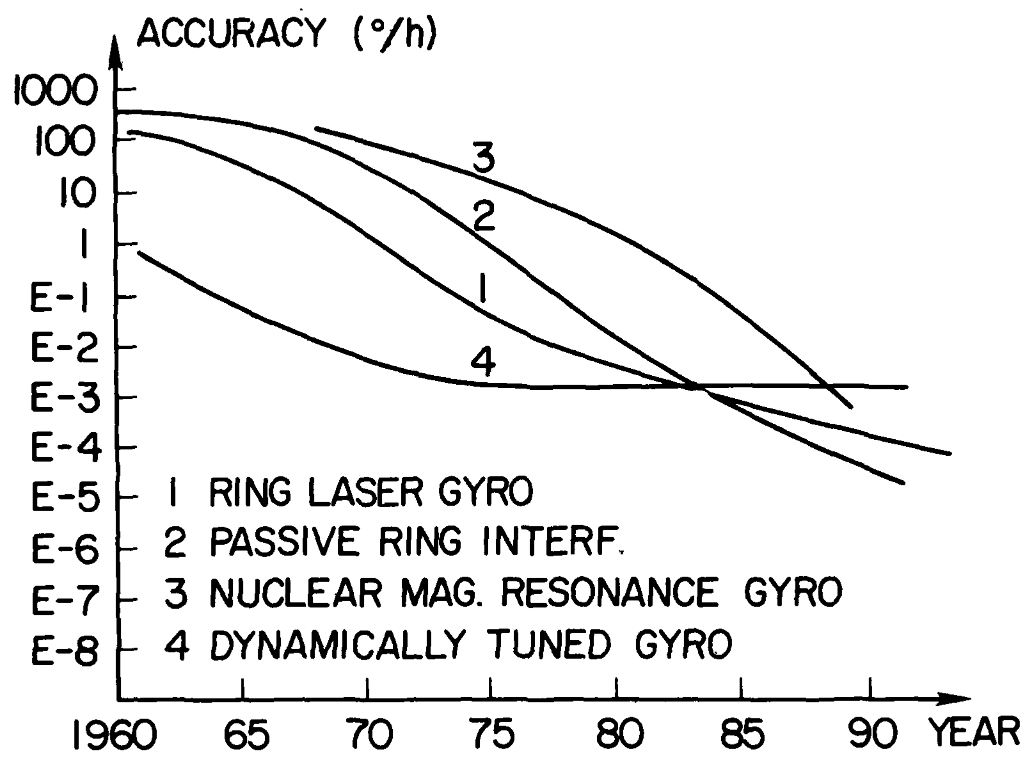

Figure 6. Projected Rate Sensor Potential

Inertial reference systems using ring laser gyros have achieved full-scale production for systems in the 1 nmi/hr accuracy range, with systems in the 0.1 nmi/hr range in advanced development. RLG's are capable of still higher accuracies but without large-scale users to drive development, specialized users such as AFGL could suffer. New concepts such as molded blocks for RLG's (with potential for cost reduction) have been addressed by Draper Labs but are currently shelved for lack of development impetus. AFGL, with specialized but low-volume needs, could conceivably work with a research institution like Draper Labs to bring some of these concepts to fruition, if AFGL had the commitment and the needs could not otherwise be met by commercially available systems. Work on second generation RLG technologies is currently being pursued by Honeywell and others. This includes utilization of thin-film integrated optics and solid-state laser diodes fabricated on a silicon substrate. These offer potential for lower cost and smaller size ring laser gyros.

8. CONCLUSIONS

Laser gyro technology has advanced to the point that there are a number of systems available that can meet the most stringent of AFGL's current pointing requirements. None of these systems have been optimized for sounding rocket application, though, so it remains to be seen whether these systems are competitive economically and under other engineering criteria besides pointing accuracy. In principle, a laser gyro system designed for sounding rocket application should be highly satisfactory, having many desirable attributes in addition to its pointing accuracy. Most systems are offered as full-fledged inertial reference systems rather than just attitude reference systems. The IRU would give capabilities to sounding rockets that have not been available in the past, such as improved booster control (see Section 5.1.4 on EXCEDE III) and better position determination during the mission phase, especially important for any mother/daughter payload. Ring laser gyros, as well as any other strapdown inertial system, might not be suitable for use in the smaller spin-stabilized sounding rockets at the present time since the high spin rates (up to 5 rev/sec) place a high demand on their dynamic range if the low rotation-rate accuracy (mission phase) is not to be sacrificed. Data presented here indicates that dithered RLG systems when compared to tuned rotor gyro systems of similar performance are larger, weigh more, draw more power, and are costlier. Before dismissing them, though, it would be well to examine data from some of the other manufacturers listed here. Also, within a very few years this picture could change dramatically as developments in RLG's improve their performance while reducing cost and size. The passive optical rate sensor technology is also maturing to a point that it can be competitive within the next few years, and eventually may supersede all other types of rotation sensors.

A follow-on to this study should, besides gathering more data on existing systems and tracking the promising technologies, expand its scope beyond the rotation sensor characteristics, to consider the entire attitude control system as it functions as a feedback system. This includes the control actuator system, whether cold gas or other, electronic hardware, and software algorithms. Since the rotation sensor technology varies widely it seems that only in the context of the total system can various trade-offs be evaluated in a way that will lead to the best selection to meet AFGL's future needs.

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