The Hemispherical Resonator Gyro: From Wineglass to the Planets

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Small size, low noise, high performance and no wear-out has made the Hemispherical Resonator Gyroscope (HRG) the choice for high value space missions. After 14 years of production the HRG boasts over 12-million operating gyro-hours in space with 100% mission success. But to get to this point has been a struggle. This paper will describe the HRG's elegant simplicity in design and operation and trace its genealogy from concept to the future. Its versatility will be shown by its use for spacecraft stabilization, precision pointing, aircraft navigation, strategic accuracy systems, oil borehole exploration and planetary exploration.

Introduction

Landing on an asteroid, circling Saturn, slamming into a comet or exploring the hottest planet; the Hemispherical Resonator Gyro (HRG) has literally proven itself through trial-by-fire. It has been a winding path that has taken this technology from its inception to its current success with surges and slumbers alternating from the 19th century to the 21st. Initially conceived in 1890 through the observation of beats from a ringing wine-glass, the concept was lost until uncovered in 1965. The concept was then validated through the rapid design, analysis, fabrication and test effort by a small team. The effort however lay dormant until 1975 from which point it saw a rapid advance of the technology only to shut down when at the point of entering production as an aircraft navigation system. From the ashes arose the smaller, lighter, improved HRG design that has become the current "sensor of choice" for high value satellites and other spacecraft having earned that position by demonstrating over 12-million operating gyro-hours in space with 100% mission success (Figure 1).

After telling this amazing development story (Figure 2) this paper will present the HRG design in all its simplicity. Its versatility will then be shown through a description of its current applications, a few dramatic missions and a quick peek at the future.

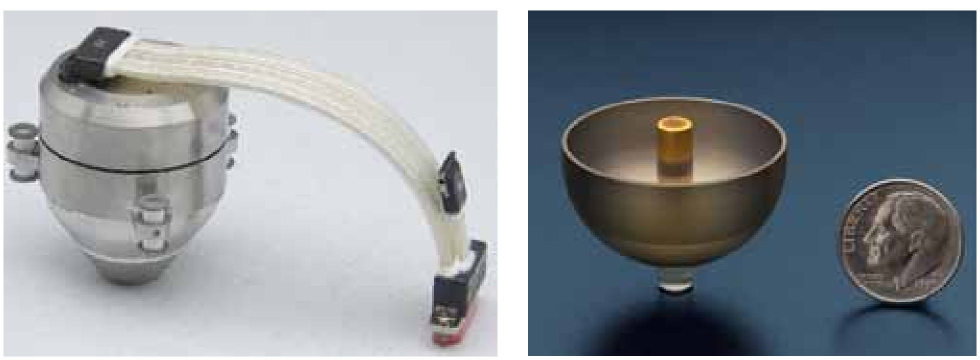


Figure 1. HRG Resonator and Sensor Assembly

Evolution of the HRG

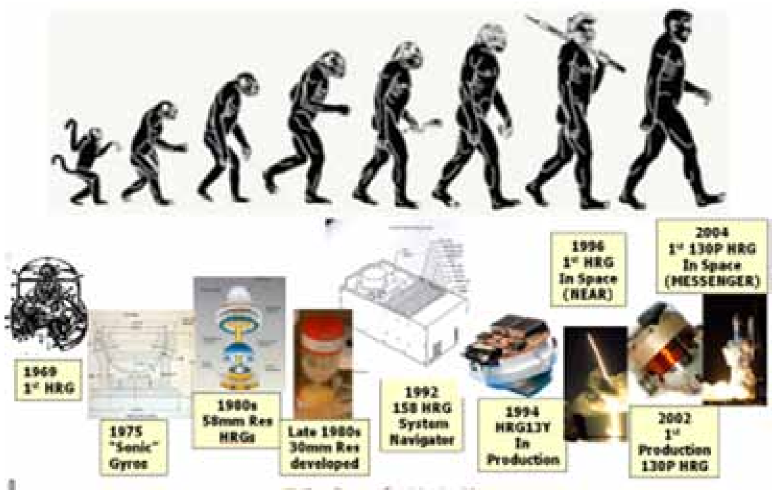
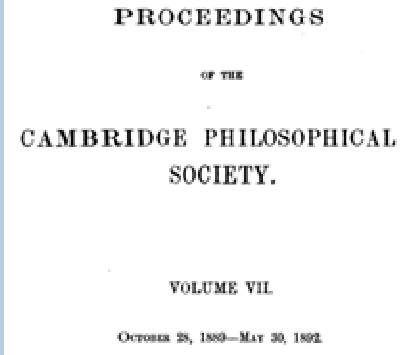


Figure 2. Evolutionary Paths Leading to the HRG of Today

The Discovery of a New Phenomenon

The physics of the HRG is based on the forces arising from Coriolis acceleration, most often associated with the phenomenon that explains why winds and currents tend to flow to the right of this direction north of the equator, and to the left of this direction south of the equator.. The effect was first described by Gaspard-Gustave Coriolis, a French scientist who in 1835 described the forces that arise from the motion of objects in a rotating reference frame[1]. The credit for originating the use of the effect relative to the measurement of rotations, however, has been given a late 19th century English scientist.

The HRG was conceived in 1890 when physicist G. H. Bryan struck a wineglass, making an interesting discovery about how the tone from the glass behaved when it was rotated about its stem. His observation that " … If we select a wine-glass which when struck gives, under ordinary circumstances, a pure and continuous tone, we shall on twisting it round hear beats" led him to the conclusions that a flexing hemisphere could detect rotation. Little did he know that this simple observation leads a chain of events that would end up taking spacecraft to the planets. An excerpt from his thesis, "On the Beats in the Vibrations of a Revolving Cylinder or Bell" shown in Figure 3 gives a view of his work on the subject[2].



PROCEEDINGS

OF THE

CAMBRIDGE PHILOSOPHICAL SOCIETY.

VOLUME VII.

October 28, 1889—May 30, 1892.

The following Communications were made to the Society:

(1) On the beats in the vibrations of a revolving cylinder or bell.
By G. H. BRYAN, M.A., St Peter's College .

In this paper I propose to investigate the nature of the beats which may be heard when a vibrating shell in the form of a cylinder or other surface of revolution has imparted to it a rotatory motion about its axis of figure.…

… If we select a wine-glass which when struck gives, under ordinary circumstances, a pure and continuous tone, we shall on twisting it round hear beats, thus showing that the nodal meridians do not remain fixed in space. And if the observer will turn himself rapidly round, holding the vibrating glass all the time, beats will again be heard, showing that the nodal meridians do not rotate with the same angular velocity as the glass and observer . If the glass be attached to a revolving turntable it is easy to count the number of beats during a certain number of revolutions of the table, and it will thus be found that the gravest tone gives about 2.4 beats per revolution. As this type of vibration has 4 nodes we should bear 4 beats per revolution if these nodes were to rotate with the glass, we conclude therefore that the nodal angular velocity is in this case about 3/5 of that of the body.

* That is meridians along which the vibration has no radial component

Figure 3. Bryan's Communication to the Cambridge Philosophical Society, 1890

A New Rotation Sensor Is Born

The conversion of this idea into practicality however didn't progress smoothly. It wasn't until the 1965 that the idea resurfaced at the small Delco Wakefield, MA R&D facility where a few young PhDs led by the "Physics Group" lead, Dr. David Lynch, were chartered to investigate "unconventional inertial instruments", striving to develop new guidance sensors utilizing technologies different from that used in the floated single degree of freedom mechanical gyros, the rotation sensors utilized in the first decade of practical inertial navigation. They approached this by investigating alternative phenomena, searching for effects that exhibited first-order sensitivity to rotation. In 1965 Dr. Alfred Emslie, an acoustics expert working as a consultant from the Arthur D. Little company, when exploring that phenomenon hit upon the rotation sensitivity of symmetrical shells undergoing flexural vibrations. At about the same time he uncovered the reference to the 1892 Bryan article in the 1894 edition of Lord Rayleigh's Theory of Sound. Based on this discovery, Dr. Ivan Simon, also of Arthur D. Little, performed experiments using vibrating metal rings to demonstrate the magnitude of the effect while Dr. Lynch constructed the first theoretical model of the vibrating hemispherical shell using a Lagrangian procedure based on the Rayleigh inextensional theory of shells as outlined in the Theory of Sound. Thus was born the HRG development at General Motors[3].

The First HRG

In that time two experimental HRGs, then called "Bell" or "Sonic" gyros, were designed, built and tested validating the concept of using acoustics for a rotation sensor. The resonator design of the first gyro was a wine-glass type (outer stem) while the second design utilized a mushroom (inner stem) approach. The wineglass gyro was gave reasonably good performance but showed a large sensitivity to temperature. The mushroom design however was a disaster. In this design the resonator was attached to the hemispherical shell using a bolt through the pole of the shell which resulted in huge environmental sensitivities. The resonators for both gyros were two inches in diameter and constructed of aluminum. The pickoff and forcers for reading the flexing hemisphere's amplitude and applying control forces were mechanized through the use of case mounted electrodes which interacted through electrostatic forces with the resonator which was biased at 300 volts. They were operated in the force-rebalance mode constraining the resonator flex pattern to a given case location and used the force required to hold the pattern in place as a measure of the gyro measured rate. Figure 4 shows drawings and photographs of these initial HRG designs.

Wineglass Resonator Design
US678762 / US3719074[2]

Mushroom Resonator Design
US3656354

Figure 4. Proof of Concept Designs – First HRG Gyros Built

Pushed Onto the Back Burner

It wasn't however an easy path to success. After the demonstration work on the project was stopped while the gyro development group was relocated twice, first to Milwaukee in 1969 when the Boston lab was closed, and then to Goleta, CA (Figure 5) in 1972 after a Delco reorganization. The focus of the instrument development team during these times was the "spinning wheel" Dynamically-Tuned Gyro (DTG) which Delco was hoping to use to replace the floated single axis gyros from the Apollo era. The only HRG effort that continued during this period was a very low level of theoretical work[4].

HRG's Rebirth in Goleta

Effort on the HRG didn't begin again in earnest until about 1975. During 1974-1975, Delco management decided that the DTG, which had been under development for the last ten years, would not be competitive in the marketplace and was searching for another approach. In search of a new direction for directing their IR&D funs, Dr. Lynch was asked to survey the possibilities and ended up recommending the restart of the HRG (or "Sonic Gyro" as called at that time) effort. The Delco management took his recommendations and agreed to that path, but would provide company funding only if funding could be acquired from an external agency. The argument was made (as it still is today) that if the promise of the technology was as good as promised they should "easily" be able to get the government to invest into its development. An energetic campaign was begun, but was a disappointment when no funding was forthcoming. Finally in 1975, NAVAIR showed interest and funded the build and test of a moderate accuracy (50 deg/hr) HRG for tactical missile applications on a program to be administered by the Naval Weapon Center at China Lake (a convenient location for a group)[5]. This new HRG team was put under the leadership of Ed Loper, for the instrument design, build and test, and Dave Lynch, for theoretical models, both reporting to Tim Hanley (Figure 6).

[2] "US" numbers are the US Patent number for that HRG design (included for ease of referencing specific gyros)

Figure 5. New Facility in Goleta

Figure 6. The HRG Development Leadership Team

It was under Tim's insistence that led to the use of fused quartz (fused silica) with its low internal damping characteristics. It was this excellent insight that has allowed the HRG to achieve the high quality factors (Q's), reaching over 10 million by the early 1980s, which enabled the gyro to reach its superior performance level. As part of the NAVAIR development program, the first on the HRG since the Boston Lab work, two designs of the "Sonic" gyro were completed and evaluated by the Navy[6]. These designs were the "Block 10" gyro which had a "true wineglass" resonator and the "Block 20" gyro which had a "mushroom" resonator with an internal stem (Figure 7).

Block 10 HRG with 58mm "Wineglass" Resonator (NAVAIR design)

Block 20 HRG with 58mm "Mushroom" Resonator (US4157041)

Figure 7. Block 10 and 20 "Sonic" Gyros

The results obtained from the NAVAIR development were exceptionally fruitful in spurring the HRG development. As a result of the work many breakthroughs were made. A list of a few of the improvements obtained is seen in Table 1.

Table 1. A Few of the Many Accomplishments from the NAVAIR Development

· Improved sealing methods/techniques – Developed use of frit to create robust hermetic electrical feedthroughs
· Resonator balancing techniques developed to match frequencies of orthogonal modes
· Improved metallization techniques & processes
· Electronics/Control Loop innovations – Loops for PLL, Amplitude and Quadrature developed – Whole Angle mechanization and standing wave position location developed
· Error models validated and updated based on actual results.
· Primary mechanisms for bias errors identified
· Performance Demonstration showing better than 1 deg/hr performance (10°/hr goal) – Bias will achieve 10 deg/hr goal with math model or electrical compensation – Short term stability of ~1deg/hr obtained

HRG Presented to the World

With the excellent performance achieved with the NAVAIR testing the excitement grew about the potential of the HRG. By the early 1980s the Block 10 & 20 designs quickly evolved into the 58mm resonator diameter ”Block 30” gyro design (Figure 8). These were also the first “double stemmed” gyros and with a series of “tines” around the resonator lip to ease the task of balancing the resonator. Balance algorithms were developed which would specify the required mass removals on a tine-by-tine basis.

Figure 8. “Block 30” Prototype HRG with 58 mm Double Stemmed Resonators (US4951508)

In 1982 Marty Stevenson, then Director of Research and Development at Delco’s Santa Barbara Operations, decided that the time was ripe to disclose our HRG activities to the public. He gave an interview with W.B. Scott of Aviation Week and Space Technology magazine on our development and plans, and the result was the short article, “Delco makes low-cost gyro prototype”, which appeared in September 30, 1991 issue.[7]. This article contained the first usage of the name “Hemispherical Resonator Gyro” or “HRG” for this instrument, a name that was coined by Marty himself so that he could spice up the image of the “Sonic Gyro” into a catchy name like the then new RLG or FOG instruments. Though not to be known until later, this article was noticed by scientists in the Soviet Union and recognized as a “must have” technology. As a result the Soviets made developing their own HRG a priority and put four large technical teams together who worked the development until the crumbling of the Berlin wall[8].

HRG for Strategic Systems Applications

During the time when the HRG 158 was developing, interest in the technology was also growing in the strategic inertial navigation community. As a result, the Navy's SP23 office (strategic missile guidance) and later the Air Force BMO (Ballistic Missile Office) funded a development and evaluation program to be run by the Draper Labs. They were chartered to assess the HRG technology and develop the gyro design maturity for use as an inertial instrument to update the Mk5 strategic inertial navigation system. This, the first of three efforts by the SP23 Navy, provided the funding that allowed the acceleration of the HRG development and have played a significant role in advancing the development of the HRG.

> HRG Trivia:
>
> Q: Why such an odd number as "58"?
> Where did the design decision to go to 58mm resonators come from?
>
> A: The first experimental gyros had been built with a 2-inch diameter hemisphere based on early calculations of Dr. Lynch. Since the 2-inch gyros performed well the new gyros were to stay the same essential design. While dormant the world was pushing the conversion to the metric system so the dimensioning of the new gyros drawings were converted too. Well, if you convert 2-inches into millimeters you get 50.8mm (not 58, but note the similarity when communicated verbally). The change in size to 58mm was actually a communications error, but the dimension stuck. Just think, if this hadn't occurred we might be flying 25 millimeter resonators into space today!

The initial effort, run from 1987 to 1990 resulted in many breakthroughs that were later essential for improving the HRG performance. Since the Mk5 application required that the new instruments fit within the space that was then occupied by the Mida-5 gyros, the size of the HRG required significant reduction. The HRG 130T (Figure 9) the first half sized HRG which was later to become the key to the HRG based products, was designed and key components developed on this program. In addition to developing the new design, the funding supported advances in resonator balancing, creating the first resonator balance station utilizing a laser for mass removals, modernized the electronics, improved key processes and developed resonator fabrication methods to improve the time constants (reduced losses) of the gyros.

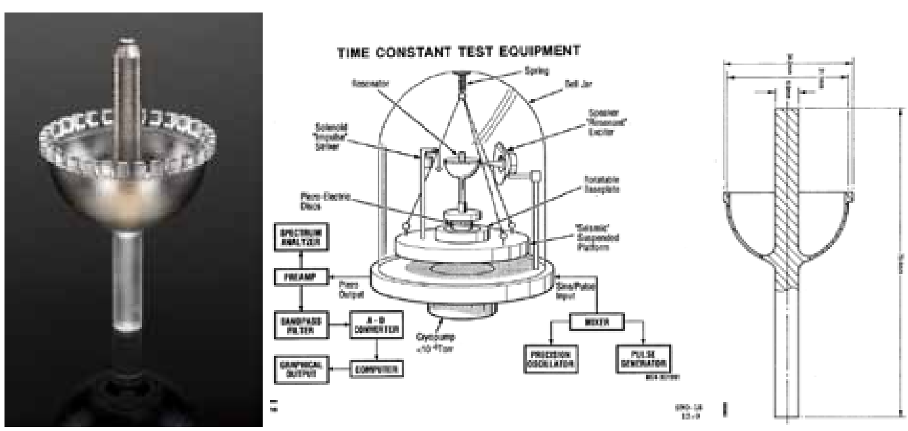


Figure 9. HRG 130T strategic gyro resonator and laser balancing fixture

Under Air Force funding the compatibility of HRG components were evaluated for possible degradation when exposed to RV and boost level radiation exposures during an underground nuclear test. Results showed absolutely no change in either metallization, quartz or indium bonds across all exposure levels except for a very slight filet cracking in the indium bonding at the very highest exposures. These results validated what was expected, that the HRG was an ideal instrument for high radiation environments be they nuclear or space sources.

From 1994-1995 Draper again was chartered to evaluate the performance and maturity of the HRG technology, this time on the HRG 130Y (described later). Testing involved noise, static and dynamic rate testing and provided estimates for all traditional error sources. While Draper found the noise and bias stability parameters to be excellent (ARW=0.0006º/rt-hr, Bias 0.005º/hr), it found that the scale factor had large trending (48-100ppm/day)[9].

Finally, from 1999 to 2004 a complete sensor evaluation was performed by Draper for the Navy, this time on the precision HRG 130P design. Testing included long term (100 day) stability, scale factor linearity, stability during strategic missile shock and vibration environments, performance during and across radiation exposures (gamma and flash X-ray), and magnetic sensitivities (Figure 10). As part of at program improvements were made to the gyro design to mitigate shortfalls uncovered in the testing. Changes included increasing bonding areas between quartz and metal parts, improved materials and metallization designs to minimize radiation influence on the electrical signals, reduced-stress electrical attachments to the quartz, and improved on-gyro electronics. The results of the testing showed that the HRG 130P met or was better than all requirements for the Trident Mk6LE system. In spite of this excellent showing by the HRG it wasn't selected for continuing integration into the Mk6LE system due to the single source nature of the technology.

Figure 10. Draper Testing: Flash X-ray, Vibration & Magnetic Environments

Aircraft Navigation with an HRG?

Through the 1980s the Carousel IV inertial navigation system was the mainstay of the Delco product line were used in many of the world's commercial aircraft. It utilized a unique system mechanization using single degree of freedom (SDOF) floated gyros mounted on a continuously rotating platform (hence "carousel"). This rotation had the effect of averaging the gyro errors, which over time resulted in better accuracy than would normally be expected from the accuracy of the gyros in the system. These SDOF gyros however were bulky, marginally reliable and costly to produce. With the new "unconventional" sensors, such as the DTG and later the RLG being introduced, the Carousel IV was quickly losing market share. When experimental HRGs began demonstrating performance far better than the medium accuracy goals originally set for the instrument, it became clear that the HRG would be able to attain aircraft navigation performance and so became the heir apparent for the SDOF gyros. This gave the HRG development team a tangible target to focus upon. The new HRG based systems were to be named the Carousel-400 series systems in order to play off the recognition value of the Carousel brand name in the commercial world but would not have a rotating platform like its predecessor. A pre-production design for the Carousel gyro, named the HRG 158X (Figure 11), was designed and integrated into a 6-axis redundant navigation system (Figure 12) which became the first HRG to "fly".

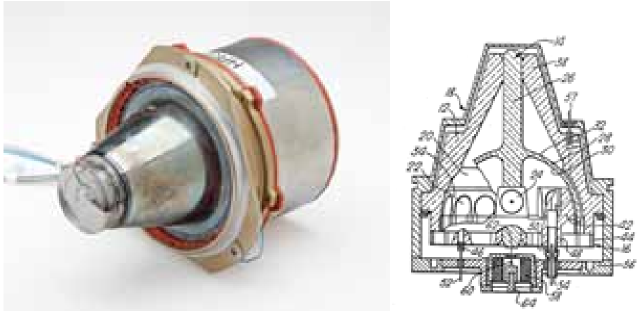


Figure 11. HRG 158X Pre-Production Gyro

Figure 12. Aircraft Nav System

By 1991-1992 the development of the Carousel-400 systems was getting close to entering into full-scale production. While the development continued to be run out of the Delco Goleta facility, the production line was being setup to build the production gyros and systems at the Milwaukee Operations of Delco Electronics. The production design for the gyro, the HRG 158Y (Figure 13), was completed & a Carousel 404 system was built and integrated with the first HRG 158Y gyros, and then began undergoing initial flight testing.. The gyros performed extremely well during this demonstration, averaging better than 0.8 nmi/hr performance during a year long residence on a Lufthansa aircraft. It was at this time that the legendary reliability of the HRG was first established when the system (the first built) went the whole year without a failure[10]. The following statements about the testing were made by Dr. Lynch at a seminar in Germany in October, 1992:

"A prototype C-404 system has recently completed a year's trial in a Lufthansa Boeing 747-400. During 4,000 hours of commercial flight, position accuracies were in the neighborhood of 0.8 nautical miles per hour, and were 1.7 nautical miles per hour on a 95-percent probability basis. There were no failures during the year's trial.

Delta Airlines will be the initial user of the new family of systems. They have placed an order for 30 C-411 systems that will replace existing C-IV systems on their L-1011 aircraft. Delco expects to certify the C-411 during the first quarter of 1993 and plans to be in full scale production by the summer"[11].

Figure 13. HRG 158Y Production Gyro for Carousel-400 Aircraft Navigation System

Unfortunately the HRG aircraft navigator was not to be. After gearing for full scale production, the plug was pulled on the effort. The downturn in the world's aircraft industry due to the first Gulf War reduced the additional orders well below what had anticipated. As a result Delco terminated the production and mothballed the production equipment, deciding to instead continue in the commercial aircraft navigation business with only its older, spinning-wheel Carousel IV systems.

A Half-Sized HRG

This could have been the death-knell of the HRG but new developments at Delco's Santa Barbara Operations kept things alive. The new work, spearheaded by Anthony Matthews, was developing a half-sized (30mm) resonator gyro, and a new system mechanization utilizing a force-rebalance mode for gyro operation. These two breakthroughs offered great potential for use in space, especially since space environments mitigated the only know HRG failure mechanism (loss of vacuum), and its established reputation gained from the Carousel-400 efforts satisfied the space industries need for absolute reliability. The 50% reduction in resonator diameter enabled a factor of eight (2^3) reduction in volume which led to an equivalent reduction in the overall sensor weight. The change from the HRG 158s open loop, whole angle operation to the FR mechanization was required to obtain the high accuracy, low noise output required for the pointing stabilization of communication satellites. By holding the standing wave at a given point, the signal voltage on that electrode was kept near zero. This allows very high gain to be used in the electronics, greatly enhancing the signal to noise ratio of the rate signal. In the mid 1980s theoretical studies were made on the effect of resonator size on HRG performance. From these analyses it was predicted that a 30mm-diameter resonator gyro would have poorer performance than those with 58mm-diameter resonators by a factor of ten[12]. To everyone's surprise, the performance of the new gyro was initially equivalent and later surpassed the performance of the larger resonator gyros. It turned out that the performance of the larger-resonator HRGs used for the scaling calculations was limited by the quality of the electronics. The new 1990s electronics had improved to the degree that the underlying performance capability of the HRG was beginning to be realized for the first time.

Heading to Space

The 30mm-diameter resonator gyro was called the HRG130Y (Figure 14). It was not only smaller, but eliminated the double stem, moving back to a "mushroom" design with the stem internal to the hemisphere. The pickoff was provided by 8 electrodes internal to the hemisphere, with the forcing functions provided by 32 external electrodes, 16 for parametric drive (amplitude), 4 for rate drive, and 12 for quadrature control.

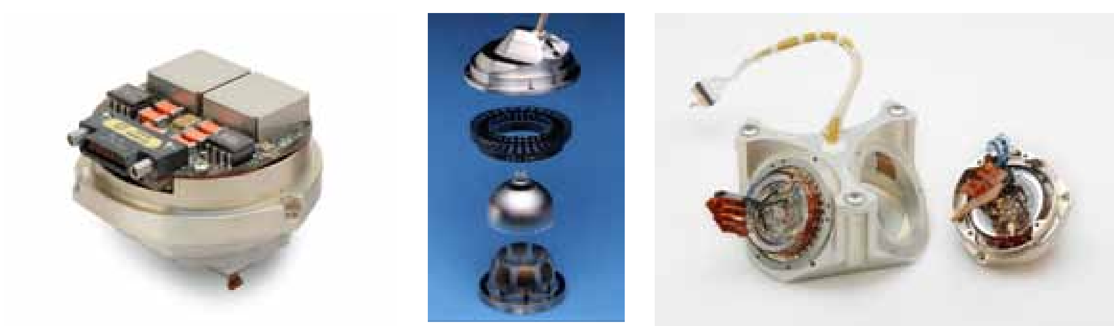


Figure 14. HRG130Y 30mm Resonator Used in the SIRU

The excellent performance quickly obtained on the HRG 130Y led to its incorporation into the newly designed Space Inertial Reference Unit (SIRU; **Figure 15**) system which was designed to exploit the unique characteristics of the HRG. This unit, specifically tailored for space use, included radiation hardened electronics, redundant processors and power supply modules, and four HRG 130Y gyros on a skewed redundant platform configuration with four sensor electronics modules which provide fault tolerant capability. The unit was designed so that it can continue with full operational capability and performance after any single gyro failure, single power supply failure, and single sensor electronics failure providing probability of success of 0.998 for completing a 15-year mission[13]. The basic performance capability realized by the SIRU was excellent and easily meet the mission requirements for communication satellites of the day (Table 2)[14]. By 1993 the HRG 130Yand SIRU were in production. Its first mission was the NEAR program which launched the first HRG based system into space in 1996. This was quickly followed by a commercial communications satellite then the CASSNI mission to Saturn.

Figure 15. HRG 130Y based Space Inertial Reference Unit (SIRU)

Table 2. Core SIRU Basic Performance

Bias Stability	**0.015 º/hr 1-sigma**
Angle Random Walk	**0.001 º/Öhr**
Angle White Noise	**0.020 arc-second/ÖHz**

In early 1966, just prior to the SIRUs first launch, Litton purchased the Delco inertial business, including the Goleta facility. The objective of the purchase was to acquire the HRG technology as a way of expending their inertial product line into the space business. Although a number of contracts for communications satellites and deep space missions were already in place, there was a lot of work required to bring HRG engineering and manufacturing to a fully mature state and Litton showed its support of the product by providing a large influx of new engineering talent from their Woodland Hills home.

Following Other Pathways

There were a number of smaller development efforts that were occurring during the time of the SIRU work. These included a precision pointing application for potential use on the Hubble telescope, a number of classified contracts, and the development of an HRG suitable for use by the oil industry to track the progress of wells during drilling.

This last gyro, the HRG 130R for rugged (Figure 16), was a unique design which was required to fit within a 1.5" diameter tube, operate over extreme temperatures (-40 to 155ºC) and survive very rough environments (20,000 500g shocks, 30 g-rms random vibration). To meet these requirements new processes and materials had to be developed, including high temperature solder and metallization, rugged resonator attachment, reduced size electrode assemblies, etc. The 130R also used an internal-only electrode configuration requiring dual use of the electrodes for pickoff and forcer capabilities. To accomplish this, high frequency AC pickoff carriers were used to separate the readout functions from the 4-8 kHz forcer signals. The HRG 130R development was successfully addressing the design upgrades for the application, but a downturn in the oil drilling industry eliminated the customers need for the units[15].

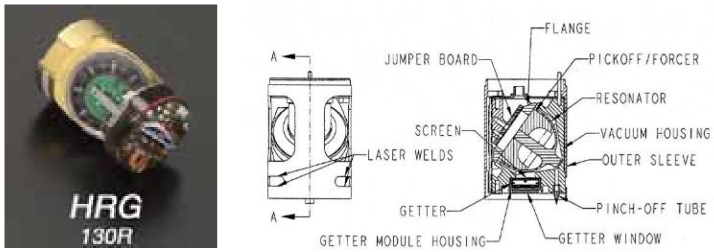


Figure 16. HRG 130R "Rugged" for Downhole Operation

To explore the potential use of the HRG for the Hubble rate sensor assembly, a program was executed where gyro and electronic modifications were made to extract the highest performance and lowest noise from the gyro that was possible. The Hubble HRG (Figure 17) was built with the sensor packaged to minimize any thermal disturbances, the amplitude of the standing wave was controlled to much higher level, and the lowest noise electronics designed and fabricated. To be able to measure the noise levels even required that new seismic isolation test pads be designed and built. In the end, testing demonstrated extremely low noise performance and excellent bias stability[16] (Table 3). Near the end of the test program the decision was made by NASA to use the existing gyro design for the repair mission since the time to mature the design of a precision pointing HRG was beyond the mission need date.

Figure 17. HRG for Hubble Rate Sensor Assembly

Table 3. Demonstrated Performance from Hubble Testing

Bias Stability	0.000080 º/hr
ARW	0.000010 º/Öhr
AWN	0.000150 arc-sec/ÖHz
	Maximum Rate 0.5 º/sec

HRG 130P "Precision" Gyro

Experience gained in the build and utilization of the HRG 130Y gyro let to a series of proof-of-concept designs in the late 1990s and eventually led to the current HRG 130P (for "Precision", Figure 18) gyro. A partial list of these improved capabilities and features is shown in Table 4. The gyro is completely sealed in a metal case eliminating the problems with the Helium permeation present in the HRG 130Y. In addition to keeping Helium out, the cavity surrounded by the metal case forms a secondary vacuum cavity surrounding the primary cavity containing the resonator. This configuration nearly eliminates any risk from leaks in the gyro since the two cavity design reduces the leak rate into the primary cavity to a rate equal to the internal leak rate times the outer leak rate. Thus if both cavities had an 1E-8 rate, an easily obtained value but one that is totally unacceptable for the HRG, then the composite rate would be an equivalent single point leak rate of 1E-16!

Figure 18. HRG 130P gyro and SSIRU Octahedral Tetrad Mount Platform

Table 4. Improved Capabilities of the HRG 130P gyro

· Enhanced forcer and pickoff geometries and metallization – Improved long-term gyro gain stability by over 2 orders of magnitude.
· A differential pickoff and forcer electrodes – Improved noise performance and channel isolation
· A sealed gyro design – Eliminated the gyro's sensitivity to Helium – Removes need for purge in the integration and launch environments.
· A larger forcer geometry – Increased gyro gain for increased rate range or decreased noise.
· A decoupling mechanical mount – Isolates critical gyro subassemblies from the mounting structure – Decreased hysteresis effects – Improved bias and scale factor performance over temperature.
· Extremely efficient individual gyro thermal control enabled by: – Electronics with minimal on-gyro heat dissipation ((17mW) – High thermal resistance between platform and gyro – Provides very stable thermal control of the sensitive resonator – Requires only 40mW/ºC per gyro. – Less than 12 W required to control 3 gyros 100ºC above ambient temperature

Internally the sensor assembly for the HRG 130P is identical to that used for the space proven HRG 130Y, eliminating the risk that would have been associated with a redesign of this critical sensing element. This new gyro design is also extremely efficient to thermally control. The heat dissipation sources in the gyro include only the resonator mechanical energy loss and the electronics heat dissipation. The dissipation from the resonator, with a Q of over $25*10^6$, is as near to zero as you can get so it can be ignored. The gyro buffer is designed so that only the first stage of a two stage buffer, which dissipates only 17mW, is mounted on the gyro itself with the rest of the components located away from the gyro on the Sensor Electronics Module. To limit heat conduction into the gyro assembly very high resistance thermal isolators have been placed between the platform mount and the gyro mounting ring. This resistance minimizes the heat loss to the platform and allows low power control from a heater attached to the mounting ring. The control setpoint for the thermal loop utilizes the extremely stable resonator frequency for a measure of the temperature. The fused quartz resonator frequency changes ~84ppm/ºC, so by controlling the frequency of the resonator to a constant value, the temperature can be easily held to 0.1ºC providing an excellent environment for precision operation of the gyro[17].

To take advantage of the much improved properties of the gyro a new-generation system, called the Scalable Space Inertial Reference Unit (SSIRU, Figure 19)[18], has been designed and is a fault tolerant cross-strapped design that provides full redundancy in a single box. By switching to the use of Pulse Width Modulation for gyro control, the scale factor linearity and stability is improved by up to 2 orders of magnitude over traditional ladder digital to analog convertors. Analog signal demodulation has been upgraded to high speed direct digital sampling of the pickoff signals and digital demodulation. By eliminating the analog circuitry the electronics have be significantly simplified and run with lower power. The new signal processing for the system has increased the bandwidth and decreased the data latency to less than 1 msec. These changes have paid off in improved performance which can be seen in the comparisons with the older SIRU system in Table 5[19].

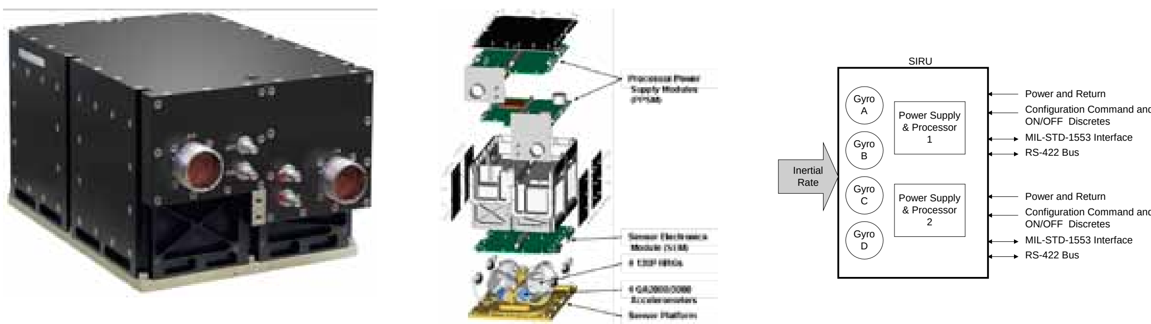


Figure 19. Scalable SIRU Unit, Exploded Assembly and Simplified Architecture Diagrams

Table 5. SCALABLE SIRU™ Performance Improvement Over Legacy SIRU Systems

Performance	Core SIRU™ ±12 deg/sec range	Scalable SIRU™ ±12 deg/sec range	Improvement factor
Angle White Noise (arc-sec/Hz1/2)	0.014	0.001	14x
Angle Random Walk (deg/rt-hr)	0.00060	0.00006	10x
Bias stability, (°/hr 1s)	0.0050	0.0005	10x
Scale factor stability, (ppm 1s)	100	1.0	100x
Scale factor linearity, (ppm 1s)	100	1.0	100x

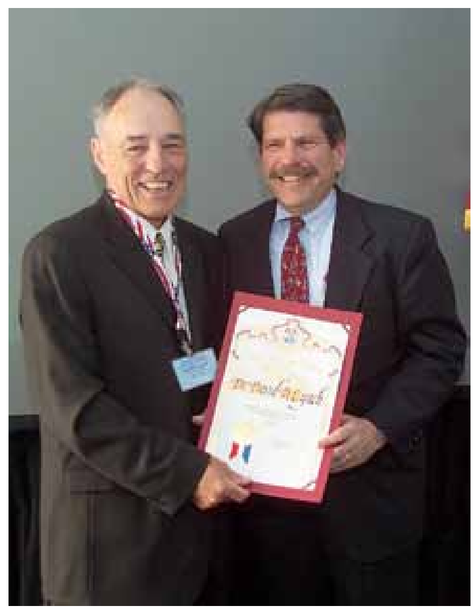
In 2000 Litton was acquired by Northrop Grumman. Soon afterwards the decision was made to close the old Delco Goleta facility and consolidate all HRG activity at the Woodland Hills, CA. During the period of 2001-2002, a consolidation team from Woodland Hills was assigned and had the job of working with the Goleta personnel to transfer the HRG "knowledge base" and facilities. This team, which at times numbered just under 100, resided in Goleta for up to a year accomplishing the task and providing for as smooth a transition of the engineering and manufacturing operations as possible. Extensive efforts were put into feeding all product line documentation into state of the art knowledge base tools, including Invention Machine's Goldfire system, to allow future engineers easy access to this huge amount of information through queries to the database.

In addition to transferring the HRG knowledge, huge investments were made to upgrade the production and test facilities for the HRG and the SSIRU. The HRG factory moved into new clean room areas specifically designed for optimal assembly flow and occupying over 2000 square feet of full gown CL 1000 and CL 100 clean room laboratory area (Figure 20a). Also new state of the art test facilities were built with 14 precision seismic isolation pads for low noise testing was also built for HRG System testing (Figure 20b).

When the consolidation began, customers were concerned about moving the HRG production, wondering if Northrop Grumman would ever regain the capability to produce such a precision sensor. Their fears were soon dispelled though after HRG production resumed in late 2002 and by March 2003 were delivering space qualified gyros for the SIRU and SSIRU systems. Since those first gyros nearly 500 HRGs (through 2008) have been built and the HRG in SSIRUs are performing at levels better than before the consolidation. That this very difficult task turned out so successfully is a credit to the skill and persistence of the engineering and management personnel involved. On March 17, 2004 the gyro production facility was dedicated the "Dr. David D. Lynch HRG Manufacturing Center" (Figure 20c) in honor to the one man most responsible for the success of HRG technology.

20a

20b



20c

Figure 20. a) Space Test Facilities, b) HRG Factory, c) Dr. Lynch honored at dedication of "Dr. David D. Lynch HRG Manufacturing Center"

The HRG is now in its 15th production year. The Scalable SIRU, now in full production, has lived up to its reputation for superior performance and unsurpassed reliability and has become the "sensor of choice" for all high value missions. This success has been accomplished through the development of the HRG through a long sequence of events, eventually creating a gyro with the characteristics most needed by mission integrators and has gained experience on numerous types of mission (Table 6).

Table 6. HRG 130P Features and Mission Experience

<table>
<tr><td>Features of the HRG 130P gyro
· High accuracy, precision instrument
· Extremely high reliability
· Small size, weight & power
· Low noise, stable performance
· Inherently radiation hard</td><td>· On contract to all major US satellite manufacturers
– Payload & Bus
– Foreign & Domestic
· Orbit Experience:
– LEO, GEO, HEO
· Mission Experience:
– Commercial Satcom
– Military Secured Communications
– ISR
– Earth Observation (EO)
– Deep Space Exploration
· Over 135 Total Systems Delivered or On-Contract</td></tr>
<tr><td colspan="2">91 systems launched (89 satellites)
12.0 million accumulated gyro hours in space
100% mission success</td></tr>
</table>

HRG Operational Theory

The HRG (the Hemispherical Resonator Gyro) utilizes the rotation sensitivity of the lowest bending mode of a hemispherical shell. When the HRG is vibrating in that mode it will respond in one cycle of the shell vibration by:

- Deforming from spherical to ellipsoidal during the first quarter of the cycle,
- Returning to spherical during the second quarter,
- Deforming into an ellipsoidal shape during the third quarter but with the semi-major and semi-minor axes of the ellipse (at the shell equator) interchanged, and
- Returning to its original spherical shape during the fourth quarter of the cycle.

The vibrating equatorial ellipse thus forms a standing wave with four equally-spaced antinodes (locations of maximum displacement) and four nodes (locations of zero displacement, at least in the radial direction) in between (Figure 21).

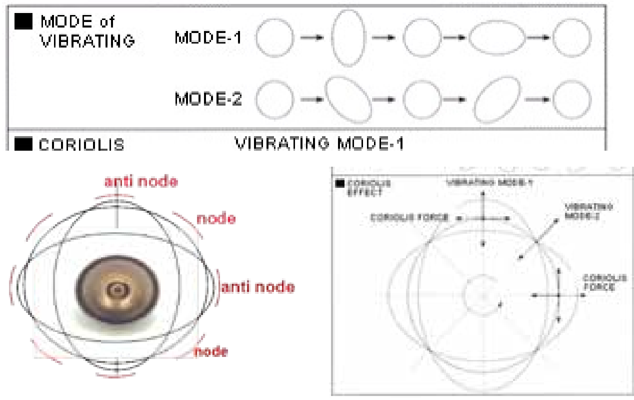


Figure 21. HRG Flex Motion in its Lowest Order Bending Mode

When such a standing wave is present in the shell, a rotation about the shell axis (the stem) produces Coriolis forces on the vibrating mass elements. The overall result is to cause the standing wave to change its location on the shell. In the case of the HRG, a rotation of the shell (i.e., a rotation of the whole gyro) through any angle results in the standing wave rotating with respect to the shell through an angle that is close to 0.3 times the inertial rotation angle (Figure 22). The number 0.3 is called the angular-gain factor. The HRG's angular-gain factor depends to first order only on the geometrical shape of the shell, not on its density, elastic constants, etc. and varies only by a predictable 0.5ppm/ºC over temperature This gain factor, with its extremely stable characteristics, is the property that gives the HRG its inherent stability required for a precision gyro.

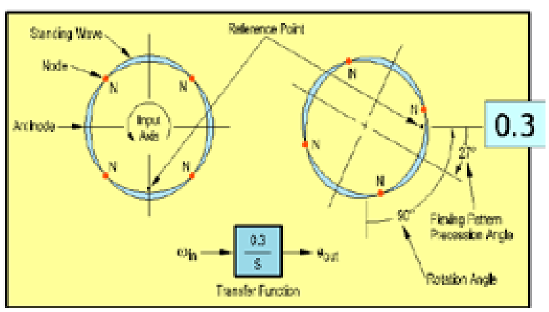


Figure 22. Rotation of Standing Wave Relative to Case from Rotation of Gyro

Whole Angle (Open Loop) Operation

In the whole-angle (WA) operating mode of the HRG, the standing wave is established with its antinodes in some initial location (usually over the excitation/readout electrodes). Voltages are placed on electrodes to keep the standing-wave amplitude constant in the presence of damping losses, and to maintain a pure standing wave with no traveling wave component. The standing wave is allowed to move freely in response to the Coriolis forces resulting from the presence of an inertial-rate input. An estimate of the gyro rotation angle is provided by the (negative of the) angle the standing has rotated, divided by the angular gain factor. The actual angular-gain factor, which is always very nearly 0.3, is determined in pre-use calibration testing.

In practice, obtaining an accurate estimate of the input inertial rate is not so simple. The location of the standing wave must itself be estimated from the outputs of the readout electrodes. The uncompensated estimates are in error largely because of electrode misalignment, gain mismatches resulting in the voltage outputs of the buffer amplifiers attached to the electrodes not accurately representing the motion of the standing wave in the vicinity of the electrodes, and nonlinearities in the behavior of the forcer (excitation) and readout capacitive transducers. This is essentially a readout error in determining the position of the standing wave. Another effect leading to inaccurate rate estimates is the presence of forces causing the standing wave to move even in the absence of inertial rate. Such forces are due, for example, to non-symmetric damping forces and to errors in the placement or magnitude of the forces used to maintain the amplitude and purity of the standing wave. This error is a bias error that varies with the position of the standing wave in the gyro case.(Figure 23). The calibration/compensation model for a WA HRG is considerably simpler than it first appears. Because the standing wave returns to its initial location after one complete rotation (of 360º) around the shell, the errors as a function of the standing-wave location angle can be represented by a Fourier series in the location angle.

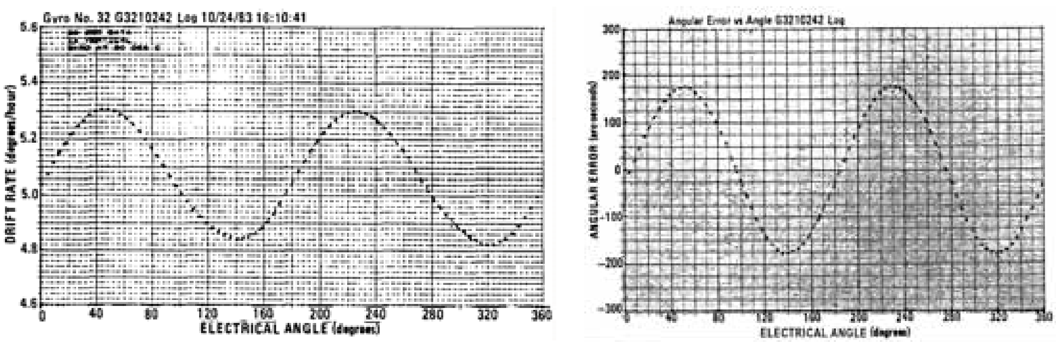


Figure 23. HRG Bias and Angle Readout Errors vs.
Standing Wave Case Location

Force-Rebalance (Closed Loop) Operation

The second operating mode of the HRG is the force-rebalance (FR) mode. In this operating mode, the forcers are used to hold the standing wave at a specific case-fixed location, usually with its nodes and antinodes lying over the centers of the forcers and pickoffs. The rate estimate is then provided by the force (voltage) required to restrain the standing wave (Figure 24). When operated in the FR mode the calibration/compensation of the HRG is simpler. Since the standing wave is maintained at a known position (say at 0°), there is no need to determine Fourier coefficients. There are still effects of forcer and pickoff misalignment and gain mismatches, but they are much easier to deal with. The drawback of the FR mode from the calibration/compensation point of view is that another element has been introduced into the scale factor involved in creating the rate estimate. In order to determine the actual force holding the standing wave at null the transfer function from voltage signal to applied force must be known. So now instead of just needing to know the value of the angular gain factor (which is very stable) as in WA, the gains of the electronics amplifiers, the electrode to resonator gap distances, the bias voltage applied to the resonator and the forcer signal amplitudes all enter into the picture.

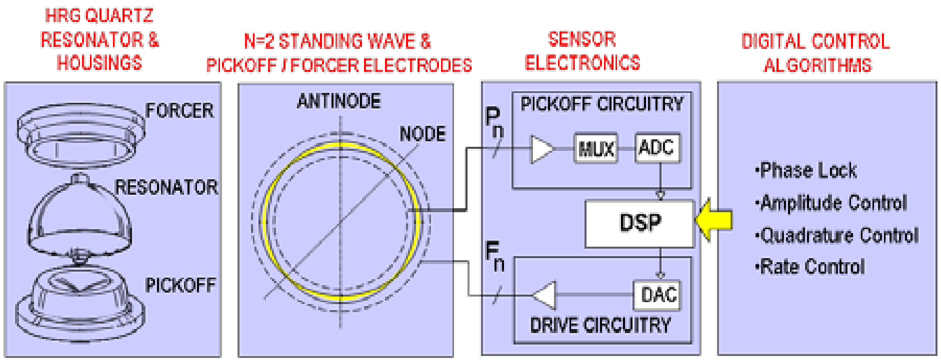


Figure 24. HRG Basic Implementation

Whole Angle vs. Force-Rebalance Considerations

The choice of gyro operation is highly dependent upon the application in which it will be used. WA operation with its extremely accurate angular gain factor will have excellent scale factor performance (<1ppm) but will have high angle noise due to low resolution and inaccuracies in reading out the position of the standing wave. It also will have bias errors that vary as the standing wave moves relative to the case and requires compensation. FR operation on the other hand will have excellent noise characteristics and easily modeled bias errors along with a high resolution, but will have a scale factor that will be limited by the stability of the electrical components and circuits, and depends upon the stability of gyro structure. A second factor in determining the appropriate mechanization is the required rate range of the application. The WA mode has the standing wave precess freely so is not limited in rate. The FR mode in contrast is limited by the force (voltage) that can be applied to return the standing wave to its null. This maximum FR rate is a function of electrode geometry, forcer to gap distance, standing wave amplitude, forcer voltage and resonator bias voltage. Both mechanizations have their place and will have to be selected based on the environments expected in the application.

HRG Control

The HRG control electronics is required to establish a fixed-amplitude standing wave, keep the standing wave at a null position, remove any traveling wave components in the wave, and synchronize itself with the frequency of the resonator. For these four parameters that need control, there are required four control loops (Figure 24). Because of the nature of the HRG and the mechanization of its operation each control loop is kept relatively simple and the coupling between loops is small. First signals from the gyros antinodal (AN) and nodal (ND) electrodes are demodulated. There are four resulting “slowly varying” variables that result from the demodulation; the in-phase and quadrature variables from the AN signal and the in-phase and quadrature variables from the ND signal. First, to maintain synchronization between the electronics and the standing wave, a phase locked loop (PLL) is used to continuously adjust the processor clock so that the AN quadrature signal is nulled. The AN in-phase variable is a measure of the standing wave amplitude which is kept at a set value. This loop employs a voltage that varies in amplitude to “pump” more or less energy into the resonator. This “parametric drive” signal is at twice the standing wave frequency and adds the same amount energy to the resonator independent of its position in the case. The ND in-phase signal is a measure of the movement of the standing wave away from null and is used to drive the force applied to keep the wave position fixed. This force is applied at the same frequency of the resonator and phased so that the pattern is “pushed” back to null. Finally, the ND quadrature signal is a measure of the traveling wave amplitude (quadrature). Since the traveling wave is a result of the resonator frequencies being unbalanced, the quadrature control is applied through DC signals placed on the forcers so that the capacitive force on the resonator is “stiffening” or “softening” the resonator “spring” force, thus putting the resonator back into correct balance. Because the loops each operate in a different frequency domains, PLL-at processor speed, the amplitude loop-at twice frequency, rate loop-at frequency and quadrature loop-at DC, the coupling between them is minimized.

Figure 25. HRG to the Planets

HRG VERSATILITY

The HRG has been utilized in many applications over its developmental lifetime: aircraft navigation, strategic missile navigation, underground borehole navigation, communication satellite stabilization, precision pointing, and in deep space missions. By far the deep space applications are the most fascinating of them all so in the next few sections several of the HRG missions will be described.

NEAR - Landing on an Asteroid

The first mission into space for the HRG was the Near Earth Asteroid Rendezvous – Shoemaker (NEAR Shoemaker) which used HRG 130Y gyros in a SIRU system. The spacecraft launched on 2/17/96 20:43:27 UTC. During the mission the spacecraft flew by asteroid 253 Mathilde on 6/27/1997 and then, after an Earth fly-by for gravity assist, entered orbit around asteroid 433 Eros on 2/14/2000. NEAR circled Eros with an orbit as close as 35 x 35km (Eros itself is 13 x 13 x 33km), continuing until 2/12/01 when, after completing its scientific mission objectives, made a successful touchdown in the “Saddle” of Eros undamaged, thus making the first soft-land on an asteroid. NEAR continued to operate and transmit signals until 2/28/2001 when its signal went silent.[20]

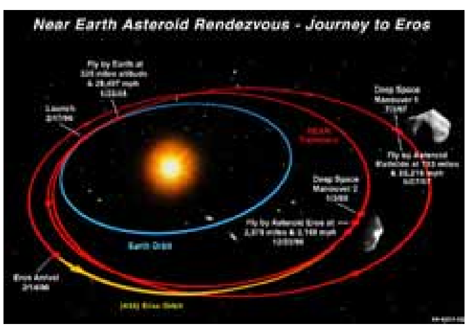
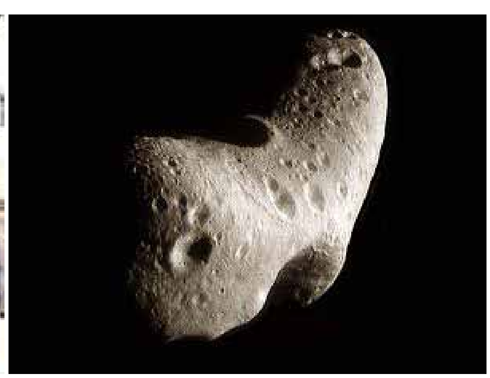


Figure 26. Mission Trajectory

Figure 27. Asteroid 233 Mathilde



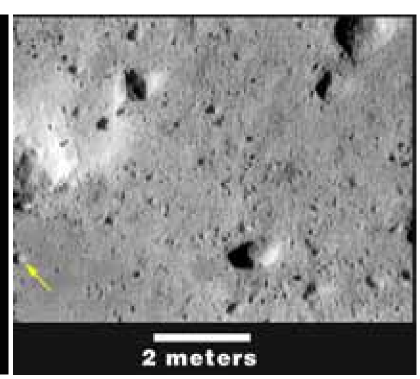


Figure 28. NEAR *Figure 29. Near Earth Asteroid 433 Eros* *Figure 30. Eros on approach*

CASSINI-Circling Saturn

The second launch of an HRG system into space was a commercial SATCOM satellite, which was followed by what was undoubtedly the highest profile mission flown to date, CASSINI. Two SIRU systems were on CASSINI when it was launched atop a Titan booster on 10/15/1997. After gravity assist flybys of Venus (twice), Earth, and Jupiter it then entered Saturn's orbit on 7/1/2004. Since then it has been sending back incredible scientific information and beautiful photos of Saturn and its moons. A major event in the CASSINI mission was the launching of the Huygens Probe which, after detaching from the main spacecraft on 12/5/2004, entered the atmosphere of Saturn's largest moon, Titan, radioing back photos and telemetry about the moon as it descended by parachute to the surface where it continued transmitting to CASSINI for another 30-minutes. The CASSINI mission schedule called for its end on 6/30/2008, but was extended for another 60 Saturn orbits because of the valuable data still being sent.

Figure 31. CASSINI Spacecraft

Figure 32. Close to Saturn

Figure 33. Launch to Saturn

Figure 34. Huygens Probe designed to penetrate Titan's atmosphere and return data on the surface.

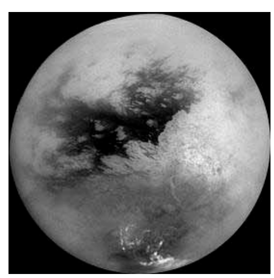


Figure 35. Titan as seen from CASSINI

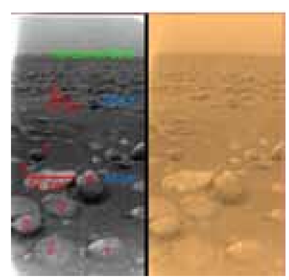


Figure 36. Photos from the surface of Titan

MESSENGER-Exploring Mercury

The MErcury Surface, Space ENvironment, GEochemistry and Ranging (MESSENGER) mission by NASA was the first launch of a HRG 130P based SSIRU system. This mission to Mercury launched 8/3/2004 and is currently on its way to orbit Mercury, which it already has flown by twice. It will have used one Earth, two Venus and three Mercury flybys to use gravity assists for insertion into orbit on 3/8/2011. During the first two Mercury flybys, MESSENGER has already given a wealth of information about the planet, mapping much of the surface not previously seen on earlier missions.

This mission was the first to show the tremendous improvement the SSIRU had achieved. A few months after launch the SSIRU engineers received a near panic call telling them that the system rate measurements coming from the SSIRU were triggering alarms indicating that they weren't operating. After some investigation it was figured out that the only problem with the SSIRU was that the rate output signal was so noise free that it fooled the alarms, in other words the HRG signals were "too good". CASSINI engineers quickly determined the fix, setting the limits for alarm much lower.

Figure 37. MESSENGER in final checkout

Figure 38. First HRG 130P in space

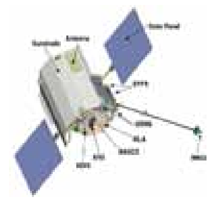


Figure 39. Instrumentation

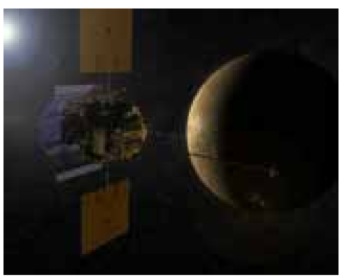


Figure 40. Artist's rendition of MESSENGER

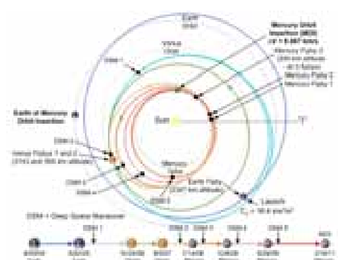


Figure 41. MESSENGER's Trajectory

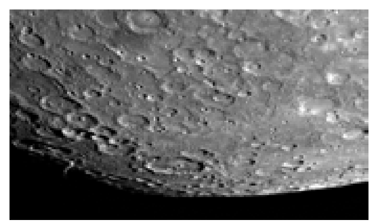


Figure 42. High resolution photo mosaic of Mercury's surface from 1st flyby

DEEP IMPACT-Slamming into a Comet

Deep Impact, the second mission carrying the HRG 130P based SSIRU into space was another high profile mission. On a relatively short mission, Deep Impact launched on 1/12/2005 and on 7/4/2005 (the 4th of July. What a firework!) had hit comet Tempel 1. This mission had two SSIRU system aboard, one on the "Impactor", which was the sub-spacecraft that was to hit the comet surface, and one on the "Flyby", which was the main spacecraft which was to fly by the comet at a safe distance and collect scientific information as the Impactor collided with Tempel 1 with a relative speed of 23,000 mph. Deep Impact is now on an extended mission designated EPOXI, which was originally planned as a flyby of Comet Boethin, but which recently has been retargeted to Comet Hartley 2.

On this mission the SSIRU was again able to demonstrate its enhanced performance. During the cruise phase of the mission the Deep Impact engineers collect rate data from the gyros for evaluation. They found a high level of noise which wasn't expected. After investigating it was found that the star trackers, which were supposed to be a precise reference for navigation, were more in error that the HRGs. When they disabled the star tracker updates the rate noise dropped an order of magnitude (Figure 43). As a result of this finding the SSIRU was made the primary reference guiding the Impactor during its final trajectory, with the star tracker disabled 2¼ hrs prior to the impact so the updates wouldn't disturb the SSIRU measurements. That is, it was the SSIRU and the SSIRU alone that brought the Impactor to its target. Don Yeomans, the mission co-investigator for JPL, confirmed a successful mission. Director Charles Elachi stated "The success exceeded our expectations"[21].

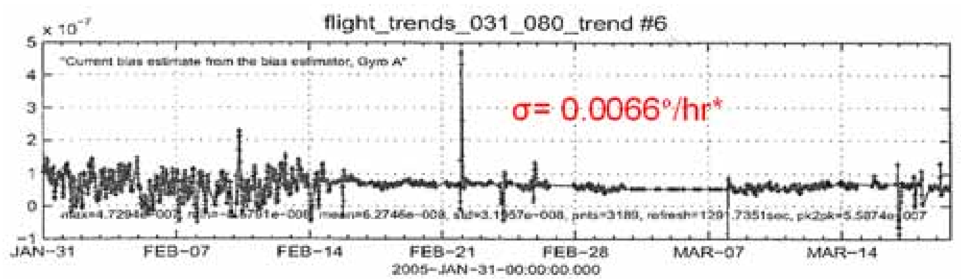


Figure 43. Deep Impact Gyro Rate Data

Figure 44. Deep Impact Assembly

Figure 45. The Launch

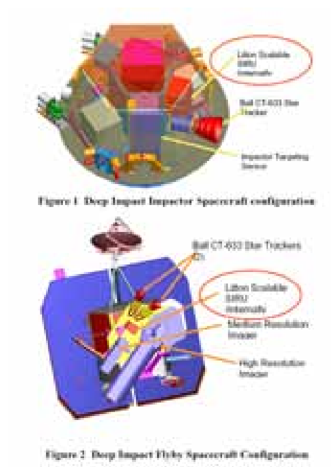


Figure 46. SSIRU on Impactor/Flyby

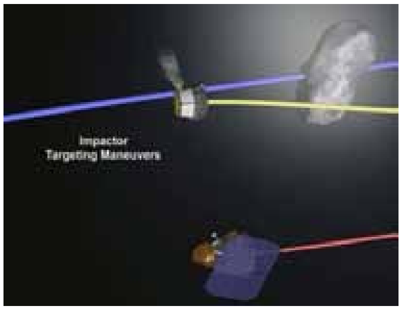


Figure 47. Diagram of Impact Maneuvers

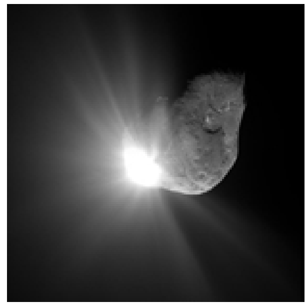


Figure 48. Hitting Tempel 1

Figure 49. Full Impact Plume

CONCLUSIONS AND FUTURE DEVELOPMENTS

Forty-four years have passed since the first step was made to turn Bryan's concept of the rotating standing wave of a wineglass into a precision rotation sensor with the multiple capabilities to guide a spacecraft, stabilize a satellite, point a telescope, tunnel down an oil well, guide a strategic missile or navigate an aircraft. The development of this rotation sensor, the Hemispherical Resonator Gyro, or HRG, has been a series of efforts carefully pieced together and supported through a combination of company, commercial and government sources. The result is currently considered by the space community as the premier gyro of the day (Table 7).

Table 7. The HRG of Today

The HRG 130P Gyro
· High accuracy, precision instrument
· Extremely high reliability
· Small size, weight & power
· Low noise, stable performance
· Inherently radiation hard
· Proven Capability
12 million operating gyro hours in space with 100% mission success

The Scalable SIRU has become the system of choice for critical and high value missions, combining the inherent high reliability of the HRG with crossed-strapped sensor and electronics redundancy to provide an inertial reference system that is virtually infallible. In the field it has demonstrated performance levels that meet or exceed even the most stringent requirements.

As we move into the future the HRG, not limited by any "quantum limit" in performance, will surely be evolving into the smaller, lighter sensor that future missions will require. And as shown historically, will do so while maintaining the superior performance that all have grown to expect.

ACKNOWLEDGMENTS

I’d like to acknowledge the contributions that Dr. David D. Lynch has made, not only for his input to this document, but also for his shepherding of the HRG through its long, erratic history and for providing insight into the HRG through his words, papers and anecdotes that brought this wonderful instrument alive.

Acknowledgement also goes to NASA for the use of their photographs which bring these exciting deep space missions to life.

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