The Elmer A. Sperry Award

1984

for advancing the art of transportation

The Elmer A. Sperry Medal

The Elmer A. Sperry Award

☐ The Elmer A. Sperry Award shall be given in recognition of a distinguished engineering contribution which, through application, proved in actual service, has advanced the art of transportation whether by land, sea or air.

In the words of Edmondo Quattrocchi, the sculptor of the Elmer A. Sperry Medal:

"This Sperry medal symbolizes the struggle of man's mind against the forces of nature. The horse represents the primitive state of uncontrolled power. This, as suggested by the clouds and celestial fragments, is essentially the same in all the elements. The Gyroscope, superimposed on these, represents the bringing of this power under control for man's purposes."

Presentation of

THE ELMER A. SPERRY AWARD FOR 1984

to

FREDERICK ARONOWITZ
JOSEPH E. KILLPATRICK
WARREN M. MACEK
THEODORE J. PODGORSKI

by

The Board of Award under the sponsorship of

The American Society of Mechanical Engineers
Institute of Electrical and Electronics Engineers
Society of Automotive Engineers
The Society of Naval Architects and Marine Engineers
American Institute of Aeronautics and Astronautics

During the Conference on Lasers and Electro-Optics/XIII International Conference on Quantum Electronics

Wednesday, June 20, 1984 Anaheim, California

Elmer Ambrose Sperry 1860–1930

Founding of the Award

☐ The Elmer A. Sperry Award commemorates the life and achievements of Dr. Elmer A. Sperry (1860–1930) by seeking to encourage progress in the engineering of transportation. Much of the great scope of the inventiveness of Dr. Sperry contributed either directly or indirectly to advancement of the art of transportation. His contributions have been factors of improvement of movement of men and goods by land, sea and air.

The award was established in 1955 by Dr. Sperry's daughter, Mrs. Robert Brooke Lea, and his son, Elmer A. Sperry, Jr.

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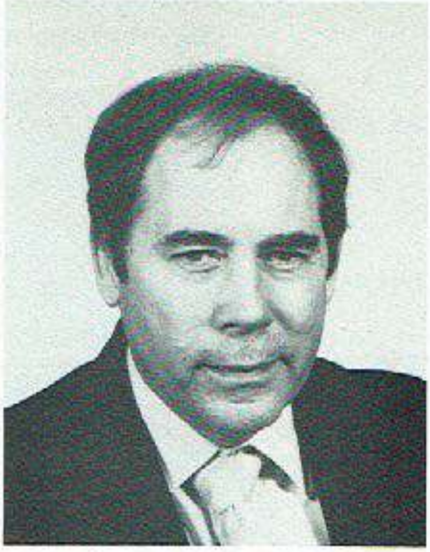

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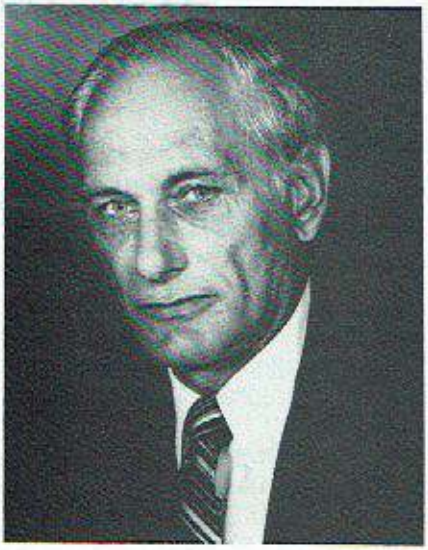

Warren M. Macek

Theodore J. Podgorski

Award Citation

☐ To Frederick Aronowitz, Joseph E. Killpatrick, Warren M. Macek and Theodore J. Podgorski for the conception of the principles and development of a ring laser gyroscopic system incorporated in a new series of commercial jet liners and other vehicles.

The Ring Laser Gyro

Introduction

Self-contained inertial navigation systems require two types of sensors: accelerometers and gyroscopes. The primary sensor is the accelerometer. Inertial navigation systems typically have three accelerometers mounted so that their input axes form an orthogonal triad. It is necessary, however, that the accelerometer assembly be referenced to a coordinate system which can be maintained or defined in a precise manner. In this case the accelerometer outputs can be integrated with respect to time to determine instantaneous velocity and distance traveled. A triad of gyroscopes is typically used to control or determine the orientation of the accelerometer cluster and to supply attitude information. Conventional spinning mass gyroscopes mounted in gimbal frames using null-seeking servo loops and torquers have traditionally served a control function (Figure 1). More recently, laser gyros rigidly strapped down to the vehicle frame have begun to replace this control function with measurement capability.

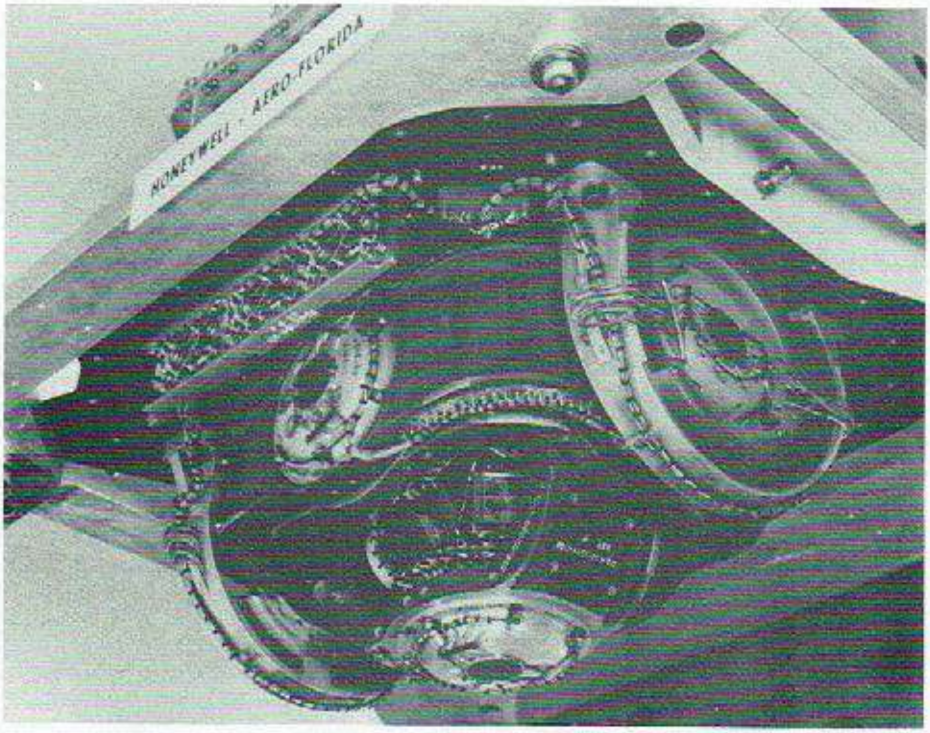

Figure 1. *A picture of an early inertial navigation system with gimballed gyros providing a stable reference system for the accelerometer cluster.*

High accuracy, high reliability laser gyros paired with modern digital computers have made this simpler approach possible.

Foundations of the Laser Gyro

The foundations of the laser gyro can be traced back to early analysis and experiments of G. Sagnac (1913) who first demonstrated the feasibility of measuring rotation rates using an optical interferometer on a turntable. The basic principle of Sagnac's interferometer is shown in Figure 2 and its operation can be described classically. When the interferometer is rotating the beam leaving the beamsplitter and traveling around the optical path in the direction of rotation travels a longer distance back to the beamsplitter than the beam traveling against the rotation because the beamsplitter moves during the light

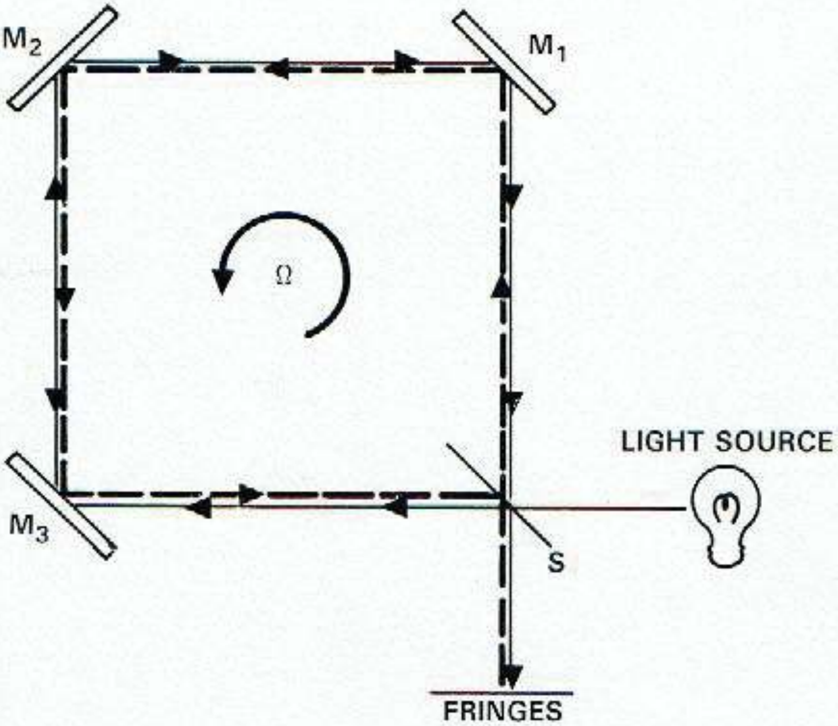

Figure 2. *Schematic of Sagnac's interferometer. A light beam impinging on a half silvered mirror S is split into two beams which travel in opposite directions around the path defined by mirrors* M_1, M_2 *and* M_3. *The beams are recombined by S to form fringes. The position of the fringes depends on the state of rotation of the interferometer.*

transit time. This classical description is essentially correct because the path length changes are first order in v/c. The path length changes are simply

$$\Delta l \pm = \pm 2 \frac{A}{c} \Omega$$

where A is the area enclosed by the optical path and c is the speed of light. Thus when the instrument is set into rotation with an angular rate Ω about an axis normal to the enclosed area, a fringe shift Δz occurs where

$$\Delta z = \frac{4A}{\lambda c} \Omega$$

and λ is the wavelength of the light source. Sagnac demonstrated that this equation was correct. In 1925 A. A. Michelson and H. G. Gale assembled a similar but very much larger (0.2 × 0.4 mile) interferometer and successfully measured the rotation of the earth. This approach to rotation measurement was not practical because of the extreme difficulty in measuring fringe location with high precision. The invention of the laser changed this.

In 1961 A. Javan et al successfully built the first gas laser and confirmed the theoretical expectations of A. Schawlow and C. H. Townes. The laser is an optical frequency oscillator which uses the neon atom in a mixture of helium and neon gases to supply the amplifier function and a set of mirrors arranged as a resonator to form the positive feedback function. A simple gas linear laser is shown in Figure 3. Typically, a dc current is passed through a small diameter tube containing a low pressure mixture of helium and neon gases. Collisions in the discharge excite the neon atoms and create a population inversion which makes amplification of light possible. When the amplification available from the neon atoms exceeds the mirror losses, oscillation will occur and a beam of light will propagate back and forth between the mirror pair. If the mirrors are partially transparent a useful beam of collimated light will be available

Figure 3. *A schematic of Javan's gas laser. A gas discharge gain tube D containing a low pressure mixture of helium and neon gases is placed in the optical path defined by a pair of parallel mirrors M_1 nd M_2 to form an optical frequency oscillator.*

outside the laser. Neon can supply gain in narrow regions centered about 1.1523 microns and 0.6328 microns. However, actual oscillations take place only on those resonances of the optical interferometer which lie in these regions. The fundamental resonant frequencies are thus determined by the reflectivity of the mirrors and their physical separation L.

C. V. Heer (1961) followed independently by A. H. Rosenthal (1962) was probably the first to suggest that this dependence of the laser frequencies of oscillatiion on the resonator path length could be used in conjunction with a Sagnac type interferometer whose path lengths are a function of rotation to make an active rotation sensor. W. M. Macek et al (1963) were the first to assemble a ring laser and demonstrate that it could be used to sense rotation. The picture of this first experimental laser gyro is shown in Figure 4 and the linear relationship between the input rotation rate and its output beat frequency is shown in Figure 5. This experimental demonstration of ring laser rotation sensing was at once an immense improvement in electromagnetic sensing and opened the door to a whole new family of laser gyro sensors.

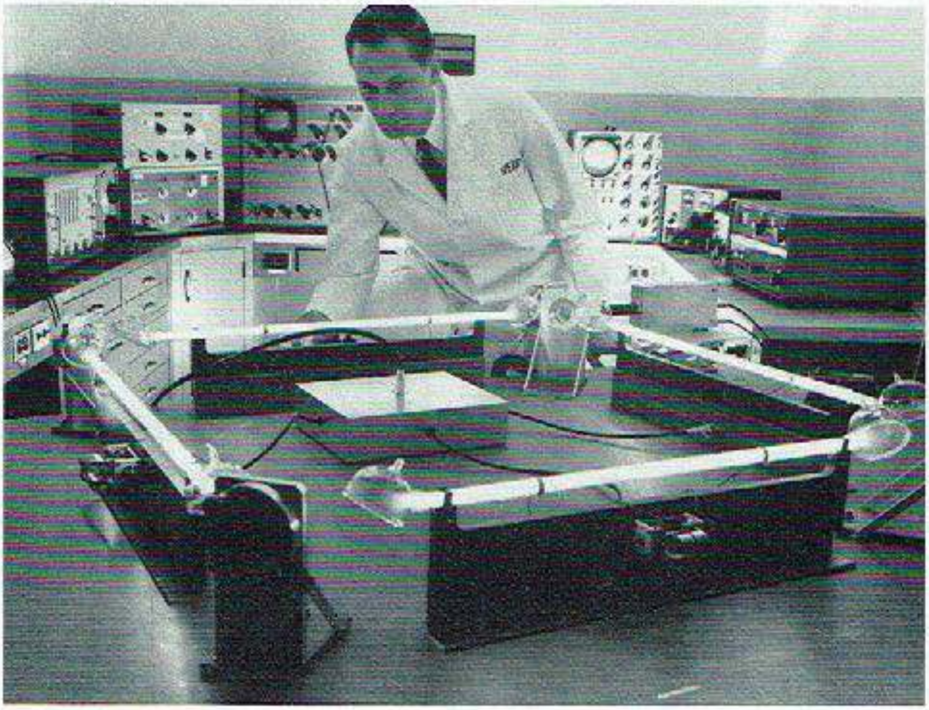

Figure 4. *A picture of the first experimental laser gyro assembled by W. M. Macek et al at Sperry Gyroscope: ca. 1962. The square interferometer was approximately one meter on a side and had a helium-neon gain tube in each leg. Tuned mirrors permitted oscillation to occur at 1.1523 micron wavelength.*

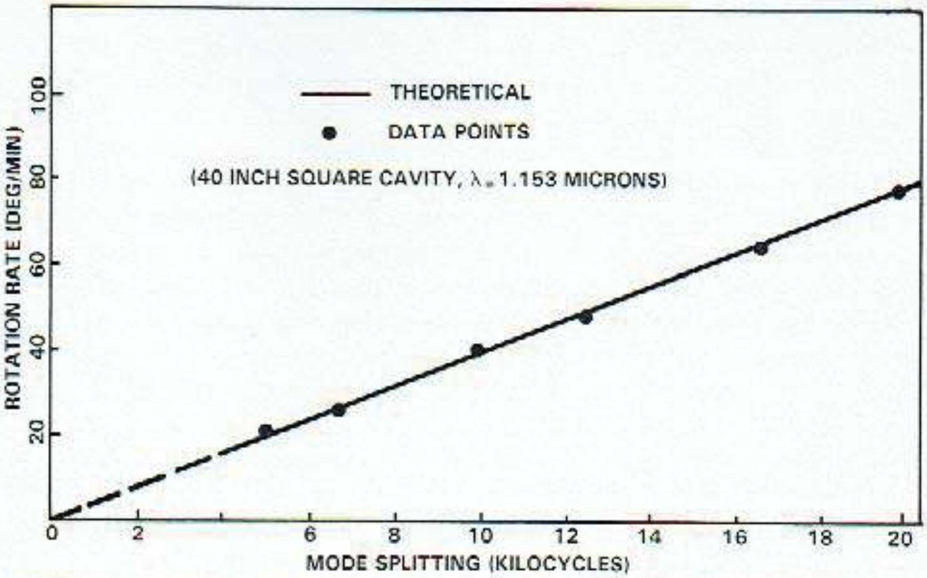

Figure 5. *Theoretical and experimental results for mode frequency splitting vs. rotation rate from the first laser gyro (W. M. Macek et al. 1963).*

In order to appreciate the sensitivity of this device, consider the path length differences that develop in a practical, rotating ring laser. A laser gyro with a 50 cm path length, rotating at earth's rate (about 10 deg/hr at 45° latitude), would develop a miniscule path difference of 10^{-4} angstroms (an impossible measurement with a Sagnac interferometer). The ring laser, however, converts this path length difference into a very measurable frequency difference. This same 50 cm laser gyro operating on the visible transition of neon would output a 10 Hz frequency difference.

A Fundamental Problem

A ring laser is a high frequency (optical) oscillator formed by a high Q optical resonator (interferometer) having three or more mirrors arranged to form a closed optical path that is immersed in a medium capable of supplying gain at the desired cavity resonance. If the gain supplied by the active medium to a resonant mode is greater than the resonator losses, oscillation will occur and beams of light will propagate around the resonator in both directions. In general, a number of resonances will fall in the gain region of the active medium and the laser will oscillate in many modes, each mode having its own characteristic frequency and field pattern. In practical laser gyros steps are taken to assure that oscillation occurs on only one fundamental mode in each direction.

The laser gyro is a ring laser whose fundamental mode frequencies of oscillation are given by

$$\nu = q \frac{c}{L}$$

where q is typically a very large integer defined by the resonant condition that the optical path length contain an integer number of wavelengths ($L = q\lambda$). For each value of q there is a traveling wave that propagates in each direction around the optical path. In the absence of rotation $L_+ = L_-$ and $\nu_+ = \nu_-$. However, upon rotation a frequency difference appears because $L_+ \neq L_-$.

$$\Delta f = \nu_+ - \nu_- = \frac{4A}{L\lambda} \Omega$$

In this ideal case where the laser oscillators are considered independent from one another the input-output relationship is linear. See Figure 6.

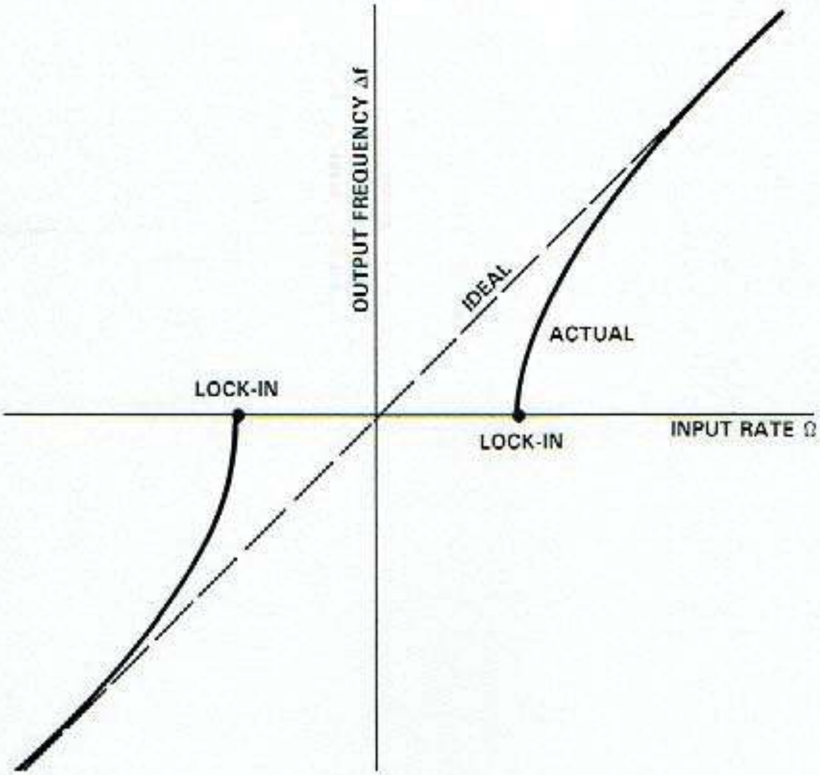

Figure 6. *The input-output function for an ideal laser gyro and the actual device which exhibits lock-in and dead-zone.*

However, extensive early experimental work with ring lasers soon uncovered the fact that the oscillators are not independent but rather are mutually coupled and exhibit a phenomena called lock-in. Lock-in is caused by imperfections in the optics of the resonator which scatter light from one beam back into the other and cause coupling. Oscillator synchronization is a general physical phenomena and all coupled oscillators (mechanical, electrical, optical, etc.) tend toward synchronization. As the oscillator frequencies are brought closer together the frequency pulling effects become more pronounced and at some point (lock-in) synchronization occurs. In a laser gyro turning at high rates where the oppositely traveling beams are widely separated in frequency, the pulling effects are barely noticeable. As the turning rate is decreased the frequency pulling becomes more pronounced until finally at some point lock-in occurs. Turning rates below lock-in are not detectable as a beat frequency (see Figure 6). This fundamental limit had to be removed if the laser gyro was ever to become a useful device.

Lock-in elimination and null-point or bias stability became key technical issues very early in the laser gyro development and remain the principal issues today.

The Evolution of the Practical Laser Gyro

The three years following W. M. Macek's feasibility demonstration were filled with intense theoretical and experimental activity by Macek and coworkers at Sperry and by Killpatrick, Aronowitz, Podgorski and coworkers at Honeywell, and by others. This activity used laboratory ring lasers typified by the instrument shown in Figure 7. Rapid progress was made in understanding the physical and geometrical properties of the ring laser and identifying the key laser gyro error terms and error sources. This work was helped immensely by the parallel development activity being conducted by others to advance the understanding of gas lasers. However, T. J. Podgorski recognized that it would be extremely difficult to build a practical sensor using the same techniques applied to the early experimental units and designed and patented (1965) the first monolithic, solid block ring laser. This design eliminated the instabilities and endless tweaking previously experienced and resulted in a quantum leap forward in ring laser technology. The basic laser structure could be machined with precision and imparted a new level of accuracy to laser gyro data.

A picture of the first solid block ring laser is shown in Figure 8. This design approach minimizes any disturbances to the measurement of the small optical path differences. From the start, low expansion materials were used to form the basic ring laser structure that establishes the optical path. Fused silica was used in the beginning but was replaced by Cer-Vit glass-ceramic. This material has a very low temperature coefficient of expansion, and is compatible

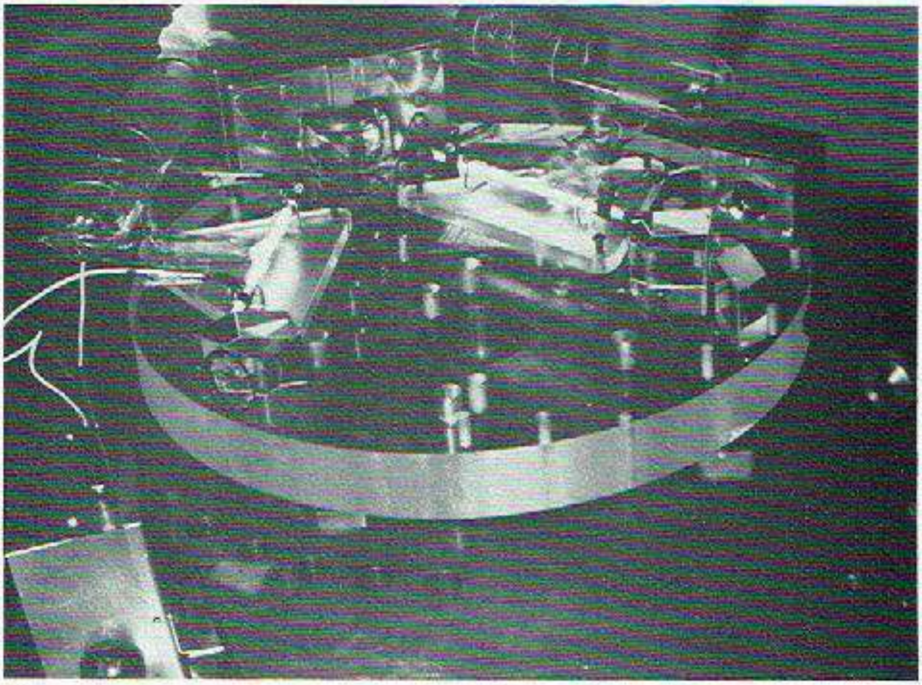

Figure 7. *A picture of an early experimental ring laser with separate RF excited gain tubes and adjustable, total internal reflection prisms that formed the resonator; ca. 1964.*

with the hard vacuum technology required to generate the laser light source. Cer-Vit also has low helium permeability which is required for a long-life, stable laser.

The two main elements of the ring laser are the resonator and the amplifier. In this solid block design, the resonator contains only two elements—the mirrors and the aperture. The mirrors are necessary for feedback, and the aperture is needed for mode control. The ring laser resonator is generated by a set of three mirrors placed triangularly in order to form a closed optical path. This configuration requires the minimum number of optical components, and is self-aligning. The use of three mirrors ensures automatic closure of the optical path in the laser plane, while the curved mirror ensures closure normal to the lasing plane. All three mirrors are of multilayer dielectric (MLD) construction and are placed in optical contact with the block, forming a stress-free, stable, hermetic seal. Originally the electrodes were epoxy sealed to the block and the gas fill station termination was a fused glass tube.

Appropriately drilled holes in the solid block permit passage of the oppositely directed traveling waves. These holes serve as apertures and, when

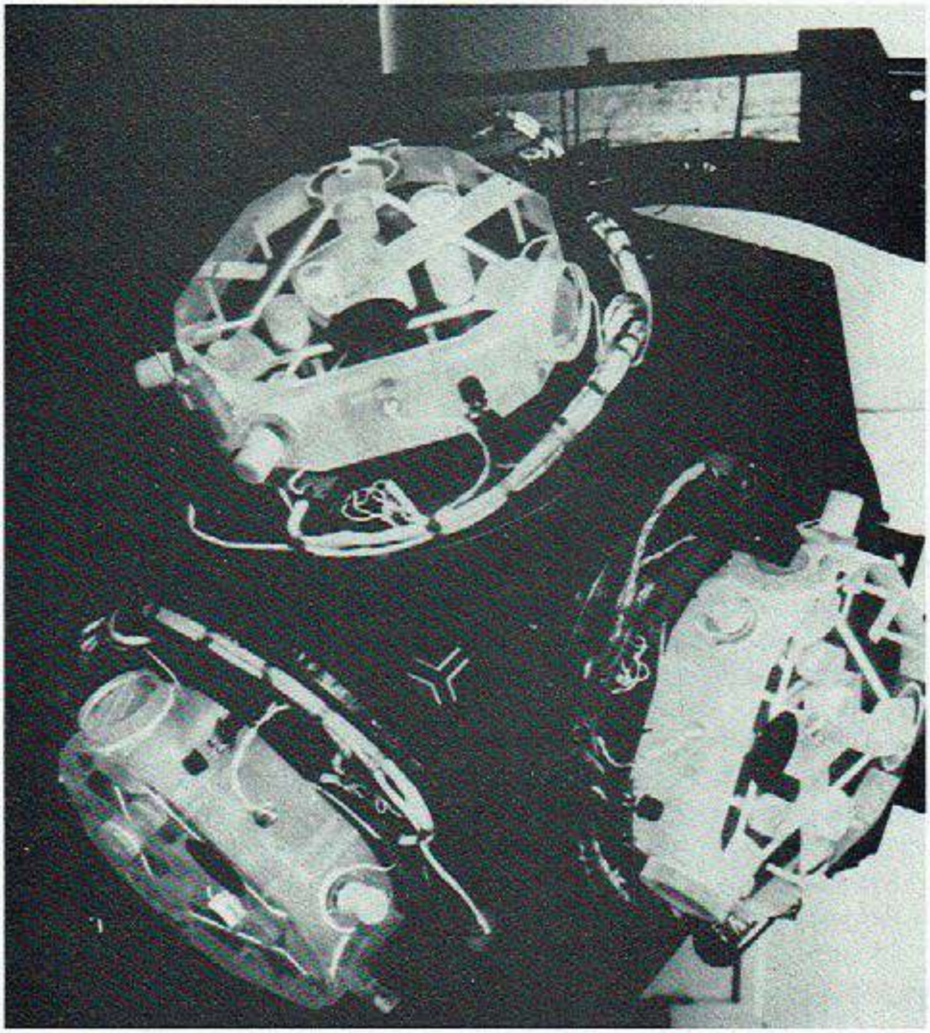

Figure 8. *A picture of the first laser gyro triad built and flight tested for the Navy; ca. 1966.*

filled with a low pressure of helium and neon, act as gain tubes. When an electrical discharge is established in the gas, gain is created and lasing action follows. A single large cathode and two anodes establish the split, balanced dc discharge. This permits precision gain control and trimming of null offsets.

The concern for null stability led J. E. Killpatrick to the conviction that the light beams in the laser cavity should not pass through solid materials. Solid elements such as Brewster windows and Faraday cells exhibit strain birefringence, which generate path differences and, hence, false rotation information when exposed to stress. Whereas others sought to eliminate the lock-in problem by using elegant electro-optic bias techniques that would permit operating about a point shifted from the normal null and dead band, Killpatrick looked elsewhere. He recognized that lock-in is a dynamic process; i.e., it takes time for the laser oscillators to lock up. Based on this fact he initially proposed that a sine wave oscillatory motion (dither) be imparted to the laser block with a peak rate such that the transit time through the lock-in zone would be small enough to prevent lock-in from occurring. He patented this technique in 1965.

After extensive computer analysis and experiments with solid block laser gyros he found that although there was some improvement using sine wave dither, an error was introduced each time the laser gyro passed through lock-in. Because the solid block ring lasers were extremely stable this error accumulated in a systematic fashion and quickly became very large. With a great deal of insight Killpatrick recognized that the addition of noise to the dither (patented in 1966) would randomize the errors and significantly improve performance. This dither technique eliminates the lock-in dead band and linearizes the input-output relationship but introduces a statistical uncertainty in the measurement process (random walk). The effectiveness of this technique is truly remarkable; it improves the rate sensing capability of a typical ring laser with a 200 deg/hr lock-in rate to about 0.002 deg/hr$^{1/2}$, 1σ.

The monolithic ring laser block with noisy dither was a significant advancement in the state of the art. It permitted independent optimization of the ring laser and the lock-in elimination techniques. A Honeywell team under contract to the Navy and led by J. E. Killpatrick used this technology to build and very successfully flight test the first ring laser triad in late 1966. A picture of this triad is shown in Figure 8.

The Theory of the Laser Gyro

Concurrent with the experimental work to identify error sources and the hardware development efforts, F. Aronowitz developed his "Theory of a Traveling Wave Optical Maser" (1965). This was a formal treatment of the traveling wave ring laser in which an assumed electromagnetic field in a rotating cavity, obeying Maxwell's equations, nonlinearly polarizes the moving gaseous atoms. The interaction was treated quantum mechanically in the frame of the moving atom. The resultant polarization, statistically summed over all velocity ensembles, was then used as a source term in Maxwell's equations. Self-consistency was used to obtain a set of equations which determined the amplitudes and frequencies of oscillation of the modes of the independent oppositely directed traveling waves in terms of parameters of the system. Stability conditions were derived for various gas isotopes. This theory of independent oscillators was expanded to include "Lock-in and Intensity-Phase Interaction in the Ring Laser" (1970). The resulting complex, self-consistent amplitude and phase equations are presented in Figure 9.

$$
\begin{aligned}
(2L/c)\dot{E}_1/E_1 &= \alpha_1 - \beta_1 I_1 - \theta_{12} I_2 - 2\rho_2 \cos(\psi + \varepsilon_2) \\
(2L/c)\dot{E}_2/E_2 &= \alpha_2 - \beta_2 I_2 - \theta_{21} I_1 - 2\rho_1 \cos(\psi - \varepsilon_1) \\
\omega_1 + \dot{\phi}_1 - \Omega_1 &= \sigma_1 + \tau_{12} I_2 - (c/L)\rho_2 \sin(\psi + \varepsilon_2) \\
\omega_2 + \dot{\phi}_2 - \Omega_2 &= \sigma_2 + \tau_{21} I_1 - (c/L)\rho_1 \sin(\varepsilon_1 - \psi)
\end{aligned}
$$

where

$$\rho_2 = r_2 E_2/E_1, \qquad \rho_1 = r_1 E_1/E_2.$$

Figure 9. *F. Aronowitz's self-consistent laser gyro equations (author's notation).*

These equations describe all the salient features of the laser gyro in exquisite detail. Agreement with experiment has been excellent and a constant interplay between the theoretical analysis and the experimental results was used to advance the instrument. Aronowitz has used these equations to describe CW and CCW mode competition effects and their dependence on neon isotopes. This work helped eliminate early stability problems. Lock-in equations were developed that contained dependencies on scattered light, gas pressures, isotopes, and gain-to-loss ratios that were used to optimize the laser cavity parameters. The theory was used to precisely determine the gyro scale factor (input-output relationship) and nonlinearities were predicted and observed that were not expected from classical models. Gas flow bias effects were described in detail and the effect of forward scattered light on bias was described. Differential gain and loss effects were included. Detailed error modeling has continued up to the present with others making contributions to this fundamental set of equations.

The basic theory with subsequent additions has now been developed into engineering design equations and guidelines which have been used to develop laser gyros for a broad spectrum of applications.

Laser Gyro Product Development

The period 1962-1968 was devoted to feasibility demonstrations and intense theoretical development. Even after the successful feasibility demonstrations of Macek et al and Killpatrick et al formidable obstacles remained. The late sixties-early seventies were trying times as attempts were made to develop laser gyros that were competitive with conventional, available gyro-

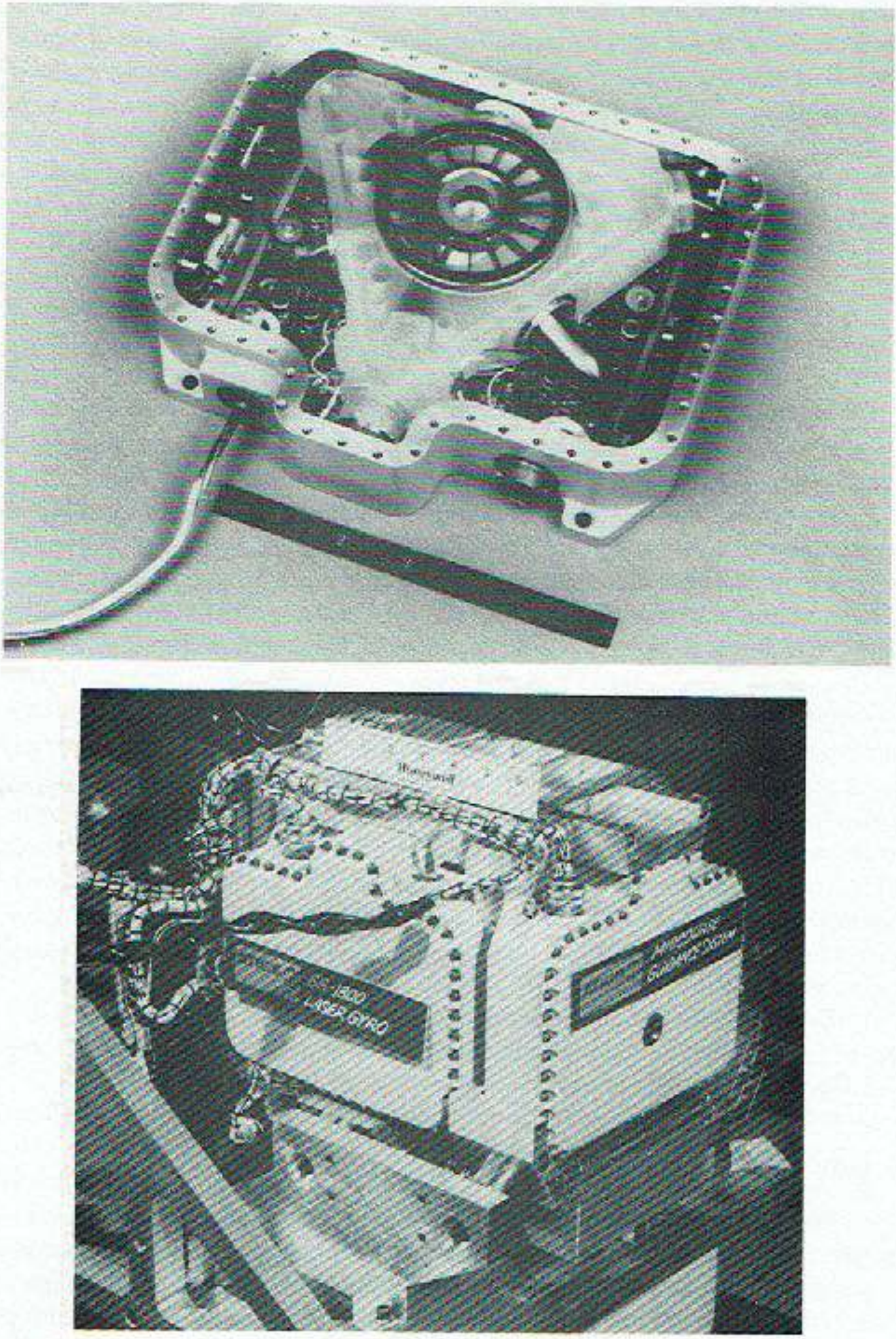

Figure 10. *A picture of an advanced solid block laser gyro and the ATIGS X-0 system—forerunners of the first production laser gyro inertial navigation system.*

scopes. Size had to be reduced, performance increased, and lifetime and reliability extended. The new technology had to be developed and sold convincingly. These efforts culminated in the development of an advanced technology laser gyro for the Navy (1974). This laser gyro incorporated a raft of new developments put together by T. J. Podgorski. A new glass-ceramic (Cer-Vit) block material and mirror substrate material were used. Hard coat, long life mirrors were incorporated, gold-indium electrode solder seals were used (after Hochuli) with a new, long life cathode design. A new monolithic path length transducer mirror was used. A simple, symmetric piezoelectric dither motor was incorporated and a case mounted readout optics system that eliminated the dither signal from the output was used. This new design was truly a breakthrough in all respects. See Figure 10. Its performance and life characteristics were so good that commitments were made for advanced systems development.

The ATIGS X-0 system (Figure 10) was developed for the Navy and subjected to extensive flight testing and van testing with outstanding performance and reliability (no failures). Performance far exceeded the 2 nmph (50% CEP) design goal. These advanced laser gyros were made available to the Boeing Company and consigned to others for test evaluation with impressive, convincing results. However, the laser gyro was too big to meet aircraft system packaging requirements and a performance improvement was needed in order to reduce the gyro size.

In 1976, T. J. Podgorski patented and developed a random drift improvement (RDI) technique that made this size reduction possible. A smaller gyro was developed with this technique and meets the size performance requirements of many commercial and military systems. This is the laser gyro that is now aboard the new Boeing 757 and 767 airliners.

Laser Gyro Production Status

The important features of the laser gyro in full-scale production at Honeywell are shown in Figures 11 and 12. The characteristics of this gyro are:

- Hermetic housing with preamplifiers
- Maximum power dissipation - 2 watts
- Heaterless operation
- Instant reaction
- Scale factor - 2 arc seconds/pulse
- Digital output
- Rate capability - 400 deg/sec
- Fully interchangeable electronics

Current control
Readout logic
Dither drive
Path length control and RDI
Power supply and starting

This gyro is used in the latest jetliners shown in Figure 13 for both flight control and navigation.

Over 1,000 laser gyros are now operating in commercial revenue service and have logged over 2.3 million operating hours (January, 1984) with outstanding reliability. Laser gyros are also being produced for military applications.

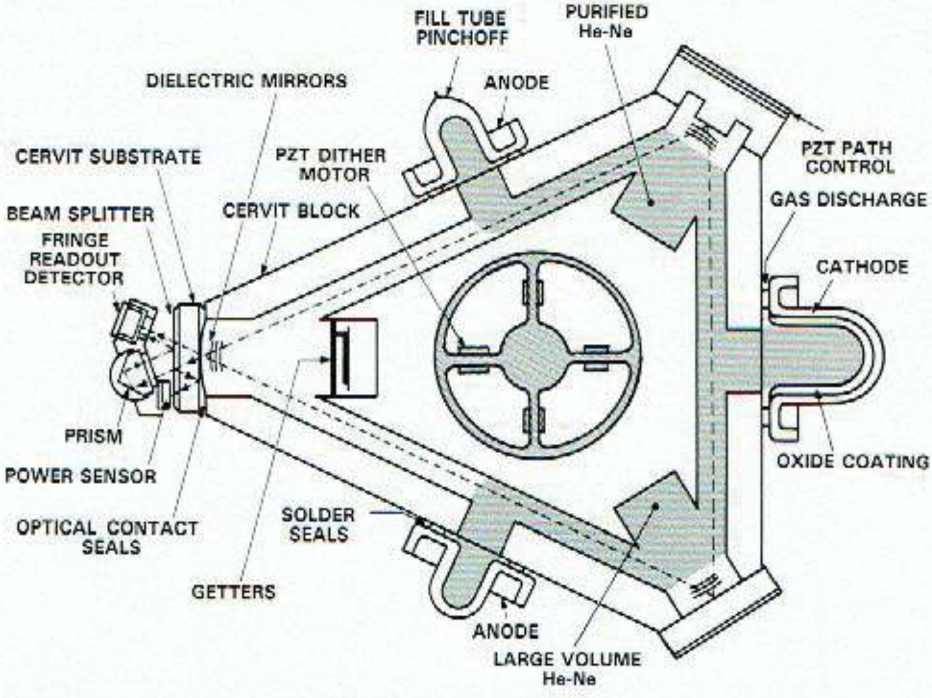

Figure 11. *The principal features of the monolithic solid block ring laser gyro. All laser gyros moving into production today have the principal features shown in this drawing.*

Figure 12. *A picture of the production laser gyro and its remote, interchangeable electronics card.*

Figure 13. *The Boeing 767 aircraft which uses the laser gyro for flight control and navigation.*

The Future of Laser Gyros

The future for laser gyros looks bright and both commercial and military applications are expanding. As the number of manufacturers increases and the supporting industry expands, laser technology should experience a large amount of synergism and laser gyros and laser gyro-based systems will make deep market inroads. Performance will continue to improve and is already becoming so good that laser oscillator photon noise (the quantum limit) is becoming a serious design consideration. Accurate, reliable inertial navigation will improve transport efficiency and safety in aircraft and ships and is available today.

FREDERICK ARONOWITZ

Dr. Frederick Aronowitz was born on July 3, 1935 in New York City. He attended the Polytechnic Institute of Brooklyn and received a B.S. in physics in 1956. He received his Ph.D. in physics from New York University in 1969. His thesis subject was the theory and operation of the ring laser. His career at Honeywell, Inc. was from 1962 to 1983. During that period most of his time was spent on the development of the principles of operation of the ring laser gyro. In 1983, he joined the Raytheon Company as Manager of Laser Gyro Development.

JOSEPH E. KILLPATRICK

Joseph Killpatrick was born on February 15, 1933 in Hillsboro, Illinois. He attended Millikin University in Decatur, Illinois and graduated from the University of Illinois in 1955. He joined Honeywell in June, 1955 in Minneapolis, Minnesota as a Research Engineer.

He also attended the University of Minnesota, taking graduate courses in Electrical Engineering. In those first years he worked on the detection of low level electric fields, control and support of the electrostatic gyro and general infrared detection, and sensor technology.

He was promoted to Section Head in 1961, and led the development of infrared sensors and the He-Ne laser. In 1963 he led the development of the RLG technology. He was involved in all aspects of the gyro development, holds several basic laser gyro patents, and designed several of the control circuits which are still in use today. He transferred to the Avionics Division in 1968 following the successful completion of the RLG technology in 1974 and returned to research activities as Manager of Physical Sciences from 1975 to 1982.

He is currently the Research Department Fellow where he is involved in a wide range of technologies but still spends a significant portion of time on RLG sensors, system advances, and new thrusts.

Mr. Killpatrick has been a member of IEEE since 1954 and the Optical Society of America since 1961.

WARREN M. MACEK

Warren Macek was born on November 7, 1932 in Mount Vernon, New York. He joined Sperry in 1954 after receiving his B.S. degree from Bates College with a major in physics and math. While at Sperry, he attended night school and received an M.S. in 1958 from Hofstra University, and completed his Ph.D. course requirements in 1966 at Polytechnic Institute of Brooklyn.

Since starting at Sperry 30 years ago, Mr. Macek has been responsible for a number of airborne radar and air-to-air rendezvous system developments, including design, build and flight test evaluation. He has also participated in various study and development programs, including orbital and thrust requirements for space rendezvous, optical space radars using microwaves and CW/pulsed high power lasers, and high frequency electro-optic light modulators and beam scanners.

Mr. Macek was primarily responsible for proposing, building and testing the first successful ring laser in late 1962. Since then he has been active in all phases of ring lasers and has devoted 22 years to their design and development. He has made many original contributions to the improved performance of laser gyros.

He is currently a Research Supervisor at Sperry responsible for the advanced development of high performance laser gyros. Based on his unique experience, he has delivered over 30 talks and papers on the current status of ring lasers. He holds 13 patents and has 4 patents pending. He is a member of the American Physical Society, the Optical Society of America and the Honor Physics Society, Sigma Pi Sigma.

THEODORE J. PODGORSKI

Theodore Podgorski was born on September 21, 1937 in St. Paul, Minnesota. He attended school at the University of Minnesota, majoring in Physics. He joined Honeywell in 1960 in the Inertial Sensors Section of the Systems and Research Division. His initial responsibilities involved research activities on new inertial sensor concepts—both gyroscopes and accelerometers. He joined the Electro-optic section in 1963 and was responsible for the design of the first operating ring laser at Honeywell. He transferred into the Laser engineering department in 1970 and assumed greater product development responsibility. This effort evolved into design and support efforts that led the laser gyro into full-scale production. He is presently a Senior Engineering Fellow in the Inertial Sensors Engineering Section and is involved in advanced development activity on high performance ring laser gyros.

Previous Elmer A. Sperry Awards

1955 to *William Francis Gibbs* and his Associates for development of the S.S. United States.

1956 to *Donald W. Douglas* and his Associates for the DC series of air transport planes.

1957 to *Harold L. Hamilton, Richard M. Dilworth* and *Eugene W. Kettering* and Citation to their Associates for the diesel-electric locomotive.

1958 to *Ferdinand Porsche* (in memoriam) and *Heinz Nordhoff* and Citation to their Associates for development of the Volkswagen automobile.

1959 to *Sir Geoffrey De Havilland, Major Frank B. Halford* (in memoriam) and *Charles C. Walker* and Citation to their Associates for the first jet-powered aircraft and engines.

1960 to *Frederick Darcy Braddon* and Citation to the Engineering Department of the Marine Division, *Sperry Gyroscope Company*, for the three-axis gyroscopic navigational reference.

1961 to *Robert Gilmore Letourneau* and Citation to the Research and Development Division, *Firestone Tire and Rubber Company*, for high speed, large capacity, earth moving equipment and giant size tires.

1962 to *Lloyd J. Hibbard* for application of the ignitron rectifier to railroad motive power.

1963 to *Earl A. Thompson* and Citation to his Associates for design and development of the first notably successful automobile transmission.

1964 to *Igor Sikorsky* and *Michael E. Gluhareff* and Citation to the Engineering Department of the Sikorsky Aircraft Division, *United Aircraft Corporation*, for the invention and development of the high-lift helicopter leading to the Skycrane.

1965 to *Maynard L. Pennell, Richard L. Rouzie, John E. Steiner, William H. Cook* and *Richard L. Loesch, Jr.* and Citation to the Commercial Airplane Division, *The Boeing Company*, for the concept, design, development, production and practical application of the family of jet transports exemplified by the 707, 720, and 727.

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1983 to *Sir George Edwards, OM, CBE, FRS, DSC, General Henri Ziegler, CBE, Sir Archibald Russel, CBE, FRS, DSC; Andre Turcat;* and *Sir Stanley Hooker, CBE, FRS, DSC* commemorating their outstanding international contributions to the successful introduction and subsequent safe service of commercial supersonic aircraft exemplified by the Concorde.