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USING ALPHA-BETA TRACKERS IN MARINE PILOTING BY RADIO NAVIGATIO--ETC(U)
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16. Abstract

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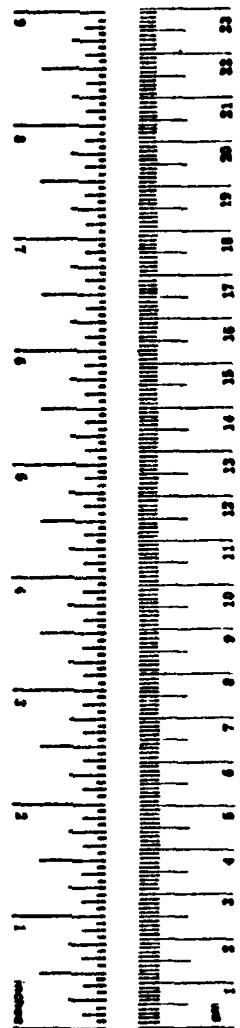
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

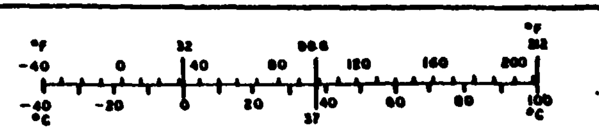
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ABSTRACT

Automatic radio aids to navigation for marine usage always employ some sort of smoothing to attenuate noise. As this smoothing period is extended, the actual ship's motion "signal" is suppressed along with the noise. When the radio aid is used for positioning in a restricted waterway, such suppression can be undesirable. This work attempts to quantify through simulation the tradeoffs in suppressing the noise and affecting the signal. A simple ship model is used to develop a ship's maneuvering signal of variable parameters, which is additively combined with simulated noise and processed by the smoothing filter. The latter is an alpha-beta tracker (so-called from its radar target history) and performance is studied parametric in tracker rise-time. These rise-times should lie between 2.5 and 8 seconds; chosen for minimum sensitivity to ship maneuver characteristics, or minimum joint sensitivity to practical noise variations and ship characteristics. This range accords with current commercial practice in Loran-C receivers signal tracking loops. Gyro compass aiding of the tracker is similarly studied, and shown to offer some advantages in maintaining good performance in the face of these variations, but improving the ability of the tracker to predict future position by a factory of three to five to one.

USING ALPHA-BETA TRACKERS IN MARINE PILOTING BY RADIO NAVIGATION

Introduction

Piloting a large ship in restricted waters such as harbors and their approaches is a complex process. Considerable research, both field and laboratory, has been conducted in recent years in this area with primary emphasis on traditional visual methods. Radio navigation aids are now playing an increasing role in these efforts, both to further raise the level of safety under normal conditions and to facilitate safe passage under conditions of poor visibility (or loss of visual marks such as buoys in winter icing conditions). There are many radio aids, the earliest in practical marine use was the radiobeacon. Today we find the low-frequency aids, Loran-C, Omega and Decca used extensively in many parts of the world, with many specialized higher-frequency systems employed in certain areas. Tomorrow the Satellite Global Positioning System will certainly find extensive marine use.*

All of these systems have various error sources which can be roughly segregated by the time-span of their affect. While the most difficult errors to deal with are those which change over periods of hours or more, every system has some level of random noise originating either as atmospheric radio noise or thermal-based noise in the radio receiver's circuits. Processing of the radio signals, or measures derived from them, must always include smoothing or filters to deal with this random noise. The filters take several different apparent forms depending upon the discipline of the engineer responsible for the design of the dominant filter. All current radio navigation systems suitable for piloting a vessel in restricted waters (i.e. accuracies in the tens-of-meters category) use coherent signal processing, and the phase locked loops that realize this usually supply the dominant filtering that suppresses random noise. The loop outputs must undergo coordinate transformation to finally result in position information that the human pilot can actually use in maneuvering the ship. Traditionally this was done by chart-plotting, an unusable technique in most restricted waterway problems. Today, the ubiquitous microprocessor can eliminate this step and couple the radio aid directly to the harbor pilot in a useful form. The chart was useful of course, but in a harbor where the pilot must continually monitor/control vessel maneuvers, other traffic, local traffic-control rules, and communications, he must have immediate and relevant position information. This requires coordinate conversion of the radio aid's fix and display of the fix in either graphical or digital form <u>with respect to</u> the harbor situation *i.e. not Lat/Long, but crosstrack error, distance to turn point or plan display).

*Note: We do not consider a shipboard radar operating with reflections from passive terrestial objects to be a radio navigation system simply because its use requires interpretive judgements by the operator, its performance cannot be analyzed by the techniques used here. Practical navigation systems will always use both an aid of the type studied here and radar, for both complementary support and safety redundancy.

The coordinate transformation is always incrementally linear, and the noise filtering supplied by the receiver's loops can in principle be performed after transformation, in cartesian space. Here, it resembles the traditional tracking function of automated radars rather than the phase locking of communication technology. In particular, the goal of estimating the position of a maneuvering object in the radar-tracker literature is directly akin to the radio-piloting problem. Hence, we are going to perform our analysis in the form of this tracking problem, but it is fully identical to the usual navigation signal processing problem for the high-accuracy application of interest. In other words we are going to ignore coordinate transformation and study cartesian trackers in marine usage, with the understanding that one may realize the tracker function in the receiver's signal processing circuits before coordinate transformation/display.

Problem Definition and Approach

In Figure 1 we see the complete marine piloting problem modeled as a control loop. "Piloting" is used rather than navigation to emphasize the complex, interdependent process that occurs in harbor transit, of which navigation (position determination) is only a phase. The plant is the dynamic ship, with vector controls over rudder and engine. The ship dynamics vary enormously, over several decades between a pleasure boat and largest oil tankers. In harbors the ship moves through the water, and the water itself can move significantly over the earth's surface under wind/tide/current influence. Only a few combinations of this complex system state can be practically observed, and the radio-based position observation of interest here is masked by a noise process whose statistics are usually a function of location and time. Our tracker must operate on these data, with specified parameters, and supply the processing and display system both a current estimate of ship state and also a future predicted position. Finally the pilot observes this information and weighted with many other factors, makes decisions as to ship controls to apply. This complete system is being studied by other workers (references 1, 2). Our work focuses on the elements to the left of the dotted line.

Modern control or signal processing theory can deal effectively with a requirement to minimize the error in the position estimate, $\hat{x}$, given an accurate description of the ship dynamics, noise characteristics and suitable linearization of the observation function $h(\cdot)$. This modern approach would be an extended linear Kalman filter, in which one would have to assume ship-model parameters, assume noise parameters, and model error sources such as gyrocompass/speed-log biases. This formal or rigorous approach quickly leads to a very complex system, and requires on-line identification of time-variable parameters. When one attempts to make complexity compromises in this situation, there is little in the way of intuition to guide the trade-offs; what is important is this complex structure?

We seek a more robust result in which a form of the tracker is assumed, and the problem is to choose parameters such that the estimate error is least sensitive to a wide range of assumptions (or lack of knowledge about) the ship's dynamic characteristics and radio aid noise. We are constrained to use only the radio aid as the ultimate determinant of true position, the gyro and speed log data must be prevented from contributing any long term or

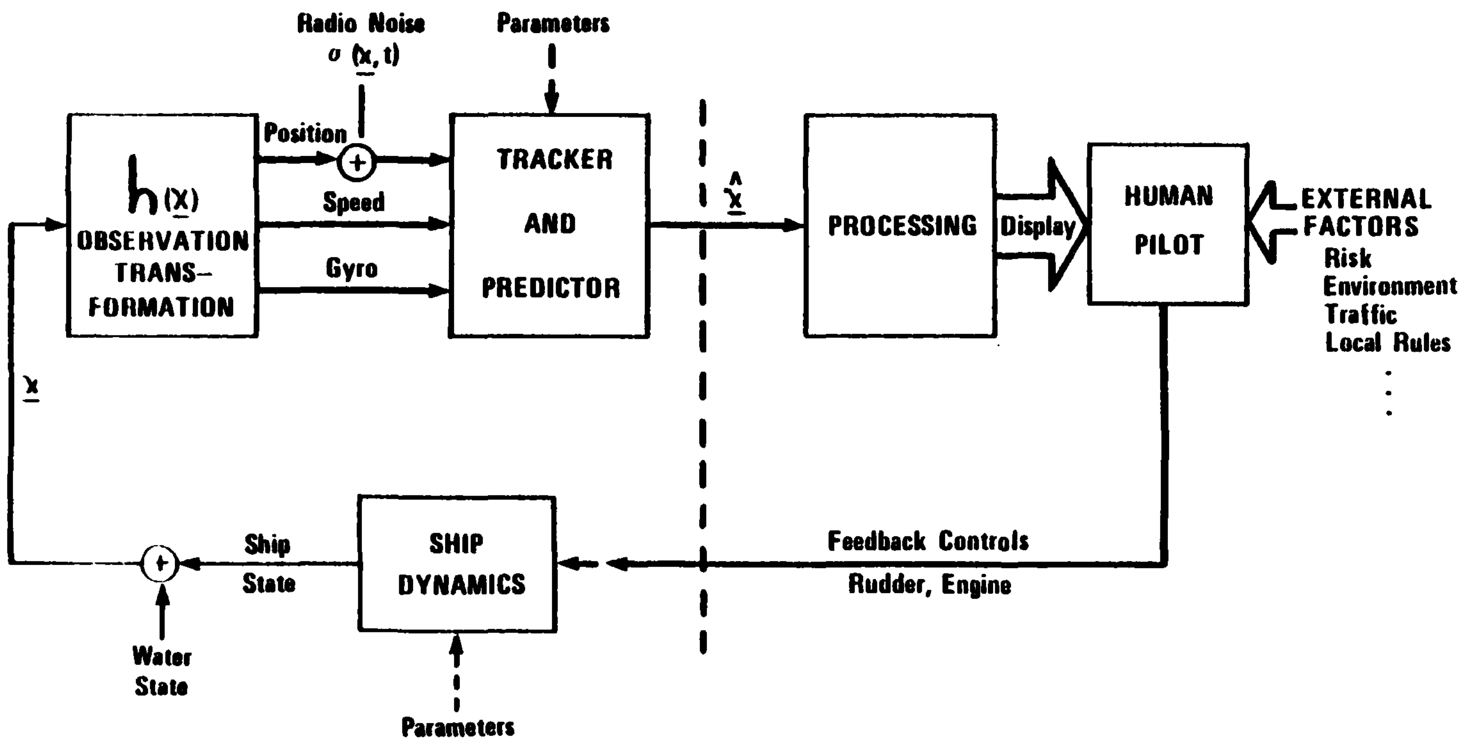


Figure 1
CONCEPTUAL MODEL OF MARINE PILOTING USING A RADIO AID—TO—NAVIGATION

average error to position estimation. The tracker and processor would form a system that could be installed aboard a wide range of ships without custom programming or ship-specific knowledge, and without having to depend upon a precise level of performance from other sensors such as the gyro. In this installation, the radio aid system would deliver a level of performance, over wide ranging conditions that would (desirably) be invariant, or at least have predictable bounds.

Our approach to this problem is via computer simulation. The ship is modeled in a very simple way that includes major non-linearities that effect the tracker's estimate, $\hat{x}$. A nominal "harbor" is maneuvered by a pilot controlling the model ship, and the ship controls recorded as a baseline. These baseline controls, driving a ship model of specified (but alterable) characteristics and corrupted by an independent noise source for each cartesian axis, is then processed by various tracker structures and with different parameters to seek the design(s) with the desired practicality and insensitivity. All of the simulations were based upon a sampling rate of once-per-second, and the role of this sampling time in the various equations is dropped. One second was chosen on practical grounds; it is the lower limit of any equivalent trackers used today in marine radio aids, and is well above the Nyquist frequency of any acceleration change that can be applied to commercial ships.

Ship Model

The mathematical equations which simulate the ship meet three basic requirements:

a. Model the two independently-controlled energy storage effects that give the ship its dynamic "feel" to the pilot, rectilinear kinetic energy and kinetic rotational energy in yaw.

b. Use a very simple structure for both economy, and direct variability of major dynamic parameters in sensitivity testing.

c. Model major non-linear effects that corrupt the observables, such as the ship pointing inside the path of the center of gravity when turning (slide-slip).

The ship model is shown in Figure 2 and consists of two first order digital filters to account for the buildup and then limiting of speed and turn-rate, in response to engine thrust and rudder-generated turning moment. The equations are

$$S_K = \exp(-1/\tau_s) S_{K-1} + (1-\exp(-1/\tau_s)) T_K$$

$$\dot{\theta}_K = \exp(-1/\tau_\theta) \dot{S}_{K-1} + (1-\exp(-1/\tau_\theta)) \dot{\psi}_k$$

Figure 2 labels the input to the rectilinear inertial filter as "Thrust" in yds/sec, with output being speed in yds/sec. Clearly this is a modeling artifice, the input represents thrust (a force) as the speed that ultimately results from the continued application of the actual force (from the ship's propeller). A more intuitive development of this idea can be seen if we

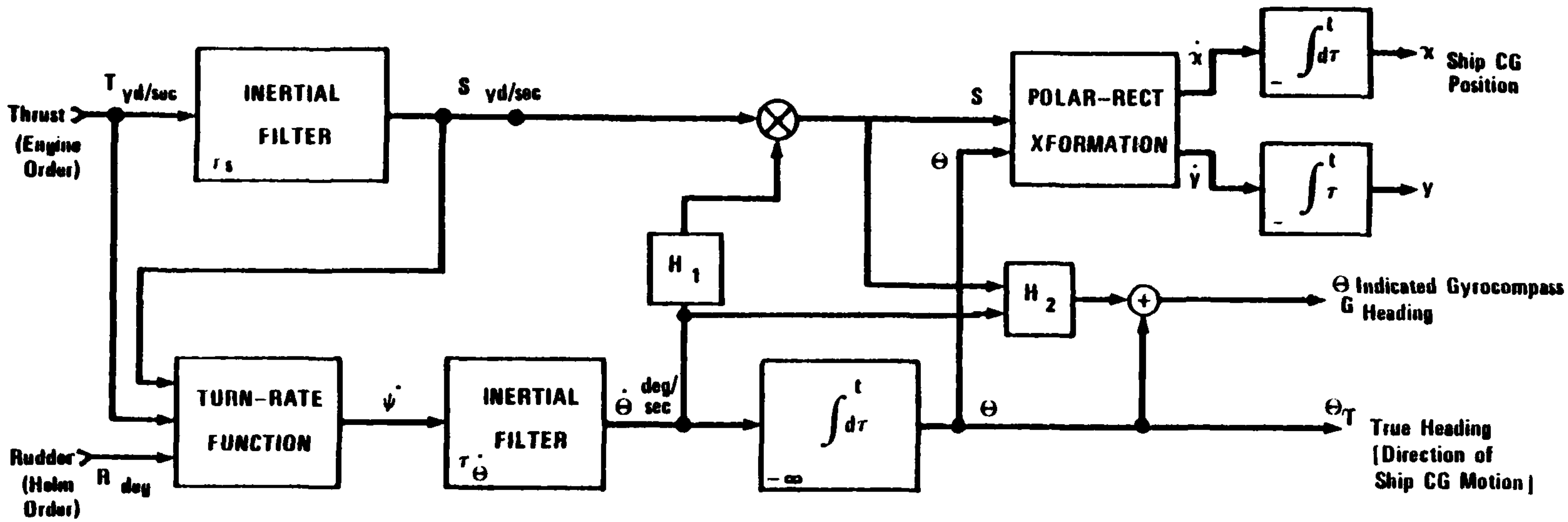


Figure 2
SHIP MODEL

take an equivalent analog filter whose step response is

$$S(t) = 1 - \exp(-t/\tau_s), \quad t > 0 \tag{2}$$

and represent it as the derivative of this response followed by an integrator

$$= \int_{-\infty}^{t} \frac{1}{\tau_s} \exp\left(-\gamma/\tau_s \right) d\gamma \tag{2-a}$$

The integrand is the net force that results from applying a step change in thrust to the ship (i.e. changing propeller RPM), which is quickly counterbalanced and exponentially reduced to a net of zero by frictional forces. The acceleration proportional to this thrust is then integrated to yield velocity. This is a simple linear model to a complex non-linear differential equation, which exhibits its most important effect. An identical thought process can be applied to the rotational inertia filter.

The multi-input function that relates engine thrust, hullspeed and rudder angle to turn rate is given by

T \ S	> 0	< 0
> 0	$k \cdot R\left[S + T(1 - S/15)\right]$	$k \cdot R\left[S/4 + T(1 + S/20)\right]$
< 0	$k \cdot R\left[S + T/2(1 - S/15)\right]$	$\left[S/4 + T/2\right] k \cdot R$

$$S, T \in \{-10, +15\}$$

$$k = \frac{1.3 * 36}{15 * 20 * 30} \ yd^{-1}$$

This complex relationship is a coarse approximation to the action of the rudder in developing a turning moment due to hull movement through the water, and also from the rudder's deflection of the propeller's water jet. It causes the model to respond to a "turning kick" of the engine often used when negotiating a turn, to turn even though the engine is stopped if the ship is moving, and to turn poorly when going astern.

Transformations H1 and H2 are given by

$$H_1 = 1 - \frac{|\dot{\theta}|_k}{3.8} \qquad H_2 = \dot{\theta}_k * S_k$$

Together they model slide-slip in a turn; H2 causing a heading error between the center of gravity's path and the ship's head measured by the gyro, while H1 reduces the hull speed when turning.

The several parameters in the model were chosen to match the various effects tabulated in reference (3) for a 600 foot dry-cargo ship. After some experimentation using the model to make Williamson turns (Reference (4)): a speed time constant of 60 seconds was selected, with 30 seconds for turn-rate. Smaller ships are modeled by a proportional reduction of these values, with 15 and 7.5 used for a 50 foot commercial fishing boat.

The baseline harbor trajectory is shown in Figure 3, when the 600 foot ship time-constants are used, with annotation for rudder/engine controls actions. The simulated transit was made using a plotter to represent ship center-of-gravity, no attempt was made to create the full effects of a ship and the actual channel view as would be done in a modern marine simulator (e.g. CAORF). These represent more control actions than a professional harbor pilot would normally use, but creates an upper bound on "signal variation"--the true path of the ship--to test trackers against and detect sensitivity to ship characteristics. In fact, we tied several different sets of controls generated by individuals of different experience with no significant difference of results reported below. We probably could have used a random controls-generator as a signal source indicating the independence of our results to a specific harbor scenario. The baseline trajectory represented a passage of 43 minutes, or 2600 samples at the one-second rate. This provides adequate stability to the statistics derived from the simulation.

Unaided Alpha-Beta Tracker

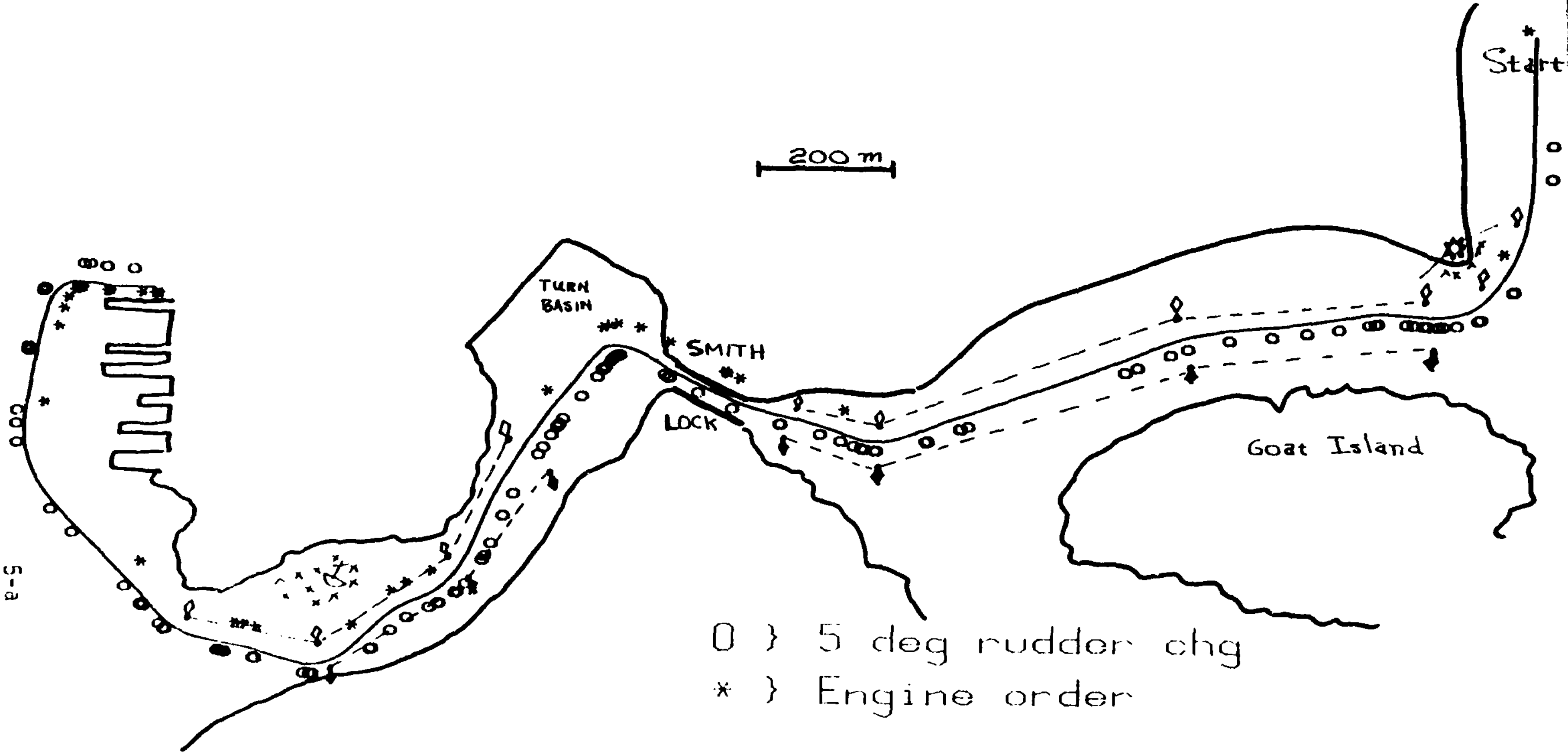
References 5 and 6 provide a few points of contact to the literature of alpha-beta trackers developed in the radar or target tracking context. The classic tracker problem is choice of the alpha and beta parameters to optimize some metric; originally related to transient performance and later to statistical measures. We are going to choose the so-called Benedict-Borodner value for the ratio of alpha to beta

$$\beta = \alpha^2 / (2 - \alpha)$$

under the assumption that the major effects we seek are not sensitive to slight changes in this ratio. This choice provides a step response that has 15% overshoot and is also the steady state gain of a Kalman filter matched to a dual-integrator signal source (reference 5). Our tracker processes the simulation data as follows:

$$\underline{\hat{x}}_k = \begin{bmatrix} \hat{x}_k \\ \hat{y}_k \\ \hat{\dot{x}}_k \\ \hat{\dot{y}}_k \end{bmatrix} = \underline{\hat{x}}_{k/k-1} + \begin{bmatrix} \alpha & 0 \\ 0 & \alpha \\ \beta & 0 \\ 0 & \beta \end{bmatrix} \begin{bmatrix} -\hat{x}_{k-1} + \hat{\dot{x}}_{k-1} + x_k + n_k \\ -\hat{y}_{k-1} + \hat{\dot{y}}_{k-1} + y_k + w_k \end{bmatrix} \qquad (4)$$

$$n_k,\ w_k \text{ are } N(0, 0);\ E(n_k \cdot w_k) = 0,\ E(n_k \cdot n_{k-1}) = 0$$



TEST TRACK OF 600' SHIP IN HYPOTHETICAL HARBOR

FIGURE 3

with an estimate at future time T seconds given by:

$$\hat{\underline{x}}_{k+T/k} = \begin{bmatrix} \hat{x}_k + T\hat{\dot{x}} \\ \hat{y}_k + T\hat{\dot{y}} \\ \hat{\dot{x}}_k \\ \hat{\dot{y}}_k \end{bmatrix}$$

In extreme applications of radio aids, the assumption of coordinate independence among the noise samples n,w, breaks down as the position error distribution becomes elliptic. We ignore this, as the piloting usability of such a radio aid also decreases dramatically. The typical harbor applications of the future will use three or more radio Lines-of-Position and the error patterns will not be nearly circular, or independently distributed errors.

Referring to Figure 1, we have fixed the ship dynamics at the nominal 600 foot value and have assumed the simplest tracker structure. Performance is defined to be the root-mean-square of the difference between the tracker estimate of position and the true position of the model ship. Performance variation will be determined versus tracker rise-time (a function of the only tracker parameter, alpha), and these performance curves parameterized by the additive level of noise which models the radio receiver's noise. Tracker rise-time must be measured experimentally, a table of values of for a 0-66% rise-time definition is

Rise-time (sec)

τ	α	τ	α
0.35	2.5	0.07	12.5
0.19	4.5	0.62	14.5
0.134	6.5	0.053	16.5
0.105	8.5	0.048	18.5
0.083	10.5		

Table 1

Figure 4 shows the simulation results; the tracker performance plotted in along-track and cross-track coordinates. These coordinates were selected in anticipation of the effects of aiding, and because they are the only relevant coordinates for the ship's pilot. Cross-track is usually the more important for the obvious reason of grounding on the sides of the channel. The error vector for each sample time is transformed to cross-track/along track by

$$\begin{bmatrix} e_{AT} \\ e_{XT} \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{bmatrix} \begin{bmatrix} e_x \\ e_y \end{bmatrix} = \begin{bmatrix} R \end{bmatrix} \cdot \begin{bmatrix} e_x \\ e_y \end{bmatrix} \quad (6)$$

FIGURE 4

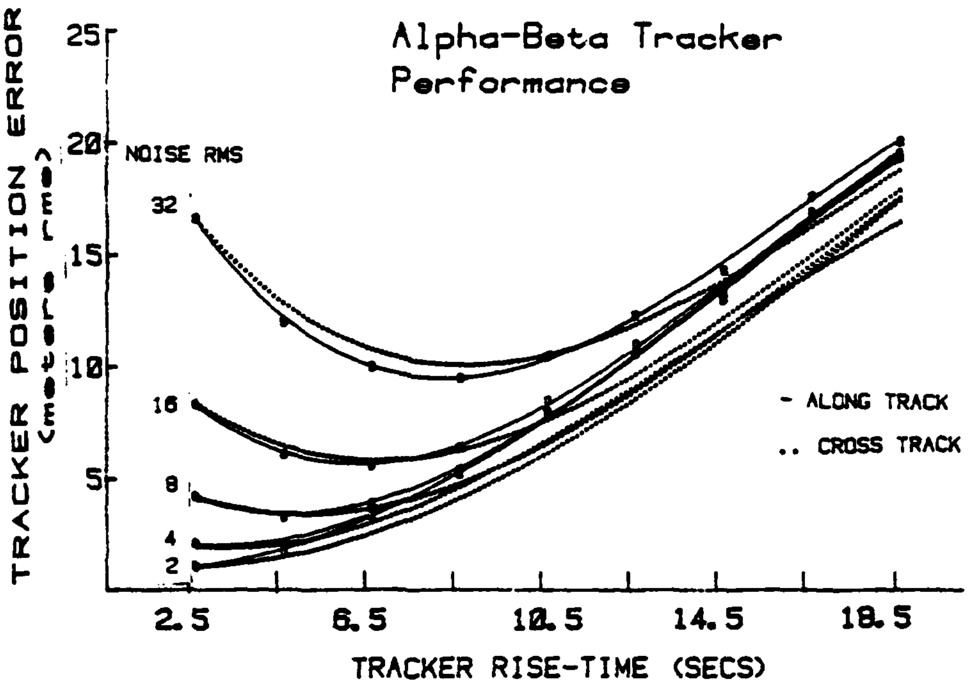
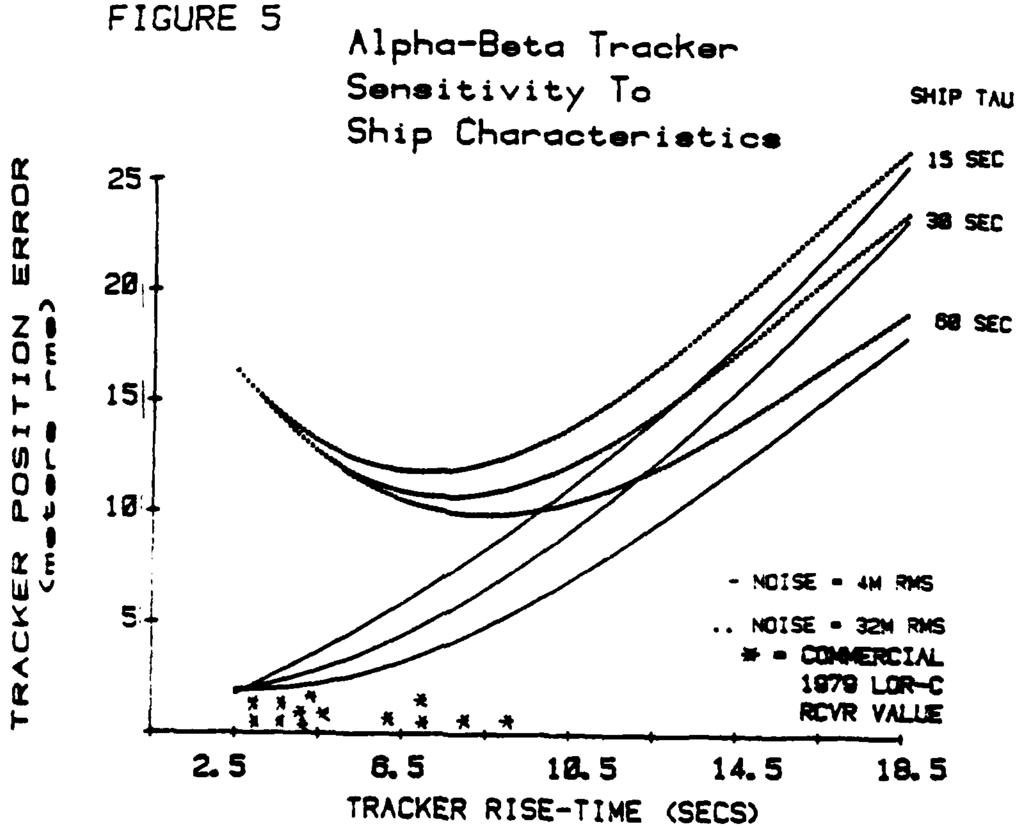


FIGURE 5



The slight differences between along track and cross track error are caused by the turning "error" sources (side-slip and speed reduction) included in the model; both couple primarily into the along-track coordinate.

The minimums in tracker error are caused by the classic tradeoff between signals and noise; at the faster rise-time (wide bandwidth) the tracker passes too much of the noise whereas at the longer rise-time or narrow bandwidth too much of the ship maneuvering signal is suppressed. The minima are the optimum balance between these competing factors. Our practical question asks how sensitive are these minima to the typical range of noise conditions the ship-and-radio aid might encounter. For any practical lower noise level, there is no advantage to decreasing rise time below 2-3 seconds. At the other extreme of noise, there is an optimum in the 8-10 second category.

In Figure 5 we vary ship characteristics over a wide range for a few values of noise level. When operating with rise-times below 10-12 seconds, we would not characterize these results as showing critical sensitivity to ship dynamics. At the maximum rise times tested of 18-20 seconds, this sensitivity approaches 2:1 and will continue to become worse for even longer integration or smoothing times. Also plotted on Figure 5 are the measured rise-times (phase locked loop) of most of the commercial Loran-C receivers on the market in 1979. These clearly show a preference for either the 2-3 second value that minimizes ship-type sensitivity at the expense of maximum noise level sensitivity, or the 6-8 second category that minimizes joint sensitivity--noise and ship-type. Loran-C receivers manufactured for military users before the commercial era (i.e. prior to 1972) generally used a rise time of 20-30 seconds, probably tracing to an original specification. The migration of these rise-times to current values must be based upon practical field experience with many different types of ships and noise conditions. The finding in this simulation study of a similar conclusion as to desirable values lends some measure of validity to the results. It is also interesting to speculate on why random errors to the left of the minimum seem more acceptable than ship-signal errors on the right. Probably the random or jitter error is easily averaged mentally by the observer, whereas signal errors are consistently lagging or overshooting errors and they cannot be averaged--they must be compensated by a dynamic bias in the observer. The operator has considerably more knowledge available to him than the filter (e.g. initiating a turn maneuver) and can make better adaptive use of the fast rise-time or nearly raw information than the systematic lag error. The work of reference 1 will solidify this speculation.

Gyro Aided Alpha-Beta Tracker

The obvious importance of the cross-track error component in our problem, coupled with the availability of gyro compass signals on a great many ships suggests using the heading signal to aid the tracker dynamically. Conceptually the gyro compass senses the ship's turn rate, and this is used to rotate the tracker's velocity vector, $\hat{x}$ and $\dot{y}$. A type of aiding was described in reference 7 and found in field tests to be effective, although its use was not rigorously studied. Recall that we can not depend upon the absolute accuracy of the gyro signal, the gyro aiding must be done such that a calibration error does not degrade the radio aid accuracy. We have also not considered explicitly the effect of the water motion shown in Figure 4, but this constraint implicitly does. Water movement combined additively with vessel motion in the water results in a net motion that cannot be separated from gyro error; true vessel motion is along a course-made-good and not identical to the course being steered and indicated by gyro.

To aid the tracker from the gyro, and exclude gyro errors but include water motion, we must use only the rate-of-change in the gyro signal to estimate changes in ship velocity, its acceleration. These velocity changes can be additively combined with the tracker's estimate of ship velocity for an improved or aided estimate. In Figure 6 the gyro aiding block diagram is shown. It is straightforward to show that there is a transfer function zero between the aiding input to the tracker's velocity estimate and its position output, thus meeting our constraint requirement. The "Resolve" function is

$$\begin{aligned} \Delta\hat{\dot{x}}_{k/k-1} &= \Delta\hat{\dot{\theta}}_k(\sin\hat{\theta}_k)(\hat{\dot{x}}^2_{k-1} + \hat{\dot{y}}^2_{k-1})^{1/2} \\ \Delta\hat{\dot{y}}_{k/k-1} &= \Delta\hat{\dot{\theta}}_k(\cos\hat{\theta}_k)(\hat{\dot{x}}^2_{k-1} + \hat{\dot{y}}^2_{k-1})^{1/2} \end{aligned} \tag{7}$$

The gyro's alpha-beta filter rise-time is not specified, potentially it is another source of a parameter choice. It is inserted to recognize the need to smooth most any measurement for noise suppression, particularly where the derivative estimate of the ship's heading is required. The results of the simulation with this aided filter are seen in Figure 7, position error versus tracker rise-time, parameteric in noise level. Clearly the gyro aiding all but eliminates ship maneuvering from contributing to position error in the cross-track dimension when rise-time is such as to exclude most random noise. This is the right side of the curves when signal error dominates. This value of tracker rise-time, 12-15 seconds, produces a rapid increase in along-track error as a penalty.

The answer to this conflict is to use the coordinate resolution implicit in the "Resolve" function to apply different rise-times in the along track and cross-track coordinates. Using primes to designate the alpha-beta gains for the cross-track coordinates and the rotation matrix, R, the gain matrix in (4) is replaced by

$$\left[\begin{array}{c:c} R^{-1} & 0 \\ \hdashline 0 & R^{-1} \end{array}\right] \begin{bmatrix} \alpha & 0 \\ 0 & \alpha' \\ \beta & 0 \\ 0 & \beta' \end{bmatrix} \begin{bmatrix} R \end{bmatrix} \tag{8}$$

This gain manipulation takes place within the dashed block of Figure 6. It rotates the tracker's updating vector, applies two sets of alpha-beta gains and then combines position and velocity corrections and rotates back to x-y space. When the simulation is run with constant cross-track rise-time a result similar to Figure 7 occurs with the dotted curves essentially straightened out to pass through the points chosen for the fixed cross-track rise-time. The along-track performance remains the same as Figure 7, and the along-track rise-time can be chosen for whatever criteria appropriate. With this form of split gain tracker and a cross-track rise-time of 24 sec, pre-smoothing of the gyro signal can be applied up to a 12 sec rise-time in the gyro tracker without discernible performance change.

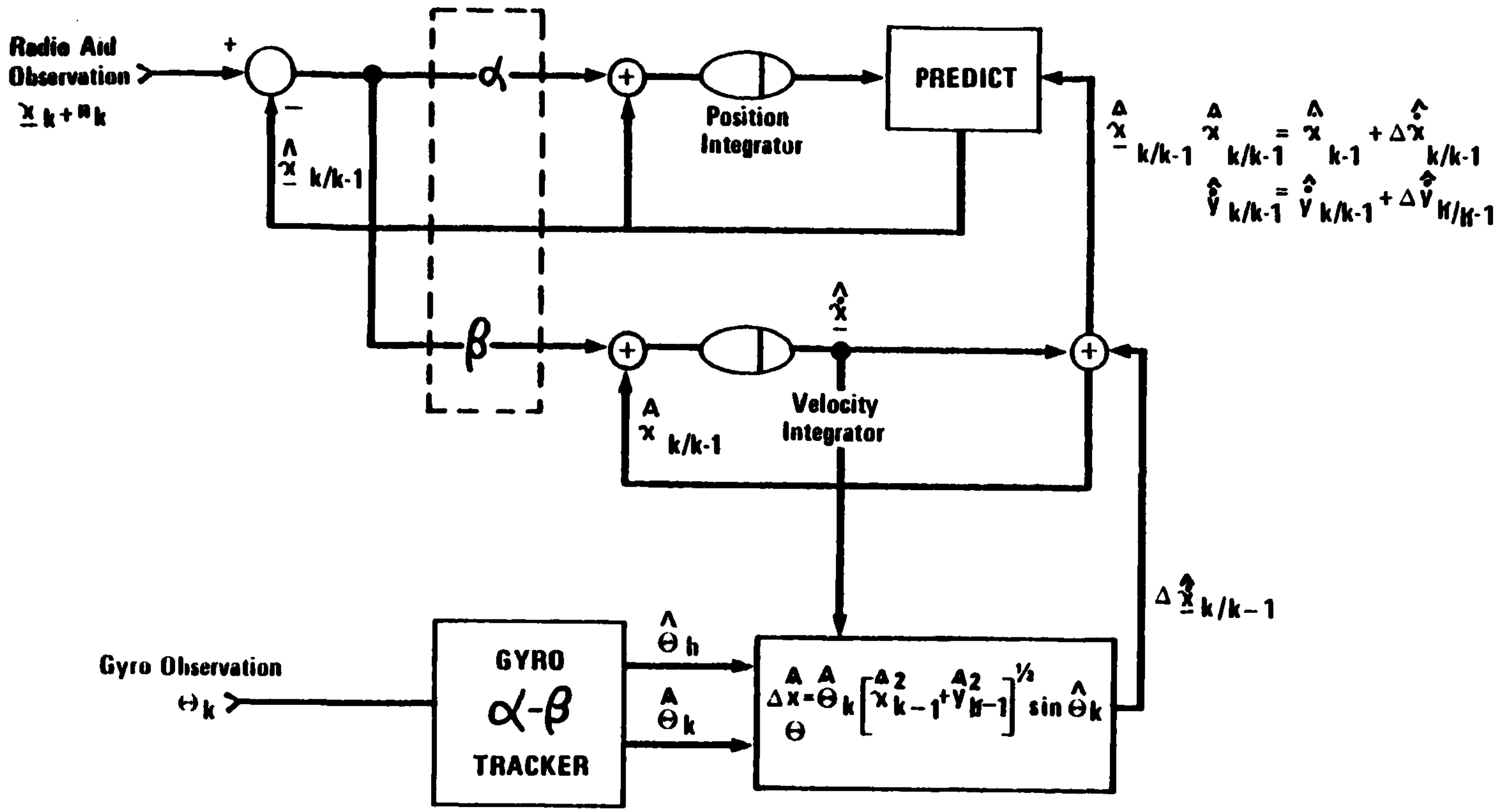
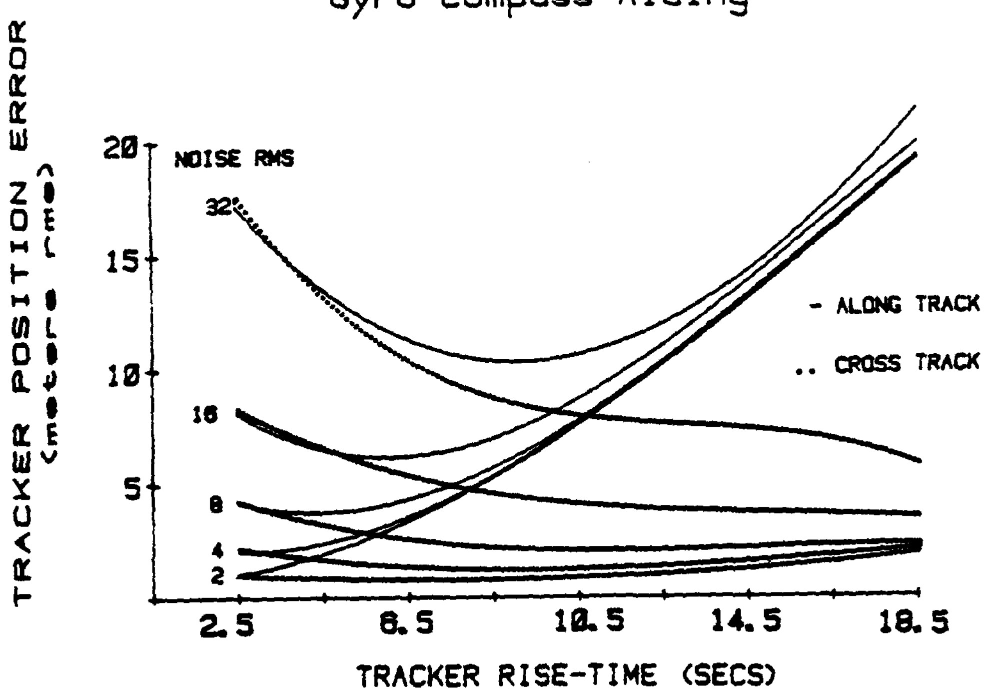


Figure 6
GYRO AIDED ALPHA—BETA TRACKER

FIGURE 7

Alpha-Beta Tracker
Performance with
Gyro Compass Aiding



Gyro and Speed Log Aiding

The logical extension of gyro aiding is the inclusion of similar signals from the ship's speed log. This further increase in complexity actually results in a conceptual simplification. We can process the gyro and speed log independently and combine these sensor's estimate of cartesian velocity with that of the alpha-beta tracker operating on the radio signals. Figure 6 and 8, block diagrams of gyro-only and full aiding respectively appear similar, but differ in important features. When using only the gyro signal, the acceleration is extracted from this and applied as an additive input to the tracker's velocity integrator, i.e. an external estimate of acceleration. For full aiding, an alternate velocity estimation path is created and combined in the main tracker as an external input to the position integrator.

These two architectures both have the important characteristic that neither degrades the ultimate position accuracy of the radio aid. The aiding signals are always combined additively so that bias errors will be removed by compensating internal offsets in the radio tracker. In the case of full aiding, the tracker's estimate of velocity will be the vector sum of gyro/speed-log errors and water motion. As an example of unacceptable architecture, if we were to modify Figure 6 by interjecting a polar-rect conversion after the velocity intergrator delay line:

$$\left(\hat{\dot{x}}^2_{k-1}+\hat{\dot{y}}^2_{k-1}\right)^{1/2} * \cos\hat{\theta}_k \longrightarrow \hat{\dot{y}}_{k/k-1}$$

we would accomplish gyro-only aiding in a manner similar to full aiding. Namely, acceleration would be implicit in θ_k. However, this non-linear transformation within the tracker would destroy our guarantee of no position bias error. A compensating offset could not build-up within the velocity integrator loop to cancel such a bias error.

The simulation performance of full gyro and speed-log aiding is seen in Figure 9. Comparison with Figure 7 reveals essentially identical cross-track performance to that found with gyro-only aiding. The improvements in along-track error are of the same type as cross-track, but not quite as extensive. The reason is the same as the slight difference between along and cross-track performance observed throughout this work; the effects of slide-slip while turning couple mainly into the along-track coordinate. This was explicitly confirmed in this simulation phase by dropping these two aspects of the model (H1 and H2 transformation) and finding nearly identical along and cross-track performance.

Finally, several tests were made with different speed log smoothing time-constants. The previous rule-of-thumb was found valid; when the speed-log and gyro signals were smoothed by with rise-time less than one-half that of the tracker, there was little degradation in overall system performance. The speed log input, however, was somewhat more sensitive to this smoothing than the gyro input.

System Sensitivity

We have seen that full aiding results in the same cross-track error performance as gyro-only, so we can now compare un-aided and aided structures

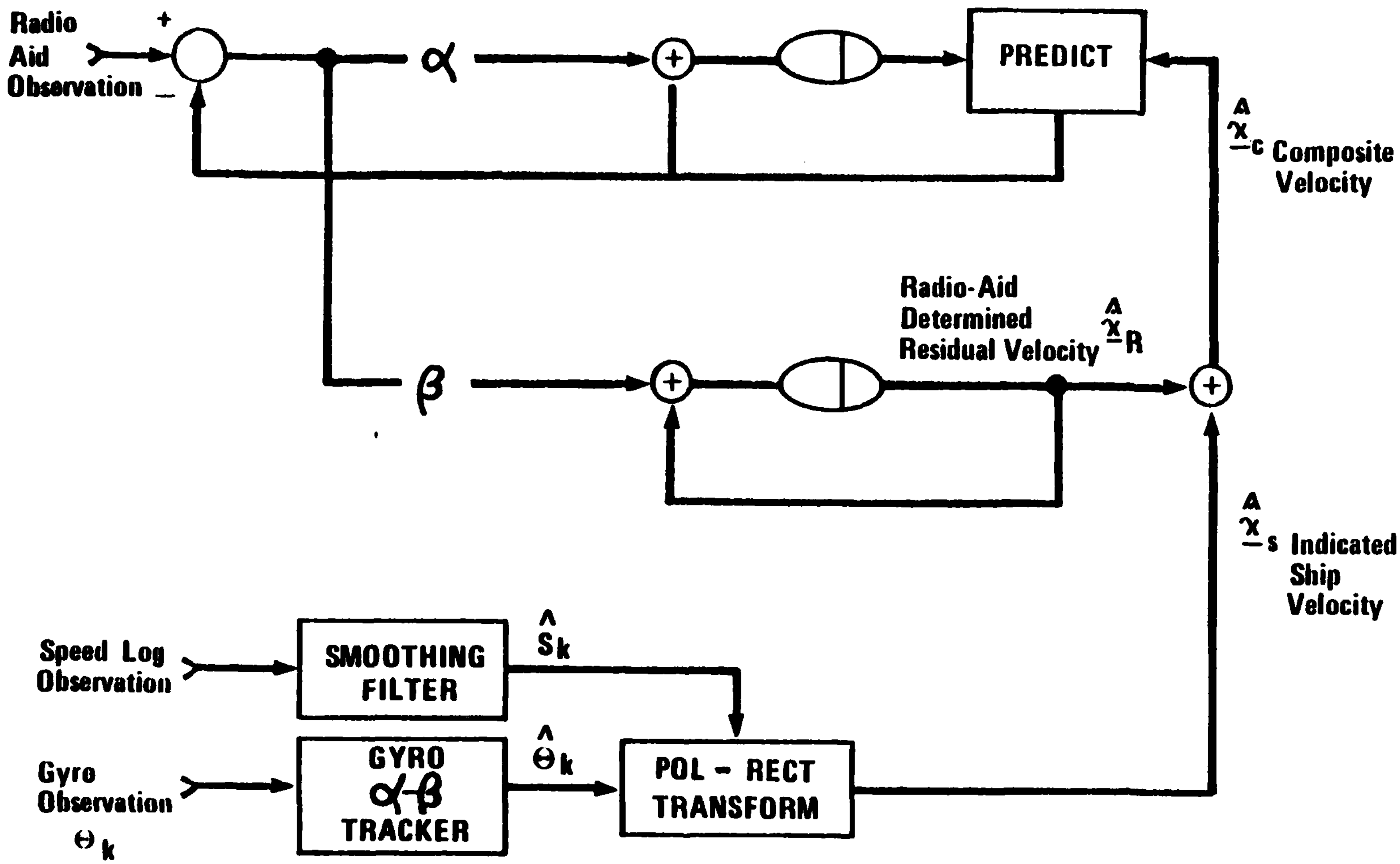


Figure 8
FULL GYRO AND SPEED LOG AIDING

FIGURE 10

COMPARATIVE TRACKER PERFORMANCE ON MID-SIZE MERCHANT VESSEL

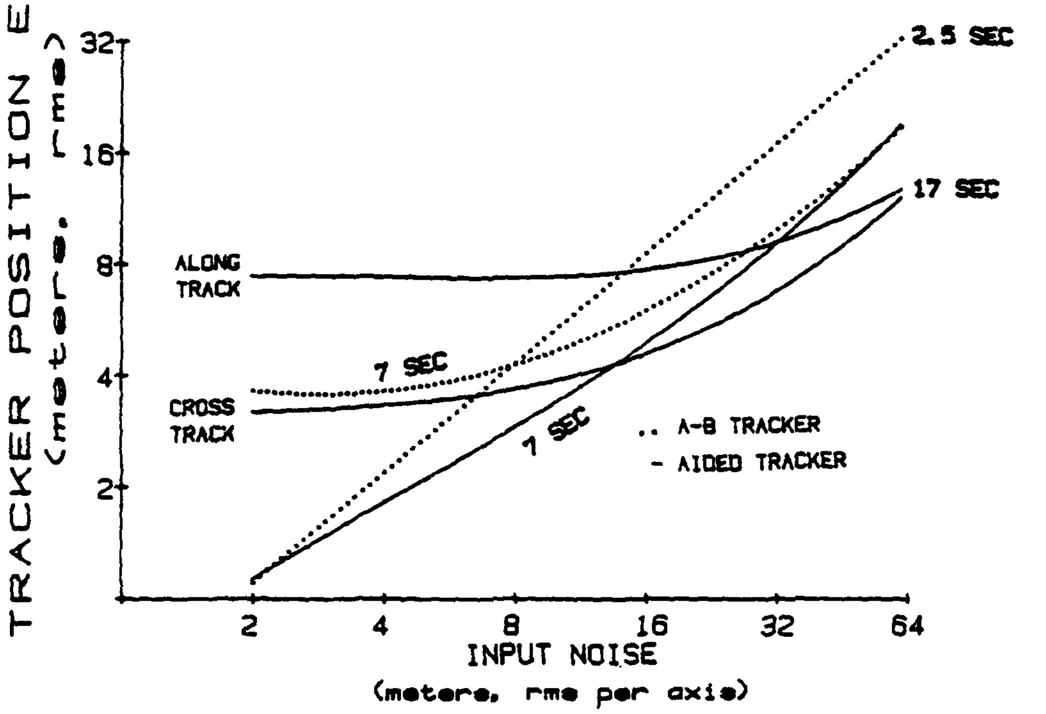
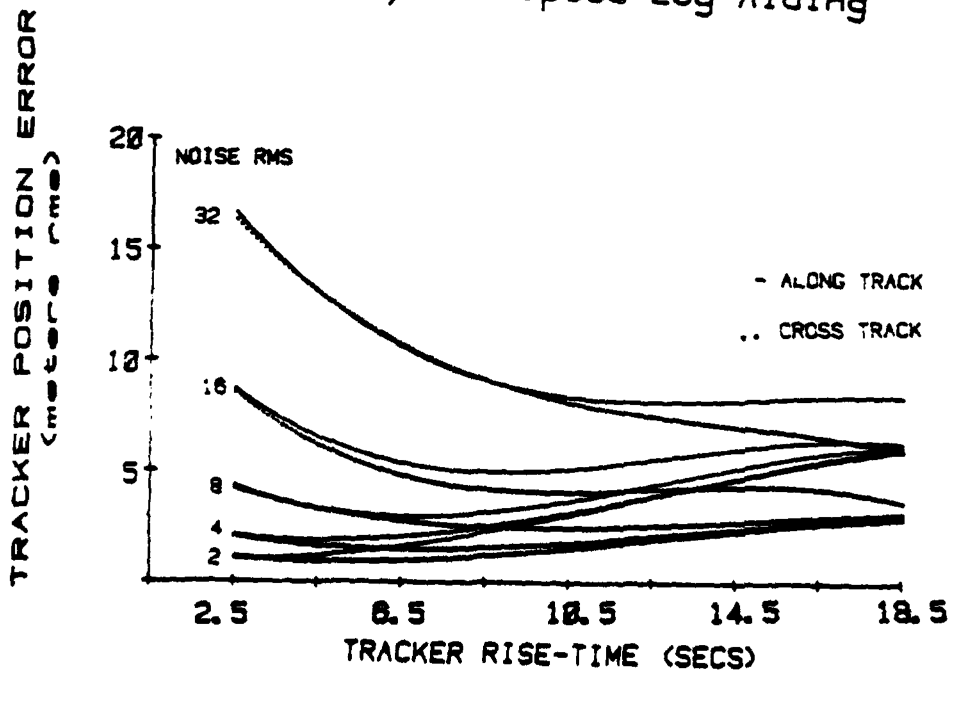


FIGURE 9

Alpha-Beta Tracker Performance with Gyro & Speed-Log Aiding



knowing that we also include the less costly gyro-only aiding. The two most important sensitivity questions to ask are variability under noise conditions,and on different ships. Recall from Figure 5 the distinct conclusion that you might choose from a range of a 3 sec to 10 sec rise-time for an unaided tracker. We use the values of 2.5 and 7 second rise-times as representative of the unaided tracker and in Figures 10 and 11 replot performance as a function of noise level. The "mid-size ship" is our nominal 600 foot cargo vessel, and "small" is reduction of the τ_s and τ_θ by 2/3 to 20 and 10 sec respectively. To translate these noise levels back into the radio aid measurement domain, recall the input noise used throughout this work is statisticaly independent between each one-second sample. A 30 meter rms level for these 1 second samples is about 100 meters observed at the output of a nine-second phase locked loop, or about 0.3 us rms Loran-C time-difference in average gradient conditions. This is a severe noise level for a radio-aid in a precision navigation usage.

The aided tracker with 7 sec rise-time plotted on these Figures is about the shortest rise-time that appears useful from Figures 7 and 9. Clearly it performs better than the unaided under all noise/ship-type conditions, but arguably not all that much better (i.e. is it worth the cost/complexity?). A dramatic change of aided rise-time makes further improvements under heavy noise conditions, but at the penalty of a performance floor at moderate and low noise. (The curves are plots of the cross-track error only--the along-track component does not differ dramatically--except in the 17 sec aided case.) The overall penalties of this tracker's rise-time do not seem worth the noise suppression advantages that accrue only under the worst conditions. We defer a stronger overall conclusion on aiding benefits until the performance of tracker prediction is considered.

Prediction

Prediction of the ship location at some time T in the future is given by (5) in the case of the unaided tracker. For aiding, a similar equation is used for the gyro compass tracker and then this prediction is combined with the radio aid tracker velocity estimate as per the block diagram of Figure 6 or 8. This occurs for each sample and is iterated for T samples, the prediction time. This coupling carries forward the affect of rotation into future position estimates via the use of velocity in subsequent predictions. The net effect of this coupling in prediction is seen in Figure 12; the aiding produces 3-4:1 improvements in position error for the 30 second prediction interval used in the simulation. For moderate (typical) noise levels the improvements due to aiding over a fast rise-time unaided tracker approach 5-6:1. The value of aiding, due almost entirely to gyro aiding, is clearly most important in the tracker's ability to predict future vessel position.

Conclusions

We have considered a portion of a complex control system involving a human operator, a ship in a narrow waterway where high accuracy navigation is essential, and a radio aid-to-navigation to supply that positioning reference. We have broken this control loop to analyze with computer simulation, the role of ship characteristics and radio aid noise, upon positioning error determined from the radio aid after filtering. The filter

FIGURE 11

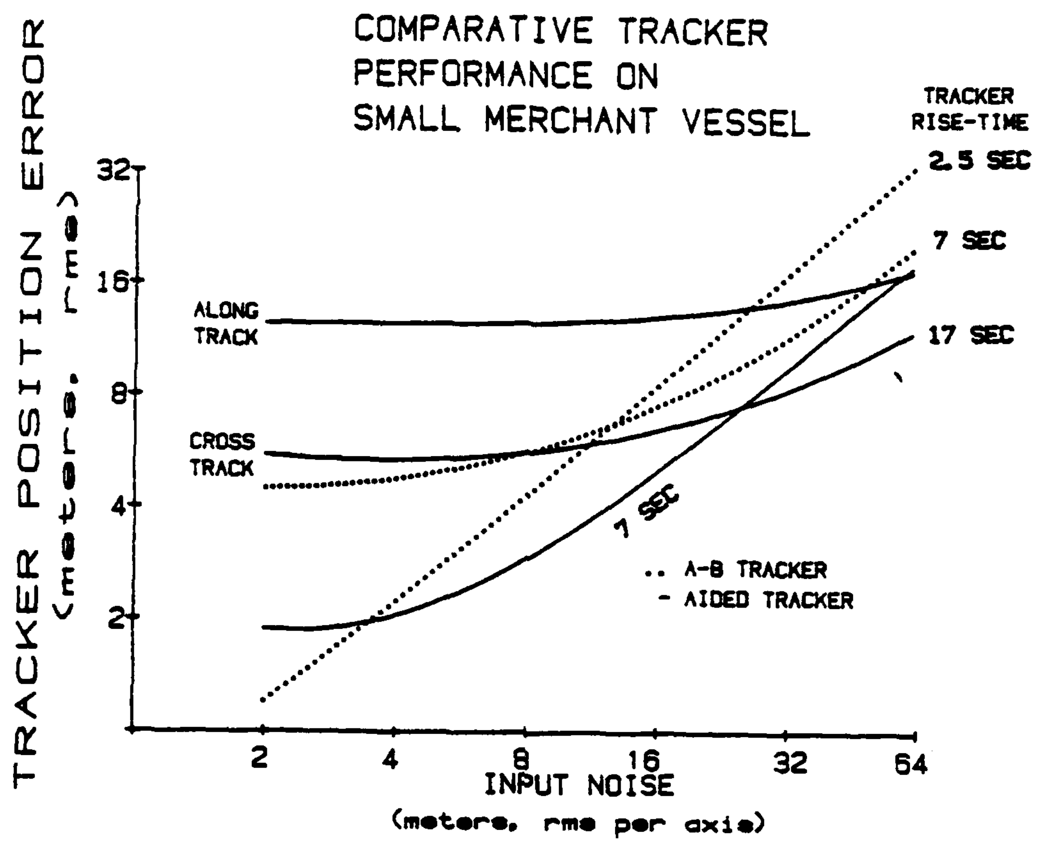
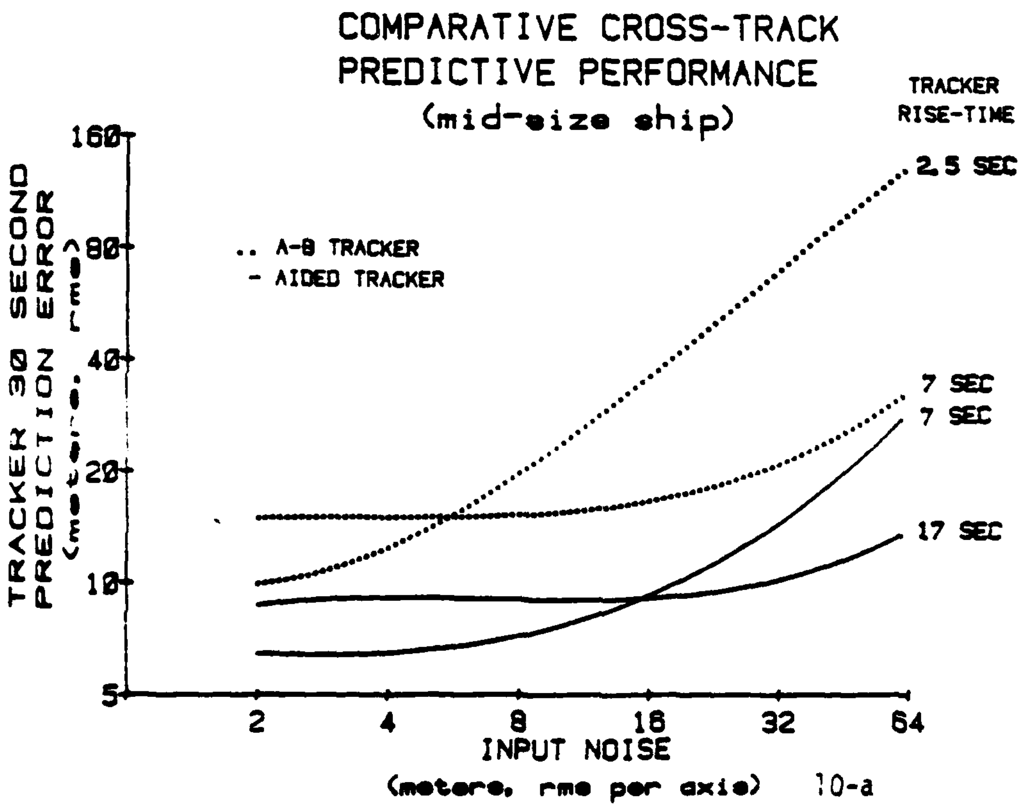


FIGURE 12



structure was restricted to an alpha-beta tracker, operating by itself on the radio aid-plus noise signal, and two forms of dynamic aiding of this tracker from gyro compass and speed-log signals available on many commercial ships. From the many simulation results we draw the following conclusions, which we caveat again with the fact that the role of the human pilot AND the unspecified form of the display of position information is not included:

i) There is no discernible benefit to using an unaided tracker rise-time greater than about 12 seconds.

ii) There is no advantage to reducing that rise-time below about 2-3 seconds.

iii) A rise-time in the 6-8 second category offers the best overall performance stability in the face of changing noise and/or ship-type.

iv) The performance "price" of such a 6-8 second rise-time is a position error "floor" of about 4 m rms for low noise conditions. This floor appears to the pilot as a lag error in indicated position when the ship is maneuvering using low-noise radio-aid signals.

v) Aiding the tracker from the gyro compass is beneficial for almost any condition when a 7-10 second tracker rise-time is used.

vi) Such an aided tracker meets or exceeds the 3-sec unaided performance under low-noise conditions, and similarly meets or exceeds the 6-8 sec unaided performance for high noise.

vii) The use of speed-log aiding is not as distinctly effective as gyro aiding, affecting only the less important along-track error component.

viii) The advantage of the gyro aiding is intimately linked to the implicit modeling of the constant acceleration turn maneuver by the gyro-aided alpha-beta tracker. This aiding structure is well matched to the acceleration signal, hence it is very effective. A similar effect is not obtainable from the speed-log signal with the simple filter structures explored in this work, no obvious method to match the filter to the speed-change signal exists. Most ship maneuvers consist of nearly constant-speed turns, a fortuitous result matching capability to need.

ix) The benefits of gyro aiding, while always positive, never exceed 2:1 and are probably marginal when the only objective function is position error.

x) Good commercial practice, and current research, all show the need for heading display/information to the pilot. Any integrated piloting system utilizing a radio aid-to-navigation can make effective use of this gyro signal within the radio-aid smoothing and predicting filters.

xi) Research in the past five years in complete radio aid guidance systems, that use alpha-numeric and/or graphical displays of pilot information, all demonstrate the benefit of predicting future ship position in improving pilot performance. In this usage, gyro aiding is necessary to obtain performance improvements of 3:1 or more over all ranges of operating conditions.

xii) All of the above conclusions for the several filter-type/parameters choices are relatively insensitive to ship type. Three-to-one reductions of ship response times do not alter the relative advantages of the choices.

Summary

An alpha-beta tracker is, from the viewpoint of modern control theory, an estimatror correctly matched to a "plant" or signal source whose structure is two cascaded integrators. Two such dual integrators represent motion in the x and y coordinates, and are presumed driven by coordinate-independent white-noise signals, the accelerations. Our simple ship model clearly shows that in reality our signal sources are non-linearly coupled at the velocity node, and the driving functions, while they are coordinate independent, are certainly not white (time independent). The autocorrelation of the derivative of the speed signal is exponential in the model, while the turning rate acceleration is correlated over many minutes (the length of time of a turning maneuver). These signal-structure insights do not provide any obvious means to improve the basic tracker. The difficulty in trying to more accurately represent the actual maneuvering accelerations are seen in reference (8), where a very complex adaptive estimator results from modeling the acceleration signals as discrete-level sources. Theory provides no intuitive help or answer to the question, "Can we improve upon the basic unaided marine tracker, which is clearly not correctly matched to real ship-maneuver signals?"

When we turn to the subject of aiding the tracker from external signal sources, we find that a single source can be used only to independently estimate acceleration. Gyro-only aiding was studied for this application; one could use a speed-log by itself in an analogous fashion. In practice one would not use speed-log alone since it does not improve performance in the crucial cross-track error coordinate. Full aiding from both gyro and speed log was demonstrated to be useful in aiding the tracker's velocity signal, although equivalent improved performance could probably be obtained with acceleration-node aiding from both sources.

Finally, the resultant improvement in position estimate error provided by aiding gives us a useful hueristic bound on the question of a better unaided tracker. If full aiding can make only the improvement upon the basic alpha-beta tracker found here, it is very unlikely that any practical change can be made to the unaided unit to significantly improve it (i.e. a better match of estimator to the actual vessel-maneuver signal). Even though we know considerably more about the underlying maneuvering signal structure than is reflected in an alpha-beta tracker, there is little hope that we can safely employ this knowledge. By "safely," we mean in a fashion that is not highly sensitive to assumptions, or sensitive to unmodeled error sources such as might arise in attempts at adaptivity.

These are not pessimistic conclusions; they confirm current good commercial practice (which validates in many ways the ship model and simulation). They support a healthy scepticism towards any radical

departure in basic navigation filters, and define what levels of improvement might be expected from aiding structure that will become more common in the future.

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