PRESENTED AT THE 1979 SAN FRANCISCO RTCM ASSEMBLY MEETING

Radio Technical Commission for Marine Services, Washington, D.C. 20554

April 24, 1979.

COMPUTERIZED NAVIGATION

AND

THE FULLY ADAPTIVE DIGITAL AUTOPILOT

by

Lloyd M. Pearson, Vice President
iotron Corporation,
Bedford, Massachusetts

ABSTRACT

Merchant ship navigation is more than just directing a ship from one point to another. Modern navigation also involves minimizing voyage time, reducing operating costs, increasing fuel savings, and providing for a maximum degree of ship safety. Electronic equipment manufacturers are recognizing navigation requirements and are producing a variety of computer ized navigation systems. These systems differ primarily in the amount of watch officer involvement needed for proper operation, their navigational and routing capability, and the amount of navigation information they provide. The fact that bunker costs have increased six times since 1974, and will continue to increase, has made the engineering development of a computerized navigation system linked to a "Hands Off" fully adaptive digital autopilot a significant development. Meaningful savings can be realized through precise navigation, improved steering, and better ship control.

This situation leads to the following questions:

- What is computerized navigation?
- What is an adaptive digital autopilot?
- Will either of these equipments really save me money?

The following paragraphs present Iotron's answers to these questions.

Author's Biography:

Lloyd M. Pearson is one of the founders of iotron, and is Vice President and Director of Sales. Before iotron, he was employed by Itek Corporation in the Optical Systems Division where he was responsible for a variety of administrative and technical assignments. Mr. Pearson has a Bachelor of Science degree in Business Administration from Northeastern University and in Naval Science from the University of Colorado. He has also completed advanced studies in Naval Electronics at the Massachusetts Institute of Technology. Mr. Pearson served in the United States Navy from 1943 to 1958, transferring to the U. S. Naval Reserve in 1958 and retiring in 1962. His assignments in the Navy included Commanding Officer of a destroyer escort and an ocean minesweeper. Executive Officer, destroyer squadron Operations Officer, Engineering Officer, EIC Officer, ASW Officer and Electronics Officer. These assignments included ship operation and control, and responsibility for the installation, maintenance and repair of communication, radar, and sonar and communications systems. At the U.S. Naval CIC Officers School in Illinois, he taught radar air and surface plotting, electronics theory and the operation of shipboard electronic equipment.

COMPUTERIZED NAVIGATION

AND

THE FULLY ADAPTIVE DIGITAL AUTOPILOT

By

Lloyd M. Pearson, Vice President
iotron Corporation,
Bedford, Massachusetts

The Conventional Autopilot

Most of today's merchant ships are equipped with an autopilot for automatic steering. These conventional autopilots are simple regulator controllers which maintain a constant set course. Adequate steering control can be established over a small range of changing weather and sea conditions by adjusting the autopilot's control parameters for the particular ship's operating characteristics. The result is that the conventional autopilot will often overwork the steering engine in adverse weather and heavy sea conditions. Heavy bow, quartering, and following seas will cause continuous large rudder actions and will often allow large yawing angles. The bridge watch officer must, therefore, cease the use of the conventional autopilot and shift to manual steering.

In any sea state, the optimum adjustment of a conventional autopilot's control parameters is a necessary and continuing bridge function for maxi mum steering efficiency and the saving of fuel. After initially adjusting the controls for rudder limit, weather helm, sea state and sensitivity, the watch officer must carefully observe the resulting course corrections in rudder action over a period of time and then make additional adjustments to find the optimum combination. Small improvements are difficult to perceive by the average bridge officer. As a result, constant control adjustment of a conventional autopilot is usually not considered an important bridge function, so this task is not adequately carried out though anything less than optimum steering results in wasted fuel.

A change of ship or sea conditions will require that the entire autopilot adjustment process be again repeated, or in any event, it must be continuously monitored. Supertankers and modern fast containerships are particularly affected since they can be subjected to sudden large differences of steering characteristics, particularly in coastal waters. Proper autopilot adjustment changes when a new course is steered and the ship's handling changes, due to wind and/or sea state, change in load, trim or speed, or the depth of water. The simple fact is that most ships do not achieve optimum steering performance using conventional autopilots over most of their voyage operating time.

The Fully Adaptive Digital Autopilot

A new type of autopilot is now available for merchant ships. It uses the modern minicomputer to eliminate the deficiencies of the conventional autopilot and provide an automatic system that continually gives optimum steering performance. This iotron engineering development of a computer zed navigation system linked to a "Hands Off" fully adaptive digital autopilot became a necessary and economically feasible development with the increase in bunker costs.

The fully adaptive digital autopilot provides significantly improved course keeping and reduced rudder action in any sea, but particularly in moderate to heavy seas. Yaw rate is continuously measured with an integral rate gyro. This measurement is combined with inputs from the ship's gyro com pass and speed log to determine the state of the vessel at any instant. For ships without a speed log or RPM-Speed Converter, the watch officer can enter the ship's speed manually. All inputs are filtered to minimize response to periodic perturbations from wave action by using a Kalman filter. Rudder control gains are determined by applying stochastic optimal regulator theory. Rudder action is determined with continuous consideration given to the minimizing of ship's hull and rudder drag. The adaptive autopilot system ignores mean drag and the oscillatory disturbances due to wave action. Gain settings are automatically adjusted without any watch officer involvement. Optimum performance is continuously provided based on present sea state, ship's speed, load and trim, as well as water depth.

Propulsion losses have been shown to be proportional to the square of the rudder angle dead band. In many ships this amounts to several degrees of rudder motion, due largely to mechanical overshoot in the steering gear. The result is a "hunting" action of many oscillations per minute around the desired rudder angle. The fully adaptive digital autopilot reduces this rudder angle dead band and minimizes the amount of rudder action. The speed loss due to the ship's yawing from this rudder motion has been deter mined theoretically by K. Nomoto and T. Motoyama[1] and is shown graphically in Figure 1. Note that a 2% speed loss results from only 2 degrees of yaw oscillation corresponding to approximately *7 1/2%* of rudder action.

Improved course keeping and reduced rudder action equates to maximum steering efficiency and more Important to the use of less fuel to achieve and maintain a desired ship's speed. As optimum steering is achieved, a speed increase over that achievable with a conventional autopilot or hand steering results. This speed increase, though extremely difficult to measure, can provide over an extended operating period, a fuel savings of more than 2% since average voyage times will be reduced.

---

[1] Japanese Society of Naval Architecture **(1966)**

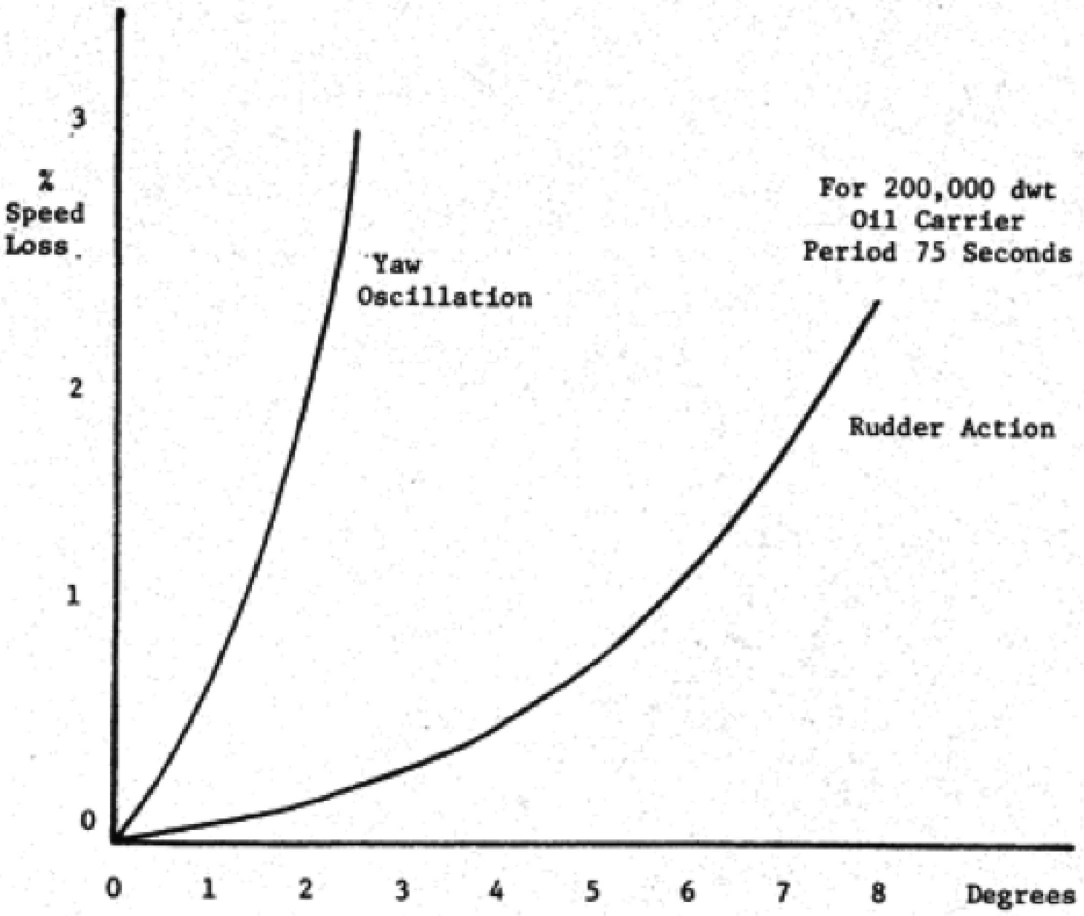


Figure 1.

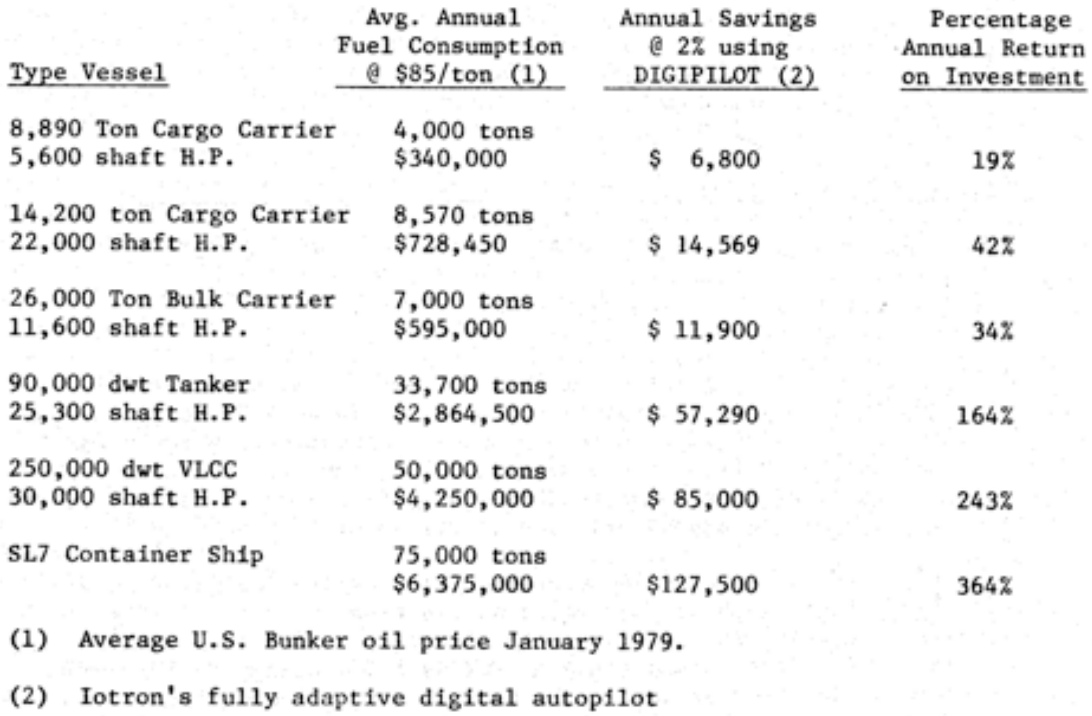
The fully adaptive digital autopilot provides another significant ship steering and fuel saving advantage. The system's integral rate gyro allows for a selectable controlled ship-turning rate. Hand steering turns and conventional autopilot turns are usually quickly completed to achieve the new-desired course at a constant rudder angle. Slow, gentle, controlled turning arcs are nearly impossible to achieve.

With the fully adaptive autopilot the watch officer can designate an extremely slow rate-of-turn and minimal rudder action is automatically applied to establish and maintain this rate. As a result, loss of ship speed due to turning is minimized. Turn rates as low as 1 and 2 degrees per minute can be achieved and provide during the turn, a nearly imperceptible speed loss. For example, 15-degree course changes at 10 degrees/minute on a VLCC will cause a decrease in speed of approximately 3/4 knot. The same turn made at 5 degrees/minute slows the ship only approximately 1/4 knot. The fuel that is required in regaining this 1/2-knot of speed is thereby saved. With turn control simple and positive, the use of a slow controlled turning rate quickly becomes standard practice for most changes in course and less fuel is used.

Many high-speed vessels tend to roll significantly during a fast turn. With adaptive autopilot's ability to maintain a controlled slow turn rate, this ship handling problem is practically eliminated and the controlled turn rate provides for a minimum loss in speed.

A controlled turn rate permits a ship to make a constant radius turn. When required or desired, this can reduce the turning error in maintaining a planned track in restricted waters.

The computerized fully adaptive digital autopilot is a present shipboard reality. Combined with computerized navigation, significant savings can be realized through precise navigation, greatly improved steering and better ship control. Tests run by various manufacturers in conjunction with major oil and shipping companies[2] have shown that a computerized adaptive auto pilot can produce a 2% overall savings in fuel costs for ships presently using a conventional autopilot. Precise navigation has been shown to produce a 1/2% overall savings. How this translates into dollars and cents can be seen in the following table, which only considers the greater efficiency of the fully adaptive digital autopilot. Continuous, precise navigation should provide additional savings.



Type Vessel	Avg. Annual Fuel Consumption @ $85/ton (1)	Annual Savings @ 2% using DIGIPILOT (2)	Percentage Annual Return on Investment
8,890 Ton Cargo Carrier 5,600 shaft H.P.	4,000 tons $340,000	$ 6,800	19%
14,200 ton Cargo Carrier 22,000 shaft H.P.	8,570 tons $728,450	$ 14,569	42%
26,000 Ton Bulk Carrier 11,600 shaft H.P.	7,000 tons $595,000	$ 11,900	34%
90,000 dwt Tanker 25,300 shaft H.P.	33,700 tons $2,864,500	$ 57,290	164%
250,000 dwt VLCC 30,000 shaft H.P.	50,000 tons $4,250,000	$ 85,000	243%
SL7 Container Ship	75,000 tons $6,375,000	$127,500	364%

(1) Average U.S. Bunker oil price January 1979.

(2) Iotron's fully adaptive digital autopilot

---

[2] Conducted aboard T/ESSO WILMELMSHAVEN, the Gotaas Larsen and **Texaco United Kingdom VLCC fleets,** and other vessels.

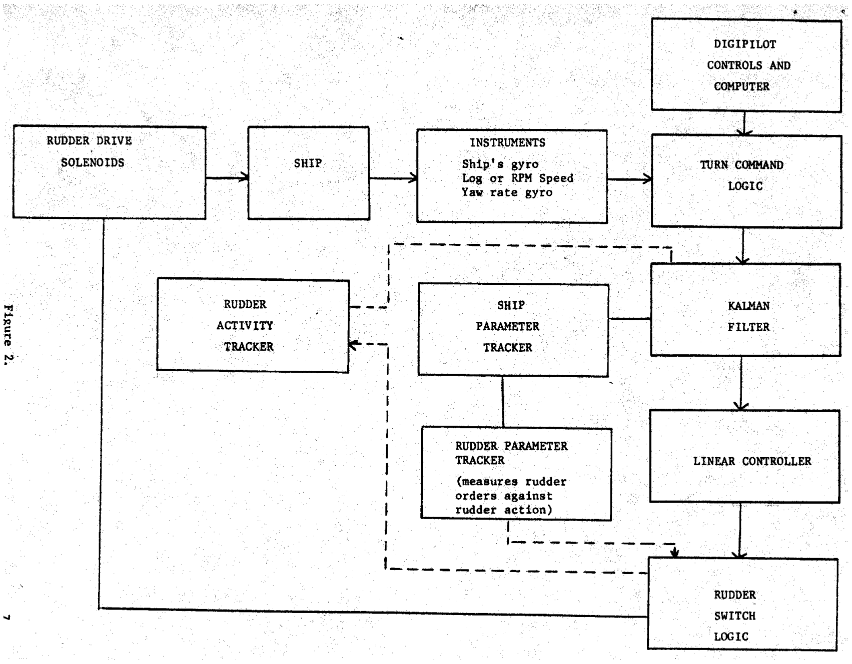
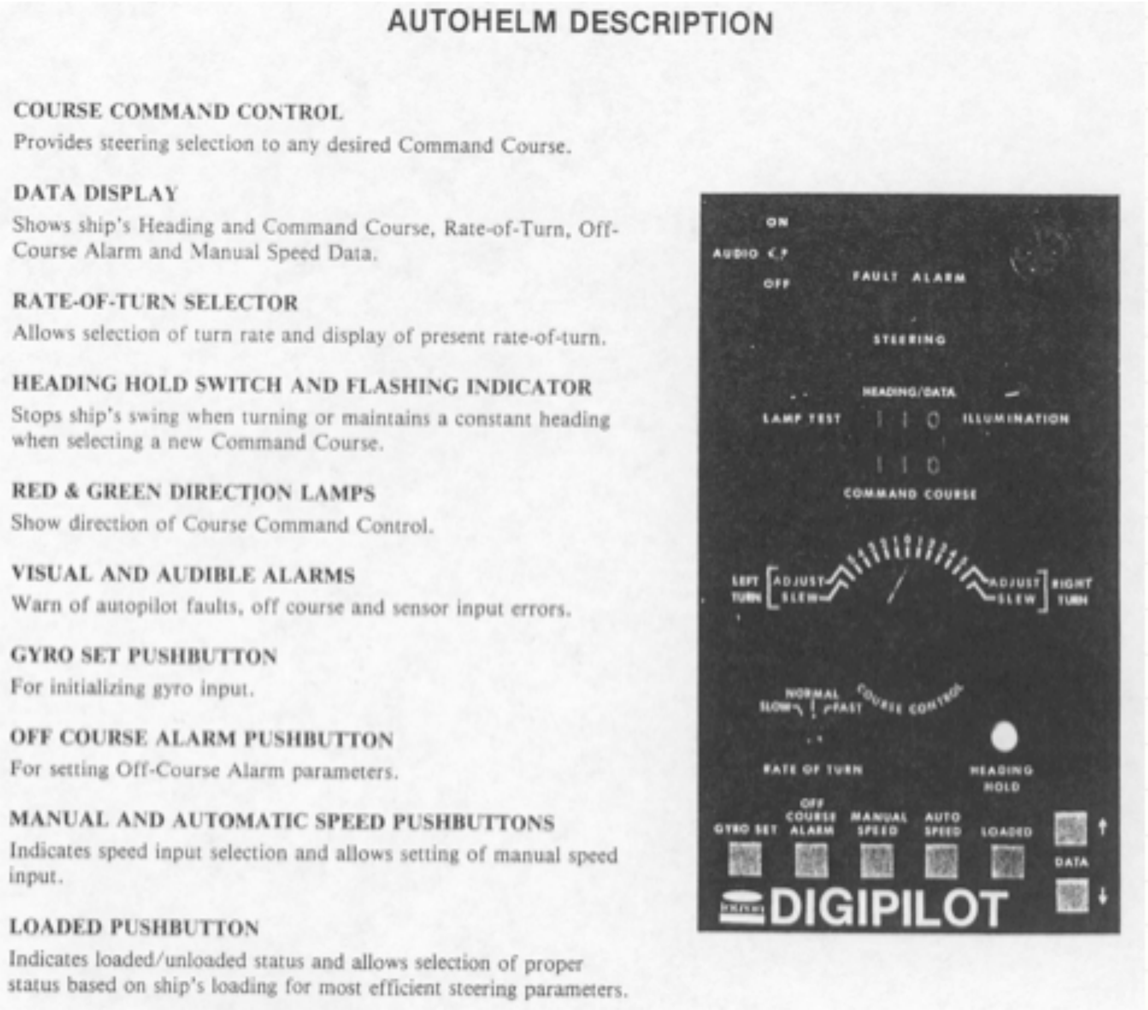


Figure 2.



AUTOHELM DESCRIPTION

COURSE COMMAND CONTROL
Provides steering selection to any desired Command Course.

DATA DISPLAY
Shows ship's Heading and Command Course, Rate-of-Turn, Off-Course Alarm and Manual Speed Data.

RATE-OF-TURN SELECTOR
Allows selection of turn rate and display of present rate-of-turn.

HEADING HOLD SWITCH AND FLASHING INDICATOR
Stops ship's swing when turning or maintains a constant heading when selecting a new Command Course.

RED & GREEN DIRECTION LAMPS
Show direction of Course Command Control.

VISUAL AND AUDIBLE ALARMS
Warn of autopilot faults, off course and sensor input errors.

GYRO SET PUSHBUTTON
For initializing gyro input.

OFF COURSE ALARM PUSHBUTTON
For setting Off-Course Alarm parameters.

MANUAL AND AUTOMATIC SPEED PUSHBUTTONS
Indicates speed input selection and allows setting of manual speed input.

LOADED PUSHBUTTON
Indicates loaded/unloaded status and allows selection of proper status based on ship's loading for most efficient steering parameters.

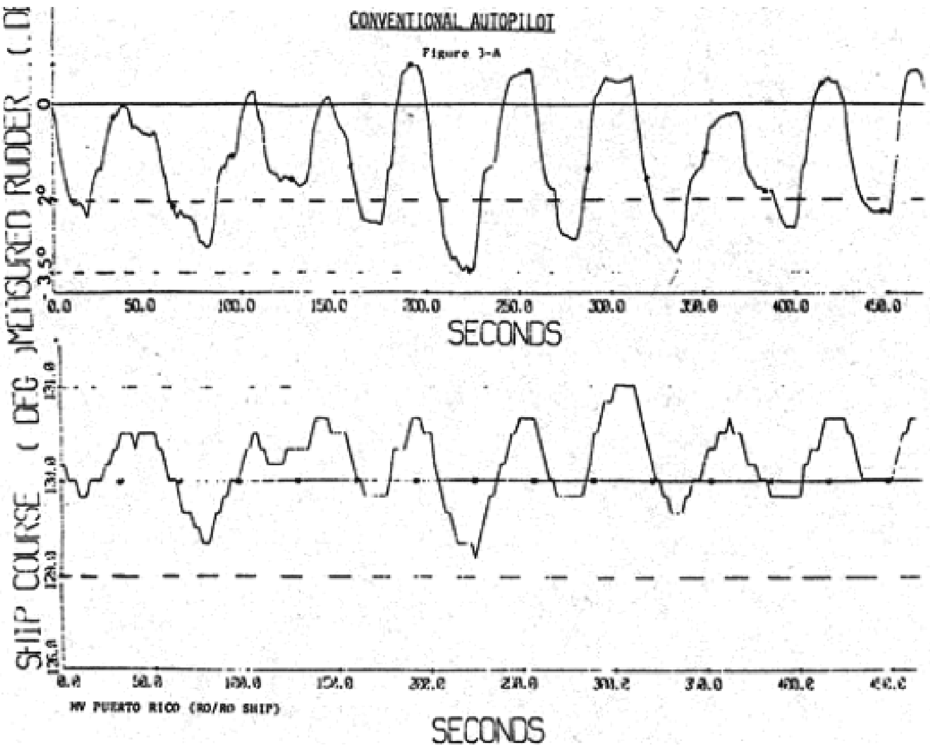


Figure 3A Puerto Rico (RO/RO)

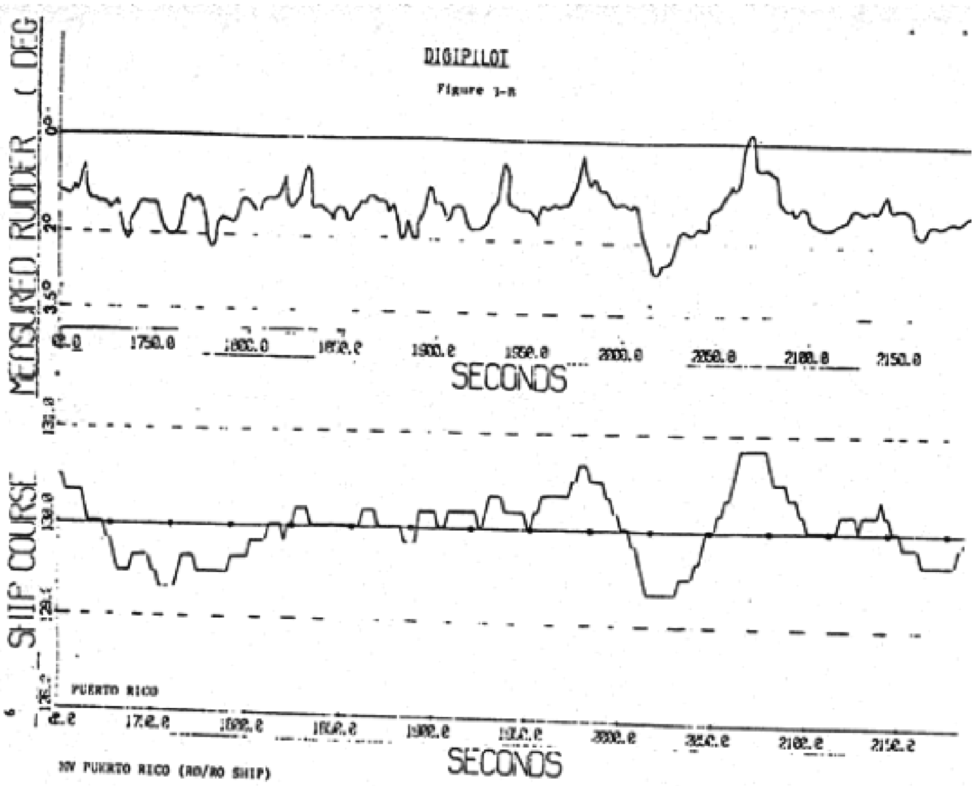


Figure 3B Puerto Rico (RO/RO)

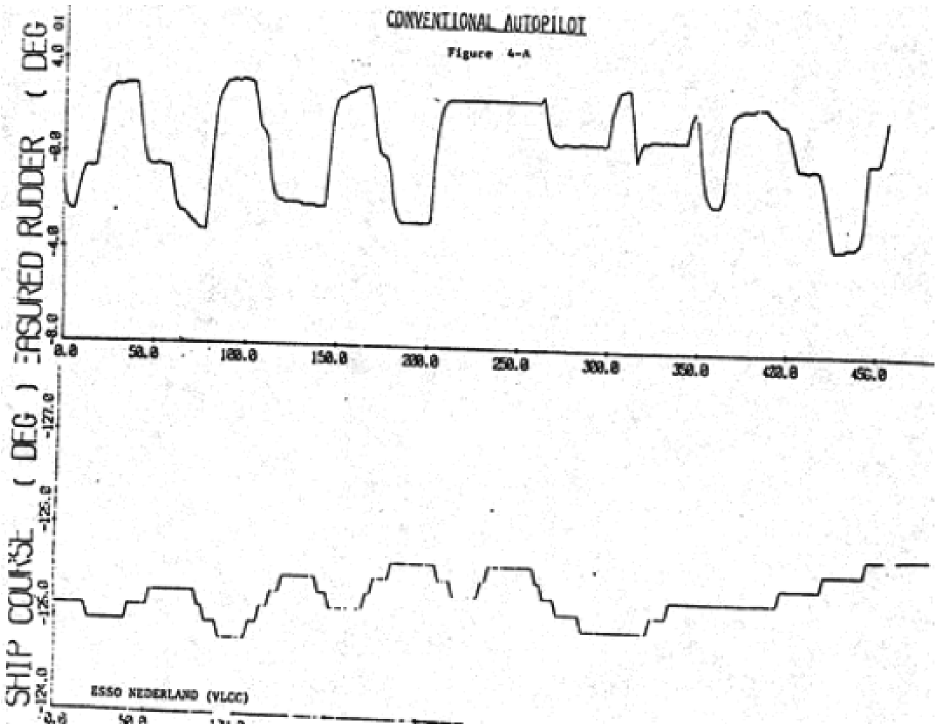


Figure 4A Esso Nederland VLCC

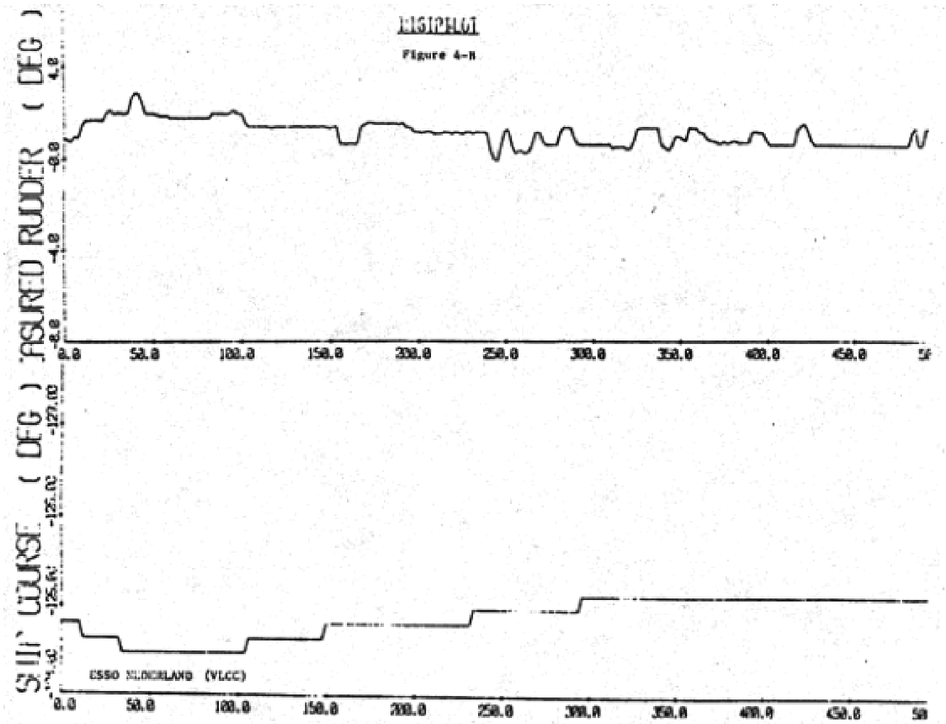


Figure 4B Esso Nederland VLCC

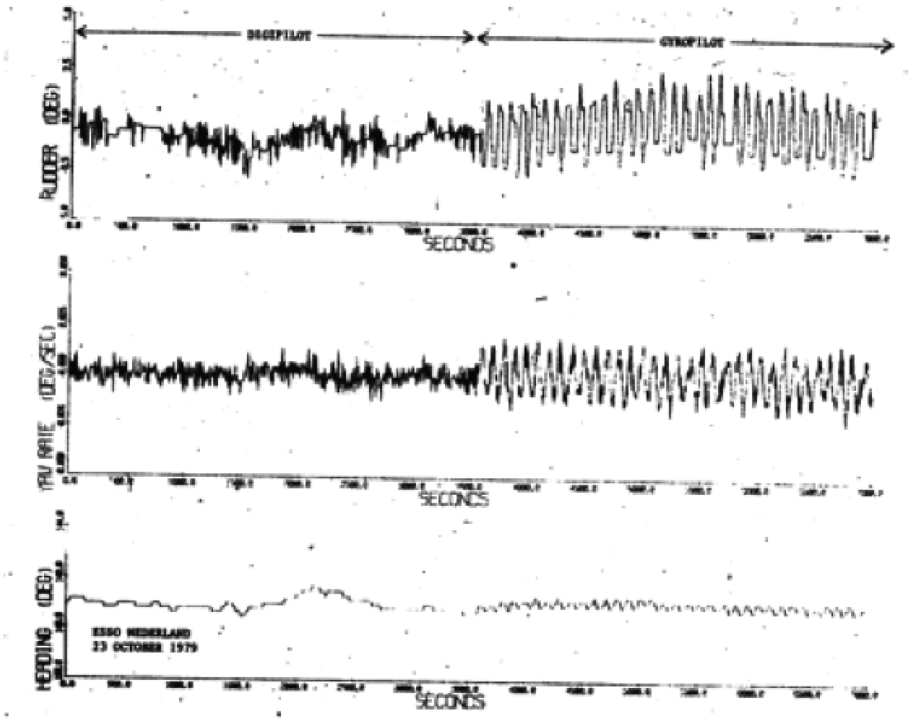


Figure 5 Esso Nederland VLCC DIGIPILOT and Gyropilot

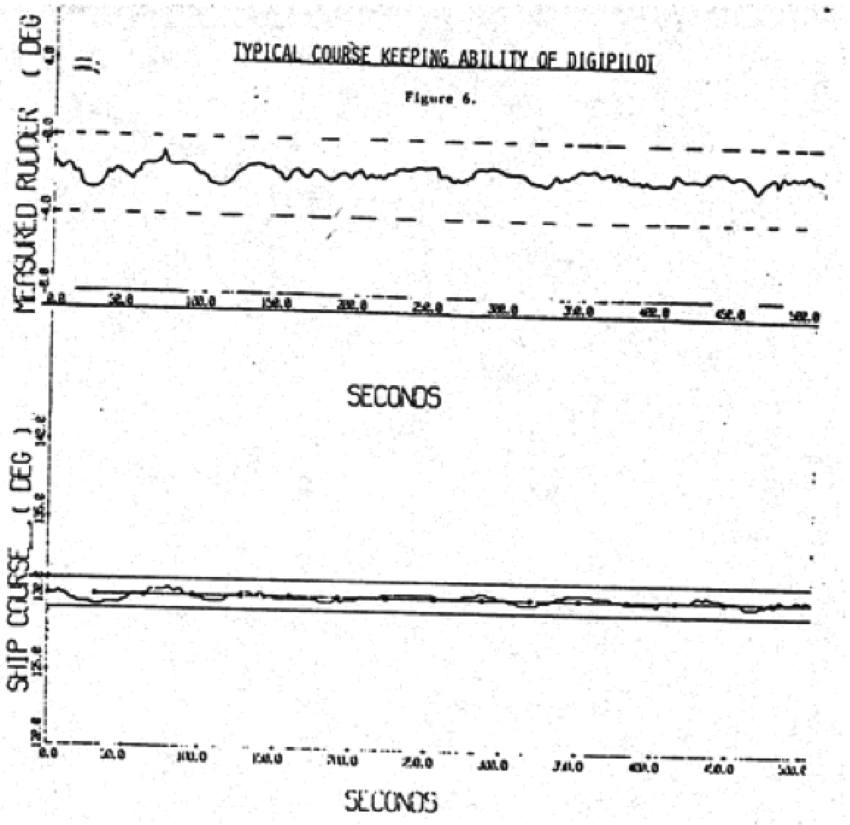


Figure 6 RO/RO in Calm Sea State

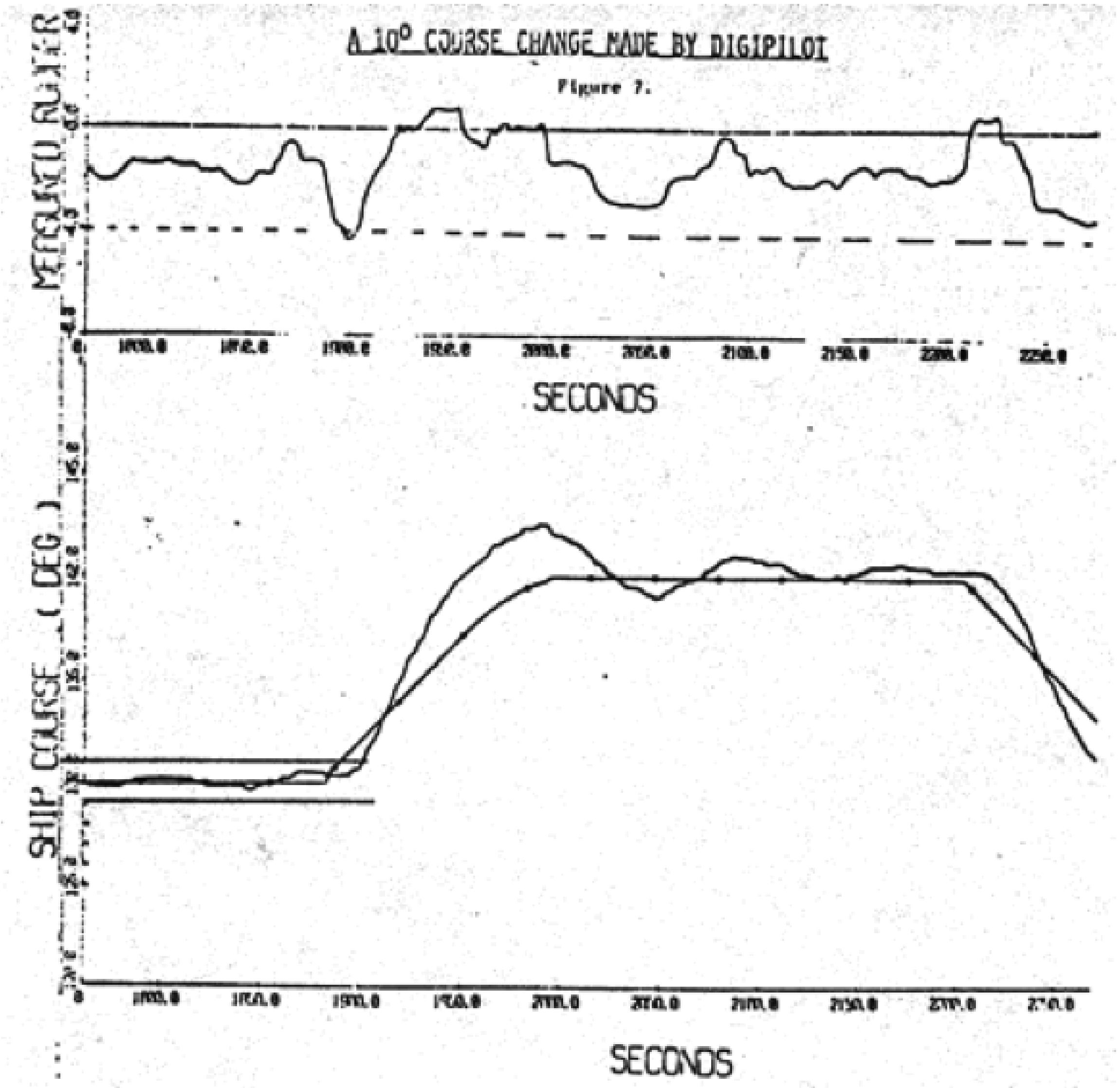


Figure 7 A 10 degrees Course Change on DIGIPILOT

The DIGIPILOT/DIGINAV System

The DIGIPILOT/DIGINAV fully adaptive autopilot and computerized navigation system has been developed by iotron Corporation to provide today's ships the fuel savings that can be realized through precise navigation, improved steering and better ship control. The versatility and ease of using DIGIPILOT/DIGINAV to automatically provide optimum steering and solve the many tedious and demanding problems encountered in ship navigation and routing can only be realized by operating the actual system.

DIGIPILOT Operation

The DIGIPILOT fully adaptive digital autopilot operates like a new helmsman learning how to handle a ship. When the ship first sails out of port with the system turned on, the ship's heading deviations caused by periodic wave motion are determined. The fully adaptive autopilot is then able to ignore these for steering commands, since the ship normally returns to its planned course following each wave cycle. Longer-term course deviations are constantly corrected to compensate for changing sea conditions.

The actual method of operation can be understood by examining the following detailed block diagram. (Figure 2)

The data from the instruments are processed by a Kalman filter, and an estimate of the motion of the ship is developed. The Rudder Parameter Tracker gets "the feel" of the hydraulic steering system by measuring its actual response against known rudder commands. Kalman Filter gains and rudder dead-band are adapted to maintain a degree of control consistent with the prevailing sea state without permitting excessive wear and tear of the steering gear. After a few minutes of operating, optimum steering can be achieved once the ship's steering is switched to the DIGIPILOT/DIGINAV control.

The rudder and course data in the accompanying recorder traces (Figures 3-A, 3-B and 4-A, 4-B) of approximately 8 minutes duration show DIGIPILOT performance for a RO/RO ship and a tanker in a moderate sea. For the VLCC, both measured rudder traces show about 1 1/2 degrees weather helm being required. The conventional, typically adjusted, proportional/derivative (PID) autopilot is also shown under the same circumstances for comparison. Figure 5 shows the ESSO Nederland’s course and rudder angle traces for DIGIPILOT and a standard conventional ship's autopilot. The improved performance with DIGIPILOT is clearly shown. Note the excessive rudder action required by the conventional autopilot that does not maintain course nearly as well. Without any manual operator involvement on turn-on, DIGIPILOT has completely ignored the wave action, improving course control and is significantly lessening the unwanted rudder motions, thus significantly decreasing hull and rudder drag.

Figure 6. shows DIGIPILOT performance on the same RO/RO) ship later in a calm sea state. The system maintained course near1y perfectly with almost

All control and data inputs to DIGINAV are made by using a keyboard display unit (Figure 10.). This simple keyboard display unit allows the operator to enter and read out all navigation data and to provide the required control for continuous automatic navigation and complete shlp routing. Ship position radionavigation data is updated and displayed every 10 seconds.

The basic navigational procedures and definitions used with DIGINAV are in accordance with the American Practical Navigator (Bowditch) and Dutton's Navigation and Piloting to reduce operator-training requirements and make the equipment easier to understand. DIGINAV provides fully automatic navigation with a simplicity that has been pioneered by iotron.

DIGIPILOT/DIGINAV Operation

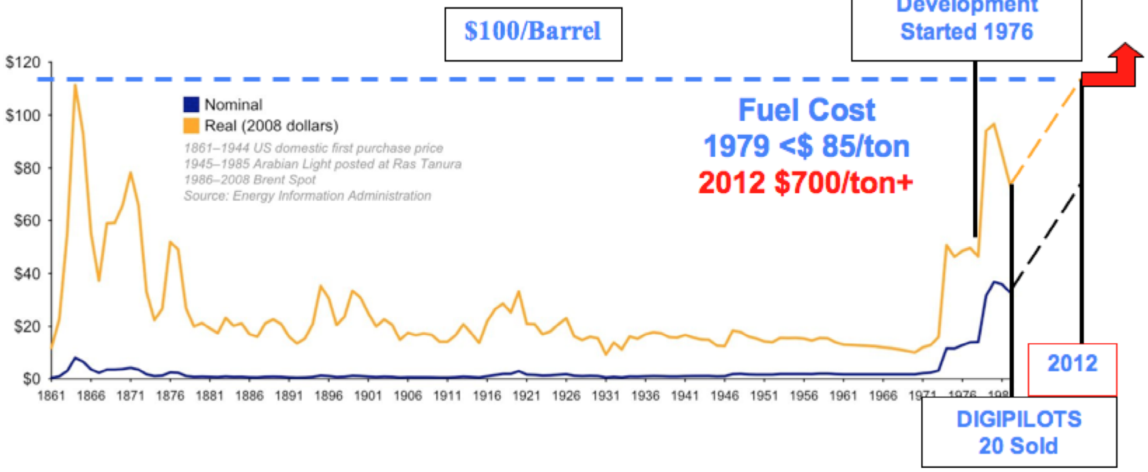
With a DIGIPILOT combined with DIGINAV, an overall ship's, position control loop is formed. This loop performs many of the navigator's functions while meeting his voyage steering requirements. Stated In more fundamental terms. given the Latitude and Longitude of the desired turning point, the system continually determines the ship's present position and correct course to steer. This automatic COMMAND COURSE is used by DIGIPILOT. On long voyage legs DIGIPILOT/DIGINAV also performs the routine duties of both the helmsman and watch *officer in* terms of OFF COURSE and/or OFF TRACK control monitoring and alarm. Added ship safety is afforded as the watch officers have time to double check the automation and system operation and provide a better visual lookout. When approaching a next waypoint, the system also assumes the function of signaling the watch officer. Once the new course is approved, DIGIPILOT automatically turns the ship with the amount of rudder action required to maintain the constant desired slow rate of turn. The system’s adaptive features it automatically monitor and readjusts rudder action control in order to achieve best fuel economy while traversing long voyage legs and a planned track line or more efficient course holding can be maintained precisely.

The remote AUTOHELM Control Unit and the DIGIPILOT/UIGINAV keyboard and display permit the watch officer to select a specific controlling navigation system, specify *and maintain the* correct course to steer to the next route waypoint and provide all data required for the proper operation and control of the fully adaptive automatic steering. On a planned route, waypoint advance is automatic and the system will indicate the next course to steer with *a time* to turn alarm sounding to alert the watch officer. The correct time to turn is determined by the DIGIPILOT/DIGINAV calculation of the ship's advance and turn for to maintain planned track with the selected turn rate. An automatic controlled turn Is made only after the flashing HEADING HOLD button Is pressed by the watch officer to acknowledge that the turn i» desired. This avoids possible dangerous course change and always maintains ultimate ship control at the Steering Console.

SUMMARY

DIGIPILOT/DIGINAV represents a shipboard equipment advance that **has never** before been available for merchant ships. Its capability to provide continuous ship's position, **voyage** routing, and automatic fully adaptive course keeping, are not equaled 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 more **profitable, safer,** commercial ship operation.

ESCALATING OIL PRICE



$100/Barrel

DIGIPILOT Development Started 1976

Fuel Cost
1979 <$ 85/ton
2012 $700/ton+

2012

DIGIPILOTS 20 Sold

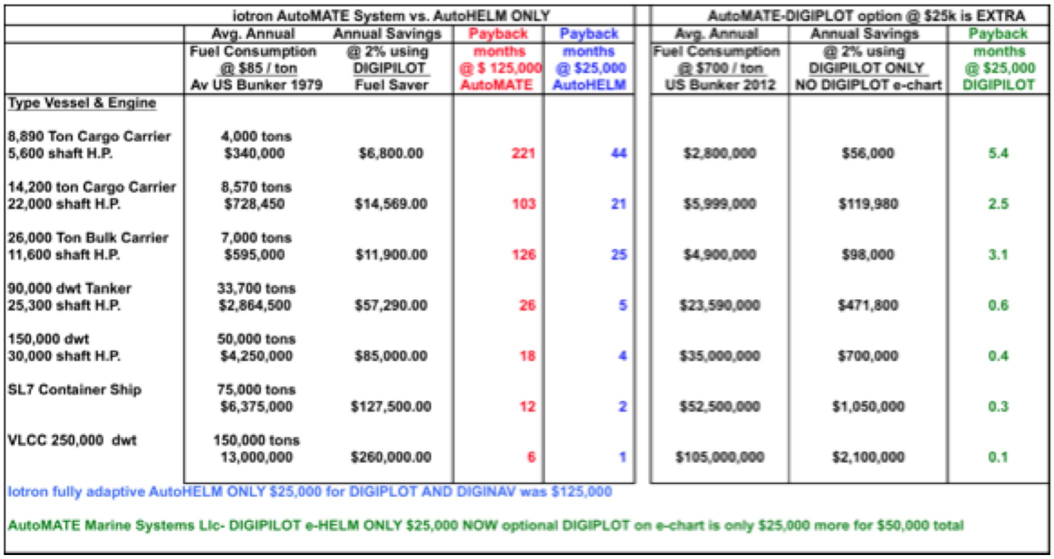
1861–1944 US domestic first purchase price
1945–1985 Arabian Light posted at Ras Tanura
1986–2008 Brent Spot
Source: Energy Information Administration

SHIP TYPE	SHIPOWNER	FLAG	SHIP's NAME	DEVELOPMENT	INSTALLED
Bulk Carrier-40K dwt	American Steamship	US	MV St Clair	1st experimental	1976
Tanker-80K dwt	Sunoco	US	America Sun	1 to 3%	1976
VLCC-253K dwt	EXXON	Neth	Esso Saba	Vessel Adjustment	1978
VLCC-250K dwt	EXXON	Neth	Esso Nederland	Vessel Adjustment	1979
Small RO/RO	Naviera	US	Puerto Rico	Vessel Adjustment	1979
VLCC-250K dwt	EXXON	Neth	Esso Europoort	1 to 3%	1979
VLCC-250K dwt	EXXON	Neth	Esso Esso Bonaire	1 to 3%	1980
VLCC-286K dwt	Texaco	Panama	Texaco Brazil	1 to 3%	1980
VLCC-286K dwt	Texaco	Panama	Texaco Ireland	1 to 3%	1980
VLCC-275K dwt	Texaco	Panama	Texaco Africa	1 to 3%	1980
VLCC-250K dwt	Pennzoil (Zapata)	US	Newport News NB#	1 to 3%	1980
VLCC-260K dwt	West Coast Shipping	Liberia	Coalinga	1 to 3%	1980
VLCC-269K dwt	Texaco	Panama	Texaco South Africa	1 to 3%	1981
VLCC-269K dwt	Texaco	Panama	Texaco Veraguas	1 to 3%	1981
VLCC-264K dwt	Texaco	Panama	Texaco Italia	1 to 3%	1981
VLCC-250K dwt	Pennzoil (Zapata)	US	Newport News NB#	1 to 3%	1981
26KT Containership	American President	US	President Lincoln	3 X VLCC Fuel Rate	1981
VLCC-264K dwt	Texaco	Panama	Texaco Japan	1 to 3%	1982
VLCC-235K dwt	Texaco	Panama	Texaco Nederland	1 to 3%	1982
VLCC-226K dwt	Texaco	Panama	Texaco Panama	1 to 3%	1982
26KT Containership	American President	US	President Washington	3 X VLCC Fuel Rate	1982
26KT Containership	American President	US	President Monroe	3 X VLCC Fuel Rate	1982

An iotron Corporation AutoMATE System consisted of digiPLOT ($75,000) Anti-Collision and DIGIPLOT/DIGINAV) $25,000 each totaling $125,000. American President's 28 kt containership customer had only the digiPILOT because a Magnavox Transit Satellite system was already installed furnishing course to steer. So APL's cost was $25,000 and control was only by using the AutoHELM rudder controller overriding the conventional autopilot for minor changes to the commanded course to steer (usually a few degrees) for avoidance type maneuvers in trans Pacific crossings. Their was NO keyboard/display The fuel use was three times VLCCs due to speed, thus 2% $ saving was much larger and on long "pendulum repeat voyage crossings" they were able to use the actual measured total fuel usage voyage data, to determine payback of <0.3 months, practically one trip!

SHIP TYPES	SHIPOWNER	FLAG	SHIP's NAME	Annual Fuel	$ Savings	mo Payback
				@ $85/ton	@2%	@ $125k
Bulk-40K dwt	American Steamship	US	MV St Clair	2864500	57290	26
VLCC-253K dwt	EXXON	Neth	Esso Saba	4250000	85000	18
VLCC-250K dwt	EXXON	Neth	Esso Nederland	4250000	85000	18
VLCC-250K dwt	EXXON	Neth	Esso Europoort	4250000	85000	18
VLCC-250K dwt	EXXON	Neth	Esso Esso Bonaire	4250000	85000	18
VLCC-286K dwt	Texaco	Panama	Texaco Brazil	4250000	85000	18
VLCC-286K dwt	Texaco	Panama	Texaco Ireland	4250000	85000	18
VLCC-275K dwt	Texaco	Panama	Texaco Africa	4250000	85000	18
VLCC-269K dwt	Texaco	Panama	Texaco South Africa	4250000	85000	18
VLCC-269K dwt	Texaco	Panama	Texaco Veraguas	4250000	85000	18
VLCC-264K dwt	Texaco	Panama	Texaco Italia	4250000	85000	18
VLCC-264K dwt	Texaco	Panama	Texaco Japan	4250000	85000	18
VLCC-235K dwt	Texaco	Panama	Texaco Nederland	4250000	85000	18
VLCC-226K dwt	Texaco	Panama	Texaco Panama	4250000	85000	18
VLCC-250K dwt	Pennzoil (Zapata)	US	Newport News NB#	4250000	85000	18
VLCC-250K dwt	Pennzoil (Zapata)	US	Newport News NB#	4250000	85000	18
VLCC-260K dwt	West Coast Shipping	Liberia	Coalinga	4250000	85000	18
Tanker-80K dwt	Sunoco	US	America Sun	2864500	57290	26
Modular Automate Subsystem for FUEL SAVING ONLY, e.g. DIGIPILOT ONLY NO DIGINAV or DIGIPL						@ $25k
Small RO/RO	Naviera	US	Puerto Rico	3400000	68000	4
28kt Containership	American President	US	President Lincoln	12750000	255000	1
28kt Containership	American President	US	President Washington	12750000	255000	1
28kt Containership	American President	US	President Monroe	12750000	255000	1

Then & Now: Ship's Fuel Savings Payback for Full AutoMATE System vs. DIGIPILOT



	iotron AutoMATE System vs. AutoHELM ONLY				AutoMATE-DIGIPLOT option @ $25k is EXTRA		
	Avg. Annual	Annual Savings	Payback	Payback	Avg. Annual	Annual Savings	Payback
	Fuel Consumption @ $85 / ton Av US Bunker 1979	@ 2% using DIGIPILOT Fuel Saver	months @ $ 125,000 AutoMATE	months @ $25,000 AutoHELM	Fuel Consumption @ $700 / ton US Bunker 2012	@ 2% using DIGIPILOT ONLY NO DIGIPLOT e-chart	months @ $25,000 DIGIPILOT
Type Vessel & Engine							
8,890 Ton Cargo Carrier 5,600 shaft H.P.	4,000 tons $340,000	$6,800.00	221	44	$2,800,000	$56,000	5.4
14,200 ton Cargo Carrier 22,000 shaft H.P.	8,570 tons $728,450	$14,569.00	103	21	$5,999,000	$119,980	2.5
26,000 Ton Bulk Carrier 11,600 shaft H.P.	7,000 tons $595,000	$11,900.00	126	25	$4,900,000	$98,000	3.1
90,000 dwt Tanker 25,300 shaft H.P.	33,700 tons $2,864,500	$57,290.00	26	5	$23,590,000	$471,800	0.6
150,000 dwt 30,000 shaft H.P.	50,000 tons $4,250,000	$85,000.00	18	4	$35,000,000	$700,000	0.4
SL7 Container Ship	75,000 tons $6,375,000	$127,500.00	12	2	$52,500,000	$1,050,000	0.3
VLCC 250,000 dwt	150,000 tons 13,000,000	$260,000.00	6	1	$105,000,000	$2,100,000	0.1

Iotron fully adaptive AutoHELM ONLY $25,000 for DIGIPLOT AND DIGINAV was $125,000

AutoMATE Marine Systems Llc- DIGIPILOT e-HELM ONLY $25,000 NOW optional DIGIPLOT on e-chart is only $25,000 more for $50,000 total