THE NATO SHIPS INERTIAL NAVIGATION SYSTEM (SINS)

BY

LIEUTENANT-COMMANDER P. H. MARLAND, BSC, CENG, MIEE, RN
(Sea Systems Controllerate, Slough)

ABSTRACT

This article covers the background, development and main technical points of the NATO Ships Inertial Navigation System (NATO SINS). This uses new technology in the form of the Ring Laser Gyro (RLG) to make a major reduction through-life cost and size/weight, compared to current equipment.

Introduction

The Gulf War highlighted the use of the satellite-based Global Positioning System (GPS) to give accurate position and time. However GPS cannot indicate accurate heading, and requires continuous signal reception, sufficient satellites in view, and that use is not deliberately denied or degraded. Submarines make use of GPS or the older Transit navigation satellites when on the surface or at periscope depth or, in the case of Omega (a LF radio navigation aid), whilst shallow. Apart from basic dead reckoning, the only method of dived navigation is by Ships Inertial Navigation Systems (SINS), which takes account of vessels' motion, sideslip, tide and ocean current. This expensive and sophisticated system allows accurate navigation for extended periods with confidence, and without constraint; it is the key to tactical weapon system performance.

The RN has relied on UK SINS Mks.1 and 2 since the 1960s and is about to introduce NATO SINS, a new generation equipment using Ring Laser Gyros. This has been developed as a NATO collaborative project, run by MOD PE/DGSW(N) from the Admiralty Compass Observatory (ACO) at Slough. This article describes the background, development and main technical points of NATO SINS, which will be widely fitted in the RN from 1993, but does not cover UK Polaris or Trident SSBN equipment. The new system differs in several respects from its predecessors and it is important that operators and maintainers alike understand the changes in philosophy and their impact. NATO SINS is also entering service with the Dutch (FIG. 1) and Spanish navies, and sales of export (Mk.49) systems have been made to AMECON for the RAN/RNZN ANZAC frigate programme.

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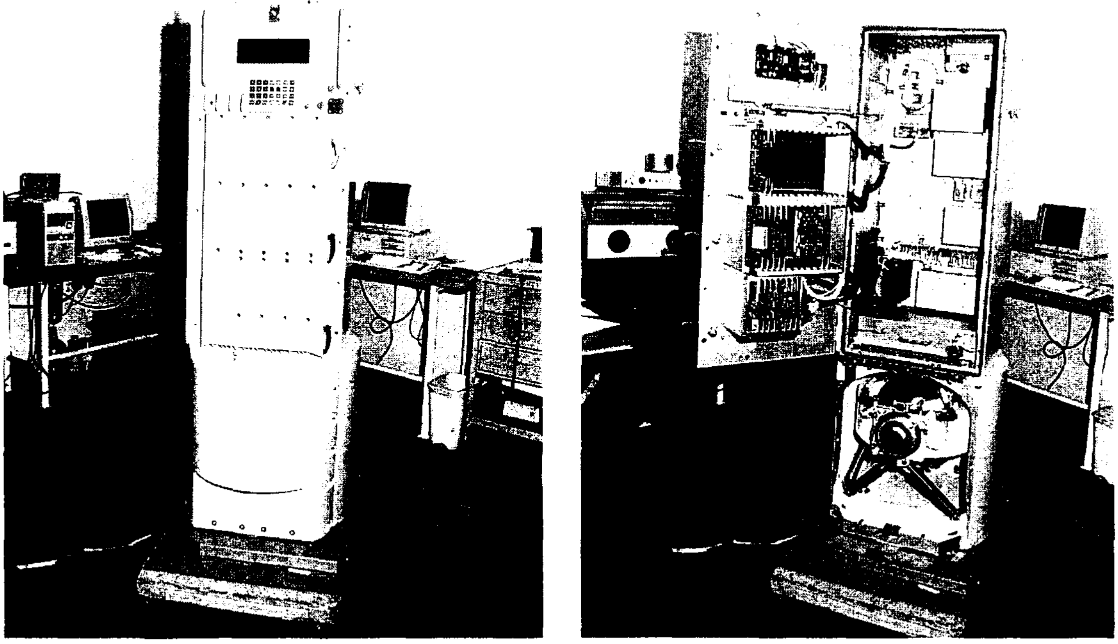

FIG. 1—DUTCH NATO SINS, CLOSED AND OPEN
photo.: Sperry

Definition

Definitions of the three main categories of gyro equipment may help the lay reader:

- *Gyro Compass*—which normally uses a single gyro to indicate true north. The element is often floated or suspended by wire, and uses the earth's rotation rate (15°/hour) to assist in north finding and keeping. Compasses require an input of latitude and ship's speed for proper accuracy. Examples include the AP5005, Sperry Mk.23 and Arma-Brown Mk.12.
- *Compass Stabilizer*—uses two separate gyros and an accelerometer to indicate true north, and give accurate pitch and roll outputs for weapon stabilization. The sensors are all mounted on a two-axis gimbal. Examples include the Sperry Mk.19 and Elliot (now GEC) NCS 1.
- *Inertial Navigation System (INS)*—uses three gyros and accelerometers mounted on a three-axis stable platform. INS normally have no ability to *fix* absolute position, and require an initial Lat/Lon in order to provide very accurate navigation thereafter, and continuous outputs of velocity and attitude. Inertial systems have many similarities with compass stabilizers, but require much more accurate gyros and accelerometers, and more complex control loops and computations. The current system is UK SINS Mk.2.

History

Inertial navigation has some very early roots, ranging from the Irishman, J. J. Murphy in 1873, to Max Schuler (Germany) in 1923 and B. V. Bulgakov (Russia) in 1932. These early inventors worked independently, but their ideas contained the main principles of inertial navigation. Attempts to produce working systems failed due to mechanical engineering limitations at the time, and the infant state of electronics. Inertial navigation received a major boost during World War II from German work on guided missiles. The Kreiselgeräte organization under J. G. Gievers produced two designs of V2 guidance systems that included a stable platform and all the elements of a modern IN system.

After the war German design expertise was split between the UK, USA and Soviets. In the USA, a German expatriate design team produced missile guidance systems for a series of land-based ballistic missiles, culminating in the Saturn rocket used for the Apollo mission to the moon. Entirely separate US design teams led by C. S. Draper, at MIT, and North American Aviation were working on inertial guidance for early Snark and Navaho cruise missiles. By 1953 Draper had produced the definitive Single Degree-of-Freedom Floated Rate Gyro, using ball bearings. The demise of the Navaho in 1957 left Autonetics prototype available to navigate USS *Nautilus* to the north pole in 1958. Thereafter ship systems were developed in parallel by Autonetics and MIT/Sperry, and entered service in 1960 with the US Polaris SSBN programme[1].

United Kingdom SINS Development

After technical exchanges with the US during 1954, the UK programme began in May 1956 with the approval of a Staff Requirement for SINS. Work started at ACO Slough in 1957 and purchase of 12 early Draper ball bearing gyros from Northrop led to a first laboratory run of the UK system in July 1961, followed by initial sea trials in September. Prototypes were fitted to HMS *Dreadnought* in 1963 and production equipment became available in 1966, but did not become fully operational until 1968. ACO also played a major part in developing the gas bearing gyro, and their detailed design for a gyro rotor/gas bearing produced an order of magnitude increase in accuracy, when fitted into the Draper designed casing in 1962. A total of 18 UK SINS Mk.1 were built and fitted to SSN 01-11 and DLG 05-09.

SINS Mk.1 was a completely analogue design, sensitive to temperature and power supply excursions and had significant limitations when operating at high latitudes. The requirement for its successor, SINS Mk.2, was re-endorsed in

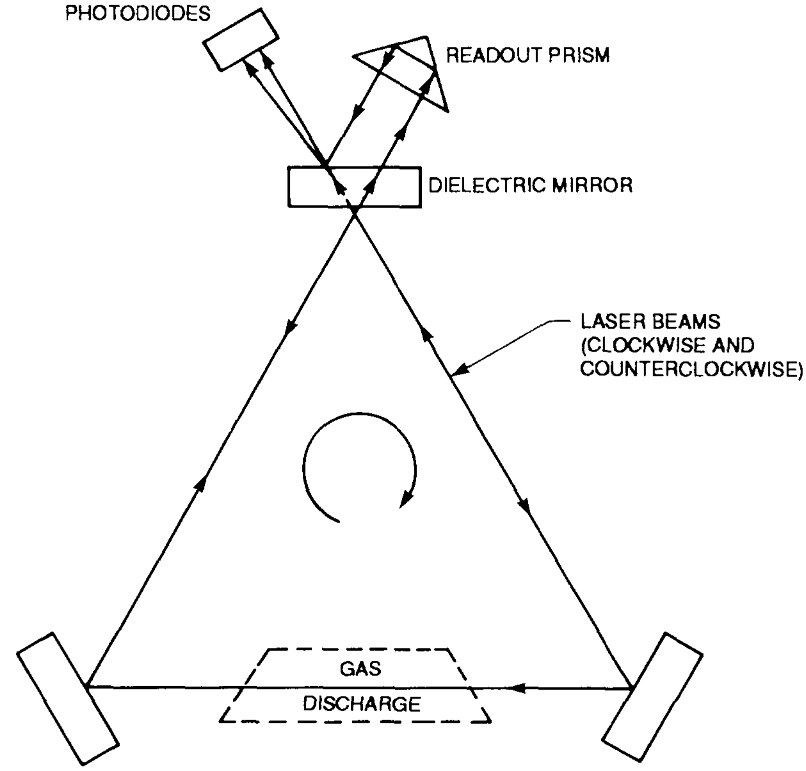

FIG. 2—RING LASER GYRO OPERATION
from Savage[3]

1965 as NSR 7861, and development ran until 1971, featuring pulse torquing, integrated circuits and digital computation. Sea trials began in 1975 and production equipments with full polar capability became available in 1976. A total of 24 UK SINS Mk.2 were built and fitted to all SSNs (except 01), three CVS and two H Class survey ships.

SINS Mks.1 and 2 were both ACO designs, with the production engineering expertise supplied by Sperry (later BAe) at Bracknell, and gyro production by English Electric (later BAe Dynamics) at Stevenage[2]. In the late 1970s the MOD (PE) emphasis shifted from intramural to contractor development, and the ACO team gradually dispersed.

SINS Mk.2 has an excellent record and performs significantly better than specification, though requiring considerable grooming, maintainer and navigator expertise and a measure of luck. This level of performance requires gyros with drift rates rather better than 0.001°/hour to provide overall performance in the 1 NM/day class. SINS Mk.2 has always required a high level of support with difficult or performance-related operational defects, but there is now little expertise at ACO and available contractor support has withered away. The last system cost over £1.2M at 1985 prices and through-life support costs have escalated due to the low numbers and obsolete technology involved, and for repair of the precision gas bearing gyros. US equivalent systems are listed in the Appendix (p.700).

Alternative Technologies

Alternative gyro technologies include:

(*a*) *Dry (or Dynamically) Tuned Gyro (DTG)*, in which the gyro wheel can flex/sense motion about its shaft, often in two axes. DTG generally have about three to ten times less performance than the equivalent gas bearing unit, but eliminate the flotation fluid and need for one gyro per axis.

(*b*) *Nuclear Magnetic Resonance (NMR)*, using cryogenic temperatures to produce gyro effects at the molecular level, and superconducting quantum effects (SQUID) in some materials. Techniques have not moved beyond the laboratory stage, and could be difficult to implement at sea.

(*c*) *Ring Laser Gyro (RLG)*. Laser beams directed round a triangular (or square) light path, in opposing directions (FIG. 2). As the glass block moves, the relative length of the light path changes and an interference fringe is detected. Widely used in commercial systems fitted to Boeing 737s and 757s.

(*d*) *Electrostatically Supported Gyro (ESG)*. Based on spinning ball in vacuum, held up by electrostatic field. Very high performance—typically ten times the best gas bearings, but extremely expensive and has poor shock resistance.

(*e*) *Fibre Optic Gyro (FOG)*, similar in principle to RLG, but uses a long length of fibre optic cable on a spool as the light path. Promises to be a low-cost sensor for missiles, but problems of birefringence and anisotropic effects must be overcome.

All these sensors have potential but at present only the RLG (in large-scale commercial use) and the ESG (in some US military systems), offer the potential to equal SINS Mk.2 gas bearing gyro performance.

NATO SINS

The process of developing a replacement began in 1983 as NST 7864 for SLINS—the Ships Low Cost Inertial Navigation System. This stressed the need for much smaller, lighter and cheaper units to allow a wider fit, including dual fits, which had been impractical with SINS Mk.2. Early work identified national options, but pressure for a collaborative solution led to the NATO PG4 grouping, involving the UK, US, Netherlands, Spain and Canada. This was terminated in 1985 when the US made a unilateral decision to proceed with the much more expensive DINS system.

The remaining partners re-grouped, and by 1987 had established a new MOU and specification for NATO SINS, with the UK undertaking programme management. An international procurement competition was run against the CPS, with all the bidders offering Ring Laser Gyro (RLG) technology. Demonstration of the prototypes at sea in 1988 and a Best and Final Offer (BAFO) exercise led to contract award on 7 Nov 1989. The selected prime contractor was Ferranti Defence Systems Limited (FDSL) (later GEC-FDSL), teamed with Sperry Marine Incorporated (SMI) as the main sub-contractor.

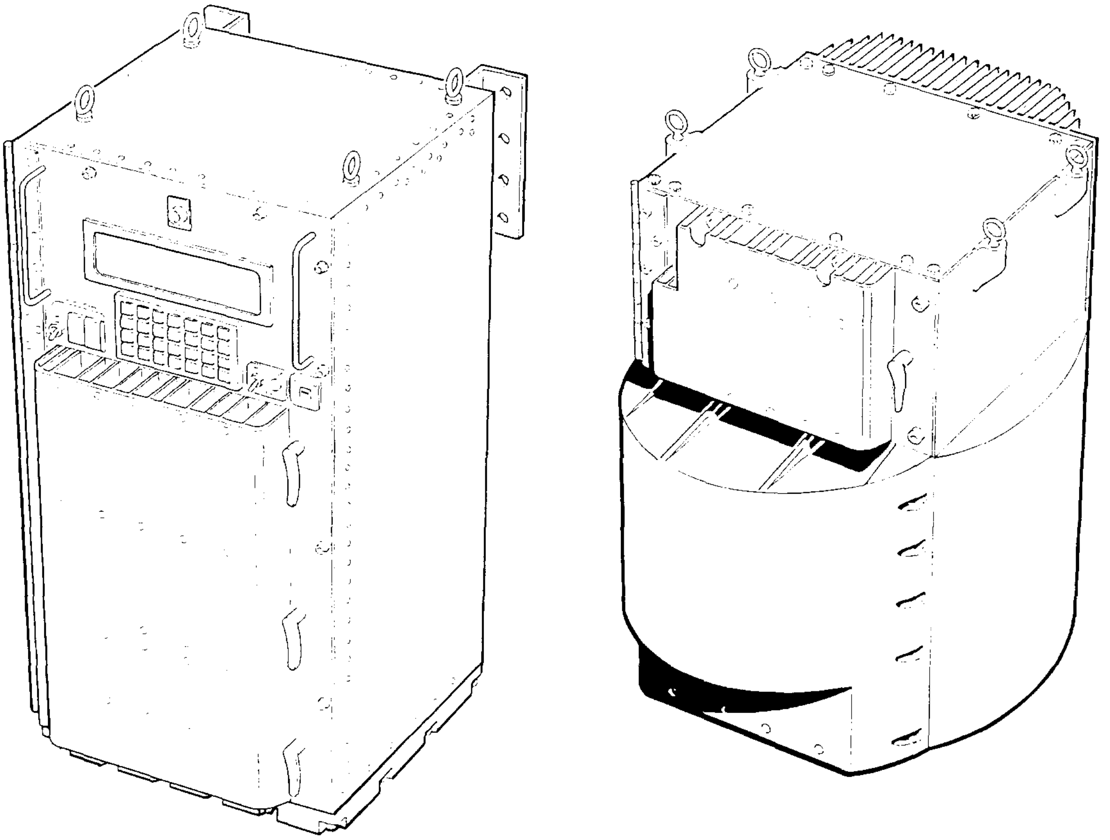

FIG. 3—NATO SINS DUAL CABINET CONFIGURATION: ELECTRONIC CABINET, LEFT; INERTIAL MEASUREMENT UNIT (IMU), RIGHT

from a Ferranti drawing[8]

The resultant NATO SINS is shown in FIG. 3, which shows the two-cabinet configuration with separate electronics pack and Inertial Measurement Unit (IMU) adopted by the UK for shock reasons. The Netherlands uses a single enclosure with the electronics cabinet mounted directly on top of the IMU. (FIG. 1). All components within both configurations are common. NATO SINS weighs 385 kg, compared to SINS MK.2 (2011 kg), Mk.19 (618 kg) and NCS 1 (410 kg); it does not require chilled water and consumes 2 kW less power.

Technical Features

There are two fundamental differences between NATO SINS and previous inertial systems: Strapdown and Indexing. Strapdown systems are widely used in aircraft, but indexing is unique to NATO SINS.

In a conventional SINS the accelerometers are mounted on an inner stable platform which is held level by the gyroscopes, inside three or four gimbals. This 'base motion isolation' (BMI) means that the accelerometers work in true level (earth plane) and see only ship's positional movement, without any components caused by pitch and roll motion. Readings are double integrated to give changes in latitude and longitude.

In strapdown systems, the gyros and accelerometers are hard mounted and sense ship's motion, seeing pitch and roll components and their rates, as well as movement. The composite rotation and acceleration measurements (in deck plane terms) are fed into a computer. The strapdown software maintains a synthetic true level from the gyro inputs, and uses two direction-cosine-matrix (DCM) to convert accelerometer readings from deck plane to true.

Integration of these accelerations, after subtraction of coriolis and gravity terms, gives north (V_n), east (V_e) and vertical (V_k) velocities. Division of the V_n and V_e components by the earth's radius, and integrating, produces change in system latitude and longitude. Lever arm corrections can be supplied to give velocities at the desired reference point on the ship. The basic block drawing is given in FIG. 5.

NATO SINS uses three Honeywell GG1342 Ring Laser Gyros (RLG) and three separate single-axis Sundstrand QA2000 accelerometers. These are mounted on a sensor block assembly, with high voltage power supplies and related electronics. Gyros and accelerometers contain individual temperature sensors, but the software currently corrects accelerometer readings only. The sensor block assembly is mounted in azimuth (inner) and roll (outer) gimbals which can be controlled by direct drive torque motors and slab synchros to give 2-axis indexing; there is no gearing. It is situated in the IMU cluster, as shown in FIGS. 4 and 6. Gyro and accelerometer have demonstrated MTBFs of 100,000 and 250,000 hours respectively in commercial service, and the overall system MTBF is over 4000 hours for the basic (digital interface) configuration.

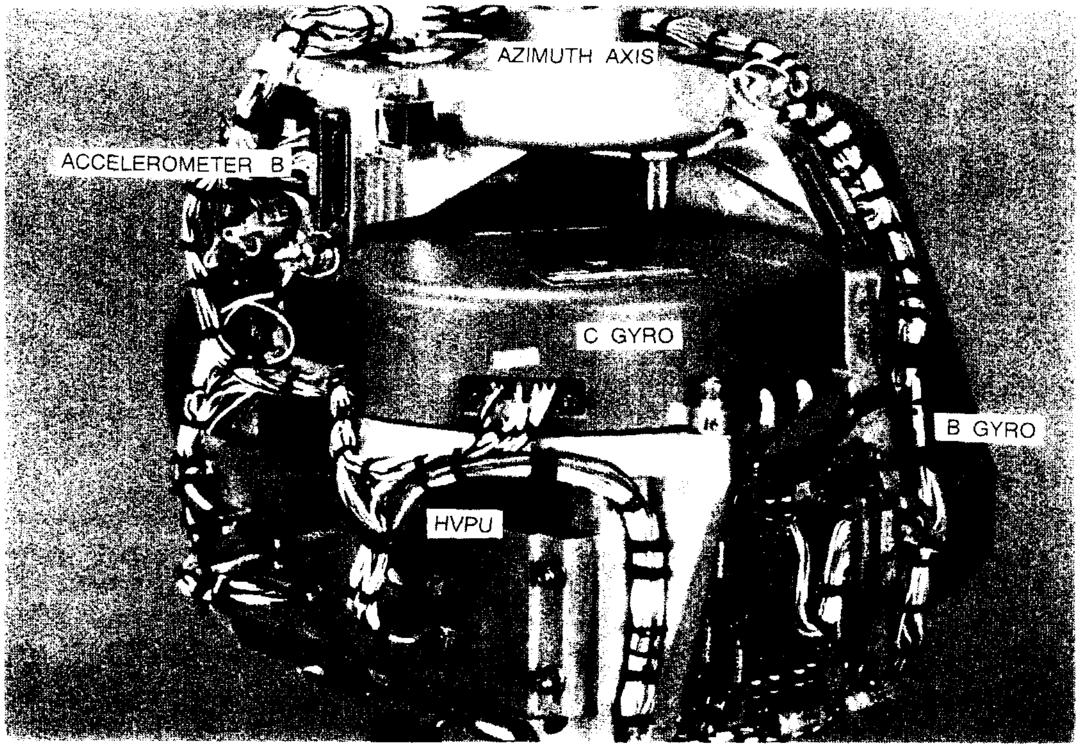

FIG. 4—SENSOR BLOCK ASSEMBLY
photo.: Sperry

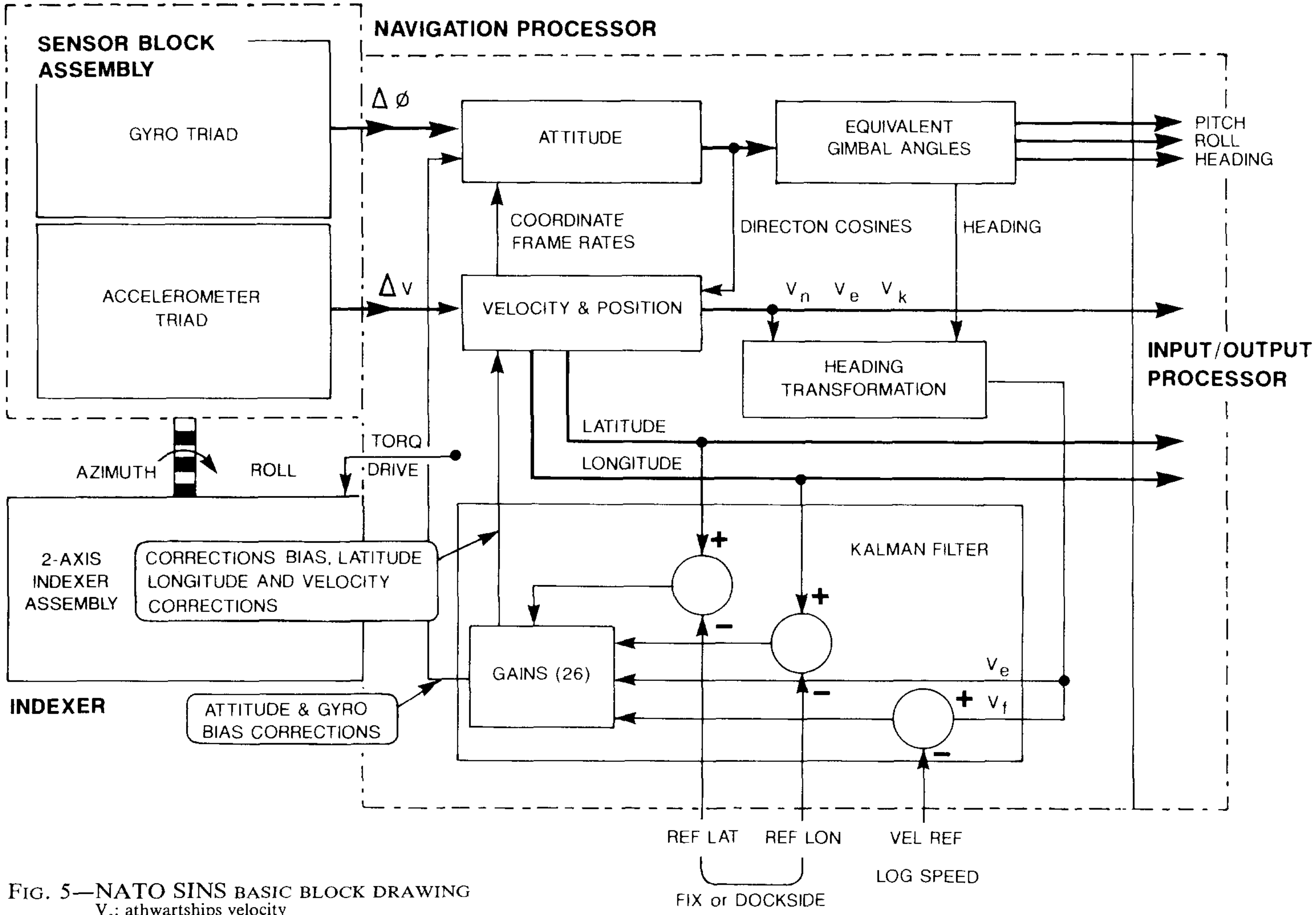

FIG. 5—NATO SINS BASIC BLOCK DRAWING

V_c: athwartships velocity
V_e: east velocity
V_f: forward velocity
V_k: vertical velocity
V_n: north velocity

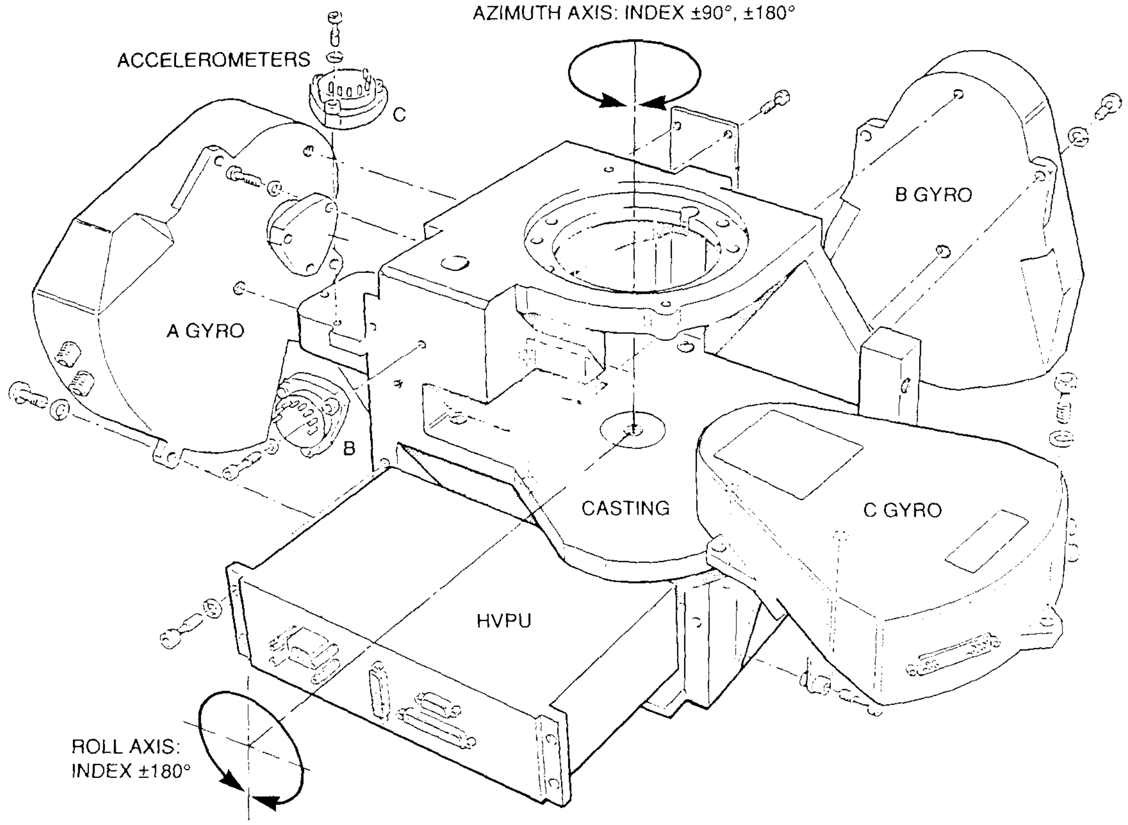

FIG. 6—SENSOR BLOCK ASSEMBLY
HVPU: High Voltage Power supply Unit

Ring Laser Gyro

Ring Laser Gyro theory and application are covered by Savage and Willcocks[3,4,5]. RLGs are subject to 'phase lock-in' at low angular rates (FIG. 7), caused by coupling between the two laser beams, principally from mirror back scattering. The problem can be overcome by rate bias, multi-oscillator operation or dither.

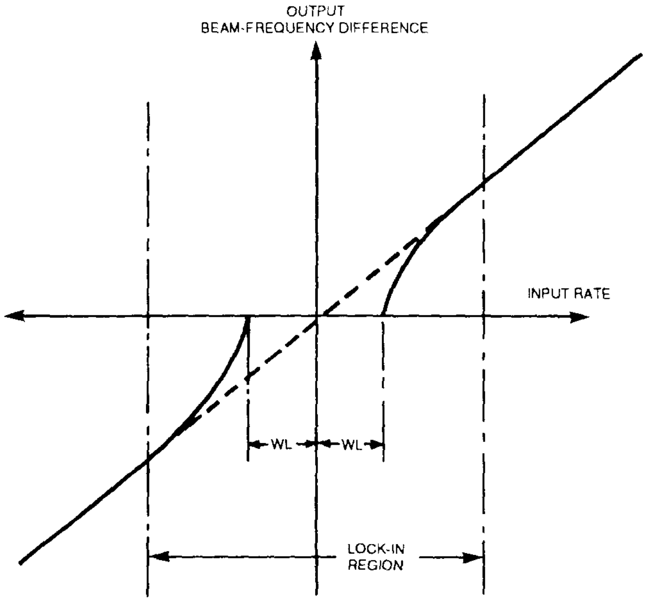

FIG. 7—RLG 'PHASE LOCK-IN'
WL: lock-in rate
from Savage[3]

In rate bias, the whole cluster is rotated at a fixed rate to shift the operating point away from the lock-in region (in a similar manner to the NCS 1 vertical package). Multi-oscillator gyros are a new development using circularly polarized laser beams to give four-frequency operation which can resolve readings within the problem region. NATO SINS uses an alternative solution—mechanical 'dither', where each gyro quartz block is vibrated at a separate frequency in the range 280–460 Hz. This avoids locking, but requires special compensation for 'coning', where oscillations in two axes translate into apparent drift in the third axis, and also noise isolation techniques to avoid creating a distinctive 'artifact'.

The RLGs used by NATO SINS have virtually no g-dependent errors, but are prone to white noise random drift, or 'random walk', expressed as degrees/$\sqrt{\text{hour}}$. These gyros would give roughly 1 NM/hour performance in aircraft strapdown systems, adequate for eight or ten hour flight times. Use in a ship environment calls for approximately 1 NM/day, about 20 times more accurate. NATO SINS achieves this increase in performance by use of Indexing.

Indexing

The Inertial Measurement Unit cluster of gyros and accelerometers (the sensor block assembly) is moved through ±90° or ±180° in roll or azimuth every 2½ minutes. The index cycle is designed to average out, or commutate, drifts in all directions. The sequence is proprietary to Sperry, but is 32 moves long (plus 32 in an inverse sequence) to a total length of 2.66 hours. As an example, the uppermost C gyro (equivalent to the Z gyro, responsible for azimuth in SINS) may drift to the left when upright, but will drift to the right when the cluster is inverted by rolling 180°. The ±90° shifts in azimuth allow A and B gyros (North and East) to be interchanged, and allows the Kalman filter to monitor both drift and misalignment.

This indexing system is only possible with RLG and strapdown technology. The RLG is a solid state sensor with no moving parts, and can handle 20°/sec movement rates and sharp acceleration/deceleration that would be fatal to a gas bearing gyro. The strapdown algorithm operates at 50 Hz and continues to compute and convert throughout the indexing cycle, including during movement[6,7].

During stationery (dwell) periods, azimuth and roll motions are stabilized by an output from the strapdown process. This apparent 'coarse BMI' is not vital for attitude or short-term navigation, but ensures that ship's motion, especially prolonged turns, does not negate an indexing move and unbalance the overall cycle, to the detriment of long-term performance.

Kalman Filters

Kalman Filters are designed to monitor and weed noisy data, whilst tracking the mean. The NATO SINS filter continuously processes 26 parameters (TABLE I), including gyro drifts and misalignments, but is separate from the strapdown and navigation software modules. The Kalman solutions are recalculated and all parameters updated when a reset (fix) is applied.

When an external fix is available, its position is compared to the system Lat/Lon and the differences are applied to the Kalman filter. Tests are applied for 'reasonableness', alerts raised, and the operator can review/validate the fix data before it is applied to the filter. It is important to stress at this stage that *once the reset has been applied the effects cannot be undone*. The filter monitors the accuracy of fixes used, and may produce a partial reset. Fixes can also be input as a slew, which updates position completely, without modifying gyro and drift parameters.

TABLE I—*Parameters monitored by NATO SINS Kalman filter*

Velocity	2	Gyro Scale Factor	2
Attitude	2	Gyro Misalignment	6
Azimuth	1	Accel Bias	2
Position	2	Ocean Current	2
Gyro Bias	3	Log Bias	2
Bias Drift	2		26

System Modes

NATO SINS has the following operation modes[8]:

OFF	—Initial settings and installation data are battery supported.
STAND BY	—Power on, followed by:
ALIGN	—Align Coarse—the system levels and gyrocompasses, on completion attitude outputs are valid. Align Fine—leads to valid position and velocity outputs. These may be achieved alongside (dockside), by slave align (from another system), or during a sea start.
NAVIGATE	—Normal seagoing mode with all facilities.
TEST	—Off-line Built In Test (BIT) facility for maintainers.
SHUTDOWN	—Automatic reaction to serious faults, BIT results stored.

Operational Features

NATO SINS has a direct digital link with the GPS receiver, though the operator can review/accept the update, and may input fix information manually. The Kalman filter operates on one fix; there is no 'history' mechanism and previous fixes cannot be re-assessed, or included/excluded, as is the case with SINS Mk.2. Once applied, a reset cannot be undone. The degree of reset is controlled by the stated accuracy of the fix used. NATO SINS will not use the traditional AMP plot, and there is no facility to control K factors within the Kalman, leaving some navigators frustrated in the belief that the system has a mind of its own.

The RLG white noise random drift makes it impossible to predict position errors, and a typical pattern is given in FIG. 8. NATO SINS works on

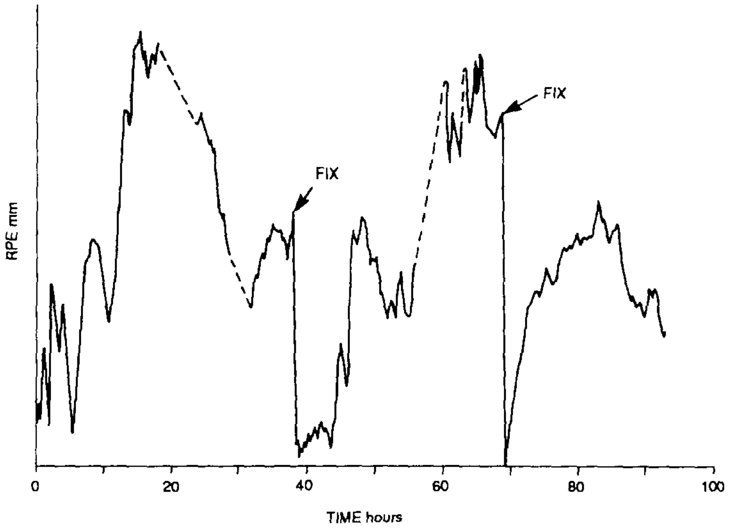

FIG. 8—TYPICAL ERROR PATTERN
RPE: Radial Position Error

uncertainty areas, rather than a ‘raw’ position to be corrected by the filter. Performance is specified to 95% limits (B/2, C/2 classified parameters), which define the envelope containing the NATO SINS position error. The uncertainty area (System Sigma Lat/Lon) grows with time since the last update. There is no option for filtering, correction or forward prediction and this is a major change in philosophy compared to SINS Mk.2.

Since the white noise error pattern is not correlated, overall performance is significantly improved (to 0.7071) by averaging between the two separate NATO SINS when dual fitted.

Polar Trials

In order to increase confidence the UK arranged loan of Sperry’s prototype which was fitted in HMS *Tireless* for ICEX 91. The system is shown installed in FIG. 9. The prototype is much smaller than production equipment since it has no interfaces or shock protection, but it does use the same components and technology. With Fit-To-Receive work completed, the cabinet was slung aboard one evening and had started its first trial run the following lunchtime. Trials in UK areas provided a steep learning curve for operators and satisfactory results during work-up. Due to software problems Phase 2 was only a qualified success, though demonstrating polar operation and good long-term accuracy. The final phase from USA to UK was very successful. Overall, the trials results taken across all three phases have given enough confidence to proceed with a wider UK fit[9].

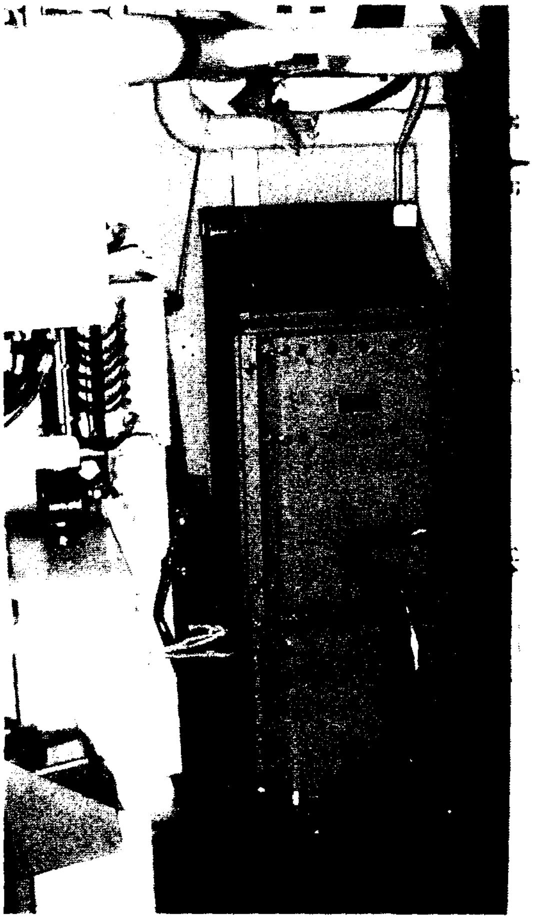

FIG. 9—PROTOTYPE IN HMS ‘TIRELESS’

Procurement Issues

NATO SINS has been selected under Cardinal Point Specification (CPS) rules, in which manufacturers are given a top level (performance) specification which often covers ‘off the shelf’, rather than bespoke equipments. Thereafter the design process is ‘hands off’ and it is not possible to incorporate ‘desirable’ features. The design may well contain detailed points we disagree with, but the CPS process concentrates on value for money over-riding such desires to ‘fiddle’.

Key features of the IMU which relate to system performance are covered by US technology transfer restrictions, including manufacturing methods, RLG compensation and software. However MOD project staff have been hard pressed to police the contractors’ progress and compliance because these limitations provide a convenient screen. It is necessary to have an overview of