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Considerations of Single Long-Range Navigational System Use in the West Atlantic Route System

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16. Abstract

This report presents the results of an investigation into the factors affecting the amount and rate of cross-course navigation error for single long-range navigational system use in the West Atlantic Route System (WATRS) airspace. Included in the analysis were factors such as the rate of single equipment carriage, the type of systems carried on board, and common navigation practice. In general, the east-west routes are shorter than the north-south routes. Recommendations are to operate most of the east-west routes with single equipment and to operate all of the north-south routes with multiple long-range navigational equipment.

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INTRODUCTION

BACKGROUND.

At the North Atlantic/Systems Planning Group's (NAT/SPG) 23rd annual meeting, a United States (U.S.) member presented a paper which reported on the analysis of the Western Atlantic Route System (WATRS). This system, which primarily bears traffic from the North American East Coast to the Caribbean Basin, was examined with respect to the risk of collision with the view toward a reduction in the lateral and longitudinal separation minima. The rationale for presenting this information to NAT/SPG was twofold. First, the very same members of many delegations who sat at NAT/SPG also had influence in decisions regarding changes to this oceanic airspace. Second, NAT/SPG had accumulated a basis of experience with the separation minima that, it was hoped, could be applied in WATRS.

Generally, the report met with success and approval. However, one aspect of the proposed implementation was received with reservation. This area dealt with the routine dispatching of aircraft in this system with a single long-range navigational platform. On the positive side were the facts that the current system had been successfully operated for a considerable time without major mishap nor evidence that the rate of larger navigational errors was excessive. In addition, the time period spent outside of the range of land-based, short-range navigational aids, VHF communications, and radar coverage was not nearly as great as in the North Atlantic (NAT). On the negative side was that, although certain routes are operated under these rules in the NAT, sufficient experience had not been built up in order to generalize that experience; however, the operational experts opined that, in consideration of the NAT, this practice was the exception rather than the rule. In any case, high traffic, minimum separation use of the single long-range navigational systems was not applied.

PURPOSE.

These considerations and additional guidance from the U.S. Flight Standards organization have led to the pursuit of a phased approach to the reduction of separation minimum for WATRS. In the condition where the separations would be equal to those used in the NAT today, it is most likely that redundant long-range navigational systems would be required. A few instances still exist where operations would warrant the use of a single long-range platform. In an attempt to examine some of the arguments supporting these practices, this report will present some of the details associated with these special routes in the WATRS.

DISCUSSION

In general, the common long-range navigational systems used today, and likely in the near-term future, are highly reliable and can achieve relatively accurate positioning. In fact, the accuracy of position is usually not influenced by the number of independent navigation systems carried on the aircraft. Concerns are raised when an aircraft that might be using a sole instrument as the primary reference and with no backup capability loses the function of this system. This

is a remote possibility and, in such a situation, reliance is then placed on the available instrumentation and the navigational ability of the aircrew. Several variables must be investigated in order to fully assess the situation. The principal determining factors that would have an effect on the ability of an aircraft to hold course and on whether or not it would pose a threat to other aircraft are:

1. The expected error of the remaining primary reference, the directional gyro (D.G.).

2. The difference between the actual winds aloft and those used for flight planning and corrections based upon known information.

3. The difference between a great-circle course and a rhumb-line course.

4. The availability of short-range, land-based navigational reference, and other supporting services.

Each of these factors will have an effect on the aircraft's position with respect to intended course and combine to produce a cross-course component which could possibly place an aircraft near another route. If these factors were sufficiently well known, an estimate of the total reasonable cross-course error could be produced. It turns out that some factors are better known than others. Information gathered with respect to the variables will be presented, and a qualitative assessment will be produced.

RATE OF SINGLE-SYSTEM CARRIAGE IN WATRS.

As a part of followup information gathering in WATRS, it was decided to determine the rate of utilization of single versus multiple long-range navigational systems. A survey of the operators within the WATRS was conducted. All the identifiable operators were provided a questionnaire from which responses were assembled with respect to the proportion of traffic an operator exhibited, the fleet of aircraft, and the equipage of that fleet. A sufficient number of responses was received in order to project the equipage across the population. The responses included the major operators, nonscheduled air carriers, U.S. military, and general aviation (business jet) components of the population. The projections are based upon a sample of flight progress data obtained during the high traffic period of late 1985 and early 1986. Table 1 summarizes the projection of single versus multiple long-range systems across the population.

TABLE 1. RATE OF SINGLE VERSUS MULTIPLE LONG-RANGE NAVIGATIONAL SYSTEMS IN WATRS

	Percent of Population	Percent Of Single System Use	Percent of Multiple System Use
Air Carrier	94	52	48
General Aviation	5	13	87
Military	2	0	100
Population		49	51

Note: Table entries are rounded.

The overall rate of single-system carriage in WATRS is approximately 50 percent. This rate is expressed as a function of flights in the system rather than according to the fleet of aircraft.

Different flight regimes and situational demands give rise to roles which are satisfied by an operator's fleet. Many of the operators in the airspace choose to equip an aircraft from its domestic fleet with the navigational systems required for these over-water routes. This provides a maximum flexibility in using an operator's full fleet of aircraft without having to devote a particular subset of fleet to the task. Adequate flexibility may be possible in a dual, long-range configuration with some of the confirmed domestic fleet equipped with these navigational systems, since Omega systems are prevalent.

COMMON NAVIGATION PRACTICE.

Discussions with pilots and other navigational experts indicate that there is common navigation practice which can be used to qualitatively gauge the effects of the loss of a single long-range system. The typical flight plan includes en route positions or fixes which lie between the oceanic entry and exit fixes. These positions are published on charts and are primary way points used for navigation. That is, on a typical flight, the progression is from intermediate point to intermediate point as opposed to flying the entire route via a great circle from entry to exit fix. The fixed reporting way points commonly lie on or very near to the great circle path, but the progression through a series of intermediate points specifically bears on calculation of the cross-course error accumulation.

Also included on the typical flight plan is the magnetic course for each segment. This can be used in the event of the loss of the long-range navigation reference to continue flight. In a normal situation, following the course will result in a parallel track to what would otherwise be a rhumb line between the way points. A common practice then, barring other sources of information, would be to use heading hold and continue by reference to the directional gyro, provided that the decision is to continue to destination rather than to divert.

In addition to other information provided to the pilot for use inflight, the pilot also has zonal wind forecasts for the winds aloft. These provide aloft forecasts varying in consistency and accuracy and must be interpreted during the progress of the flight to provide the best results. Since the various operators use different sources for the predicted winds (e.g., their own base of information and forecasters, the National Weather Service, et al.) and these forecasts vary with respect to their age and the wind information base, it would require substantial resources which are currently unavailable to statistically assess the difference between the forecast and actually experienced conditions. Interviews with experts revealed that prior to the potential loss of the primary long-range navigation reference, the wind component is provided from the navigation instrumentation. This wind component is noted by the pilot and the resulting vector used for flight (exhibited in the heading) is compared to the flight planned heading. Should there be a loss of the long-range navigational system, this difference between the measured wind component and the flight planned heading is applied to the subsequent legs of the flight. Insofar as the actual winds aloft are concerned, it is in some cases possible to use very high frequency (VHF) communications between adjacent aircraft to acquire information with respect to the current situation. The orientation of the principal routes with respect to the major prevailing wind patterns also affects the cross-course component of the wind vector. The prevailing wind pattern for the WATRS is a general west to east flow.

All of these factors contribute to the cross-course deviation when one loses the long-range navigational system. As a result of the experience and judgement that the aircrew brings to the situation, these common practices tend to reduce the deviations over what would be if the aircraft continued the flight holding the present heading. Clearly, when faced with such a situation, the aircrew will apply the maximum available information to the problem and attempt to gain as much information as possible.

A BOUNDING ARGUMENT.

Based upon information obtained from a certification specialist with respect to the level of error associated with the directional gyro, a deterministic approach to bounding the magnitude of the deviations from course was pursued. This section elaborates the assessment of those bounds.

The orientation of any particular route affects the lateral deviation from intended track which will accrue as an aircraft proceeds in a dead-reckoning situation. Significant factors affecting the lateral deviation include the dead-reckoning procedure followed by the aircraft, the general direction of the route, the length of subsequent route segments, the number of turns on the subsequent route segments, and the angular magnitude of those turns. Only the error of the directional gyro and the contribution of the difference between a great-circle and dead-reckoned course are considered here.

For the purpose of this analysis, the dead-reckoning procedure assumes a change in the aircraft's course as the aircraft passes abeam of each subsequent, compulsory fix on the route. For each new leg, the course will equal the rhumb-line course between the current, abeam route fix and the subsequent, next route fix. This rule causes the aircraft to parallel each new leg of the route which will minimize the accrued lateral deviation from route centerline as the dead reckoning proceeds in time. With regard to this intended course, however, the analysis will introduce a predetermined directional gyro compass error in the direction which will cause the aircraft to deviate away from the desired track as the dead-reckoned leg is flown. Additionally, the aircraft will be forced to "lose" long-range navigational ability on the first route segment flown, at the point which maximizes the lateral offset from route centerline when the aircraft later passes abeam of the first segment's end point. This is the worst case, and it will maximize the accrued lateral offset as the entire route is dead reckoned. Thus, the results which follow later in this section are not the expected lateral offsets, in statistical parlance, but rather represent bounds on the offsets which are likely to occur, based on the assumptions.

This analysis includes no errors other than the directional gyro compass error and errors of course plotting as described above. Factors such as magnetic variation (declination), precession, and other directional gyro compass anomalies are second order effects. Also note that the directional gyro is usually slaved to a remote-indicating magnetic compass; this tends to minimize magnetic errors since the flight plans have accounted for magnetic variation. In addition, errors due to winds aloft were not considered for this quantitative assessment.

The rationale behind this approach to the analysis stems from the complexity of the route geometries, the uncertainty of where the aircrew would consider the aircraft abeam of successive route fixes (and thus initiate course changes), and the low probability of single long-range navigational equipment failure. The approach considers the directional gyro compass as the primary instrument for course reference when the long-range navigation platform fails. Thus, after navigation platform failure, the lateral offset from desired route centerline accumulates based on an angular measure; this measure is mainly influenced by the errors in the directional gyro compass.

Typically, the directional gyro compass error is assumed Gaussian in distribution. Based on discussions with an expert certification specialist, the standard deviation of the compass-error distribution equals 2°. Thus, approximately 68 percent (1 sigma) of the single, long-range-navigation-equipped aircraft would exhibit a 2° or less compass error; about 95 percent (2 sigma) of the aircraft would exhibit a 4° or less compass error.

The analysis was performed for the principal routes in the WATRS. For each route in the system, the failing aircraft follows the first route segment until the point on the great-circle track which has maximum deviation from the rhumb line which connects the segment's end points. At this point, the single navigation system fails and the aircraft begins dead reckoning along a rhumb line with a course which will make the aircraft "parallel" the first route segment. In order to force maximum lateral deviation along the entire route, a specified directional gyro compass error will be applied (1 sigma or 2 sigma) and the rhumb-line course will be altered in the direction which will cause the aircraft to deviate away from the desired great-circle track as the dead-reckoned leg is flown.

Once the aircraft is determined to be abeam of the next compulsory route fix, a new rhumb-line course is established based on the rhumb-line course between the currently abeam route fix and the following compulsory fix on the route. Once again, to force maximum lateral deviation along the entire remaining route, the specified directional gyro compass error is again applied (1 sigma or 2 sigma) and the rhumb-line course established for dead reckoning the new leg will be altered in the direction which will cause the aircraft to deviate away from the desired track as the leg is flown. This algorithm then repeats for each new leg as the aircraft passes abeam of the subsequent route fixes.

The net result of this algorithm is to compute a region of angular containment for the expected lateral error. Given the 2 sigma compass error of 4°, one would expect about 95 percent of the single, long-range-navigation-equipped aircraft that experience navigation system failure to exhibit a direction gyro compass error of 4° or less. Thus, by assuming a worst-case position along the first route segment at which the equipment failure is invoked and by always adding the 4° compass error (maximum) in the worst-case direction as far as lateral deviation from route centerline is concerned, the aircraft proceeds along a dead-reckoned track which approximates the maximum deviation expected from the route. At each point along the dead-reckoned track, the lateral offset distance to the desired route centerline is computed. The maximum deviation from each route segment is recorded as calculations are performed iteratively along the dead-reckoned track.

Figures 1 and 2 highlight the major U.S. Coast to Bermuda and New York to San Juan route systems that were considered for this analysis. By studying the route geometries, it may be envisioned that the deviation along a route depends on the direction in which the dead-reckoned track is flown. Losing long-range navigational ability while flying from Priss to Bacus on R12 will show a different maximum lateral offset than when losing navigational ability while flying from Bacus to Priss on R12, for example. Thus, for each route in the systems considered, the analysis was applied by flying the route in both the northerly and southerly directions. Also, to give a feel for the containment of maximum lateral deviations, each route was analyzed with a 2° and a 4° directional gyro compass error.

Tables 2 through 5 present the results of the analysis. The route lengths reflect the great-circle distance which would be flown by aircraft that unerringly navigate the route's centerline between each compulsory fix. They are the sum of the great-circle-arc distances between successive route fixes. The maximum offset shown represents the maximum lateral deviation which accrues as an aircraft dead reckons the route from oceanic entry point to oceanic exit point according to the previously described algorithm. This is the containing lateral offset previously discussed. Table 2 shows, for example, that with a 2° directional gyro compass error, a northerly dead-reckoned flight along R12 (Priss-Swaps-Emary-Lever-Bacus) exhibits a containing lateral offset of 9.27 nautical miles (nmi) as the aircraft passes abeam of the Bacus oceanic exit point. In contrast, a southerly dead-reckoned flight along R12 (Bacus-Lever-Emary-Swaps-Priss) exhibits a 10.17 nmi containing lateral offset as the aircraft passes abeam of the Priss oceanic exit point. Note that tables 2 and 3 present the results for a specified directional gyro compass error of 2°; tables 4 and 5 present the results for a 2-sigma compass error of 4°.

This analysis was performed to highlight some factors which contribute to cross-course error. It did not attempt to produce an expectation of the magnitude of an actual error. If one were to assume that the expectation of a directional gyro error is identically zero, errors associated with course plotting would dominate. In this case, if the aircraft was to proceed point-wise along the routes once there was loss of the single system, plotting errors could account for error on the order of 1 to 2 nmi in cross-course deviation. The use of 1- and 2-sigma values does not necessarily imply that the degree of containment of the outcomes associated with those numbers is the same. It is likely because of the way the problem was constructed that the containment would be better than the associated proportion.

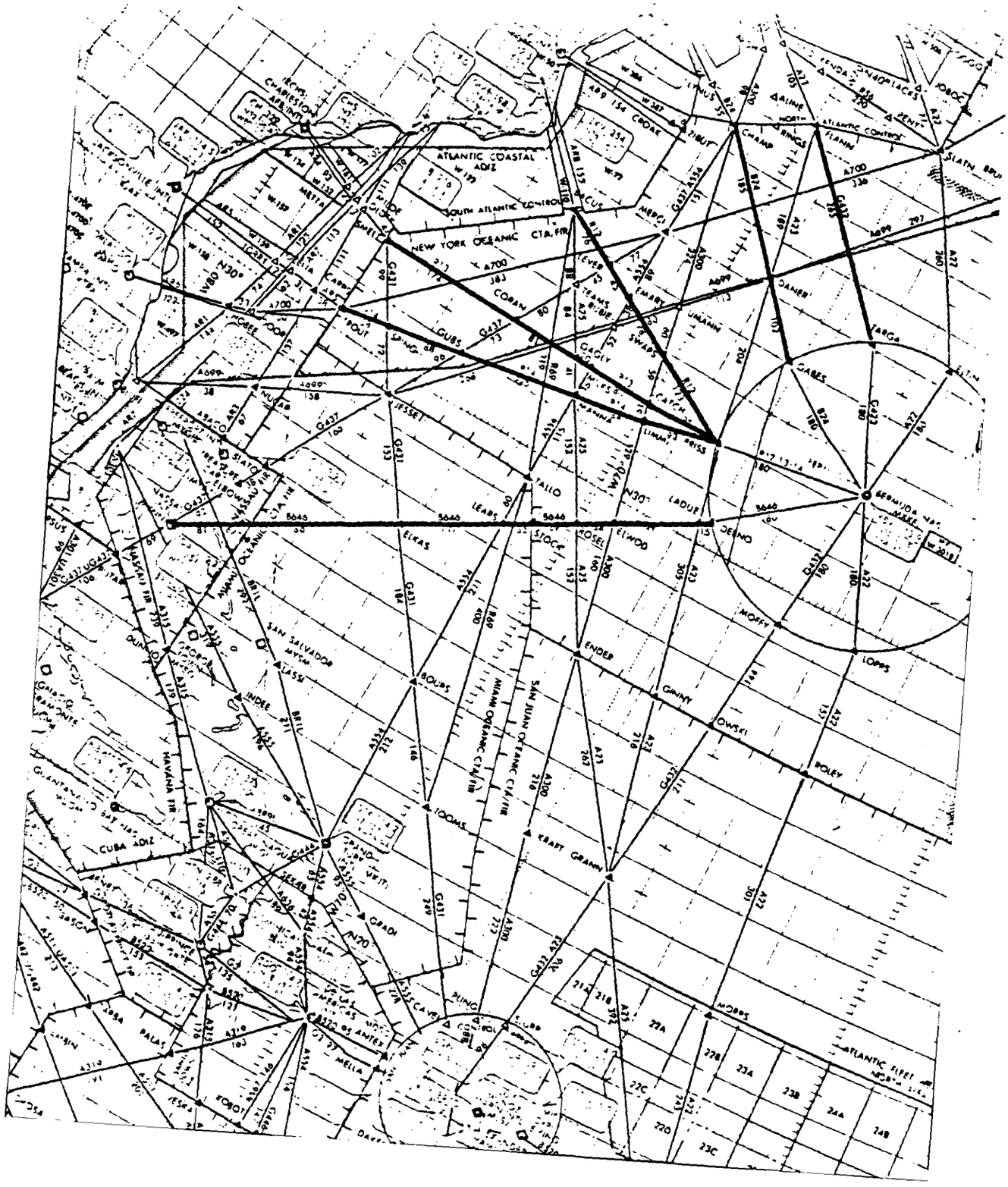

FIGURE 1. MAJOR EAST-WEST WATRS ROUTES

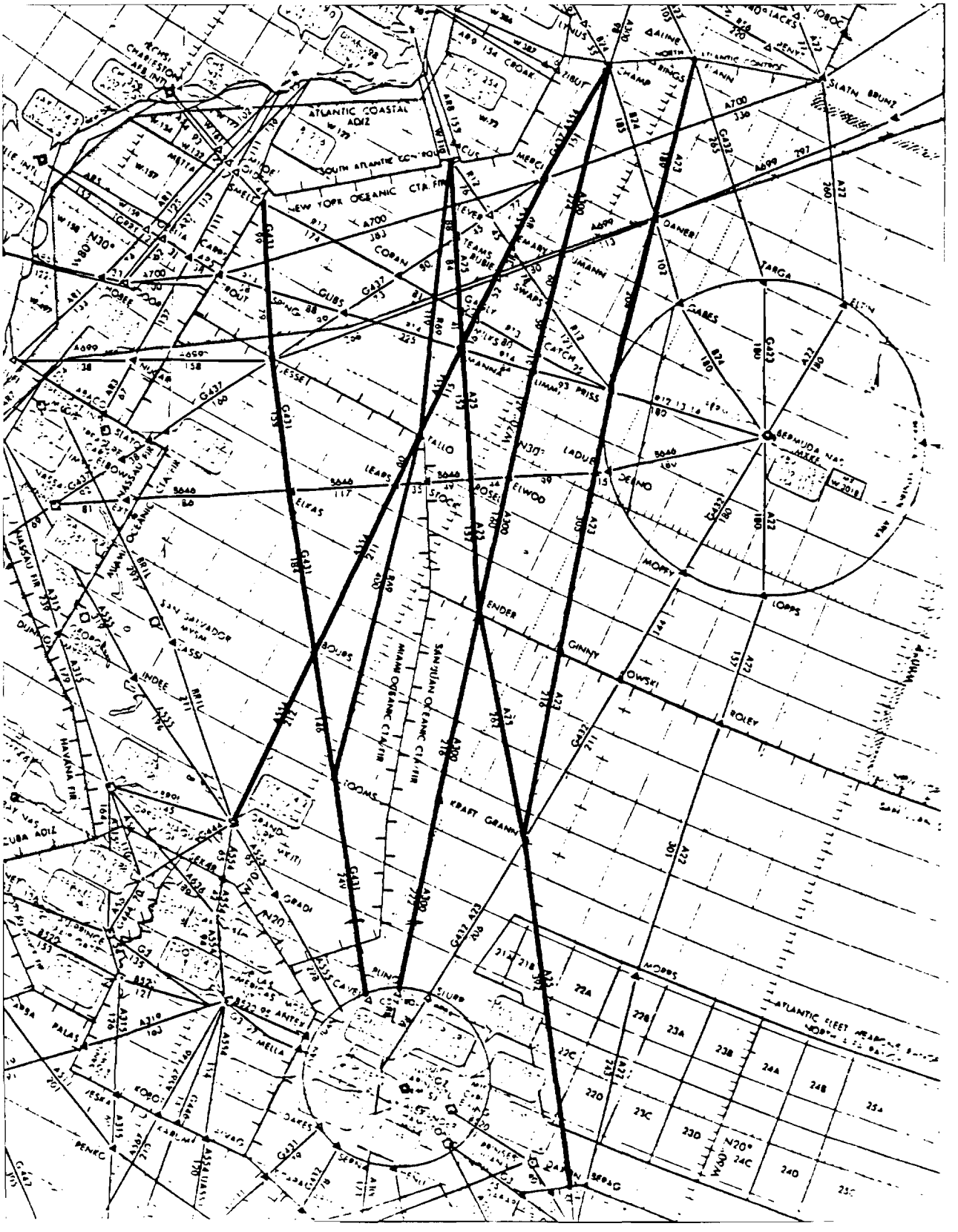

FIGURE 2. MAJOR NORTH-SOUTH WATRS ROUTES

TABLE 2. ESTIMATED MAXIMUM OFFSETS - U.S. COAST TO BERMUDA (2° DIRECTIONAL GYRO COMPASS ERROR)

Route	Route Length (nmi)	Northerly Flight Maximum Offset (nmi)	Southerly Flight Maximum Offset (nmi)
G432	265.2	5.77	6.04
B24	287.2	8.23	7.56
R12	322.2	9.27	10.17
R13	450.0	14.20	4.54
R14	463.3	15.07	14.82
B646	624.2	19.93	22.02

TABLE 3. ESTIMATED MAXIMUM OFFSETS - NEW YORK TO SAN JUAN (2° DIRECTIONAL GYRO COMPASS ERROR)

Route	Route Length (nmi)	Northerly Flight Maximum Offset (nmi)	Southerly Flight Maximum Offset (nmi)
A23	913.3	26.10	30.65
A300	1085.1	31.21	36.66
A554	962.2	27.51	32.97
A25	1172.8	32.35	41.63
R69	718.9	17.64	21.26
G431	908.9	26.34	31.34

TABLE 4. ESTIMATED MAXIMUM OFFSETS - U.S. COAST TO BERMUDA (4° DIRECTIONAL GYRO COMPASS ERROR)

Route	Route Length (nmi)	Northerly Flight Maximum Offset (nmi)	Southerly Flight Maximum Offset (nmi)
G432	265.2	10.25	10.71
B24	287.2	16.23	14.43
R12	322.2	18.18	20.13
R13	450.0	28.08	9.82
R14	463.3	29.96	29.34
B646	624.2	39.62	43.85

TABLE 5. ESTIMATED MAXIMUM OFFSETS - NEW YORK TO SAN JUAN (4° DIRECTIONAL GYRO COMPASS ERROR)

Route	Route Length (nmi)	Northerly Flight Maximum Offset (nmi)	Southerly Flight Maximum Offset (nmi)
A23	913.3	51.92	60.83
A300	1085.1	62.13	72.70
A554	962.2	54.91	65.73
A25	1172.8	63.58	82.77
R69	718.9	34.58	41.44
G431	908.9	52.06	62.49

RELIABILITY OF NAVIGATIONAL EQUIPMENT IN WATRS.

Reliability is the probability that a device, such as a single long-range navigation sensor, will perform within design limits for a period of time under normal operating conditions. A parameter generally defined as the mean-time-between-failures (MTBF) is a measure of the average time at which failures occur. Failures occur at random intervals, and the expected number of failures is the same for equally long operating periods. The function which relates the reliability of a component and time is generally exponential in nature. Figure 3 shows such a relationship between the probability of a failure expressed in hours of operation for Omega equipment.

Generally, it was assumed for this analysis that components will be replaced before deterioration sets in, thus holding the failure rate constant. As a result, the useful life of the component will only be considered, since wear-out reliability depends on the age of the component and usually takes on a Gaussian shape. The MTBF for Omega, inertial navigation systems (INS), and ring laser gyro navigation equipments were obtained from operational personnel and used in conjunction with projected annual flight hours to produce estimates of expected failures. In the WATRS, Omega operations accounted for approximately 96 percent of the single long-range navigation system use in this region. An estimate of the MTBF for this type of equipment is about 6000 hours. INS-equipped aircraft made up the remaining 4 percent of the population. This type of equipment is estimated to have a MTBF of approximately 2000 hours. Although the estimate of the MTBF for the ring laser gyro equipment was substantially greater than conventional INS units, a sufficient base of experience has not been acquired from which to reliably extrapolate. The order of this estimate is 105 hours. Few aircraft in this system use this type of navigation equipment.

For the analysis, results of a survey of principal users in the WATRS with respect to the type of navigation systems on board was used. The flight hours were calculated from flight progress data that were collected during a high traffic period in 1985. Tables 6 and 7 show a linear projection of the annual flight hours on routes within the WATRS region. It should be noted that the data were collected during one of the busiest times of the year for travel in the WATRS, including two holiday periods. As a result, the projected yearly accumulation of flight hours is inflated over the actual case. This leads to conservatism in calculating the expectation of the number of failures. For the analysis, the system was partitioned into the east-west routes serving Bermuda and the north-south routes serving the New York-San Juan corridor.

The apportionment of the flight hours to the different kinds of navigation equipment and on the particular routes is displayed under the headings of INS and Omega in tables 6 and 7. Clearly, the proportion of traffic on the New York-San Juan routes represents the majority of flight hours, along with Omega being the most utilized single long-range navigation system. Although some other types of long-range navigation systems were observed in this airspace, they represented a very small proportion and were not considered principal to the analysis.

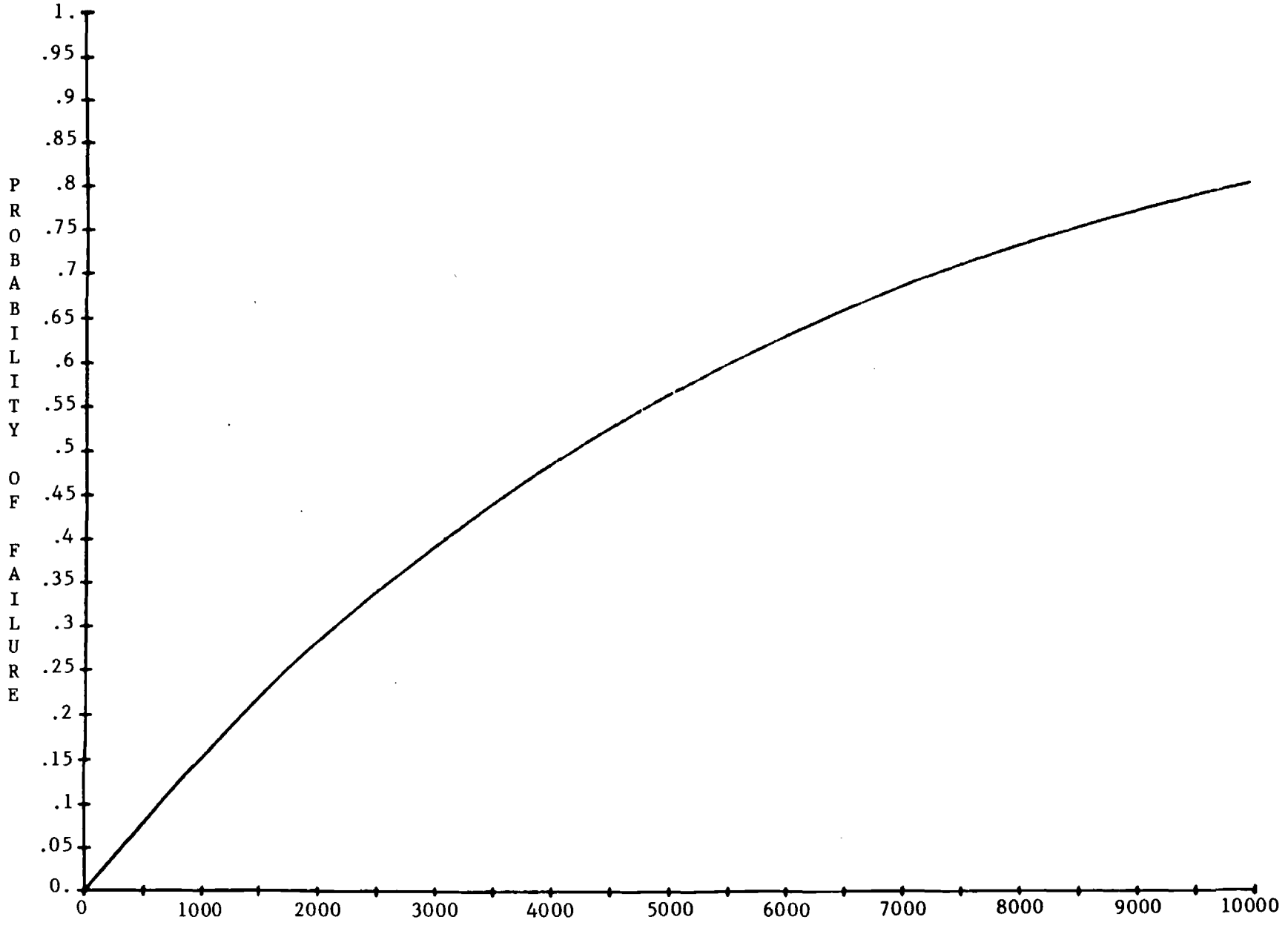

FIGURE 3. PROBABILITY OF FAILURE FOR OMEGA NAVIGATIONAL SYSTEM AFTER HOURS OF OPERATION

TABLE 6. PROJECTED YEARLY FLIGHT HOURS PER UNIT NAVIGATION FOR SINGLE LONG-RANGE NAVIGATION (NORTH-SOUTH ROUTES)

Route	INS	Omega	Total
A23	414	9931	10345
A300	992	23823	24815
A554	635	15243	15878
A25	70	1700	1770
R69	83	1999	2082
G431	131	3156	3287
	2325	55852	58177

TABLE 7. PROJECTED YEARLY FLIGHT HOURS PER UNIT NAVIGATION FOR SINGLE LONG-RANGE NAVIGATION (EAST-WEST ROUTES)

Route	INS	Omega	Total
G432	78	1879	1957
B24	15	353	368
R12	1	21	22
R13	20	504	524
R14	4	105	109
B646	61	1456	1517
	179	4318	4497

For the projections that follow, it was assumed that each flight that accumulated hours in the system did so only by reference to a single long-range navigation sensor. The expected number of failures is derived from the total flight hours per year adjusted to reflect (1) single system use, (2) navigation equipment use, and (3) MTBF of equipment used. These figures are summarized in tables 8 and 9.

TABLE 8. EXPECTED FAILURES PER YEAR (NORTH-SOUTH ROUTES)

Route	INS	Omega	Total
A23	0.207	1.655	1.862
A300	0.496	3.971	4.467
A554	0.318	2.541	2.859
A25	0.035	0.283	0.318
R69	0.042	0.333	0.375
G431	0.066	0.526	0.592
	1.164	9.309	10.473

TABLE 9. EXPECTED FAILURES PER YEAR (EAST-WEST ROUTES)

Route	INS	Omega	Total
G432	0.039	0.313	0.352
B24	0.008	0.059	0.067
R12	0.001	0.004	0.005
R13	0.010	0.084	0.094
R14	0.002	0.018	0.020
B646	0.031	0.243	0.274
	0.091	0.721	0.812

The projections show that the expectation of failures in navigational equipment for the north-south routes is substantially higher than the east-west routes and is directly related to the flight hours. While there is an expectation of less than 1 for the east-west routes, an excess of 10 is expected for the north-south routes. Considerable conservatism was used in making these estimates. The actual number experienced in the system (as it would be if the usage rates of multiple equipment and number of flight hours were accounted more accurately) would be fewer.

CONCLUSION

Estimates have been provided, mostly qualitative and some quantitative, as to what contributes to the cross-course navigational error when an aircraft in the WATRS airspace loses its primary long-range navigational system. Operational judgement is required in order to interpret whether such an event, in frequency and severity, could pose a safety hazard.

For routes which generally have an east-west orientation, several factors argue for their routine operation with a single long-range navigational system in the fleet. These routes in WATRS likely would connect the North American Northeast Coast and Bermuda.

The distance outside of radar range, short-range land-based navigational aids, or direct VHF communications is small and is approximately 350 nmi. The prevailing wind patterns are generally west to east, thus an unknown cross-course wind component which would adversely affect navigation is less likely to occur than for the longer, north-south oriented routes. The relative amount of flight hours is quite small. Flight hours on the east-west routes currently account for less than 10 percent of the overall WATRS operation hours. Given the reliability of the current and near-term future navigation systems, it is unlikely that a failure would occur. The expectation of an event is less than one per year with the current equipment mix and on the basis of the current use. Even if these routes or similar ones were to be certified for single system operations, it is unlikely that all flights would be conducted with a single system.

In the WATRS, for routes which are oriented north-south, there is reason to believe that cross-course error is likely to be greater. First, the time or distance outside of radar, short-range land-based navigational aids, or direct VHF communications is greater and is approximately 1000 nmi. Since the error associated with the remaining primary flight references (the directional gyro) is angular, there would be an accumulation of the cross-course component due to this source. For the north-south routes this could be considerable. Aggravating this is the fact that the prevailing wind patterns produce a greater cross-course component, and while the exact magnitude may be unknown, it can be reasoned that, in comparison to routes with a different orientation (e.g., east-west), the same general wind would have a more deleterious effect on the ability to hold the centerlines. Since the north-south routes bear the bulk of the traffic, considerably more flight hours are expended on these routes. This produces two effects. First, the expectation of a system failure grows in direct proportion to the amount of hours flown. Second, since more traffic is on the routes, the

likelihood of encountering another aircraft in the event of a large deviation would be increased. One factor does tend to reduce the likelihood for total system failure. Since many of the aircraft which use the north-south routes are likely to be used in other nondomestic roles, the proportion of multiple navigational systems on board is greater. Having two or more independent systems on board reduces considerably the probability of total system failures. Thus overall, the general failure rate should be quite small.