BLAZING GYROS – THE PRESENTATION

THE EVOLUTION OF STRAPDOWN INERTIAL NAVIGATION TECHNOLOGY FOR AIRCRAFT

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WBN-14030
www.strapdownassociates.com
December 14, 2022

Presented To The Local Chapters Of The AIAA And ION
For The "*Avionics In Minnesota"* Lecture Series
Minneapolis, Minnesota, December 2012

A Detailed Summary Of The Forthcoming Technical Article:
"Blazing Gyros –The Evolution Of Strapdown Inertial Navigation Technology For Aircraft", AIAA Journal Of Guidance, Control & Dynamics
Vol. 36, No. 3, May - June 2013

10073041-101
FSCM 94580
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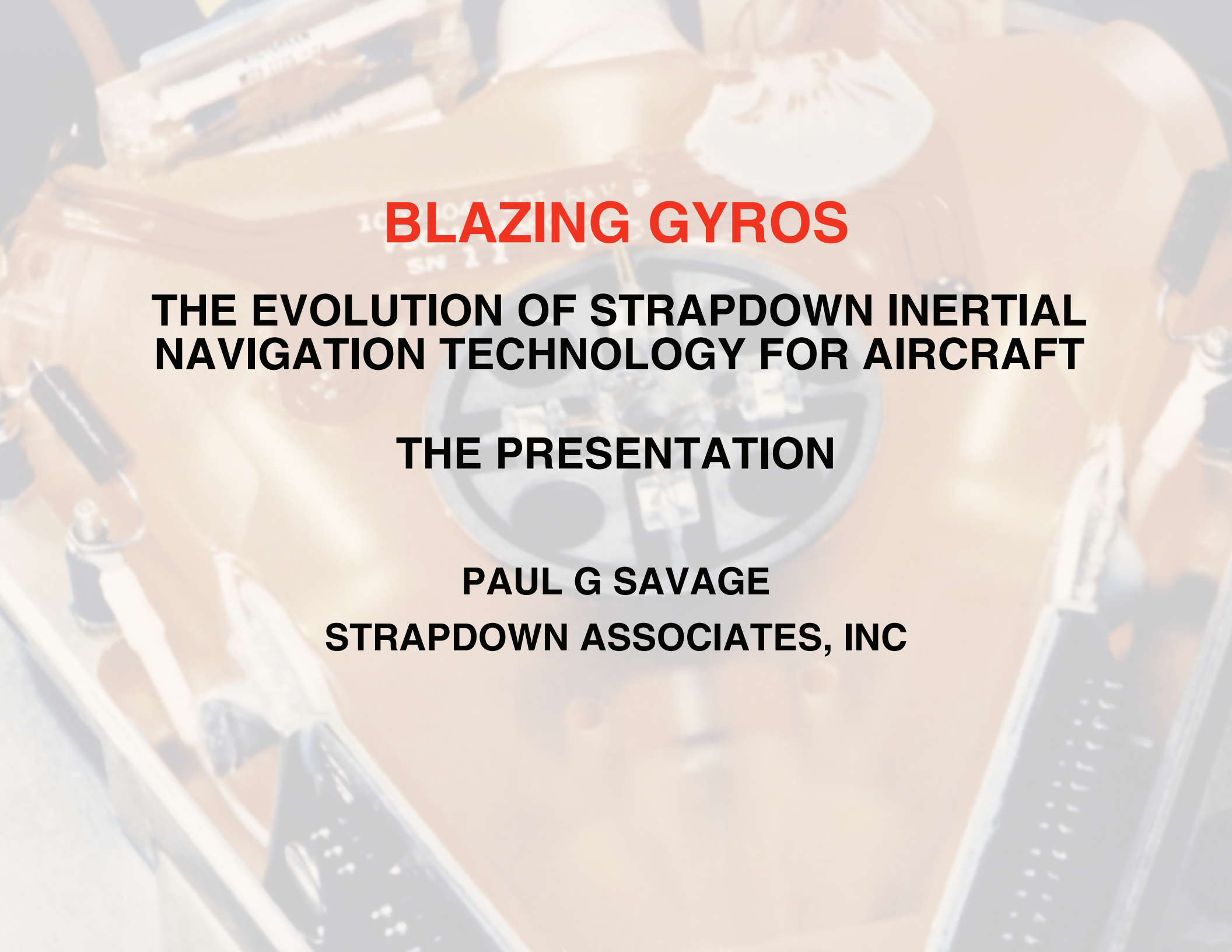
THE EVOLUTION OF STRAPDOWN INERTIAL NAVIGATION TECHNOLOGY FOR AIRCRAFT

THE PRESENTATION

PAUL G SAVAGE

STRAPDOWN ASSOCIATES, INC



BLAZING GYROS

THE EVOLUTION OF STRAPDOWN INERTIAL NAVIGATION TECHNOLOGY FOR AIRCRAFT

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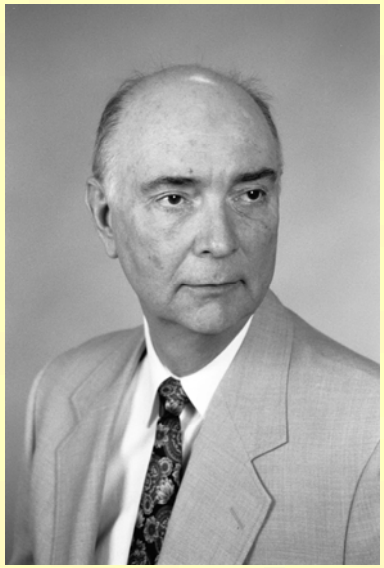
From The History Of Key Technologies Article

"BLAZING GYROS: THE EVOLUTION OF STRAPDOWN INERTIAL NAVIGATION TECHNOLOGY FOR AIRCRAFT" By Paul G. Savage

Published In The AIAA Journal Of Guidance, Control & Dynamics (Vol. 36, No. 3, May - June 2013)



Paul G. Savage is an internationally recognized expert in the design and test of strapdown inertial navigation systems, and president of Strapdown Associates, Inc., the company he founded in 1980. Strapdown Associates has provided software and engineering services to government agencies and aerospace companies for strapdown inertial system configuration definition, flight software development, system simulation, and testing. Mr. Savage has published and presented several papers on strapdown inertial navigation systems and associated computational elements. From 1974 to 2009 he served as author/speaker on several NATO AGARD and RTO technology transfer lecture series tours. Since 1981 Mr. Savage has provided his *Introduction To Strapdown Inertial Navigation Systems* course to the aerospace industry. He has written and published the textbook *Strapdown Analytics* detailing the analytical aspects of strapdown inertial navigation system design. From 1963 to 1980, Mr. Savage was employed at Honeywell Avionics Division as Senior Principal Engineering Fellow where he led engineering design teams and provided technical consultation to Honeywell engineering managers for system design, analysis, software development, simulation, integration and test in the evolutionary development of laser gyro strapdown inertial navigation systems for military and commercial aircraft. From 1971 through 1975, he was the engineering manager and system design engineer for the Honeywell LINS strapdown inertial system, the first to prove the readiness of laser gyro strapdown inertial navigation technology for aircraft applications as demonstrated during a landmark flight test series at Holloman Air Force Base in 1975. Mr. Savage is a graduate from the Massachusetts Institute of Technology where he received his MS and BS degrees in Aeronautical Engineering in 1960.

TOPICS

TECHNICAL BACKGROUND

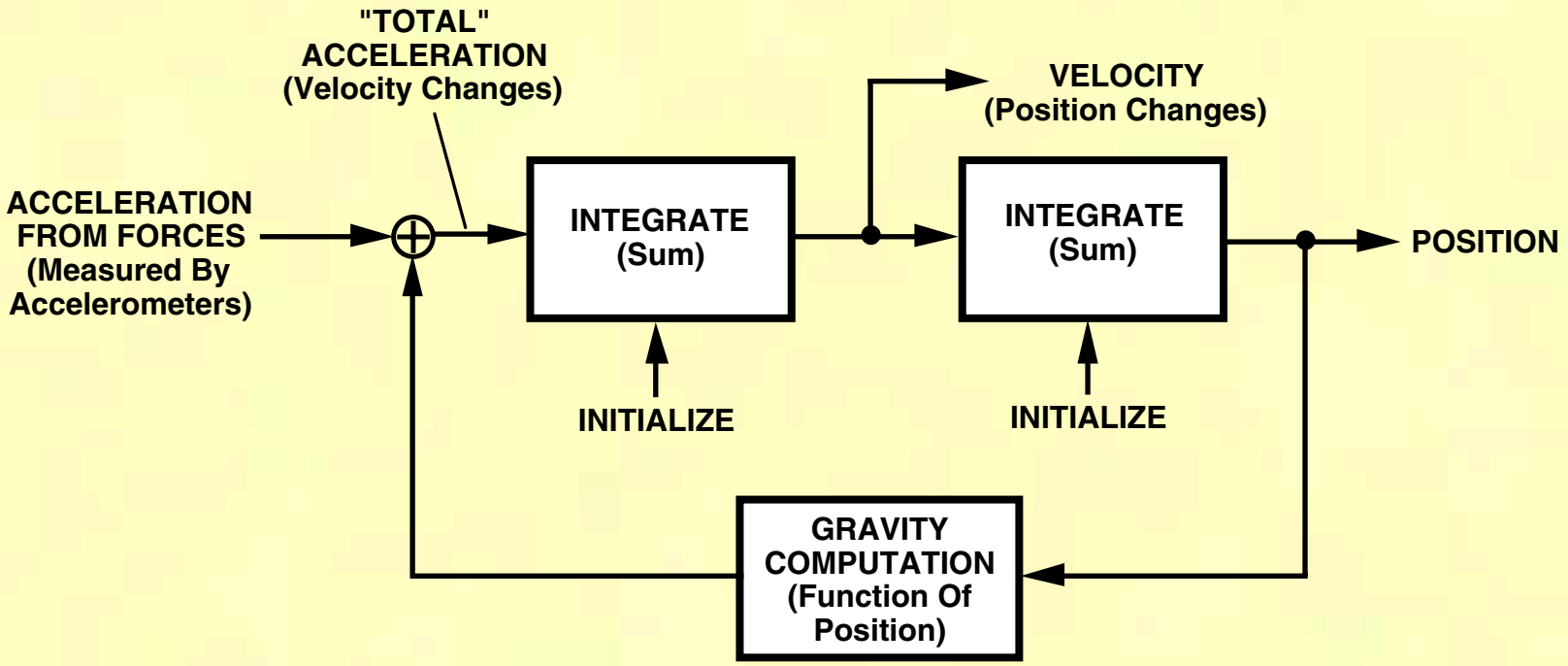
- INERTIAL NAVIGATION SYSTEM (INS)
- ORIGINAL GIMBALED VERSUS NEW STRAPDOWN INS CONFIGURATIONS
- ASSOCIATED INERTIAL SENSORS
  - ORIGINAL MECHANICAL SPINNING WHEEL GYROS
  - THE NEW TECHNOLOGY OPTICAL RING LASER GYRO (RLG)

EVOLUTIONARY DEVELOPMENT OF TODAY'S AIRCRAFT STRAPDOWN INS

- ORIGINAL GIMBALED SYSTEMS AND SUPPLIERS (1960 - 1978)
- HONEYWELL GG1300 LASER GYRO PERFORMANCE BREAKTHROUGH IN 1974
- KEY HONEYWELL STRAPDOWN INS CONFIGURATIONS THAT LED THE WAY (1974 - 1978)
  - ATIGS (ADVANCED TACTICAL INERTIAL GUIDANCE SYSTEM) - DEMONSTRATED GG1300 RLG SYSTEM ACCURACY POTENTIAL IN 1974.
  - LINS (LASER INS) - FIRST TO PROVE STRAPDOWN RLG INS ABILITY TO MEET AIRCRAFT ACCURACY REQUIREMENTS IN LANDMARK 1975 C-41 CARGO AIRCRAFT FLIGHT TESTS AT HOLLOMAN AIR FORCE BASE.
  - RLGN (RING LASER GYRO NAVIGATOR) - REDUCED SIZE UNIT FOR NEW MILITARY STANDARDS PROVED READINESS IN ACCURACY/RELIABILITY/MAINTAINABILITY IN 1977 FOR RLG STRAPDOWN INS APPLICATION UNDER MILITARY FIGHTER AIRCRAFT DYNAMIC ENVIRONMENTS.
  - LASER IRS (INERTIAL REFERENCE SYSTEM) - FIRST PRODUCTION STRAPDOWN INS - DEVELOPED UNDER 1978 CONTRACT TO HONEYWELL FOR ALL BOEING 757/767 COMMERCIAL AIRCRAFT.

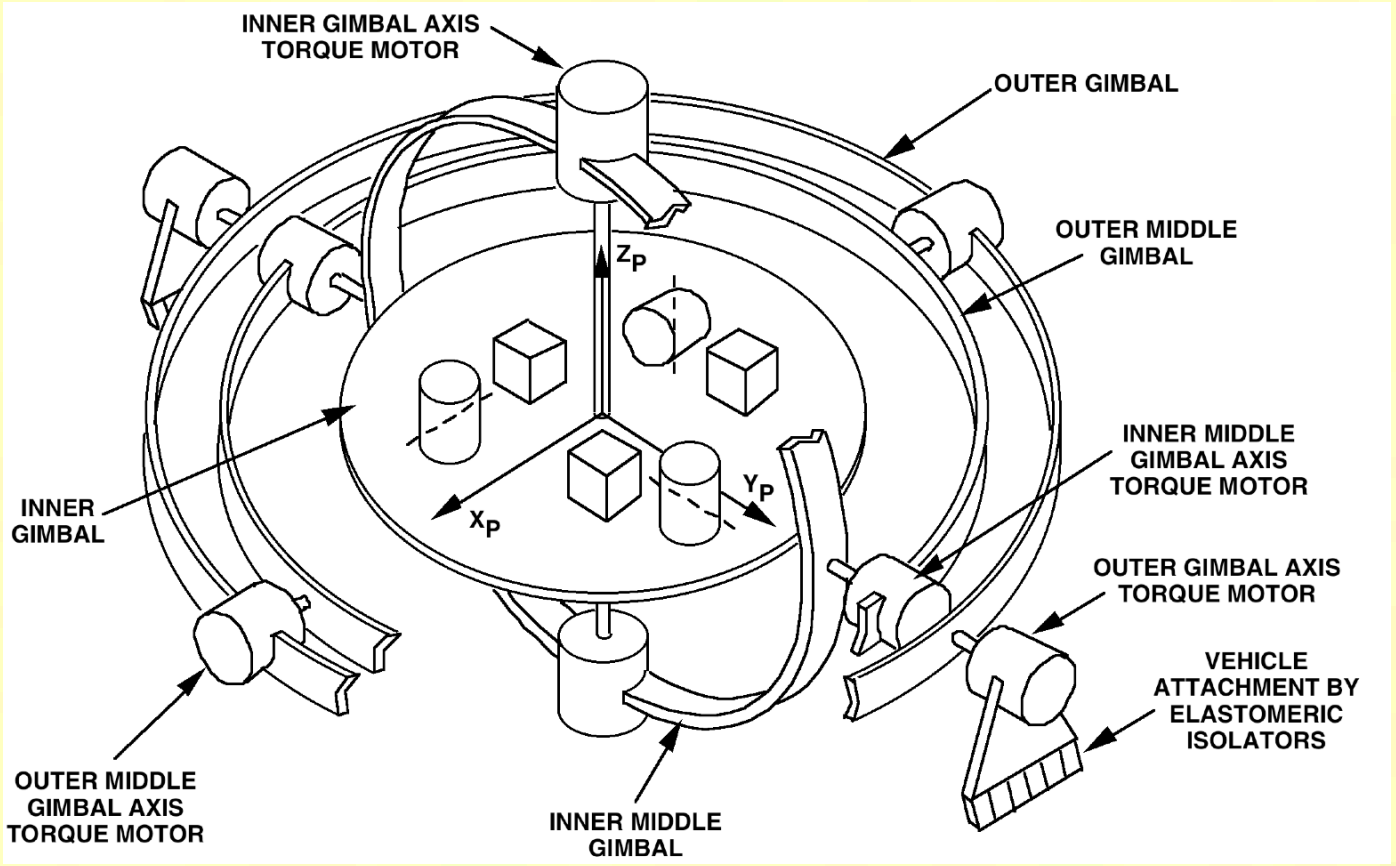
RESULTING CONVERSION OF INS TECHNOLOGY/SUPPLIERS ON ALL AIRCRAFT

FUNDAMENTAL INERTIAL NAVIGATION CONCEPT



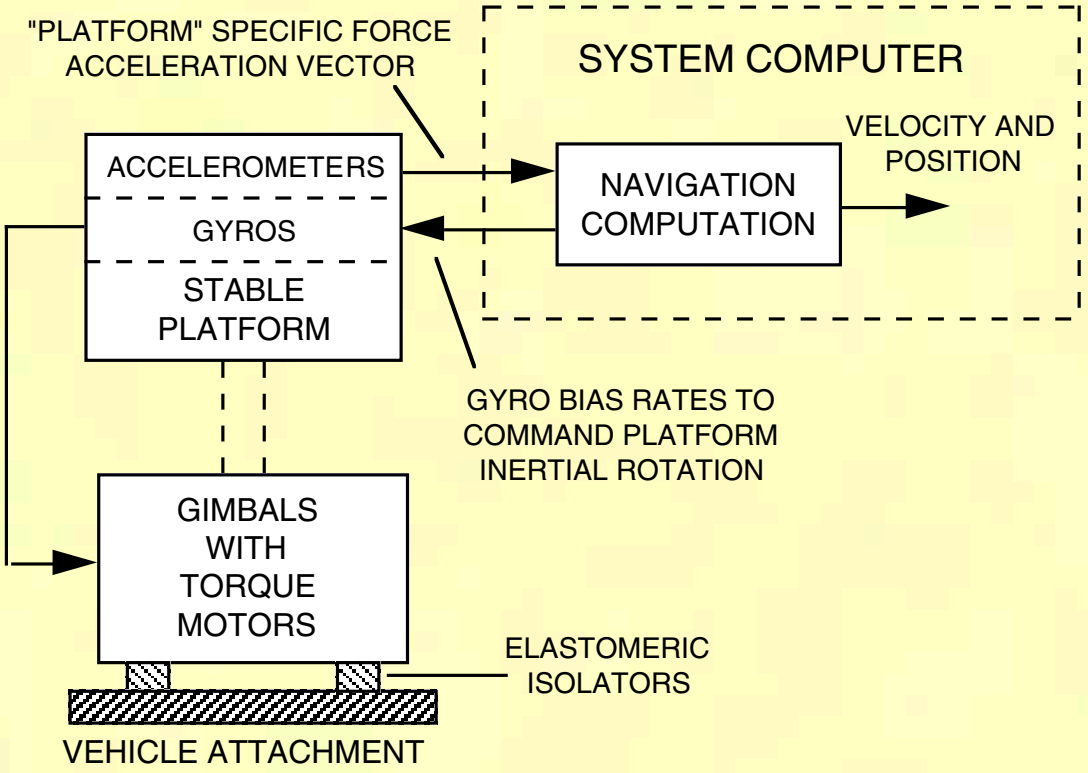
Note: Accelerometers Do Not Measure Gravitational Accelerations

GIMBALED GYRO STABILIZED PLATFORM CONCEPT



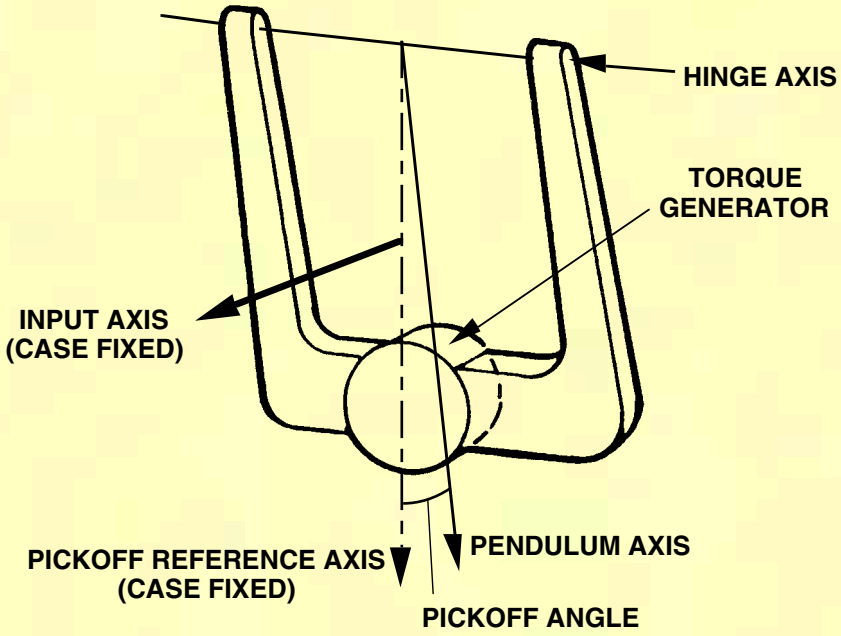
Gyros (Cylinders) Mounted On Platform Measure Platform Angular Rotation Caused By User Vehicle Angular Rates. Gyros Provide Control Signals To Gimbal Torque Motors To Prevent Platform From Responding To Vehicle Rotation. Accelerometers (Cubes) Mounted On Gyro Stabilized Platform Measure Acceleration Components Along Platform Axes - Provide Inputs To Navigation Computer For Integration Into Velocity And Position. Controlling Platform Rotation Also Prevents High Vehicle Rotation Rates From Exciting Angular Rate Sensitive Gyro Errors.

GIMBALED INERTIAL NAVIGATION SYSTEM



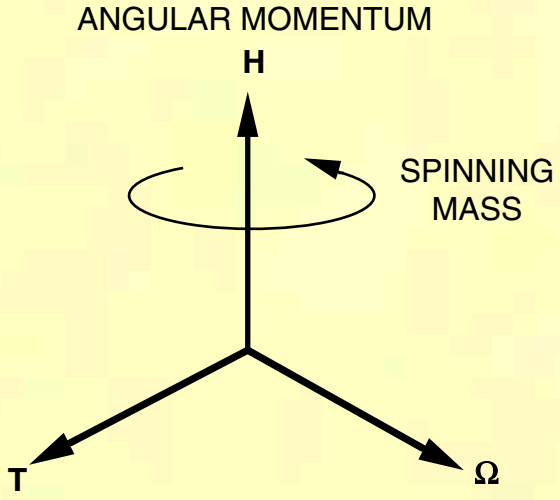
Small Biasing Signals Are Applied To The Gyros So That The Platform Remains Aligned To Local Horizontal/Vertical Axes For A Vehicle Translating Over A Rotating Earth.

ELECTRICALLY SERVOED PENDULOUS ACCELEROMETER CONCEPT



- INERTIAL REACTION TORQUE ABOUT HINGE AXIS EQUALS (PENDULUM MASS) x (INPUT AXIS ACCELERATION) x (MOMENT ARM TO PENDULUM CG)
- ELECTRICAL RESTRAINING TORQUE IS SUPPLIED BY TORQUE GENERATOR DRIVEN BY PICKOFF AMPLIFIER TO KEEP PICKOFF ANGLE SERVOED TO NULL (PENDULUM ALIGNED WITH CASE AXES)
- TORQUER CURRENT BECOMES PROPORTIONAL TO INPUT AXIS ACCELERATION

MOMENTUM WHEEL GYRO PRINCIPLE OF OPERATION



$$T = \Omega \times H + \frac{dH}{dt}$$

RESIDUAL TERM POTENTIALLY NEEDING COMPENSATION

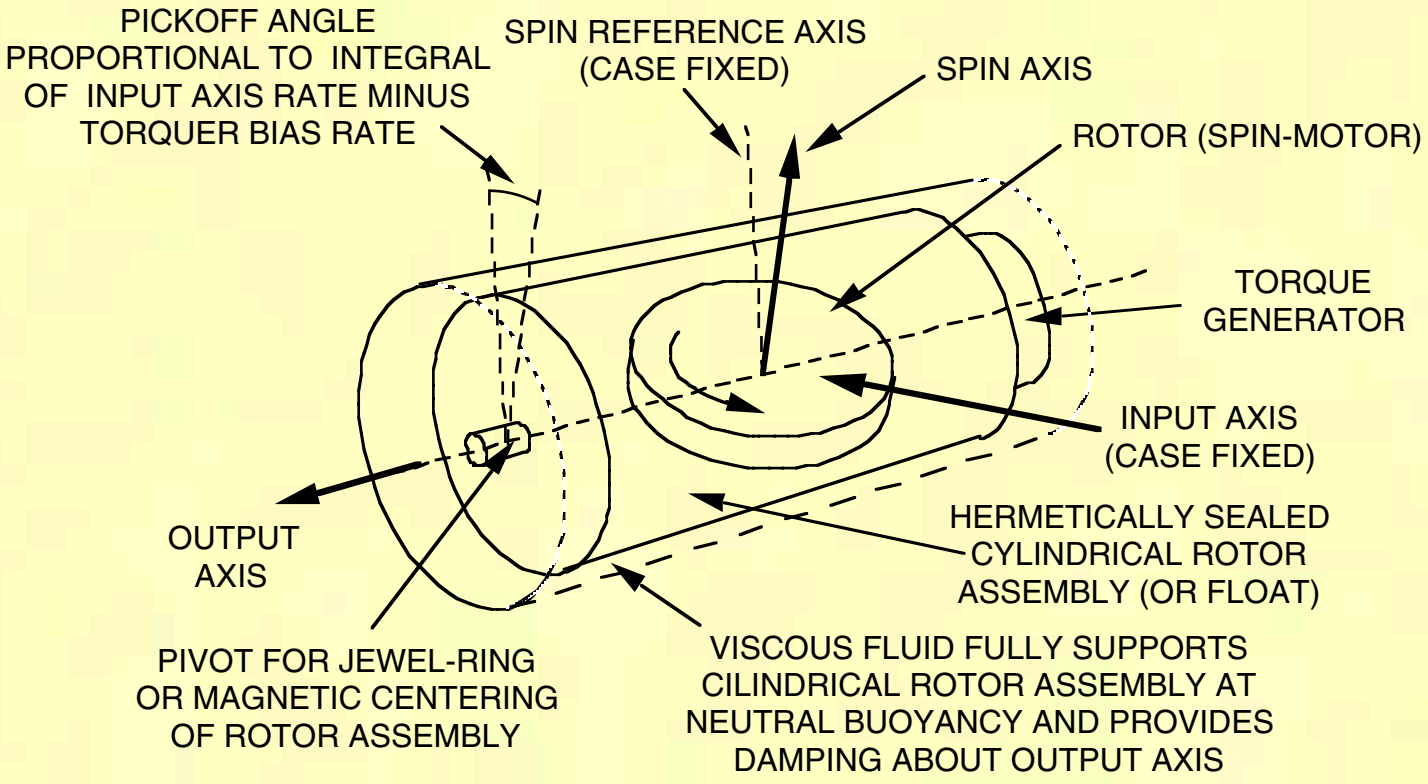
T IS ELECTRICALLY GENERATED TORQUE APPLIED TO SPINNING MASS

Ω IS COMPONENT OF GYRO CASE ANGULAR RATE PERPENDICULAR TO **H** (SPIN AXIS) AND TO **T** (GYRO TORQUE GENERATOR INPUT AXIS)

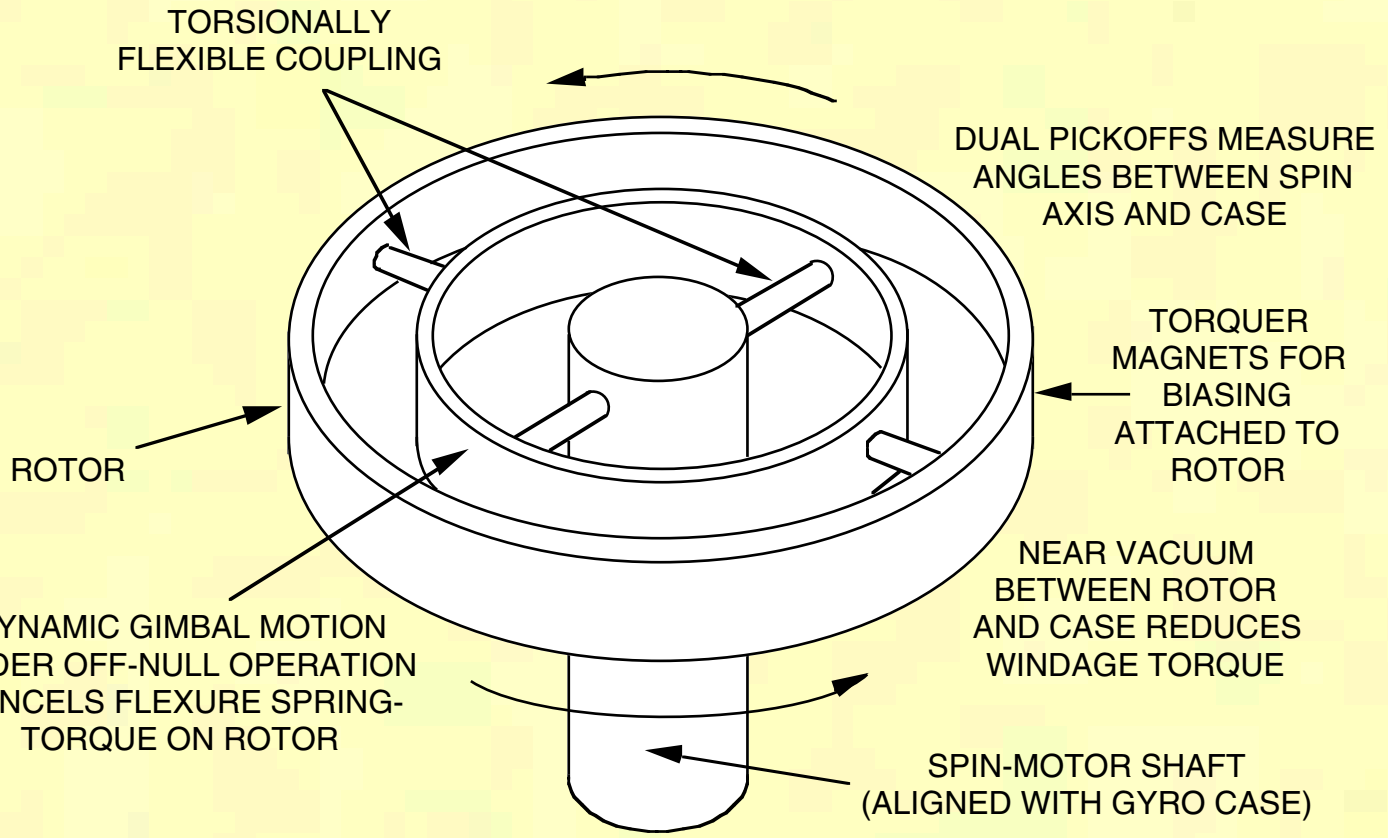
ANGULAR ATTITUDE MEASUREMENTS - IN ABSENCE OF APPLIED TORQUE **T**, ANGULAR MOMENTUM **H** REMAINS NONROTATING. GYRO PICKOFF SIGNAL (GYRO OUTPUT) MEASURES ANGULAR ORIENTATION OF GYRO CASE MOUNT RELATIVE TO **H**.

ANGULAR RATE MEASUREMENTS - TORQUE **T** IS APPLIED TO FORCE ANGULAR MOMENTUM **H** TO REMAINED ALIGNED WITH GYRO CASE MOUNT (TO CONTROL GYRO PICKOFF SIGNAL TO ZERO). TORQUER CURRENT (GYRO OUTPUT) BECOMES PROPORTIONAL TO ANGULAR RATE Ω OF GYRO CASE MOUNT.

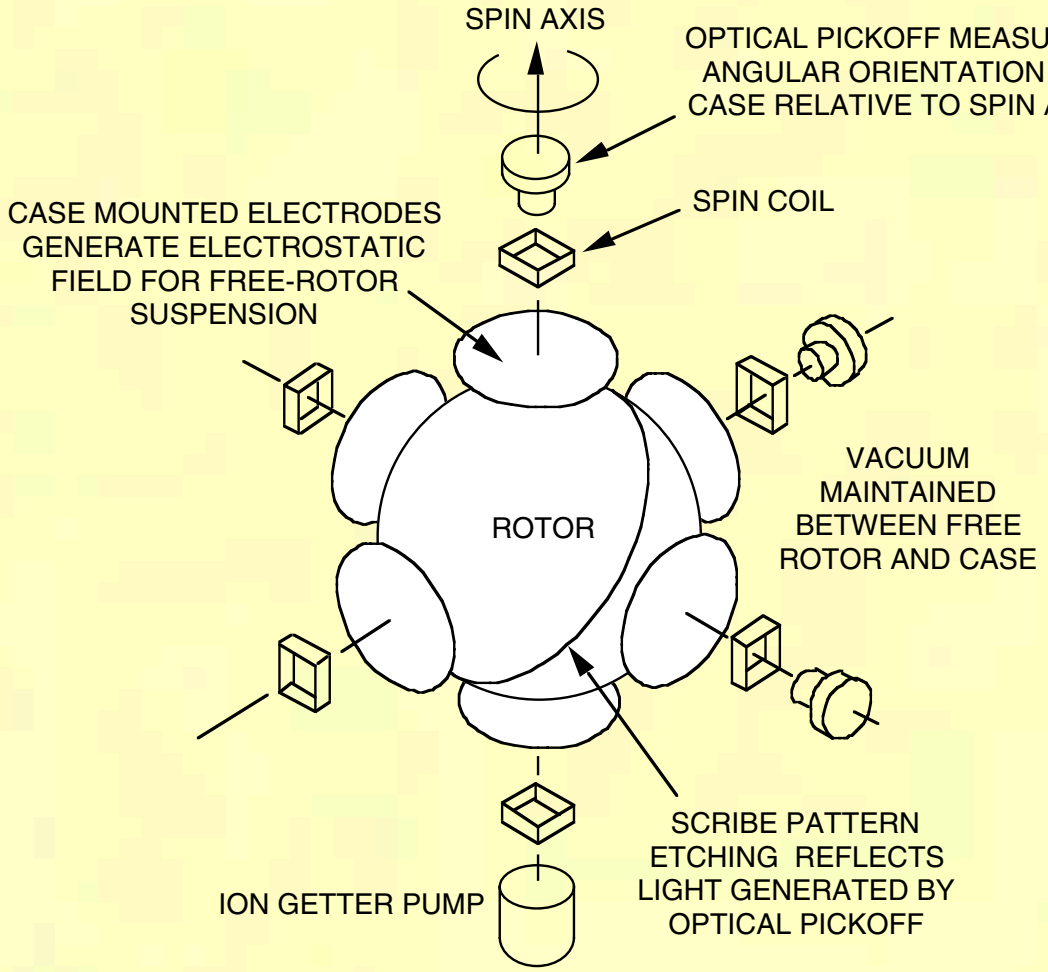
SINGLE-DEGREE-OF-FREEDOM FLOATED RATE INTEGRATING GYRO (RIG)



TWO-AXIS DRY TUNED ROTOR GYRO (TRG)



HONEYWELL HOLLOW-SHELL ROTOR
ELECTROSTATICALLY SUSPENDED GYRO (ESG)



MAJOR EARLY INS MANUFACTURING COMPANIES

(ALL USING GIMBALED PLATFORMS FOR SENSOR ISOLATION)

HONEYWELL AEROSPACE AND DEFENSE GROUP

- **> GYRO DESIGN/MANUFACTURING - MINNEAPOLIS, MN**
- **> INS DESIGN/DEVELOPMENT/MANUFACTURING - CLEARWATER, FL**

KEARFOTT - WAYNE, NJ

LITTON GUIDANCE & CONTROL DIVISION - WOODLAND HILLS, CA

DELCO ELECTRONICS DIVISION OF GENERAL MOTORS - MILWAUKEE, WI

> LITTON AND KEARFOTT DOMINATED HIGH VOLUME MILITARY TACTICAL AIRCRAFT AND CRUISE MISSILE MEDIUM ACCURACY INS PROGRAMS - USED TRGs FOR REDUCED COST

> DELCO DOMINATED HIGH VOLUME MILITARY TRANSPORT AND COMMERCIAL AIRCRAFT INS PROGRAMS - USED RIGS WITH GIMBALED TURN-TABLE TO REDUCE ERRORS: "CAROUSEL" SYSTEM

> HONEYWELL DOMINATED LOWER VOLUME HIGH ACCURACY MILITARY AIRCRAFT INS PROGRAMS - USED ESGs FOR HIGH ACCURACY

HONEYWELL INVESTIGATED NEW STRAPDOWN APPROACH TO INERTIAL NAVIGATION AS REDUCED COST APPROACH TO ENTER HIGH VOLUME INS MARKETS

INERTIAL SENSORS DIRECTLY ATTACHED TO VEHICLE
"STRAPDOWN"

ELIMINATES GIMBALED PLATFORM

- REDUCED COST, IMPROVED RELIABILITY

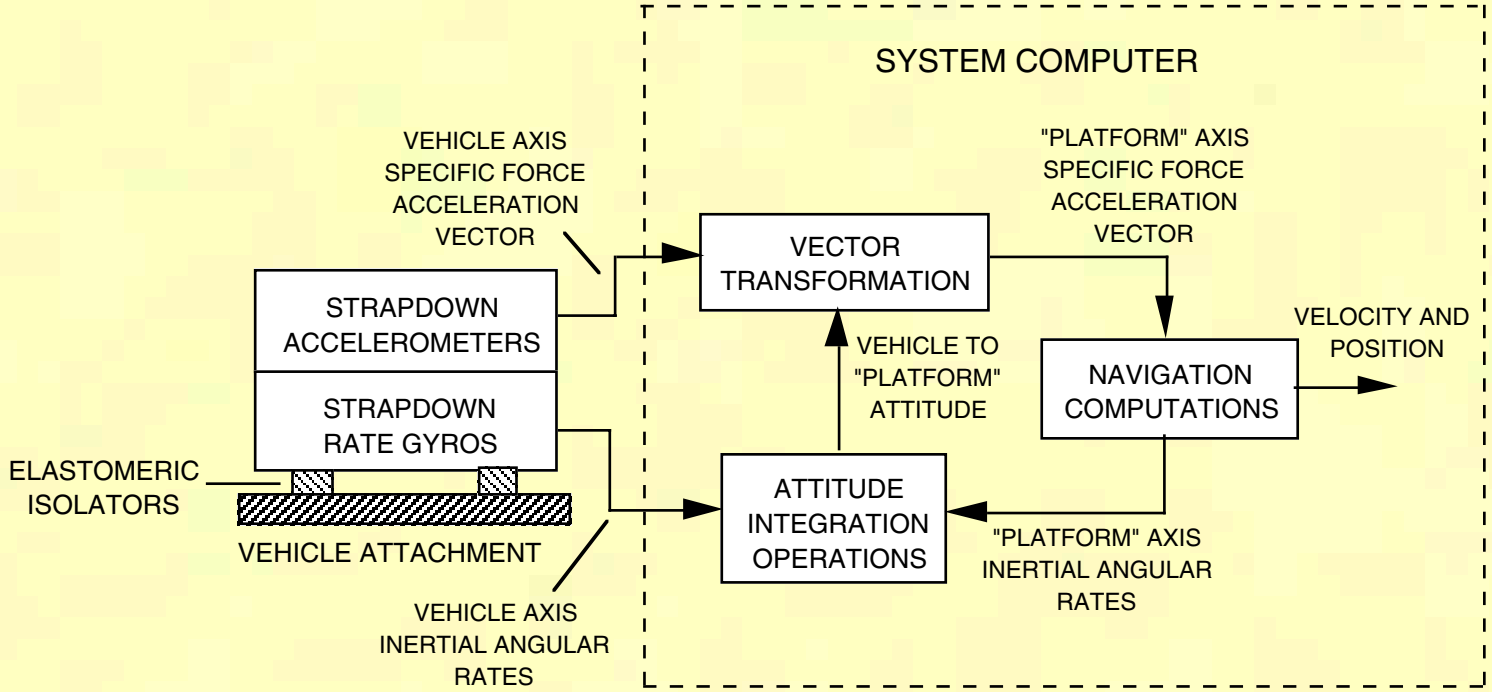
PLACED NEW PERFORMANCE DEMANDS ON GYROS FOR ACCURACY UNDER VEHICLE ROTATION RATES

> POTENTIAL FOR REDUCED INS COST BASED ON FUTURE DEVELOPMENT OF NEW LASER BASED ANGULAR RATE SENSOR FOR REQUIRED ACCURACY AT LOW COST

NEW HIGH SPEED PROCESSING REQUIREMENTS FOR INS COMPUTER

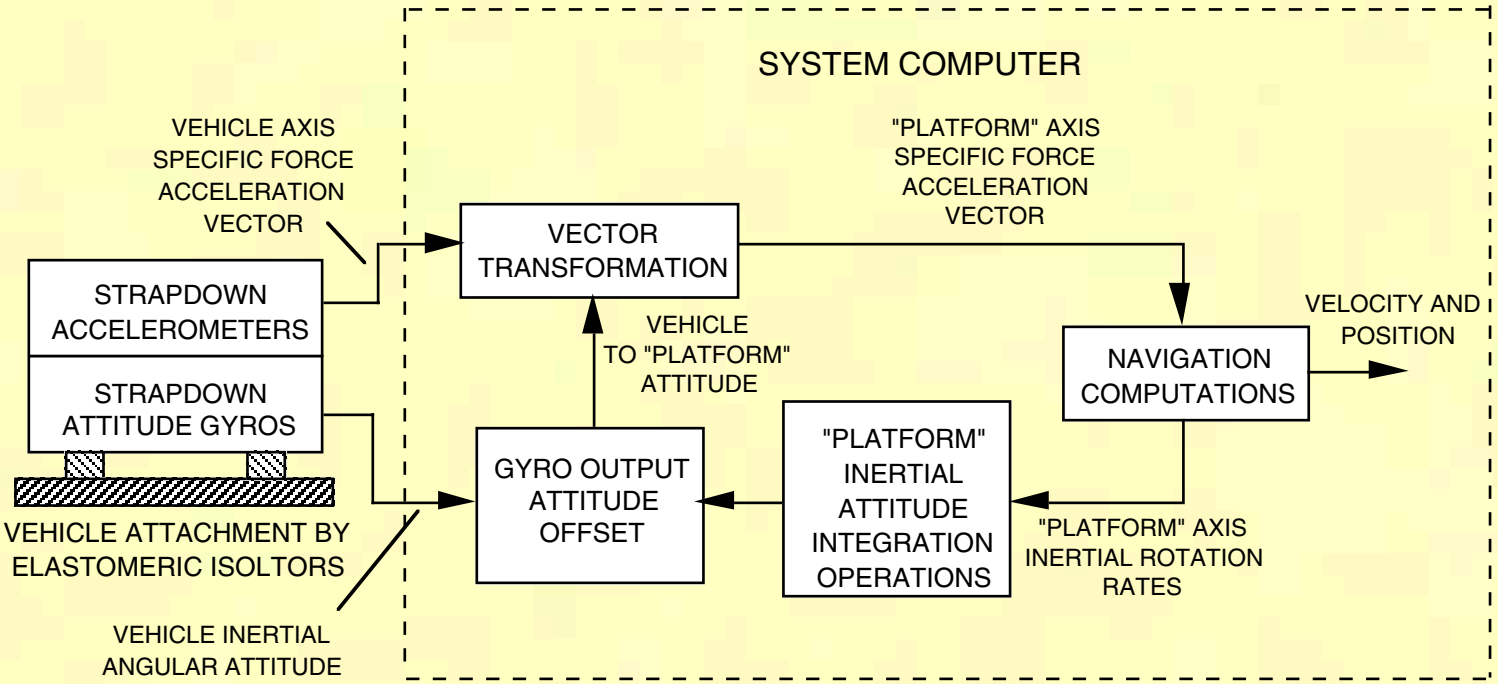
> POTENTIAL FOR REDUCED INS COST BASED ON FUTURE ADVANCES IN COMPUTER PROCESSING CAPABILITIES WITH REDUCED COMPUTER COST

RATE-GYRO BASED STRAPDOWN INERTIAL NAVIGATION SYSTEM



Gyros Mounted Directly To The Vehicle (Strapdown) Measure Vehicle Angular Rotation Rates. Gyro Output Rates Are Processed At High Speed In Navigation Computer To Calculate Vehicle Angular Orientation (Attitude) - An Integration (Summing) Operation. Biasing Signals For The Gyros ("Platform Inertial Angular Rates") Are Used In The Attitude Computation So That Attitude Becomes Referenced To Local Horizontal/Vertical Axes For A Vehicle Translating Over A Rotating Earth. Accelerometers Mounted Directly To The Vehicle (Strapdown) Measure Acceleration Components Along Vehicle Axes. Attitude Calculated In Computer Is Used To Transform (Rotate) Measured Vehicle Axis Accelerations Into The Equivalent To What Would Be Measured Directly By Accelerometers Mounted On A Gimbaled Platform. Equivalent "Platform" Accelerations Are Then Processed (Integrated) To Calculate Position And Velocity.

ATTITUDE-GYRO BASED STRAPDOWN INERTIAL NAVIGATION SYSTEM



Attitude Gyros Mounted Directly To The Vehicle (Strapdown) Directly Measure Vehicle Angular Orientation - Without High Speed Integration Operation Required For Rate-Gyro Based Strapdown Systems. Gyro Attitude Outputs Are Offset So That Computed Attitude Becomes Referenced To Local Horizontal/Vertical Axes For A Vehicle Translating Over A Rotating Earth (The Offset Angle Is Calculated By Integrating Computed Vehicle And Velocity Data At Low Speed). Accelerometers Mounted Directly To The Vehicle (Strapdown) Measure Acceleration Components Along Vehicle Axes. The Offset Gyro Attitude Data Is Used To Transform (Rotate) The Measured Vehicle Axis Accelerations Into The Equivalent To What Would Be Measured Directly By Accelerometers Mounted On A Gimbaled Platform. The Equivalent "Platform" Accelerations Are Then Processed (Integrated) To Calculate Position And Velocity.

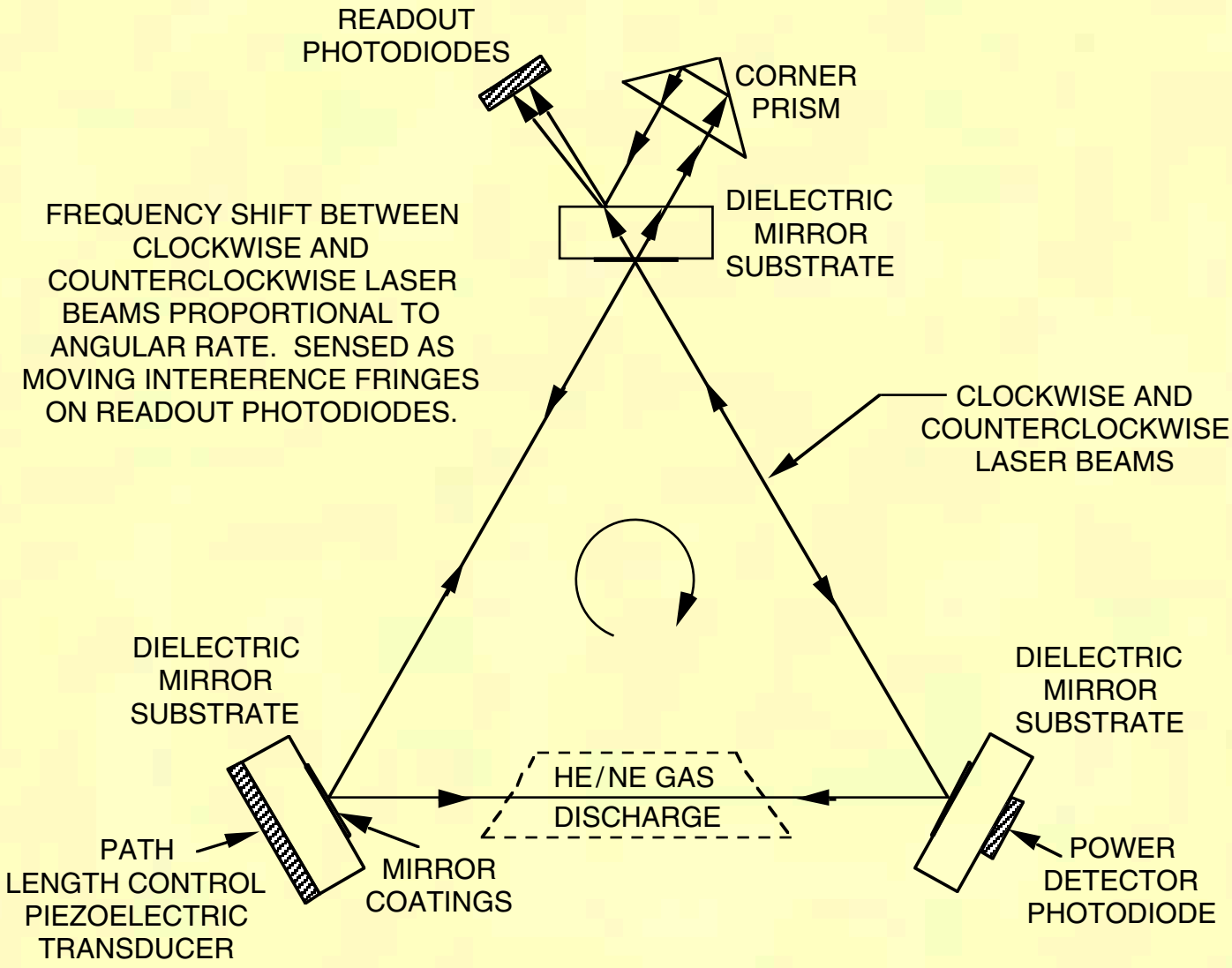
THE RING LASER GYRO (RLG)

NEW NON-MECHANICAL
ANGULAR RATE SENSING CONCEPT

PROMISED LOW COST AND HIGH ACCURACY
UNDER HIGH ANGULAR ROTATION RATES

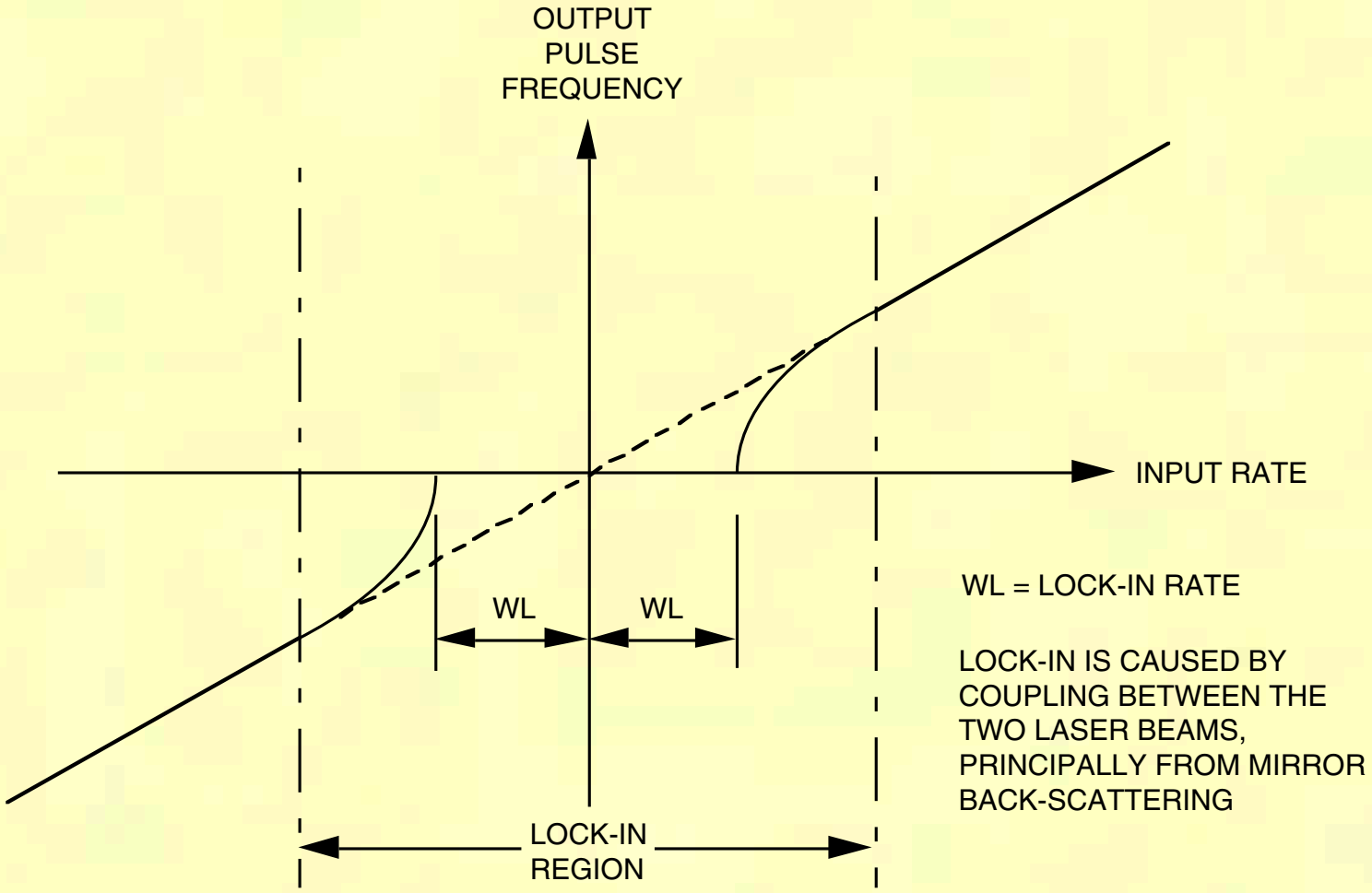
BUT DEVELOPMENT SUCCESS WAS LONG IN COMING, FRUSTRATING INS DESIGN GROUP GOALS FOR A NEW LOW COST STRAPDOWN INS

RING LASER GYRO OPERATING ELEMENTS



A NEW MAJOR ERROR SOURCE HAD TO BE OVERCOME FOR LASER GYROS TO BECOME A PRACTICAL REALITY:

"LOCK-IN"



WL = LOCK-IN RATE

LOCK-IN IS CAUSED BY COUPLING BETWEEN THE TWO LASER BEAMS, PRINCIPALLY FROM MIRROR BACK-SCATTERING

EARLY LASER GYRO DESIGN COMPANIES
(WITH DIFFERENT APPROACHES FOR LOCK-IN COMPENSATION)

SPERRY GYROSCOPE DIVISION OF SPERRY RAND - GREAT NECK, NY

- MODULAR INSERT CONSTRUCTION, MAGNETIC MIRROR BIASING OUT OF LOCK-IN

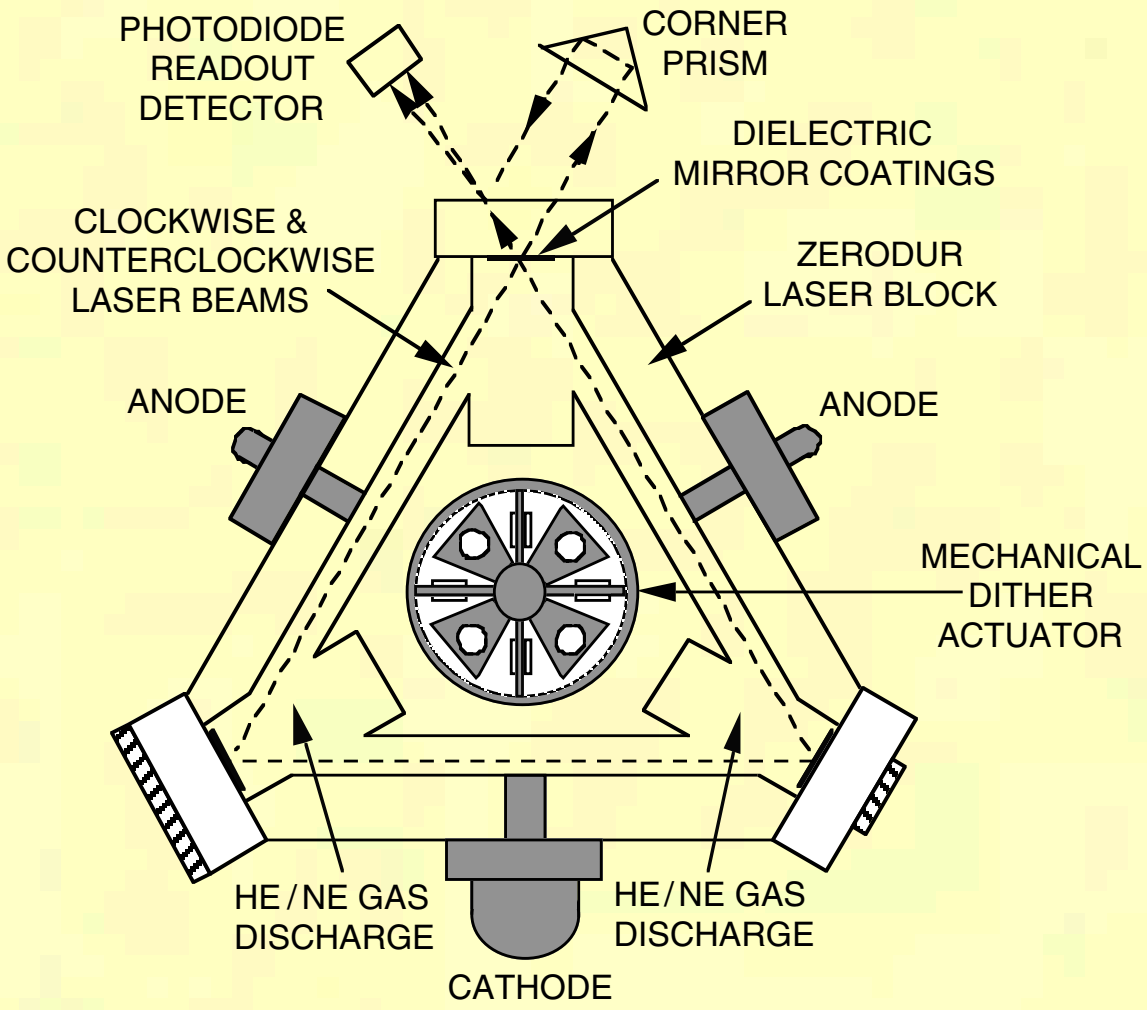
HAMILTON STANDARD DIVISION OF UNITED TECHNOLOGIES - WINDSOR LOCKS, CN

- DILAG (DIFFERENTIAL LASER GYRO) - MONOLITHIC CONSTRUCTION, CAVITY INSERTS WITH FARADAY MAGNETIC BIAS FOR LOCK-IN
- DUAL 2-BEAM LASER SETS IN SAME CAVITY (ONE RIGHT CIRCULARLY POLARIZED, THE OTHER LEFT CIRCULARLY POLARIZED)
  - SUBTRACTING ONE OUTPUT FROM THE OTHER DOUBLES OUTPUT RATE SENSITIVITY AND CANCELS MAGNETIC BIASING ERRORS

HONEYWELL AEROSPACE AND DEFENSE GROUP - MINNEAPOLIS, MN

- MONOLITHIC WITHOUT INSERTS, MECHANICAL DITHER BIAS FOR LOCK-IN COMPENSATION - AVOIDS ERRORS INTRODUCED BY INSERTS AND MAGNETIC BIAS

HONEYWELL RING LASER GYRO BLOCK ASSEMBLY



HONEYWELL 1970 REORGANIZATION

AIRCRAFT PRECISION GIMBALED ESG INS PROGRAMS REMAINED AT HONEYWELL FLORIDA DIVISION

AIRCRAFT FLIGHT CONTROL AND FIRE CONTROL PROGRAMS REMAINED AT HONEYWELL MINNEAPOLIS DIVISION

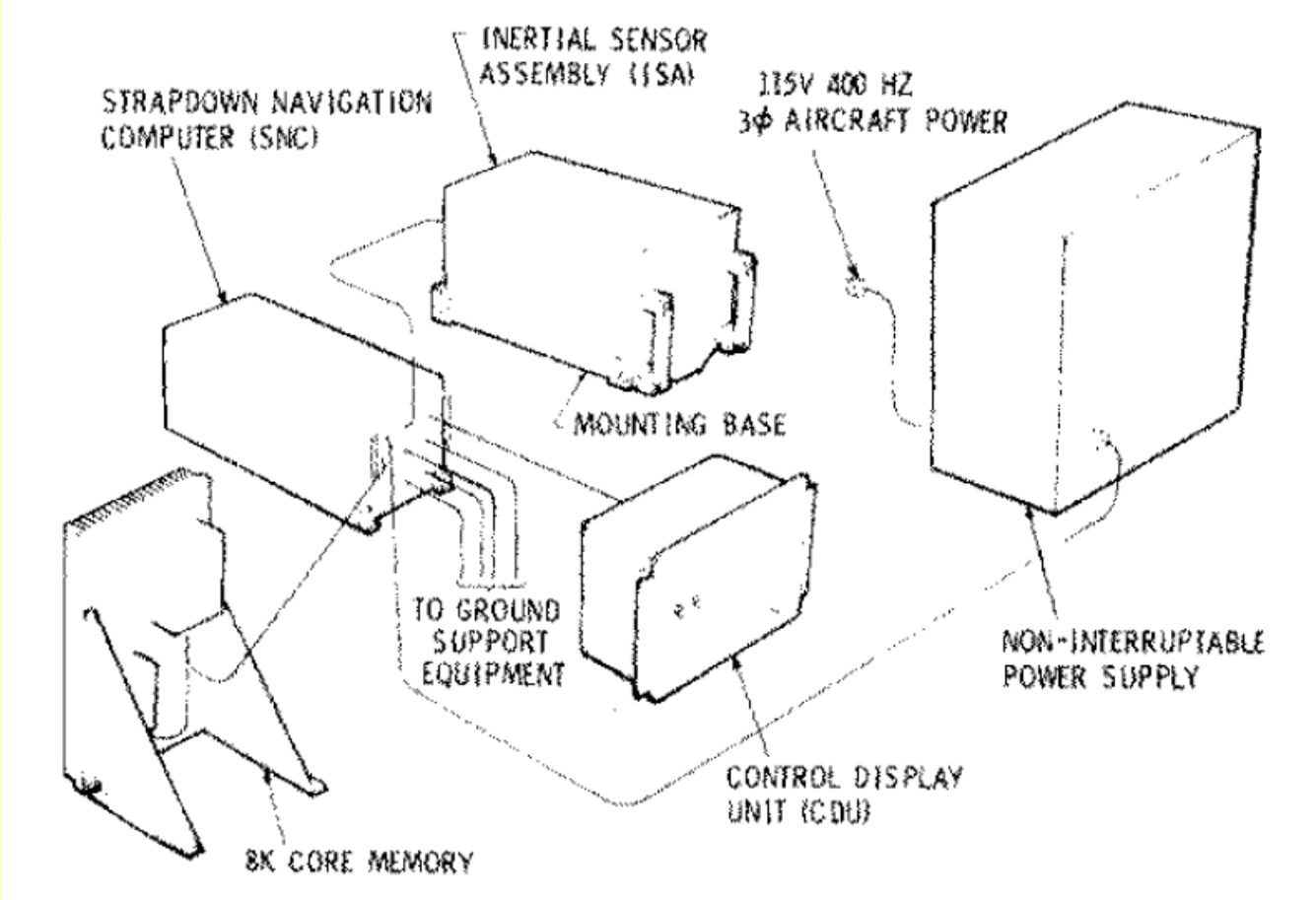
SPACECRAFT, SPACE LAUNCH, MISSILE, AND SPACE SHUTTLE PROGRAMS TRANSFERRED FROM HONEYWELL MINNEAPOLIS DIVISION TO FLORIDA

MEDIUM ACCURACY AIRCRAFT STRAPDOWN INS PROGRAMS TRANSFERRED FROM HONEYWELL FLORIDA DIVISION TO MINNEAPOLIS

(WHEN COMPUTER TECHNOLOGY WAS FINALLY BEGINNING TO ACHIEVE FORECASTED LOW COST, BUT STILL WITHOUT THE HOPED FOR NEW LASER GYRO TECHNOLOGY)

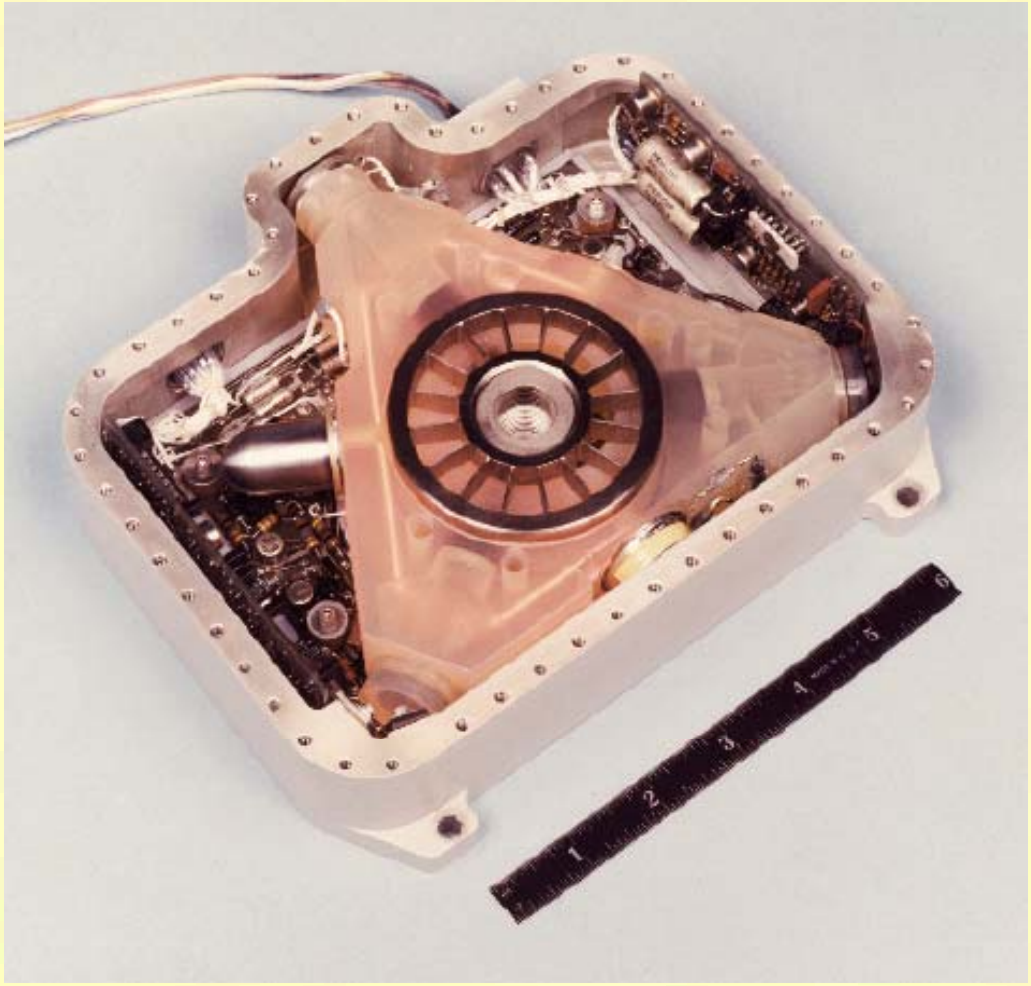
HONEYWELL MINNEAPOLIS DEVELOPMENTAL STRAPDOWN INS DEMO SYSTEM

(DESIGNED UNDER NEW INS CHARTER RESPONSIBILITY USING STRAPDOWN FLOATED RATE INTEGRATING GYROS)



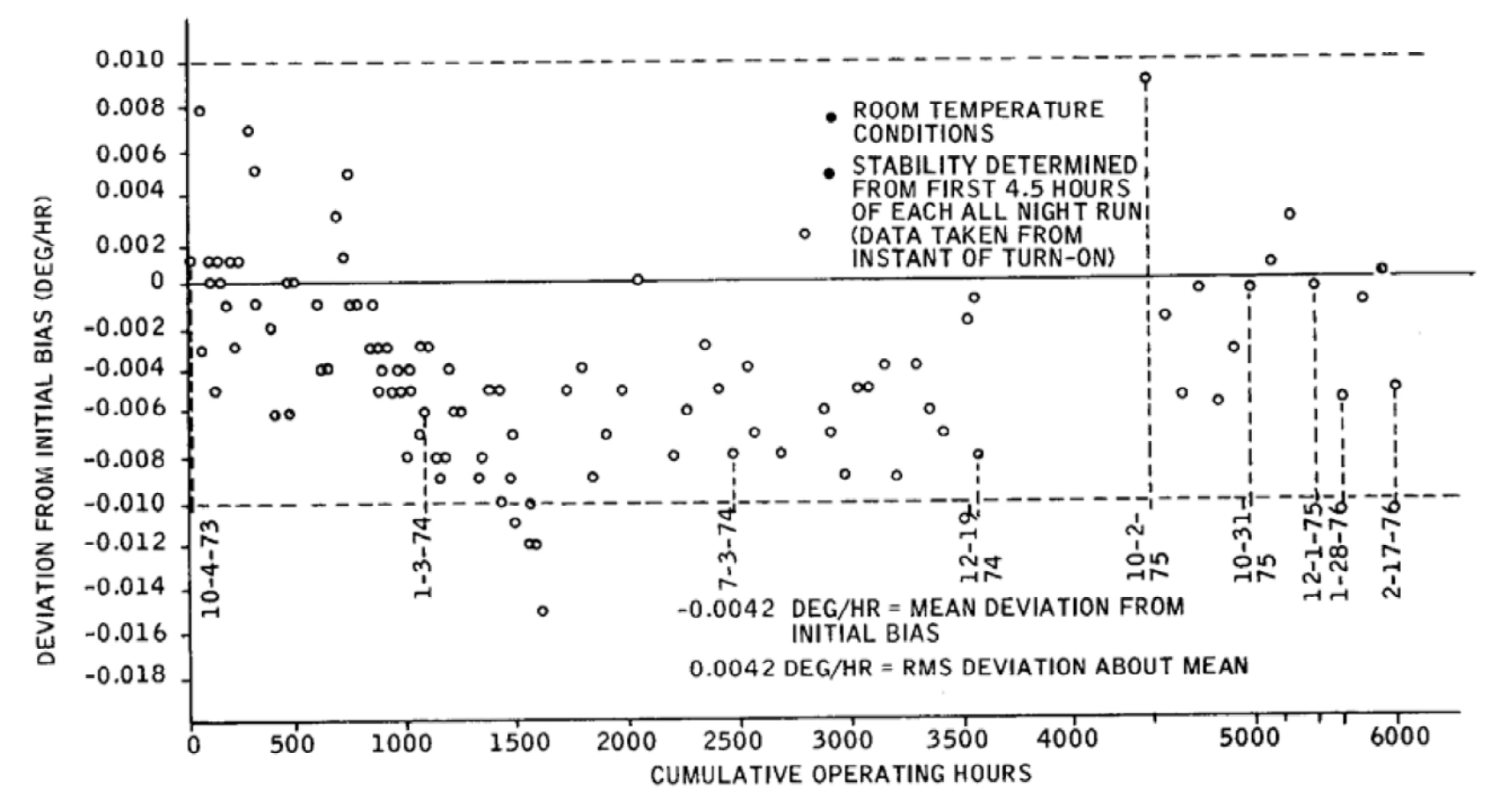
HONEYWELL GG1300 RING LASER GYRO
(WITH 6 - INCH RULER)

WITH 1974 PERFORMANCE BREAKTHROUGHS, THE GG1300 BECAME THE FIRST RLG TO MEET ACCURACY REQUIREMENTS FOR AIRCRAFT STRAPDOWN INERTIAL NAVIGATION



GG1300 BIAS STABILITY TEST DATA

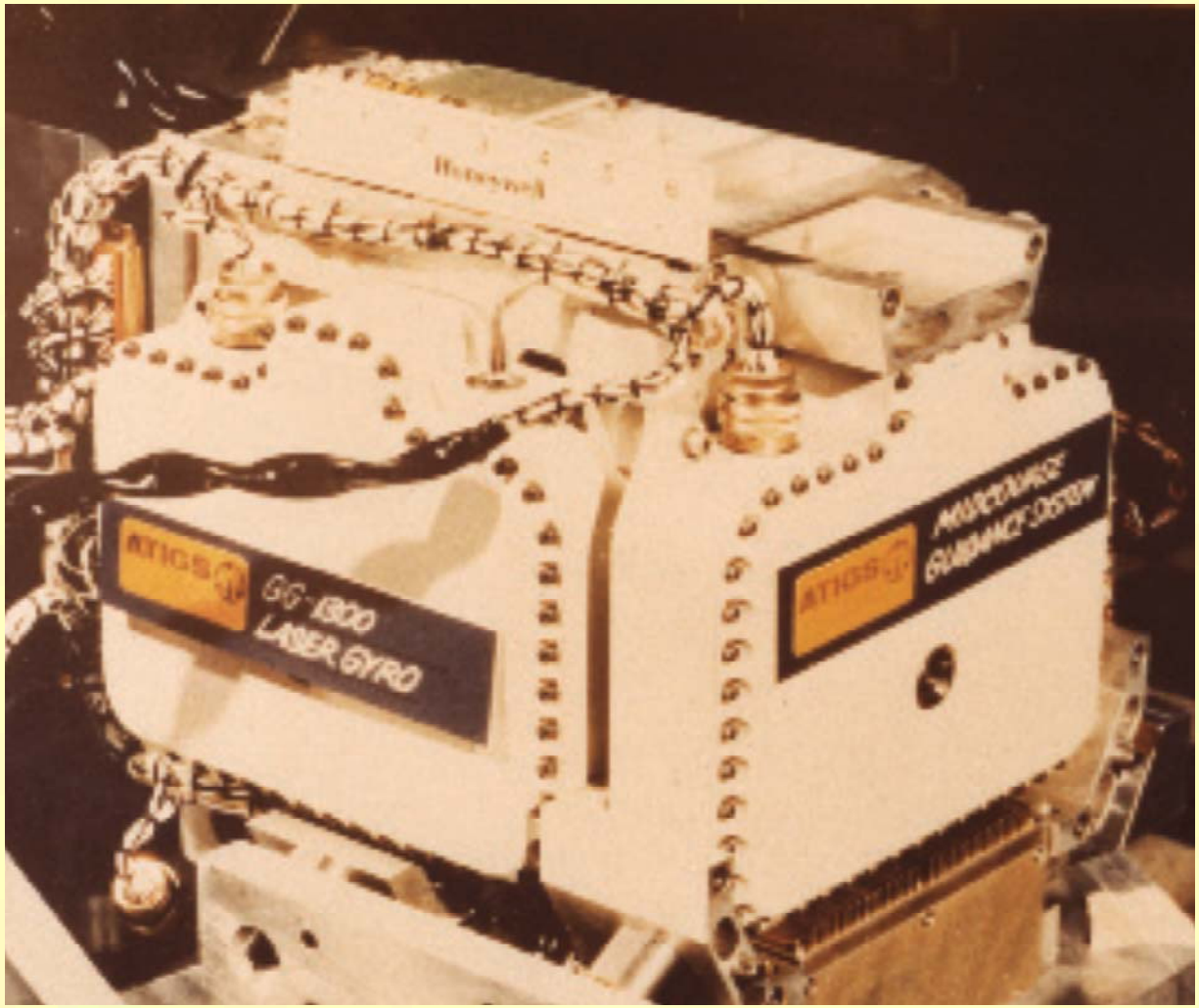
FIRST RLG PERFORMANCE DATA MEETING 0.01 DEG/HR AIRCRAFT STRAPDOWN INS REQUIREMENTS



ATIGS (ADVANCED TACTICAL INERTIAL GUIDANCE SYSTEM)

- ORIGINAL SYSTEM TEST BED FOR GG1300 RLG
- DESIGNED BY HONEYWELL FLORIDA DIVISION
- FUNDING PROVIDED BY US NAVAL WEAPONS CENTER (NWC)
- DESIGNED FOR ADVANCED TACTICAL MISSILE FLIGHT TEST DEMO
- ACCURACY REQUIREMENTS 10 TIMES LESS SEVERE THAN FOR AIRCRAFT INS APPLICATIONS (ALLOWED LESS ACCURATE ACCELEROMETERS)
- FLIGHT TESTED AT NAVAL WEAPONS CENTER (NWC) ON A-7 AIRCRAFT WING POD MOUNT
- UNCOVERED SIGNIFICANT GG1300 THERMALLY SENSITIVE ERRORS THAT LIMITED FLIGHT TEST DEMONSTRATION ACCURACY
  - > DRIVEN IN PART BY MOUNTING GYROS ON CASTING SURROUNDING HIGH POWERED SYSTEM COMPUTER
- STILL DEMONSTRATED MORE THAN TWO TIMES HIGHER ACCURACY THAN REQUIRED FOR ATIGS ADVANCED TACTICAL MISSILE APPLICATION
- SUGGESTED POTENTIAL FOR FUTURE AIRCRAFT INS APPLICATION

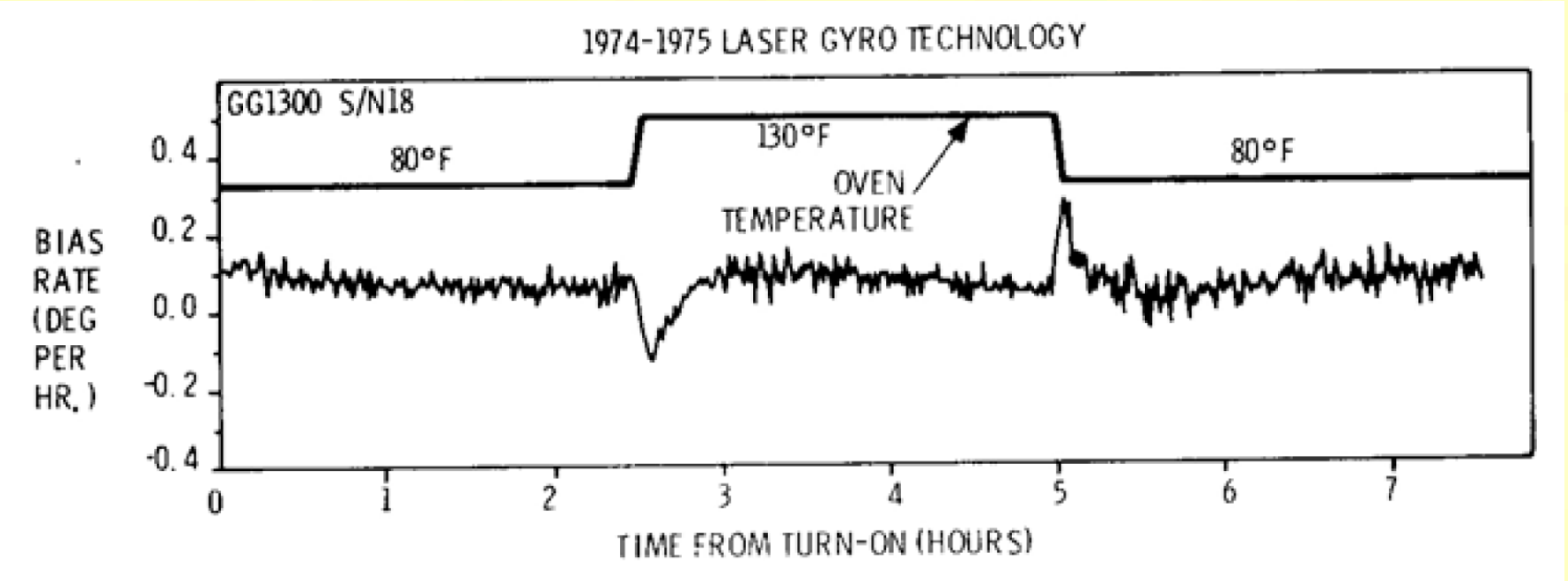
ADVANCED TACTICAL INERTIAL GUIDANCE SYSTEM (ATIGS)



LTV A-7 CORSAIR US NAVY FIGHTER AIRCRAFT
(USED AT NWC FOR ATIGS TESTS)

HONEYWELL GG1300

TEMPERATURE SENSITIVITY EXPERIENCED WITH ATIGS



LINS (LASER INERTIAL NAVIGATION SYSTEM)

INERTIAL SENSOR ASSEMBLY (ISA)

- DESIGN INITIATED IN 1974 USING GG1300 RLGs BASED ON MEASURED OUTSTANDING LABORATORY PERFORMANCE CAPABILITIES

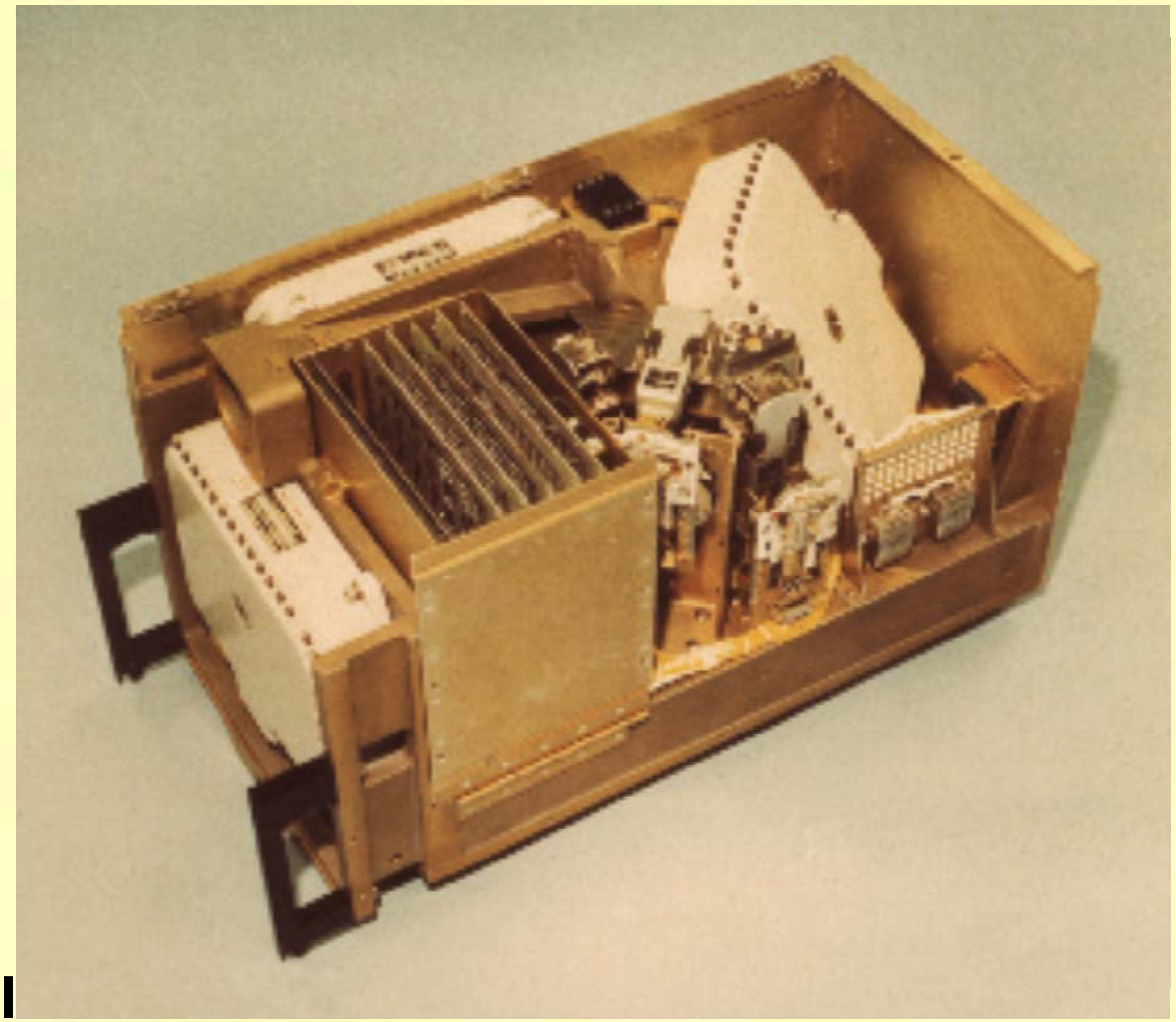
  > CHANGED FROM ORIGINAL PLAN TO USE STRAPDOWN FLOATED RATE INTEGRATING GYROS

- LARGE SENSOR MOUNT CASTING SEPARATED GYROS FROM OTHER SYSTEM ELECTRONICS

  > MINIMIZED RLG THERMAL ERROR EXCITATION

- FOLLOWING ATIGS TEST RESULTS, INITIATED INVESTIGATION OF SOFTWARE COMPENSATING RESIDUAL GG1300 THERMALLY SENSITIVE ERRORS USING TEMPERATURE MEASUREMENTS

LINS INERTIAL SENSOR ASSEMBLY (ISA)



DEMONSTRATING RLG INS FEASIBILITY FOR US MILITARY AIRCRAFT

- CENTRAL INERTIAL GUIDANCE TEST FACILITY (CIGTF)
  HOLLOMAN AIR FORCE BASE, ALAMOGORDO, NM
  - > ARM OF AIR FORCE AVIONICS LAB / WRIGHT PATTERSON AFB
  - > CERTIFIES ALL US MILITARY AIRCRAFT INS EQUIPMENT

- ORIGINAL PLANS FOR NEW INS US GOVERNMENT FUNDING -

  AIR FORCE COMMITTED TO AUTONETICS STRAPDOWN ESG MICRON:
  - > $25 M PLANNED FOR FULL SCALE PRODUCTION DEVELOPMENT
  - > CIGTF FLIGHT TESTS PLANNED FOR MICRON ADVANCED DEVELOPMENT SYSTEM PRIOR TO PRODUCTION COMMITMENT

- HONEYWELL WASHINGTON DC FIELD OFFICE

  ENTHUSIASTIC HONEYWELL SALES REP INFORMED INFLUENTIAL COLONEL AT US DEFENSE DEPARTMENT OF GG1300 PERFORMANCE BREAKTHROUGHS

  RESULT - LIMITED FUNDING PROVIDED FOR VERIFICATION BY HOLLOMAN CIGTF FLIGHT TESTING OF HONEYWELL GG1300 RLG INS (PRIOR TO MICRON FULL SCALE PRODUCTION COMMITMENT)

- DEMO FLIGHT TEST ACCURACY GOAL
  - > LESS THAN 1 - 3 NAUTICAL MILES PER HOUR (NM/HR) ERROR RATE (50 % LIKELIHOOD - "CEP")

ORGANIZATIONS INVOLVED IN RLG INS SELECTION FOR HOLLOMAN FLIGHT TEST - ATIGS OR LINS

NAVAL WEAPONS CENTER (NWC) - CHINA LAKE, CA

- NAVY AIRCRAFT WEAPONS SYSTEM INTEGRATOR
- RLG AND HONEYWELL ATIGS MISSILE SYSTEM DESIGN SPONSOR

NAVAL AIR DEVELOPMENT CENTER (NADC) - WARMINSTER, PA

- NAVY AVIONICS (INCLUDING AIRCRAFT INS) DESIGN SPONSOR
- RLG DESIGN SPONSOR

AIR FORCE AVIONICS LAB (AFAL) - WRIGHT PATTERSON AFB, DAYTON, OH

- AIR FORCE AIRCRAFT AVIONICS/INS DEVELOPMENT/SPONSOR
- HONEYWELL ESG GEANS INS SPONSOR
- AUTONETICS ESG MICRON (MICRO NAVIGATOR) SPONSOR
  - > TARGETED AS NEXT GENERATION TACTICAL AIRCRAFT INS
  - > COMPLETING ADVANCED DEVELOPMENT
  - > $25M PLANNED FOR FULL-SCALE PRODUCTION DEVELOPMENT

HONEYWELL MINNEAPOLIS - LINS AIRCRAFT SYSTEM DESIGNER

HONEYWELL FLORIDA - ATIGS MISSILE SYSTEM DESIGNER

SELECTING THE HOLLOMAN FLIGHT TEST DEMO SYSTEM

LINS OR ATIGS

HONEYWELL STRATEGIC PLANNING OFFICE MEETING

WASHINGTON DC

ATTENDEES

NWC, NADC, HONEYWELL FLORIDA, HONEYWELL MINNEAPOLIS

LINS PRESENTATION

EMPHASIZED LOW RISK FOR RLG THERMALLY DRIVEN ERRORS

> ISOLATED INERTIAL SENSOR ASSEMBLY FROM SYSTEM ELECTRONICS

> LARGE SENSOR MOUNT CASTING REDUCED HEAT TRANSFER TO GYROS

DECISION - FLY LINS AT HOLLOMAN

> DELIVER TO HOLLOMAN IN 6 MONTHS) FOR FLIGHT TEST DEMO IN CIGTF C-141 TRANSPORT AIRCRAFT

> BUT LINS ISA BUILD WAS NOT YET INITIATED

LINS PRE-FLIGHT-TEST HURDLES COMPLETED TO MEET 6 MONTH BUILD/DELIVERY SCHEDULE

- ORDER ISA CASTING - DELIVERED IN ONE MONTH

- ACCELEROMETERS - FIND/ORDER STRAPDOWN AIRCRAFT INS ACCURACY HEATERLESS ACCELEROMETERS

  > SYSTRON DONNER 4841s RECOMMENDED BY BOEING - DELIVERED IN ONE MONTH

- PROCURE NON-INTERRUPTABLE POWER SUPPLY

  > REQUIRED FOR CIGTF C-141 TEST FOR LINS OPERATION DURING HANDOFF FROM AUXILIARY TO/FROM AIRCRAFT PRIMARY POWER

- THE VAN TEST

  > REQUIRED PRIOR TO HOLLOMAN DELIVERY BY MPLS VP FOR CONFIDENCE. PURCHASED AND OUTFITTED VAN WITH SPECIAL LINS TEST INTERFACES.

ASSEMBLED/TESTED ISA AND INTEGRATED WITH LINS COMPUTER

  > LEARNED HOW TO MEASURE AND COMPENSATE REPEATABLE SENSOR ERRORS (BIAS, SCALE FACTOR, MISALIGNMENT) WITH IMPROVISED TEST EQUIPMENT - NO BUDGET FOR AIRCRAFT INS TEST FIXTURING IN MINNEAPOLIS.

INSTALLED NEWLY DEVELOPED METHOD FOR COMPENSATING RLG THERMALLY SENSITIVE ERRORS - USING GYRO TEMPERATURE MEASUREMENTS

LINS TEST VAN

"MOBILE LASER INERTIAL NAVIGATION LABORATORY"

(ON THE WAY TO HOLLOMAN WITH LINS AFTER VAN TESTING IN MINNEAPOLIS)

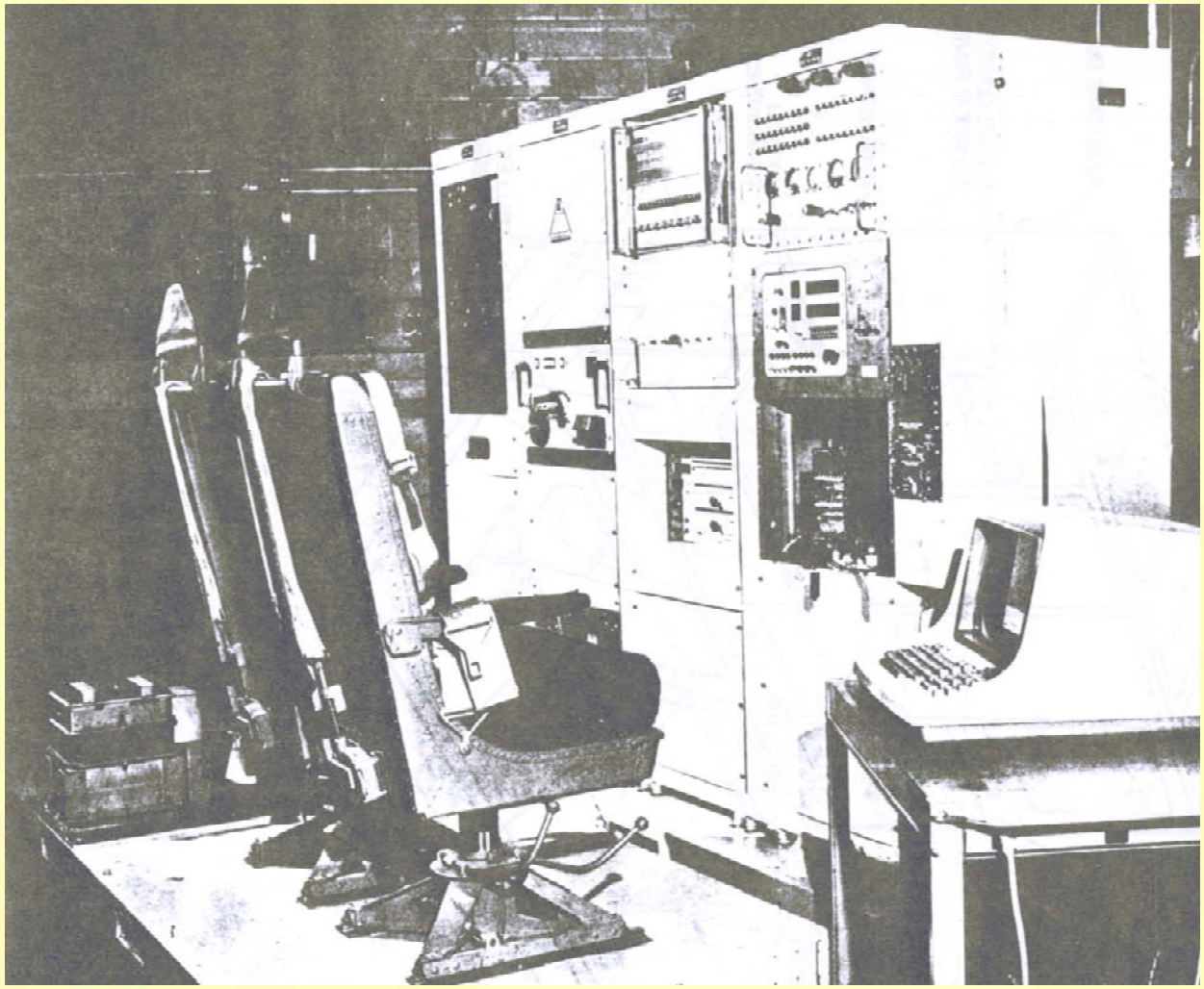
"RV 'FLIES' THROUGH ON-THE-GROUND FLIGHT TESTS"

From Onan News No. 3, 1975
Provided Courtesy Of Cummins Power Generation Inc.

(Cummins Provided Power Generators For LINS Test Van)

LOCKHEED C-141 STARLIFTER US AIR FORCE CARGO AIRCRAFT (USED AT CIGTF FOR INS AND OTHER AVIONICS TESTING)

LINS ON C-141 FLIGHT TEST PALLET



LINS FLIGHT TEST RESULTS AT HOLLOMAN (1 - 3 nmph CEP Goal)

Flight Test	Location	Align Orientation	Flight Path	Flight Time (Hrs)	Nav Time (Hrs)
1	Holloman (N. M)	N	N-S	2. 83	4. 17
2	Holloman (N. M.)	N	W-E	6. 13	7. 67
3	Holloman (N. M)	N	N-S	2. 97	4. 17
4	Holloman (N. M.)	N	W-E	6. 05	8. 00
5	Holloman (N. M.)to Elmendorf (ALAS.	N	N/W	9. 17	10. 37
6	Elmendorf (ALAS.)	E	N-S	3. 00	4. 25
7	Elmendorf (ALAS.)	E	N-S	3. 18	4. 67
8	Elmendorf (ALAS.)	N	W-E-W-E	7. 13	8. 00
9	Eielson (ALAS.)	N	W-E	2. 93	4. 33
10	Eielson (ALAS.)	N	W-E	2. 85	3. 92
11	Eielson (ALAS.)	N	N-S-N-S	6. 98	8. 33
12	Eielson (ALAS.) to Holloman (N. M.)	N	S/E	10. 23	11. 50
13	Holloman N. M.	N	Cir-cling	1. 35	3. 00
	Summary Data	Total Hours		64. 80	82. 38

Flight Test	Radial Error (nm/hr)
1	0.71
2	0.47
3	0.35
4	0.5
5	0.89
6	2.00
7	1.38
8	0.55
9	0.49
0	0.77
11	0.51
CEP	0.89

Note: Flight Test 12 (0.86 nm/hr) Largely Over Water With Few Checkpoints - Excluded From Average
Flight Test 13 Circling Flight Path Cancelled Navigation Errors - Excluded From Average

LINS "PRECISION" ROTATION TEST FIXTURE

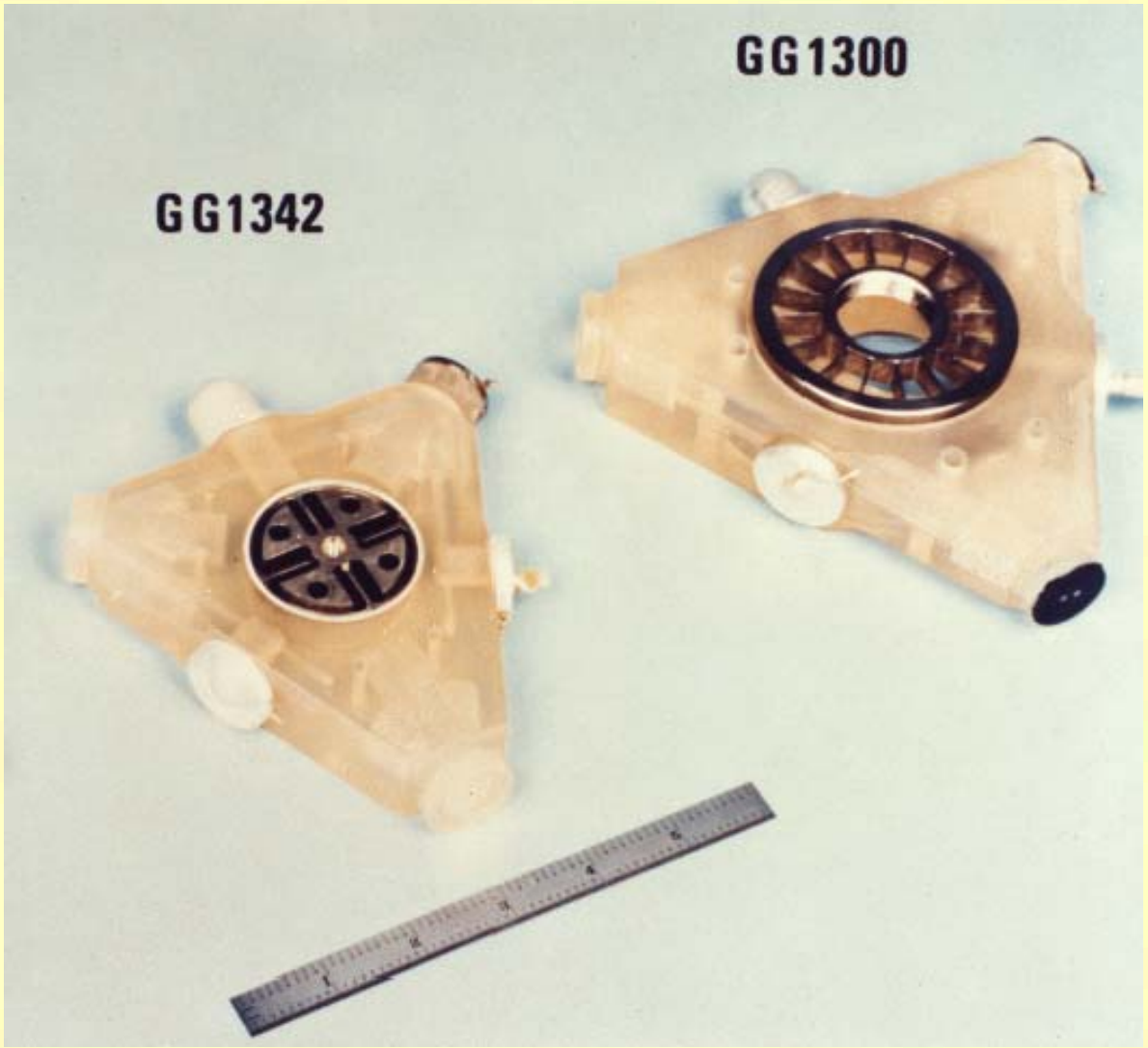
USED IN TEST VAN AT HOLLOMAN FOR LINS CALIBRATION TRIM. USED LATER IN MINNEPOLIS TO DEVELOP NEW ROTATION TEST METHOD FOR PRECISION MEASUREMENT OF SENSOR MISALIGNMENTS WITH LOW COST ROTATION TEST FIXTURING (FOR SYSTEM SOFTWARE CALIBRATION CORRECTION) - COMPATIBLE WITH MINNEAPOLIS LINS DEVELOPMENT PROGRAM BUDGET LIMITATIONS. NEW TEST METHOD THEN USED WITH MORE SOPHISTICATED ROTATION TEST FIXTURING FOR RLGN AND OTHER HONEYWELL LASER GYRO SYSTEMS. EVENTUALLY BECAME INDUSTRY STANDARD USING AUTOMATIC ROTATION TEST FIXTURING.

PROVING RLG INS READINESS FOR PRODUCTION

- JOINT SERVICES FUNDING TO DEMONSTRATE RLG INS ACCURACY/ RELIABILITY/MAINTAINABILITY IN MILITARY FIGHTER AIRCRAFT
- THE RING LASER GYRO NAVIGATOR (RLGN)
- TO ACHIEVE 1 NMPH CEP (50% RADIAL ERROR)
  - > IN 6 MINUTES FROM TURN-ON TO NAVIGATION MODE ENGAGEMENT (VERSUS 10 + MINUTES AT HOLLOMAN)
- TO IMPROVE VELOCITY ACCURACY
  - > FROM 6 FPS AT HOLLOMAN TO 3 FPS
  - > ALL ELECTRONICS IN SAME CHASSIS
    - * REQUIRED SENSOR ASSEMBLY ISOLATION FROM HEAT TO MINIMIZE RLG THERMAL ERROR PLUS NEW RLG THERMAL COMPENSATION
  - > USED NEW ROTATION TEST PROCEDURE FOR SENSOR ALIGNMENT CALIBRATION
- NEW AIR FORCE FORM/FIT/FUNCTION (F3) SIZE REQUIREMENT
  - > GG1300 TOO LARGE TO FIT - REQUIRED SIZE REDUCTION, BUT WITHOUT ACCURACY LOSS
  - > TASK A - SECRETIVE RLG PROGRAM IN MINNEAPOLIS THAT DEVELOPED NEW METHOD TO REDUCE RLG RANDOM ERROR.

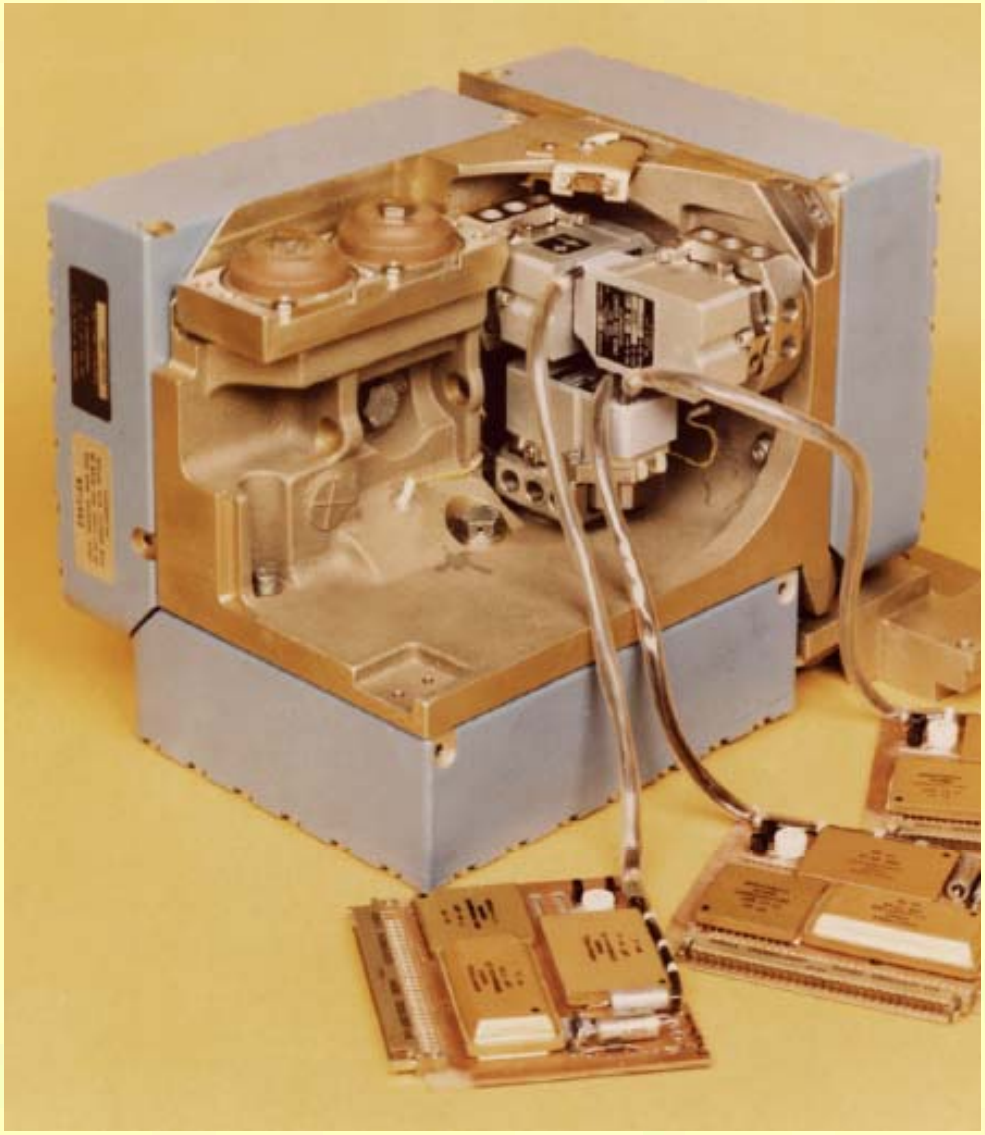
    ALLOWED RLG SIZE REDUCTION. RESULT: THE GG1342 RLG

HONEYWELL GG1342 REDUCED SIZE RLG




RING LASER GYRO NAVIGATION UNIT

RLGN SENSOR ASSEMBLY



IMPROVED STRAPDOWN INS MANUAL TWO-AXIS ROTATION TEST FIXTURE USED FOR RLGN CALIBRATION

WITH SOME MEMBERS OF MINNEAPOLIS STRAPDOWN INS CREW - BLAZING GYROS AUTHOR ON RIGHT

LTV A-7 CORSAIR US NAVY FIGHTER AIRCRAFT
(USED BY NADC TO TEST RLGN)

LOCKHEED ORION US NAVY P-3C SURVEILLANCE AIRCRAFT (USED BY NADC TO TEST RLGN)

RLGN FLIGHT TEST RESULTS

FOR 6 MINUTE REACTION TIME FLIGHT TESTS
(TIME FROM TURN-ON TO NAVIGATION MODE ENGAGEMENT)

> 0.5 MINUTE WARM-UP + 5.5 MINUTE INITIAL SELF-ALIGNMENT

> ACCELEROMETERS USED FOR VERTICAL ALIGNMENT DETERMINATION
(BASED ON GRAVITY REACTION FORCE MEASUREMENT)

> GYROS USED FOR NORTH HEADING ALIGNMENT DETERMINATION
(BASED ON MEASURED HORIZONTAL EARTH RATE DIRECTION)

A-7 FLIGHT TEST RESULTS

26 FLIGHTS

> 0.74 NM/HR CEP RADIAL POSITION ERROR (50% PROBABILITY AVERAGE)

> NOT INSTRUMENTED FOR VELOCITY ACCURACY ASSESSMENT

P-3C FLIGHT TEST RESULTS

24 FLIGHTS

> 0.6 NM/HR CEP RADIAL POSITION ERROR (50% PROBABILITY AVERAGE)

> 2.79 FPS ONE SIGMA VELOCITY ACCURACY (ONE SIGMA PER AXIS)

VERSUS PERFORMANCE GOALS OF 1 NM/HR CEP POSITION ERROR AND 3 FPS ONE SIGMA VELOCITY ERROR

COMPETING FOR BOEING 757/767 STRAPDOWN IRS PRODUCTION

- COMPETITORS
  - > LITTON AND TELEDYNE WITH TRGs
  - > HONEYWELL WITH RLGs
- CENTRALIZED STRAPDOWN INERTIAL DATA SOURCE FOR NEW 7X7 GENERATION OF BOEING AIRCRAFT (BECOMING 757, 767)
  - > FLIGHT CONTROL, ATTITUDE/HEADING DISPLAYS, NAVIGATION, ETC.
  - > TO REPLACE TRADITIONAL MULTIPLICITY OF DEDICATED INERTIAL SENSORS FOR EACH FUNCTION
- 4 NMPH (95% RADIAL ERROR) INERTIAL ACCURACY REQUIREMENT
  - > EQUIVALENT TO 2 NMPH CEP (50 % RADIAL ERROR) COMPARED WITH 1 NM/HR CEP TRADITIONAL MILITARY INS REQUIREMENT
  - > FACTOR OF 2 PERFORMANCE CUSHION FOR TRG COMPETITORS
- BIDDERS TO SUBMIT PROTOTYPE DEMO UNITS FOR FLIGHT TEST
  - > HONEYWELL PROVIDED 7X7 LASER IRS DEMO UNIT
  - > USED SAME GG1342 SENSOR ASSEMBLY CONFIGURATION AS RLGN
  - > TO DEMONSTRATE CONFIDENCE IN RLG TECHNOLOGY, HONEYWELL ALSO INITIATED BUILD OF $4M GG1342 MANUFACTURING FACILITY IN MINNEAPOLIS PRIOR TO ANY RLG PRODUCTION CONTRACT AWARD

BOEING 727 COMMERCIAL AIRCRAFT
(USED TO TEST 7X7 RLG IRS FLIGHT TEST PROTOTYPE)

7X7 LASER IRS PROTOTYPE TEST RESULTS

RADIAL POSITION ERROR

LESS THAN 2 NMPH (95 % PROBABILITY)

EQUIVALENT TO LESS THAN 1 NMPH CEP (50 %)
(VERSUS 4 NMPH 95 % REQUIREMENT)

PER AXIS VELOCITY ERROR

7.2 KNOTS TWO SIGMA

EQUIVALENT TO 6 FPS ONE SIGMA

(VERSUS REQUIRED 8 KNOTS TWO SIGMA)

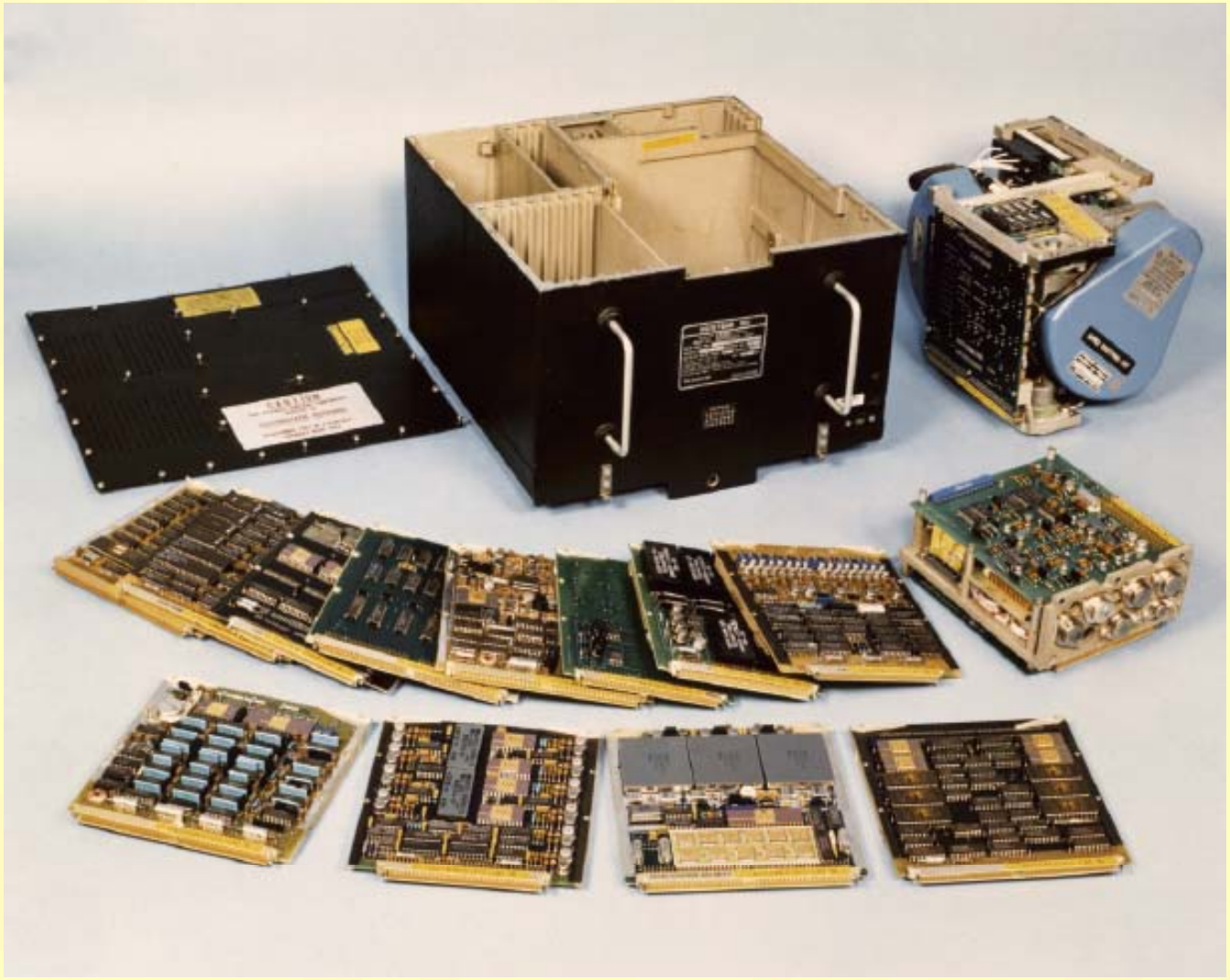
NOTE: LARGER THAN UNEXPECTED 7.2 KNOT ERROR WAS LATER DEMONSTRATED TO BE CAUSED BY ELECTROMAGNETIC INTERFERENCE ON 727 TEST AIRCRAFT POWER INPUT. EXPECTED ERROR TO BE LESS THAN 4 KNOTS SINCE USED SENSOR ASSEMBLY AS RLGN WHICH DEMONSTRATED EQUIVALENT TO 3.3 KNOTS TWO SIGMA AT NADC (I.E., 2.79 FPS ONE SIGMA) IN P-3C FLIGHT TESTS.

IN 1978 HONEYWELL WAS AWARDED RLG IRS PRODUCTION CONTRACT FOR NEW BOEING 757 AND 767 AIRCRAFT

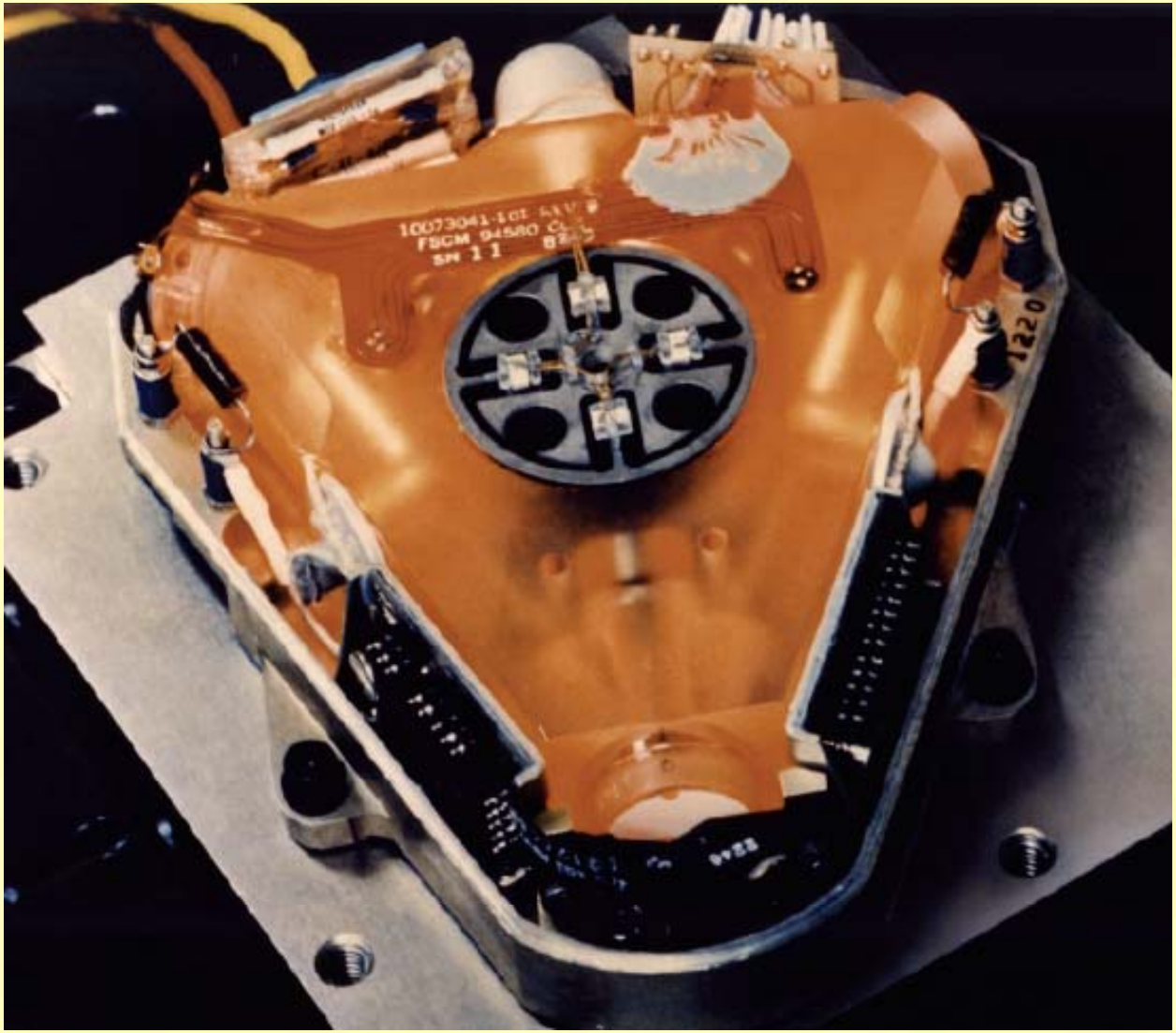
> BASED ON 7X7 LASER IRS TEST RESULTS, HONEYWELL'S FAVORABLE COST PROPOSAL, AND HONEYWELL CONFIDENCE IN RLG TECHNOLOGY AS EVIDENCED BY PREVIOUS BUILD OF THE GG1342 PRODUCTION FACILITY

HONEYWELL LASER IRS FOR BOEING 757/767

(FIRST PRODUCTION STRAPDOWN INERTIAL NAVIGATION SYSTEM FOR AIRCRAFT)



GG1342 RLG PRODUCTION CONFIGURATION



BOEING 757 COMMERCIAL AIRCRAFT

(FIRST AIRCRAFT EQUIPPED WITH RLG NAVIGATION EQUIPMENT)

EPILOGUE

- THE AIR FORCE PLAN FOR AUTONETICS STRAPDOWN ESG MICRON FULL-SCALE DEVELOPMENT WAS CANCELLED FOLLOWING THE 1975 LINS TESTS AT HOLLOMAN

- FOLLOWING THE 1978 LASER IRS CONTRACT AWARD TO HONEYWELL FOR 757/767 AIRCRAFT, HONEYWELL BECAME THE DOMINANT SUPPLIER OF INERTIAL NAVIGATION EQUIPMENT FOR NONMILITARY AIRCRAFT

  > EXPANDING TO BOEING 737, 747, 777, 787, AIRBUS 310, 320, AND NUMEROUS GENERAL AVIATION BUSINESS AIRCRAFT.

- AFTER COMPLETING DESIGN OF A MILITARY PRODUCTION GG1342 RLG INS CONFIGURATION IN MINNEAPOLIS, HONEYWELL AGAIN REVISED THE COMPANY CHARTER, TRANSFERRING ALL MILITARY STRAPDOWN INS DESIGN/PRODUCTION PROGRAMS TO THE FLORIDA DIVISION

  > COMMERCIAL RLG SYSTEM PROGRAMS AND ALL RLG DESIGN/PRODUCTION HAVE REMAINED IN MINNEAPOLIS

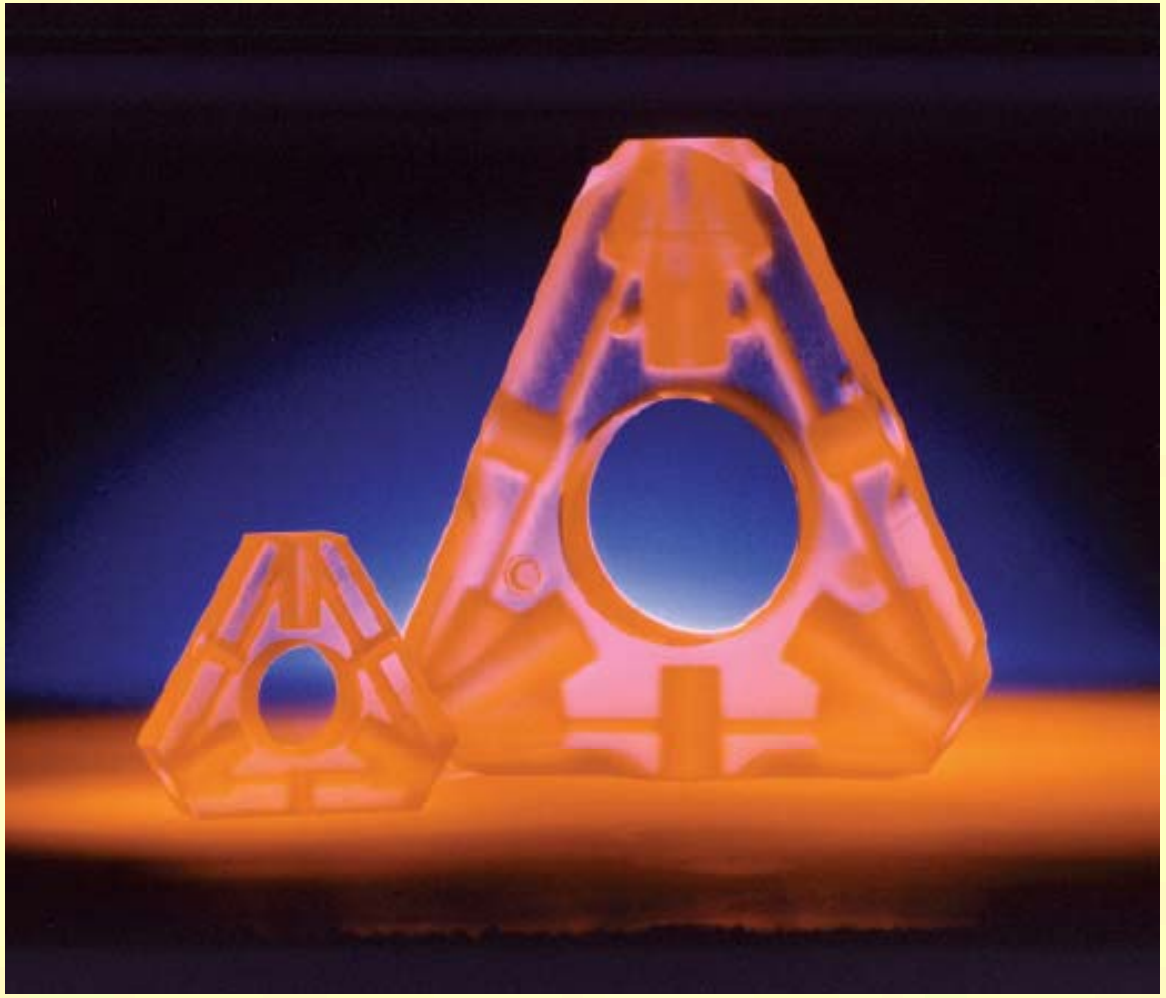
  > IN 1983 (5 YEARS AFTER THE BOEING IRS CONTRACT AWARD AND RLGN PROGRAM COMPLETION), HONEYWELL FLORIDA RECEIVED ORDERS TO RETROFIT THE MILITARY F-15D STRIKE AIRCRAFT WITH GG1342 RLG STRAPDOWN INS EQUIPMENT. THIS WAS THE FIRST OF MANY MILITARY STRAPDOWN INS PRODUCTION PROGRAMS TO FOLLOW.

- LITTON AND KEARFOTT DEVELOPED RLG STRAPDOWN SYSTEM DESIGN/PRODUCTION CAPABILITIES, LITTON EVENTUALLY BECOMING COMPETITIVE WITH HONEYWELL FOR US MILITARY AIRCRAFT AND CRUISE MISSILE INS PRODUCTION PROGRAMS.

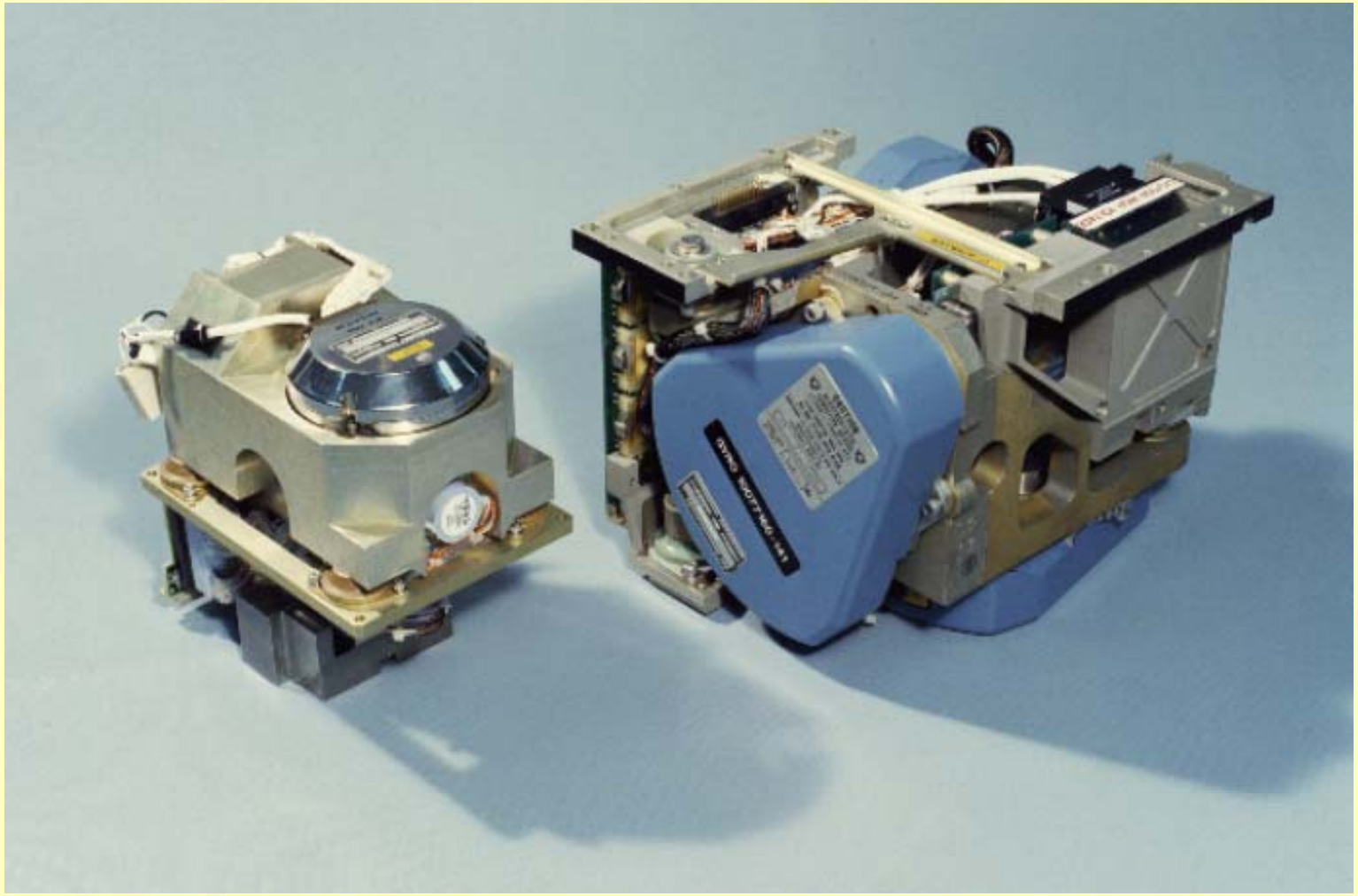
- BY 1990, VIRTUALLY ALL WORLDWIDE INS PRODUCTION FACILITIES HAD BECOME STRAPDOWN TECHNOLOGY BASED.

REDUCED 2.0 INCH/SIDE GG1320 RLG BLOCK USED IN CURRENT HONEYWELL STRAPDOWN INERTIAL SYSTEMS

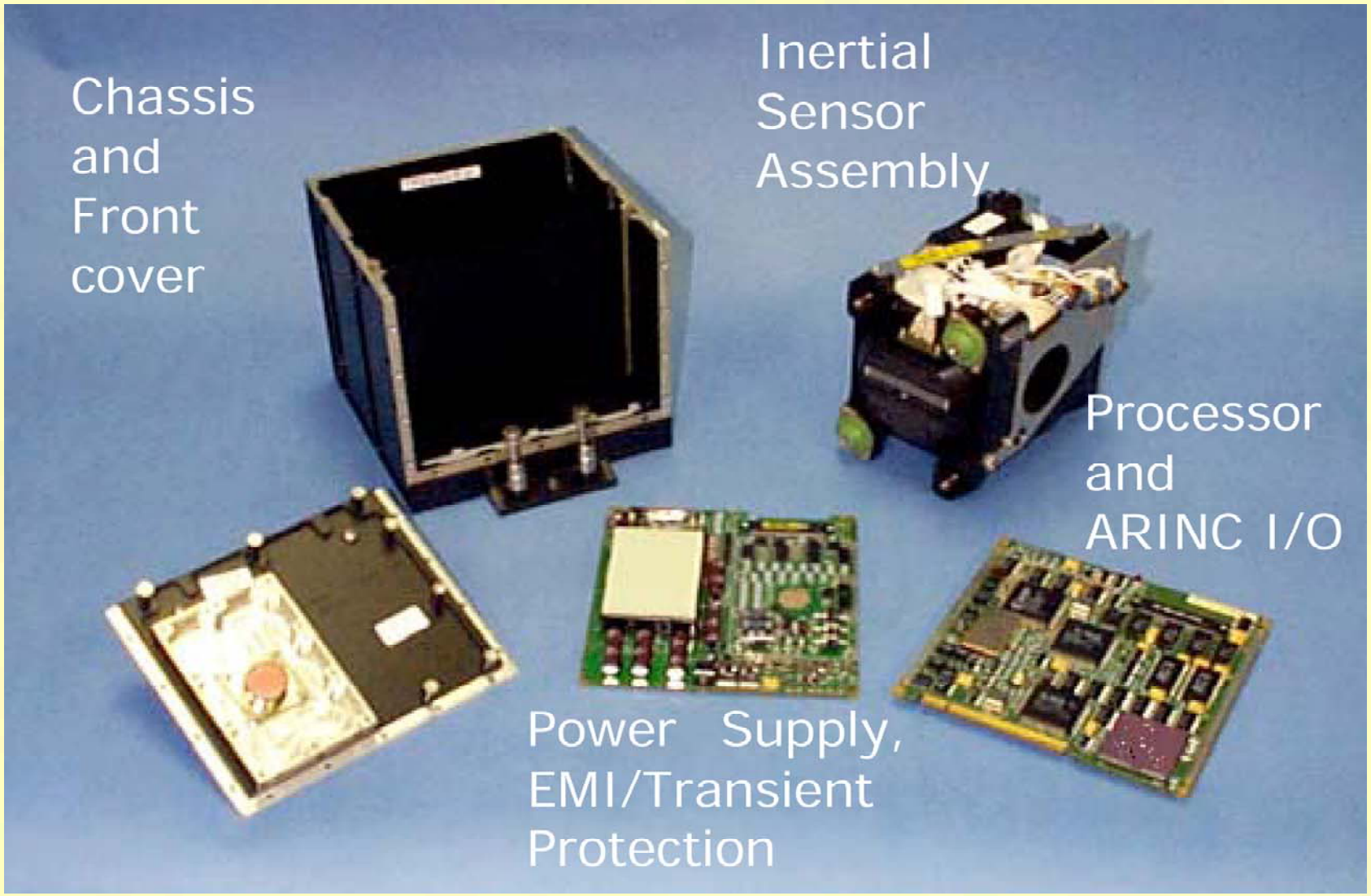
(COMPARED WITH ORIGINAL 4.2 INCH/SIDE GG1342 RLG BLOCK)



GG1320 COMPARED TO GG1342 STRAPDOWN SENSOR ASSEMBLIES



HONEYWELL GG1320 RLG IRS USED IN BOEING 787 COMMERCIAL AIRCRAFT



SOME NOTABLE PLAYERS IN THE STORY

JOE KILPATRICK - PIONEERING LEADER OF RING LASER GYRO DEVELOPMENT AT HONEYWELL

GLEN PETERS - VICE PRESIDENT OF OPERATIONS AT HONEYWELL MINNEAPOLIS. INITIATED AND MONITORED SECRETIVE TASK A THAT DEVELOPED NEW SMALL SIZE GG1342 RLG. CONVINCED HONEYWELL CORPORATE MANAGEMENT TO INVEST $4M TO BUILD GG1342 PRODUCTION FACILITY TO DEMONSTRATE HONEYWELL CONFIDENCE IN RLG TECHNOLOGY

TED PODGORSKI AND DAVE THYMIAN - LED SECRETIVE TASK A ENGINEERING TEAM FOR NEW SMALL GG1342 RLG DESIGN. FIRST LASER GYRO TO MEET MILITARY AIRCRAFT PERFORMANCE AND SIZE REQUIREMENTS, AND FIRST RLG TO ENTER LARGE SCALE PRODUCTION

JACK SHAW - BOEING STRAPDOWN TECHNOLOGY ENGINEERING DEVELOPMENT MANAGER WHO SPEARHEADED CENTRALIZED DIGITAL STRAPDOWN SYSTEM CONCEPT AT BOEING FOR NEW AIRCRAFT. CONVINCED HONEYWELL OF IMPORTANCE FOR LOW IRS COST PROPOSAL TO JUSTIFY RATIONALE FOR CONVERSION TO CENTRALIZED STRAPDOWN INERTIAL SENSING.

PHIL FENNER - NAVIGATION SENSORS/DISPLAYS 737/757/767 FLIGHT SYSTEMS ENGINEERING MANAGER AT BOEING. FOLLOWING 1978 HONEYWELL IRS AWARD, DROVE ACCEPTANCE OF CENTRALIZED STRAPDOWN SENSING CONCEPT WITHIN EACH 757/767 AIRCRAFT FLIGHT SYSTEM DESIGN GROUP TO REPLACE TRADITIONAL DUPLICITY OF DEDICATED INERTIAL SENSORS FOR EACH SYSTEM WITH CENTRALIZED IRS OUTPUT DATA

PAUL G SAVAGE - HONEYWELL STRAPDOWN SYSTEM ENGINEERING DESIGN LEADER. CHOSE TO REMAIN IN MINNEAPOLIS IN 1970 TO RUN STRAPDOWN AIRCRAFT INS DEVELOPMENT PROGRAM UNDER REVISED HONEYWELL DIVISIONAL CHARTER. LED LINS PROGRAM IN 1975 TO SUCCESSFUL HOLLOMAN FLIGHT TEST. LEFT HONEYWELL IN 1980 TO FORM INDEPENDENT MINNEAPOLIS BASED STRAPDOWN ASSOCIATES, INC. AUTHOR OF BLAZING GYROS.

THE END

OF THE PRESENTATION