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Genesis of Three-Axis Spacecraft Guidance, Control, and On-Orbit Stabilization

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John C. (Jack) Herther (http://www.peterson.af.mil/hqafspc/history/herther.htm) graduated from North Carolina State in 1953 with a B.S. in mechanical engineering. He graduated from Massachusetts Institute of Technology (MIT) in 1955 with a master's degree in aeronautical and electrical engineering. His thesis proposed a satellite guidance and stabilization system that he was later able to implement: over the years, hundreds of USAF, NASA, and other satellites would orbit successfully using the Herther three-axis active stabilization. He became an Air Force Space Pioneer and was inducted into the Space Hall of Fame in 2003. Aerospace historian Dwayne Day has called Jack Herther "one of the unsung pioneers of the early space age." In 1969, after 13 years at Itek on several generation satellite reconnaissance cameras [including the Large Format Camera (LFC), a high-altitude aerial mapping camera, which was operated from the NASA Space Shuttle Challenger Mission STS-4-G on 5–13 October 1984. It achieved a ground resolution of 14–25 m in Earth-orbital altitude of 180 nautical miles, continuing post-CORONA space mapping for the WGS84 Geoid, which became the basis for Transit and GPS satellite navigation systems (http://www.fas.org/spp/military/program/imint/at_950525.htm). Original development of the lens and prototype camera was done in Herther's Research and Development Directorate during his time at Itek (http://academic.emporia.edu/aberjame/geospat/space/space.htm)], Herther founded Iotron Corporation and served as its first president. The company developed the world's first fully automatic radar plotter for merchant ship collision avoidance. Transit satellite navigation was added, but due to ship speed inaccuracy, dead reckoning between fixes was not sufficiently precise to maintain Transit's accuracy. After obtaining a Loran receiver and testing it at sea, Herther used the repeatable accuracy of Loran to display traffic separation lanes designated by the International Maritime Organization (IMO) accurately on the radar PPI, by integrating Transit satellite and Loran C signals to provide a continuous 100-m ship position. Dead reckoning using conventional ship's through-the-water speed logs was totally inadequate when near land sailing in up to 5-knot currents that exist where the traffic lanes were mandated. Iotron's proprietary innovation was the first to use Transit satellite navigation's 100-m fixes every hour and a half to "calibrate" by using the better than the 18–90-m "continuous repeatability" of Loran C. This unpublished maritime navigation accuracy essentially equaled the 100-m accuracy of GPS for 20 years until GPS selective availability (SA) was removed in 2000. Iotron pioneered not only "hands-off" anti-collision self-plotting radar, which was installed on over 500 large ships, but also integrated Transit satellite/Loran C navigation, fitted on 34 super tankers. In 1983, Herther joined MITRE Corporation in Bedford, Massachusetts and was involved in communications and electronic systems engineering programs, including NAVWAR and GPS III, and on various classified Air Force, Army, Navy, and NSA contracts. At 75, he sails, water skis, and is still working and innovating full time.

Jim Coolbaugh (http://www.peterson.af.mil/hqafspc/history/coolbaugh.htm) is a 1947 graduate of the United States Military Academy, and a 1952 graduate of the University of Michigan, where he was awarded a master's degree in aeronautical engineering upon completion of the guided missiles course that the University was conducting for the Air Force. In the summer of 1952, Coolbaugh was assigned to the New Developments Office of the Wright Air Development Center. There he conducted studies to improve the performance of air-to-ground rockets in Korea, the use of drone aircraft for reconnaissance missions, and the feasibility of a tactical ballistic missile. These studies resulted in the development of guided air-to-ground rockets, drone reconnaissance aircraft, and the THOR intermediate-range ballistic missile. In December 1953, Coolbaugh was named the head of the Air Force's first satellite development program. The program was unfunded, but he was able to put together a fully operational development program that employed 225 Air Force personnel. This program became the satellite reconnaissance system that led to developments discussed in this paper. He became an Air Force Space Pioneer and was inducted into the Space Hall of Fame in 2002. He left the Air Force in 1960 and worked on research and development programs of the Itek Corporation, United Technology, and Raytheon. In 1969, with Jack Herther, Coolbaugh founded the Iotron Corporation, which developed an automatic self-plotting radar that revolutionized the use of radar at sea. From 1984 to 2000, he operated a classic car business that he founded.

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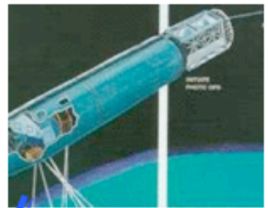
Abstract

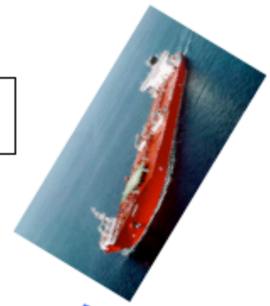
On February 22, 1995, President William J. Clinton signed an executive order declassifying imagery collected by CORONA–the program that put cameras aboard satellites for the first time in history. Long before the Soviets launched Sputnik, a small group of junior United States Air Force officers was working on the technology that enabled starting development of an accelerated program for a recoverable film capsule photoreconnaissance satellite system. This work eventually led to the invention of the three- axis active spacecraft stabilization technique that permitted evolutionary resolution improvements in aerial photography. This engineering breakthrough, adapted from RAND's three-axis multi-role satellite concept of 1954, provided the "stable table" in space that was needed to take high-resolution photographs of the Soviet Union's military installations. The intelligence gleaned from these missions dispelled one of the nation's greatest fears—surprise enemy attack—at a critical moment in the history of the Cold War. It not only dispelled both the purported "bomber gap" and "missile gap," but also contributed to a revolution in cartography that led to World Geodetic System 1984 (WGS 84), a global reference frame for the earth. This aerial stereo photography, when it was declassified, was largely responsible for the WGS-84 coordinate system now underlying GPS, and became an invaluable resource on ecology and the environment. Lockheed's Agena spacecraft, designed specifically for Earth observation, carried high-acuity (Hi-AC) cameras developed by the Itek Corporation that would provide more intelligence information in the first successful CORONA mission than had been amassed by the CIA's U2 spy aircraft in all of its flights. Starting as Air Force Weapon System WS 117L, the SAMOS/MIDAS program had nearly completed the three-axis inertial guided Agena vehicle design for two years in spite of its lack of funds for two years. Although Agena had not yet flown, its Hustler rocket engine had been proven on the B-58 bomber program and Dr. Charles Stark "Doc" Draper's MIT Instrumentation Laboratory was well along in developing its inertial guidance system. When CORONA was split off from WS-117L, right after Sputnik was launched in October 1957, the program was adequately funded for early operational flights. To the dismay of all involved, its first 13 missions were ostensibly failures. However, in spite of this shaky start, President Dwight D. Eisenhower and his advisors stood by the program, which eventually produced 800 thousand pictures of the Soviet Union on 145 satellite missions between 1960 and 1972. As it turned out, what was to be a stopgap, supposedly interim system became the backbone of the entire national intelligence collection system for the next 12 years. This paper describes the history and development of the engineering innovation, three-axis satellite stabilization, which enabled Itek Corporation cameras carried by the Lockheed Agena to capture high-resolution photographs of Soviet military installations, and then went on to revolutionize the way all earth observation satellites were three-axis controlled. Its on-orbit stabilization accuracy also permitted the optimum precise reentry angle of CORONA's film recovery capsule, enabling it to be jettisoned and subsequently parachuted to earth and caught in mid-air, rather than plunging into a large ocean area where it would risk being lost or recovered by Russian trawlers. These capsule parachute techniques led the way for all of NASA's human space flight recovery programs preceding the space shuttle. The Agena was actually the first general-purpose booster satellite vehicle, and formed the core system for many operational satellites and experimental space vehicles. The three-axis, on-orbit stabilization innovation was pioneered for CORONA and used on 300 National Reconnaissance Office imaging and signals intelligence satellite missions between 1960 and the mid-1980s. It was also used on 200 Agenas flown by NASA.

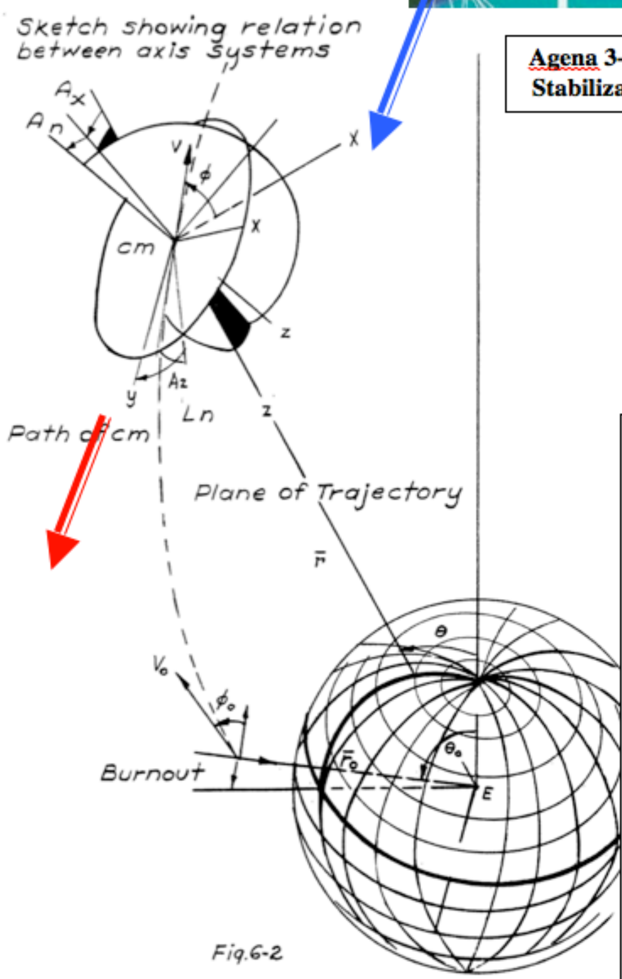
1 American Institute of Aeronautics and Astronautics
Full article may be ordered at **AIAA-type Herther**: http://www.aiaa.org/

Genesis of three-Axis Spacecraft Guidance and Control, and On-Orbit Stabilization
Excerpts and Comparison with DIGIPILOT concept development MIT Thesis Axes



Agena 3-Axis Stabilization





Steering Command-Open Sea

- **Course (Heading) or**
- **DGPS COG/SOG or**
- **GNSS – dual antenna**
- **eLoran True Course**
- **Track Keeping in Close Quarters for safety only not fuel saving**

Now 3-Axis - roll, pitch & yaw and surge, sway, and heave with 6 accelerometer MEMS, enables a cost effective DIGIPILOT improvement for to maximize fuel savings and lessen voyage times for all commercial vessels: large and small as well as large yachts

Figure 1 Same Coordinate systems for Satellite Guidance Thesis[6] and DIGIPILOT

[6] A Transition Control System, Master Of Science at the Massachusetts Institute Of Technology-1955 by John C. Herther, Lieutenant, USAF and Malcolm R. Malcomson, Lieutenant, USAF

Steering Command-Open Sea

- **Course (Heading) or**
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2-Agena Stabilization-basis of DIGIPILOT's 3-axis control concept:

A. Guidance System Module[1]

[1] ****Genesis of Three-Axis Spacecraft Guidance, Control, and On-Orbit Stabilization:*** Herther/Coolbaugh
AIAA Journal of Guidance, Control, and Dynamics Vol. 29, No. 6, November–December 2006, pages: 1247-1270
http://dialnet.unirioja.es/servlet/articulo?codigo=2178367

The Agena guidance and control system (Fig. 16) was designed to perform autopilot and flight-event programming functions in ascent and on-orbit flight modes. From the beginning, the basic Agena subsystem was common to all mission applications. Its attitude-sensing elements consisted of a three-axis, body-mounted gyro reference system and a pair of horizon sensors, an integrating accelerometer to sense vehicle accelerations, a flight- control electronics system and sequence timer to perform logic and sequencing functions, a cold gas jet system for vehicle attitude control during coast periods and for roll control during engine burn, and hydraulic actuators to gimbal the main rocket engine nozzle during engine burn periods.

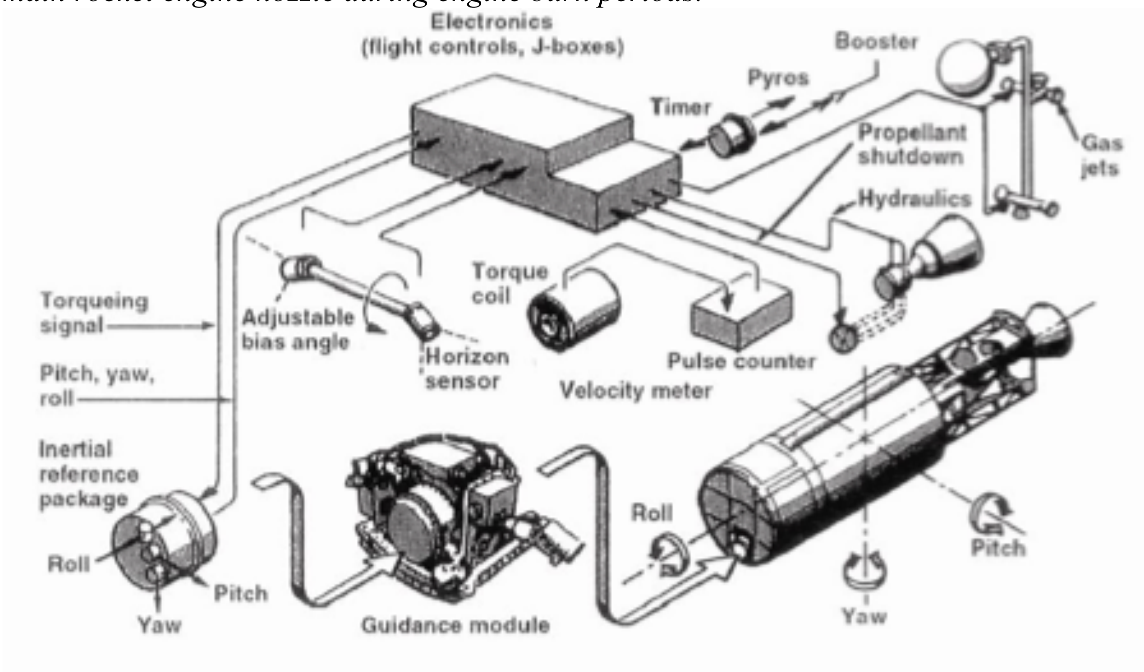

Figure 2 Functional Schematic of 3-Axis Satellite Control System

Fig. 16 Overall Functional Diagram of Agena Guidance and Control System

All of the sensing and logic elements for the Agena guidance system were packaged in a single guidance module that was installed in the forward equipment racks to facilitate handling, checkout, and alignment. Included in the module with the reference components were the flight-control electronics and J-boxes. The control components (gas jets, hydraulic actuators, and their associated parts) were electrically connected to the guidance module. This unitized guidance package (common to all Agena configurations) was in Agena D, the production model. The unitized packaging concept simplified procedures for the factory-to-launch sequence. The unit "plugged into" the Agena forward rack, complete with the horizon sensors. The gas jets and main engine gimbal actuators were separate.

B. Attitude Sensing Function

The basic attitude sensor was the three-gyro inertial reference package (IRP) built by Minneapolis-Honeywell. ***It contained two hermetic integrating gyro (HIG) units to sense pitch and yaw, and one miniature integrating gyro (MIG) unit to sense roll and***

acting as a gyrocompass for yaw angle. *The pitch and roll gyros were torqued by signals obtained from two Barnes Model IIA infrared horizon sensors. For Agena's first burn, the yaw reference was established by the booster attitude at burnout. For long coast periods (15 minutes or more), the* ***technique of gyro compassing was employed to establish the yaw reference****. Control Moment Gyro compassing (CMG) oriented the vehicle to an orbit plane yaw reference by detecting a component of the programmed pitch rate through the roll horizon sensor. The geocentric pitch rate (typically 4 deg/min for a low-altitude orbit) was programmed as a constant torque to the pitch gyro. If there was a yaw error, this pitch component would be sensed differentially when compared with the roll components of the two horizon sensor heads. The differential would be seen as a function of yaw error. The roll output was separated into a constant yaw-induced angular error and a normal roll oscillation by integrating the output over time. The roll-error component caused by yaw was fed as a torqueing signal to the yaw gyro, the output of which then corrected the vehicle's yaw orientation.*

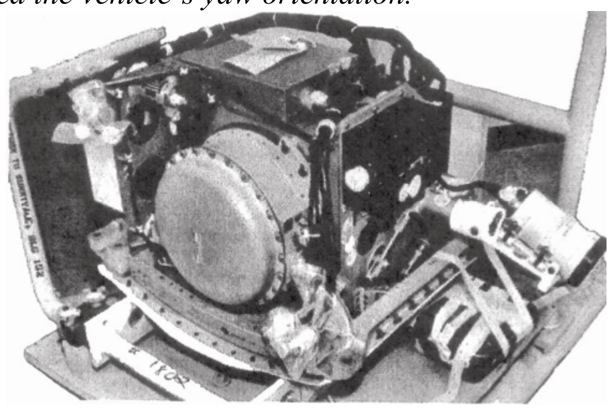

Fig. 3 Agena Guidance and Control IMU Module

The booster's radio guidance system sent commands to the Agena to either start the primary timer (for Atlas flights) or to reset it (for Thor flights). The timer was a resettable electromechanical device that had a running time of 6,000 seconds and was capable of programming 24 events. It was used during ascent to provide separation signals, engine start commands, change in pitch rates, and other events required by the Agena or the mission profile.

C. Velocity-Sensing Function

A single-axis velocity meter built by Bell Aerospace Corporation was used to measure the velocity changes imparted by the Agena propulsion system and to shut the engine down when it reached the proper speed. The velocity meter consisted of a pendulous torque coil that detected acceleration on the longitudinal axis that would cause the coil to move off-center. The coil was returned to center by a series of electrical pulses proportional to the acceleration. These digital pulses were summed in a binary counter to determine the integral of acceleration, or velocity. The digital pulses from the accelerometer were used to count down from the preset binary number representing the desired velocity increment. Two such binary numbers were preset in the velocity meter. These numbers represented the predetermined velocity increments required for first and second burns, if required. When the prescribed speed was attained, the counter registered zero coincidence and a signal was given to close the propellant shutdown valves.

3- "Corona-based iotron Skunk Works" Fuel Saving DIGIPILOT Development

The DIGIILOT fuel saving autopilot is an almost identical inertial control concept for the AGENA guidance and on-orbit attitude control system. Agena had a 3-aixs IMU and for ascent guidance that used a pitch/yaw gimbaled engine to maintain the ascent trajectory plane with vehicle roll control using gas jets. On orbit, 3-Axis stabilization for horizontal flight, kept the camera axis pointed earthward for image motion compensation while minimizing blur from pitch, roll and yaw cross track motion. This maintained the diffraction limited static high resolution lens/film reconnaissance photography by using the pitch and roll gyros (updated continuously using infrared horizon sensors for determining the vertical to <0.1 degree accuracy) A one degree **dead zone was allowed with bang-bang micro-pulse gas control jets.** A rate gyro, along the roll axis, was used for a **gyro-compassing type** yaw angle measurement so that by removing the constant average orbital rate, a yaw angle was measurement continuously that permitted yaw gas jets to keep the vehicle axis in the orbital plane. The Agena system controller modulated the micro gas jets time off-and-on.

The improved DIGIPILOT has a 3-Axis IMU with 6 accelerometers (or for some fast ships, only a precision rate gyro for yaw rate in the horizontal plane may be adequate) as sensors for the inertial control parameter sensors to maintain course (using a gyrocompass, GPS, or dual GPS for more accurate true north, and where GNSS is **augmented by eLoran, its true north compass accuracy is much better at 1 millirad 95% and is a more solid signal in heavy seas than a gyrocompass since it is not influenced by time lags due to ship's motion particularly from the on board older mechanical type ship's gyro-compasses.** Similarly, in the DIGIPILOT software, the port and starboard hydraulic or electrical pulse control is on and off for time control of the steering system rudder position as the simplest and effective control interface to any type of ship steering system. MEMS inertial components, **Apple Mac/MINI computers and iPAD type marine displays** are all now available and extremely cheap. Mandatory e-chart updates will be routine, so taking advantage of sea testing of improvements will be routine for a steady improvement in the amount of fuel saved due to an incentivized royalty fee for use of the DIGIPILOT and AutoHELM evolving SW improvements that are all downloadable and could be easily accommodated by the Apple network in port on line that routinely does auto-download changes etc. with all of its own and application partner's digital products. This use of a 50 year old well proven, at that time very expensive, 3-Axis inertial concept needing the readily adaptable inertial space technology is a "swords into plow shares" application to meet the now desperately needed and recently mandated **globally green IMO SEMP[2] objectives** with sufficient funds for developers and a significant fuel saved profit for ship-owners in the current and continually rising oil prices.

At iotron, DIGIPILOT's development evolved over six years of at sea testing by tackling the problems, one at a time, similar to the famous "Kelly Johnson Lockheed

[2] 4.18 Optimum use of rudder and heading control systems-autopilots- timid SEMP statement: "*Retrofitting of a more efficient autopilot to existing ships COULD BE CONSIDERED*

skunk works" type aircraft state-of-the-art improvement development operations for the U-2, SR 71 and Corona programs. On the Corona program, as the optics experts, Itek's QRC engineering approach supporting the CIA prime overall system contractor, Lockheed, the organizational style was replicated for developing the very high-resolution Corona space reconnaissance panoramic cameras in an evolutionary manner by improving resolution from ~40ft to 6ft over three years during the flight operational use improvement program for the CIA's 144 flights over 12 years supporting the Cold War with Itek's-3-axis stabilized cameras.

Similarly, after the 13 years of developing and building advanced reconnaissance satellite cameras. Herther[3] founded iotron and with a small ex-Itek space experienced engineering staff produced state-of-the-art ship bridge automation equipment innovations including "self plotting" radars with Transit updated Loran C referenced IMO traffic separation charts continuously displayed on the PPI and accurate to 100 m, 20 years ahead of GPS. In addition, a 1-3% fuel saving "Agena like" inertial no manual adjustment autopilot control system for ships 30 years before oil price made that equipment marketable (and eventually mandated by the IMO) on a short enough financial payback basis, although 20 were sold.

DIGIPILOT's, original rudder control design was to sense only the yaw axis, for very low rate yaw motions similar to a helmsman's feel for synchronized canceling of a ship's wave induced motion on the ship. To determine wave action on the ship, the ultra sensitive yaw rate gyro with the system's Kalman filter in controlling so that the rudder control completely ignores sea motion effects on the ship, but also on the ship's gyro as a North reference sensor whose heading measurement lags can also interfere in a conventional gyro autopilot control. Only minor infrequent rudder corrections are needed to maintain the commanded course and save fuel. The concept was first improved by adding a pendulum as a roll angle sensor to geometrically correct the yaw rate measurements in calm and mild sea states in the Great Lakes experiments, a narrow beam ship. This roll correction was succeeded since the system had an expensive high quality very accurate military type rate gyro to sense the yaw rate that complemented the ship's gyrocompass and the correction was successful. However, in heavier Atlantic seas, on 17 VLCCs the roll sensor software sometimes did not reliably synchronize a phase locked roll loop since occasional pitch waves introduced cross coupling to roll, so the system did not reach its full potential in rough seas, it only achieved ~ 2% fuel savings amounting to $25k/year savings on VLCC's at the oil price at that time. For shipowners, this was an in-sufficient payback on full VLCC full AutoMATE IBS system bought at $125k. (Now @ $100/bbl. 2% a VLCC is $250k/year). On the last 3 AutoHELM's sold, installed on ~28kt on Pacific ocean crossing vessels, the roll sensor was not used at all, since these containerships, because their speed alone, eliminated some of the rough sea pitch wave

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[3] Herther having graduated in an ASAF Institute of Technology course called Weapons Systems under Doc Draper, known as the "father" of inertial guidance, and doing his 3-axis guidance thesis under Joe De Lisle, he learned a "can do attitude" that is carried out by using a small staff that can often accomplish state of the art systems. As the responsible USAF project officer he contracted with the MIT Instrumentation Lab's Delisle to develop the ascent guidance and on orbit attitude control system. Joe said he would select 3 engineers and do the job for $1.5M in 2 years and not being inhibited with communication with a large group or company politics. The design Agena system described was done as promised.

motion that coupled interference in roll on the yaw rate occasionally, even in high Pacific seas. The ship-owner was ecstatic at the nearly consistent 3% or more savings achieved because the payback was very short and the subsequent savings were pure profit going straight to the bottom line! (On board real time fuel measurements was not used for comparison in the same sea state with the gyrocompass conventional autopilot, repetitive trips actual consumed fuel over other gyro pilot steered trips)

SUMMARY

DIGIPILOT/DIGINAV Integrated Bridge system (IBS) represented a shipboard equipment automation advance that **has never** before been available for merchant ships. Its capability to provide continuous ship's position, **voyage** routing, track keeping for safety in narrow waterways and "no adjustment" automatic fully adaptive course keeping for long voyage fuel saving, are not equaled even today by any other commercially available system. The experienced merchant ship officer operating the system and observing the improved ship's steering will quickly see that it offers the means to achieve fuel saving for more **profitable, safer,** commercial ship operations.