NASA TECHNICAL MEMORANDUM

NASA TM X-62,199

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AMES-AIDED INERTIAL NAVIGATION WORK – THE FIRST TWO YEARS OF PROGRESS

Gerald L. Smith

Ames Research Center
Moffett Field, Calif. 94035

April 1973

FOREWORD

This paper presents a brief description of work whose broad objective is to attain improved aircraft navigation performance through exploitation of the concept of combining navigation data from several sources in an optimum manner. The system developed as a result of the work, called RAINPAL (Recursive Aided Inertial Navigation for Precision Approach and Landing) is designed to combine precision radio range measurements with data from on-board inertial sensors to achieve precision navigation for approach and landing. The paper describes RAINPAL and the rationale of its design, and also serves as a sort of planning document, including a progress report, a summary of objectives past and present, and an exposition of reasons for doing the work.

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SUMMARY

The objective of the Ames aided inertial navigation investigation is to show that the Kalman filter aided inertial (KFAI) approach can yield a practical and effective solution to specific complex aircraft navigation problems. The following specific applications have been emphasized.

<u>SSV Application</u>. - Determine the capability of a KFAI-type system, using a commercial inertial navigation system, aided by (1) precision range and/or range rate measurements, or (2) conventional navaid measurements, to provide navigation adequate for automatic landing of the unpowered SSV.

<u>STOL Application</u>. - Develop a KFAI-type system for use as part of a fully integrated guidance, navigation, and control system on STOLAND, and determine the performance attainable and characteristics of the system in typical STOL operations.

<u>SIRU Evaluation</u>. - Support the evaluation of the MIT/SIRU system by providing the navigation segment of a fully integrated guidance, navigation, and control system on STOLAND, using the KFAI principle, and a precision reference system. (This can be achieved via a modification of the systems developed for other applications).

Accomplishments to date are:

1. A versatile simulation program has been constructed, and extensive simulation analysis performed, principally for the SSV application (references 13, 14, and 15).

2. An efficient flight operational program for the SDS920 computer, embodying the KFAI concept, has been produced which also serves as a post-flight analysis tool when used on the laboratory SDS920 (reference 11).

3. The basic routines for the Sperry 1819A computer have been coded and checked out (the input/output and some other routines have not been written). These routines can find direct application in development of a STOLAND navigation system.

4. Analysis of data obtained at WSMR and at Crows Landing indicates that the RAINPAL system with the Cubic Precision Ranging System, is capable of navigation accuracies on the order of a few feet in position and a fraction of a foot per second in velocity, provided that several system problems identified in the course of the tests are resolved (e.g., see reference 16).

5. Work on the SSV application has resulted in great interest by NASA/MSC in the use of a RAINPAL-type system for SSV navigation. Other organizations have also expressed interest, to the extent of using some of the RAINPAL software concepts.

INTRODUCTION

A little over two years ago we undertook to investigate the use of a Kalman filter aided inertial navigation system on the Ames CV340 aircraft. This work was an outgrowth of previous efforts to smooth the range data from the Ames/Cubic Precision Ranging System (ACPRS) using a simple Kalman filter (reference 1) and other filter schemes. These studies showed the desirability of incorporating accelerometer data to obtain reasonable velocity estimates and to eliminate the time lag inherent in schemes using only range data. It was also evident from these studies that, in order to realize the full potential of high quality inertial system accelerometer measurements and the precision range measurements, a sophisticated algorithm ("optimal filter") was required. Otherwise modeling errors would significantly degrade performance.

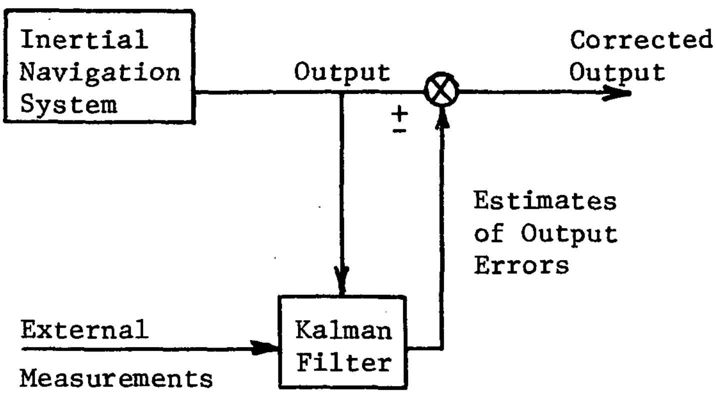
The theory of aided inertial or "hybrid" inertial systems using the Kalman filter principle was already well established (references 2, 3, and 4). A number of actual implementations had also been made, perhaps the most successful being the C5 system (see reference 5). There were several new problems implicit in the Ames application, however. One was that the system was to be at least an order of magnitude more accurate than in any previous application (due to the use of precision ranging data). This implied much greater demands on the software, and also meant that the system would be inherently more sensitive to modeling errors. Higher data rates than in most other similar applications also promised to put greater demands on the software. Another element not present in most previous applications was the emphasis on terminal area operations, including navigation all the way to touchdown. This dictated that the navigation equations be formulated and implemented in runway coordinates rather than in the usual local level coordinates. A further problem was that although the LTN-51 INS we were to use had sufficient accuracy for our application, its input/output capabilities were not well suited to our use. Procurement of a specially designed interface unit was therefore required, and more complex software would be necessary than if we had had ready access to the LTN-51 computer.

At Ames we were in a particularly good position to carry the development of an experimental high grade system through to flight tests because of our possession of the ACPRS, interfaced with a general purpose digital computer of ample capacity on the CV340 aircraft. Furthermore, because of our familiarity with numerous implementations of Kalman filter theory as applied to navigation we were well aware of the problems likely to be encountered and of the approaches and techniques available for the design and construction of the specialized software required in the present application.

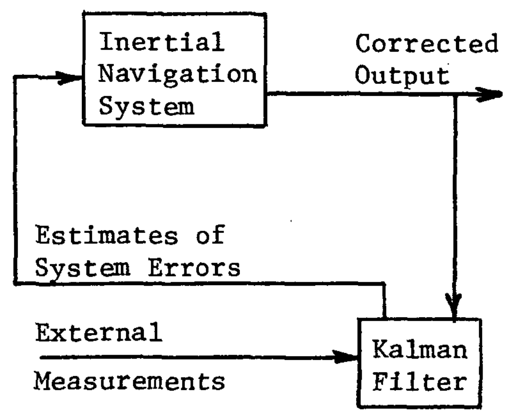
This paper is a progress report covering the first two years of the Ames work. We begin with a tutorial discussion of the Kalman filter aided inertial concept, and its advantages in various applications. Next, we summarize the objectives, past and future, of the Ames work. Then we present a description of the RAINPAL system which we developed as a means of meeting these objectives, a brief history of the development, and the accomplishments of our work to date. We end with a discussion of the prospects for future work.

THE KFAI CONCEPT

The basic Kalman filter aided inertial (KFAI) concept is illustrated in figure 1, which is borrowed from reference 8.



(a) Feed-forward configuration



(b) Feedback configuration

Figure 1 - KFAI Systems

Two possible configurations for the Kalman Filter are discussed in reference 8. They are shown in figure 1. In the feed-forward configuration (a) the inertial navigation system (INS) provides "free inertial" estimates of vehicle position and velocity. The external measurements ("aiding" data) go into the Kalman filter and are compared with estimates of these measurements derived from the free inertial estimates. The difference quantities are weighted, using statistics of the measurement errors and the free inertial errors, to obtain estimates of the latter errors, which are then used to apply corrections. In the feedback configuration (b), used in this study, the Kalman filter estimates, not just output errors, but errors internal to the INS, and applies corrections directly to the INS. In other words, the feedback configuration performs an INS "alignment" rather than simply correcting its output.

The feedback configuration is better than the feed-forward in regard to accuracy because INS errors are corrected within the system, thereby keeping them samll and assuring linear behavior in error propagation so that the filter can operate more effectively. It also permits the feedback correction of any sensor errors (i.e., gyro drifts, accelerometer biases) which may be estimated by the filter. The disadvantages of this configuration are that it does not provide an independent free inertial output (which might be desirable if it were possible for the Kalman filter to malfunction), and does not lend itself to "tacking on" a Kalman filter to an existing INS. However, there are other ways to provide an independent free inertial output as will be described in the sequel.

The principle of the KFAI concept is the same as in any aided, "augmented", or "hybrid" inertial system; namely, with no external data the system operates in a free inertial mode, but when aiding dada is available, corrections are applied. The difference between Kalman filter aiding and other types of aiding is mainly one of sophistication. For instance, the Kalman filter uses time-varying weightings based on flight kinematics and system error models, whereas other filters use fixed or programmed weightings usually determined heuristically. In the Kalman filter weightings are automatically adjusted for such variations as sensor outages and arbitrary measurement schedules.

Another very important feature of the Kalman filter is that it provides for estimating significant auxiliary variables (such as platform tilts and sensor biases) which cannot be treated in a natural way in any other type of aided system. The result is that better performance is obtainable because error sources are better modeled and the system is more versatile.

It is commonly believed that the Kalman filter approach is excessively complicated, that simpler approaches such as the complementary filter can do an adequate job. Partly, this belief stems from an aura of mystery which surrounds the statistical estimation theory on which the Kalman filter is based. The actual fact is that when the navigation task is a simple one the Kalman filter equations are relatively simple. For example, the navigation filter designed by Sperry for the STOLAND system is relatively simple, but a Kalman filter to serve the same function would be equally simple (in fact, it would have very nearly the same structure) as long as one were satisfied with the assumptions and approximations implicit in the Sperry design. The advantage of the Kalman filter approach over the heuristic approach used by Sperry is that the assumptions in the former case would be explicit, and shortcomings of the filter could be more readily explained and rectified.

When the navigation task is a demanding one, there is no such thing as a "simple" design. Any simplistic approach will quickly bog down in a morass of auxiliary logic and equations, whereas the Kalman filter approach provides a theory-based synthesis procedure for the orderly design of the complex software required. The net result is that the design based on the Kalman filter theory is likely to be the simplest possible system provided that good judgement, based on considerable practical experience, is employed in the application of simplifying approximations.

POTENTIAL APPLICATIONS

The KFAI concept is so general that it can be applied to a broad range of aircraft navigation provlems. Our interests, however, are in those problems with the greatest payoff. One or both of two characteristics should be present in order to make the approach worthwhile. The problem should be such that (1) high precision is required, and/or (2) the navigation task is highly complex.

Problems having the first characteristic include:

a) Navigation for category III landings, such as would be required to provide all-weather capability for any type of aircraft, or for automatic landing of such vehicles as the unpowered SSV. In these applications high precision close to touchdown is paramount, but can be relaxed for earlier segments of the trajectory.

b) Navigation for 4-D guidance or for two segment approach guidance, which is required for high density short haul air transport applications (reference 9) or noise abatement. Here, close control of the aircraft trajectory is required over a much longer period of time than in the type (a) applications.

c) Navigation to provide a precisely known aircraft trajectory for reference purposes, for use in evaluation of other navigation systems and sensors, and for a variety of research tasks. This application has the highest requirements for accuracy. Ultimately, depending on the specific use, one shoud strive for the maximum precision theoretically attainable from the data types utilized by the system.

Problems having the second characteristic are those in which a variety of data types must be handled, the measurement geometry changes markedly, the sensor outages and bad data must be coped with. Such factors are prominent in approach and landing navigation for all types of aircraft, and for enroute navigation as well in V/STOL applications.

Complex navigation tasks are best exemplified in integrated avionics systems. Here, all navigation data is brought to a central computer for generation of integrated displays for the pilot and computation of a state estimate to drive an autopilot. The ideal method of combining all types of data to produce these outputs is a Kalman filter algorithm. Only this approach has the flexibility and versatility necessary for the task. An ability to apply reasonableness tests to each measurement type, edit bad data, and generate warning signals for malfunctioning sensors is essential in an integrated avionics system, and the Kalman filter algorithm also lends itself quite well to this function. It should be pointed out, too, that automatic transition from one data type to another, as in typical area navigation or terminal area "window" problems, is quite simple using Kalman filter algorithms. In principle, navigation for an entire flight, incuding takeoff, climb, enroute, terminal area, approach, landing and roll-out can be accomodated in a single KFAI algorithm.

OBJECTIVES OF AMES WORK

The following outline of objectives includes the original objectives of the Ames work two years ago and additional objectives which in the course of time have been identified as being reasonable, given sufficient funding and manpower. The success in meeting these objectives to date, and the prospects for the future, are summarized in the following two sections.

A. Generate design information for advanced navigation. - Show that the KFAI approach can yield a practical and effective solution to specific complex aircraft navigation problems.

   1. Develop techniques for the efficient implementation of KFAI systems, particularly at the software level (e.g., the "squareroot" filter, time-sharing computation logic, synchronization of digital subsystems, initialization or "in-flight alignment" routines, data preprocessing, etc.).

   2. Discover, by flight testing an experimental system, those operational and error modeling problems which are inevitably overlooked in analysis.

   3. Obtain subsystem performance information and design experience, necessary for the preparation of specifications for navigation sensor/systems and for estimating development costs.

B. SSV application. - Determine the capability of a KFAI-type system, using a commercial inertial navigation system, aided by (1) precision range and/or range rate measurements, or (2) conventional navaid measurements, to provide navigation adequate for automatic landing of the unpowered SSV.

C. STOL application. - Develop a KFAI-type system for use as part of a fully integrated guidance, navigation, and control system on STOLAND and determine the performance attainable and characteristics of the system in typical STOL operations. This system, although similar to RAINPAL in principle, will be more complex because STOL operations require: (1) navigation over a longer trajectory, including take off and enroute phases as well as approach and landing; (2) processing a greater variety of data types, including provisions for automatic switching; (3) coping with greater uncertainties in sensor error models; and (4) incorporation of a wind estimation capability.

D. SIRU evaluation. - Support the evaluation of the MIT/SIRU system by providing the navigation segment of a fully integrated guidance, navigation, and control system on STOLAND, using the KFAI principle. (This can be achieved via modifications of the systems developed under the A and C objectives to provide for SIRU inputs and the KFAI porcessing of SIRU data). Such a system can also serve as a precision reference system onboard the CV340.

THE RAINPAL SYSTEM

Description. RAINPAL is an acronym for Recursive Aided Inertial Navigation for Precision Approach and Landing. It is the name which was given the system developed to meet objective A (see preceding section), and subsequently modified to partially meet objective B. The system is shown in block diagram form in Figure 2.

In the RAINPAL system the LTN-51 INS is used primarily as an inertial measurement unit (IMU). Outputs of the accelerometers are processed in the International Imaging Systems interface (IIS I/F) to obtain digital ΔV words. In the SDS 920 computer these are transformed from platform into runway coordinates (T) and then used in the navigation equations to obtain position and velocity estimates. The transformation T is continuously recomputed from the best estimate of the aircraft position.

External measurements, which in the present RAINPAL system consist of range measurements from the ACPRS and altitude measurements from both a barometric and a radio altimeter, are processed in an 11-state variable Kalman filter to obtain corrections for (a) the position and velocity estimates, (b) the transformation T, (c) the vertical accelerometer bias, and (d) the baro altimeter bias. Not shown in figure 2 are a variety of output functions (for monitoring and recording purposes).

It can be seen from Figure 2 that the RAINPAL system does not apply corrections to the LTN-51 INS. Nevertheless, it is essentially a feedback configuration like that of Figure 1(b). The navigation equations and transformation computations in the SDS920 constitute a complete INS (except for the acceleration measurements), and corrections are made to this system rather than to the LTN-51, whose computations are ignored. This arrangement was chosen for RAINPAL because it allowed us to add our system to the existing LTN-51 without interfering with its normal independent operation. The alternative would have been to reprogram the LTN-51 computer and probably also to add new input/output capabilities, which would have entailed substantial technical risks.

The price we paid for using this approach was that we had to duplicate many of the functions already performed in the LTN-51 computer, and we had no control over torquing of the LTN-51 platform. However, in return we gained a degree of flexibility which may not have been available to us otherwise, by having all of our computations in the more readily accessible and more versatile SDS 920 computer, a highly desirable feature in an experimental system of this sort. Examples of this flexibility are: (1) we are able to connect to any INS, including strap down systems, with only modest modifications;

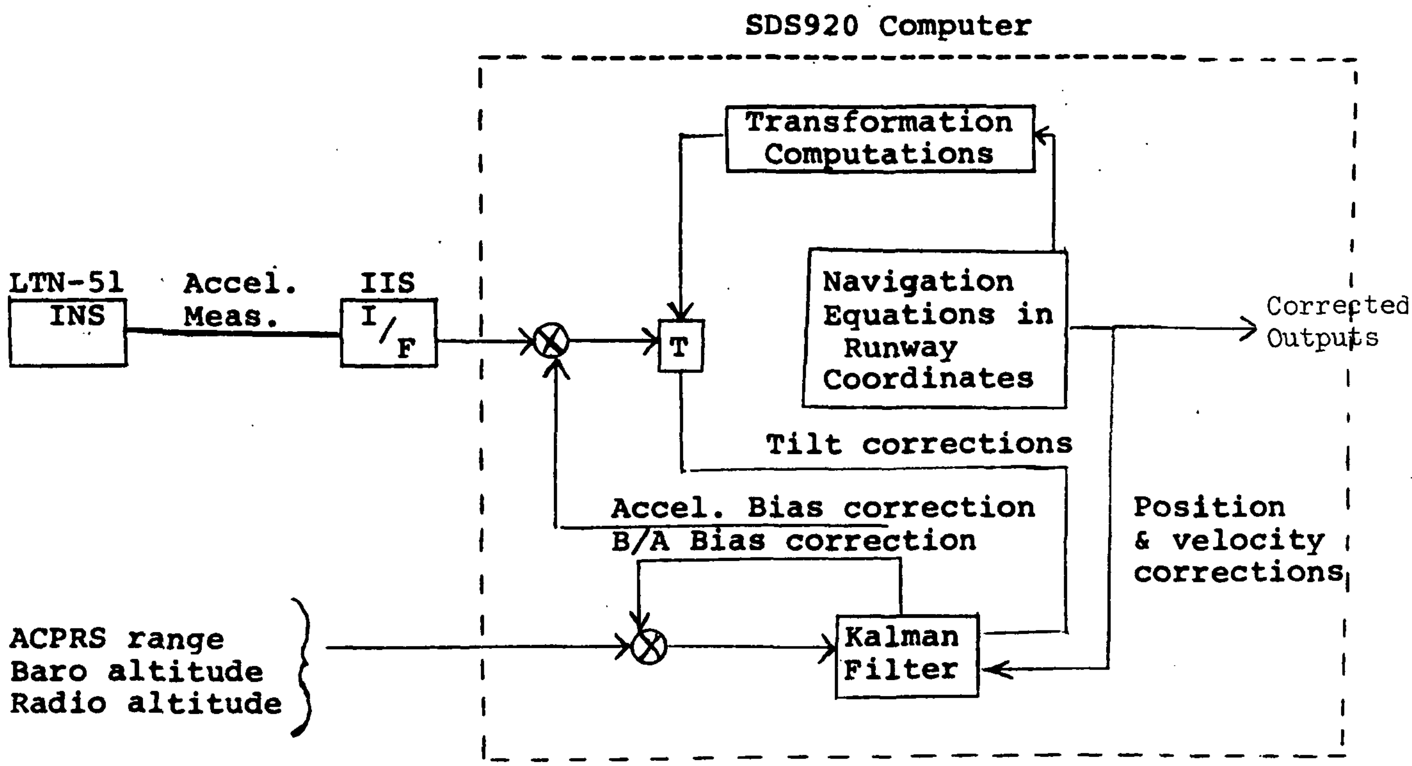


FIGURE 2 - RAINPAL SYSTEM

(2) we can use our on board program as a post flight analysis tool on the laboratory SDS 920; (3) we retain an independent free-inertial capability along with the aided-inertial solution.

The RAINPAL program for the SDS 920 duplicates the navigation equations of the LTN-51, but uses earth fixed local tangent plane coordinates instead of local vertical coordinates. This coordinate frame is particularly convenient for approach and landing problems because its origin can be chosen to coincide with a target point on the destination runway, which minimizes scaling problems when the navigation equations are coded for a fixed-point computer. It may be noted that the same scheme could be used if the application of the RAINPAL system were extended to enroute or area navigation, simply by changing the origin of the coordinate frame to suitable stored way points from time to time.

History of Development. At the outset, some two years ago, our intent was simply to prove the KFAI concept (objective A) by building a precision approach and landing navigation system for the CV340 using components already on hand. The only new equipment needed was an interface to bring data from the LTN-51 INS into the SDS920 computer. For assistance in the formulation of equations and development of software, we sought the services of Stanley F. Schmidt, (AMA, Inc.), whose experience with the C5 system (reference 5) we knew would be immediately applicable and thus give us a head start in the development.

However, to obtain funding for the AMA contract and for procurement of the LTN-51/SDS920 interface, we adopted an additional objective (B in the previous section). This required that we do some extensive simulation studies of the SSV problem, instead of restricting such studies to more limited CTOL approach and landing situations. Also, plans were made to implement a RAINPAL system on the CV990 aircraft so that the system could be tested for trajectories more like those of the SSV. This required that a RAINPAL algorithm be coded for the Sperry 1819A computer, and to accomplish this an extension to the original AMA contract was negotiated.

Substantial delays were experienced in procuring the LTN-51/SDS920 interface, which handicapped us by requiring us to begin our flight testing with a preliminary version of the RAINPAL system which used body-mounted accelerometers. Also, our original flight test schedule was accelerated due to difficulties in scheduling range time at White Sands Missile Range (WSMR) and a desire to obtain results for the SSV objective as quickly as possible. The result was that we did not have time to carry out as complete a system check out as desired before the WSMR flight tests.

Another change was occasioned by the decision to install the AROD ranging system on the CV340 for the WSMR tests and to carry out a one-week preliminary test at WSMR. The added effort included modifying the RAINPAL software to handle the AROD data, installing the equipment, operating the system, and reducing the AROD data.

The CV340 flight tests at WSMR (preliminary tests in September 1971, full scale tests in January 1972, see reference 10) were for the purpose of providing an independent trajectory determination from the WSMR cinetheodolite data for evaluation of RAINPAL navigation performance. The CV340 system was not really ready for these tests since insufficient time had been allowed for validation of the system in local flight tests. However, the tests were adjudged reasonably successful, with large quantities of data recorded for post flight analysis.

Since the WSMR tests, time has been spent in analyzing some of the best of the data and preparing two papers for the 1972 JACC (references 11 and 12). Just before the CV340 left Ames (mid April) some final flight tests at Crows Landing were made to check out a fix for an accelerometer bias problem discovered in the course of earlier flight tests.

In the meantime, coding for the 1819A computer was proceeding. Delay of the CV990 flight tests resulted in our not being able to check out the 1819A program with inflight recorded data by the end of the AMA contract period (July 30, 1972). This together with a truncation of the planned CV990 tests, dictated that the RAINPAL system not be flown on the CV990.

Accomplishments to date. - The major accomplishments of the past two years of work may be summarized as follows:

1. A versatile simulation program has been constructed, and extensive simulation analysis performed, principally for the SSV application (references 13, 14, and 15).

2. A flight operational program for the SDS920 computer, embodying the KFAI concept, has been produced which also serves as a post-flight analysis tool when used on the laboratory SDS920 (reference 11). This software, which incorporates several innovative ideas (including efficient square-root covariance computation routines, time-sharing logic for data processing at a variable rate, and a novel formulation of the filter equations), demonstrates an advanced level of technology in the application of filter theory to aircraft navigation problems.

3. The basic 1819A routines have been coded and checked out, (the input/output and some other routines have not been written). These routines can find direct application in development of a STOLAND navigation system.

4. Analysis of data obtained at WSMR and at Crows Landing confirmed the predictions of simulation studies indicating that the RAINPAL system is capable of navigation accuracies on the order of a few feet in position and a fraction of a foot per second in velocity, provided that several system problems identified in the course of the tests are resolved (e.g., see reference 16).

5. Work on the SSV application has demonstrated that a RAINPAL-type system could provide the navigation accuracy required for landing the SSV. NASA/MSC interest in this work has resulted in their mounting a continuing effort for evaluation of this approach. Also, they have an interest in the use of a precision ranging system as a reference for navaid evaluation, if not for SSV navigation, and have contracted for procurement of a new system from Cubic. Another spin-off of our work is that certain of the RAINPAL implementation concepts are now being incorporated into the Air Force's CIRIS development (reference 7).

THE FUTURE

The success we have had in our work to date, and everything we have learned in the process, convinces us that the KFAI application to aircraft navigation is a part of the "wave of the future". We feel that Ames has made, and should continue to make, a significant contribution to this future.

There is still widespread resistance to the idea of using inertial sensors and sophisticated computer software as integral parts of civil aviation systems because of fears of reduced reliability and higher costs. However, increasingly sophisticated avionics are going to be required to meet requirements for reliable performance of the increasingly complex aviation systems of the future. Significant technological advances are needed to meet these requirements. For navigation, guidance, and control specifically, low-cost inertial sensors are an obvious solution, and these are forthcoming. Equally if not more important are means for utilizing the inertial sensors and other subsystems efficiently and reliably.

It is in the latter area (specifically, the effective utilization of data from navigation subsystems) that we have achieved significant advances. We have made only a start, however, and there seems every reason for us to continue towards full realization of the objectives stated earlier, and even look beyond these to a full exploitation of the technology advances we will then have produced. A brief rundown on the work we envision for the future follows.

Objective A. - Realization of the original basic objective has at this time been about 80% achieved. Things that remain to be done to bring this aspect of the work to fruition are the following:

1) More complete documentation, so that we can better communicate our achievements, and at the same time record them for our own use;

2) Improvements in the CV340 avionics system so as to more nearly realize the full potential of the system (see Appendix B in reference 17);

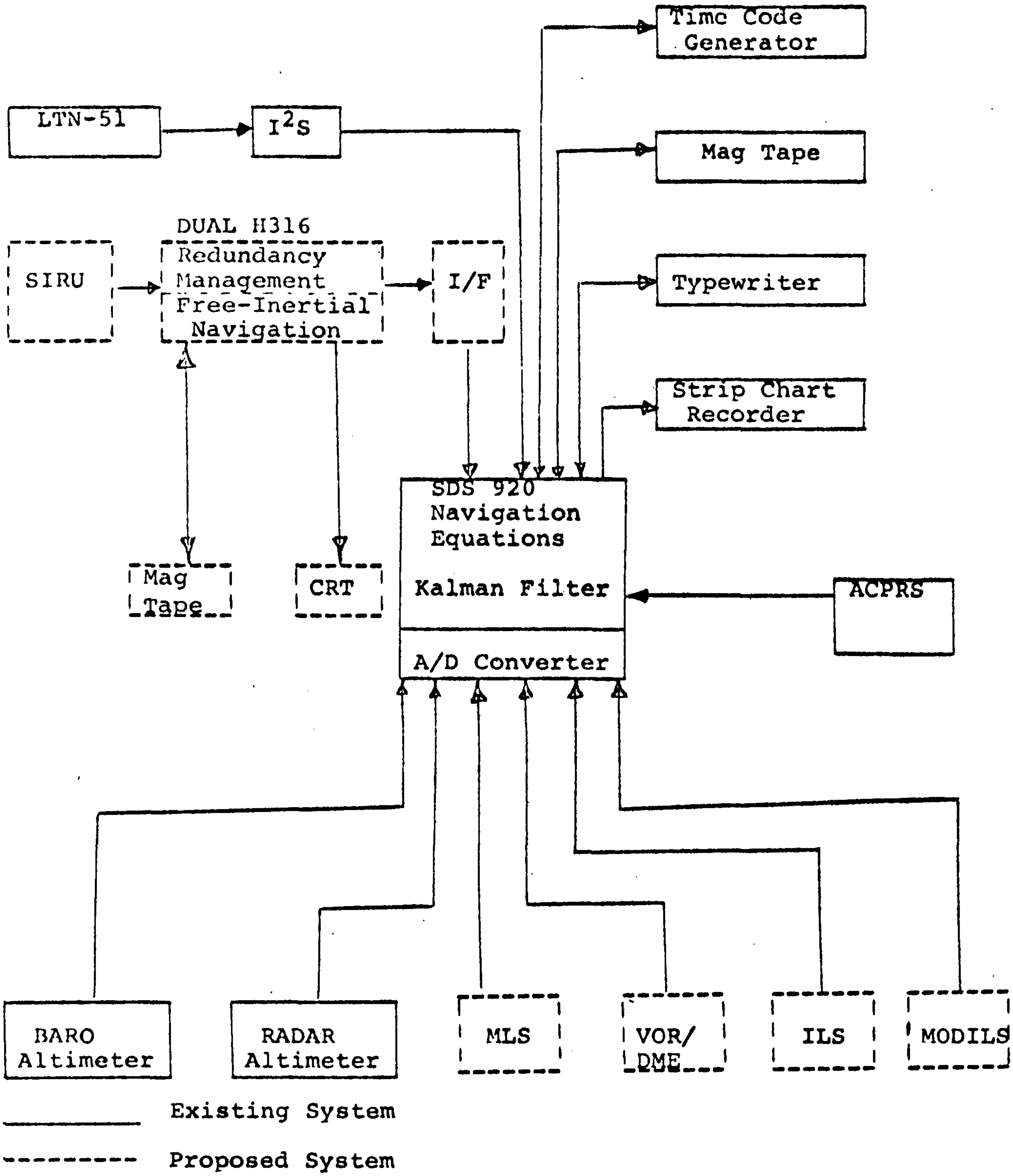


Fig. 3 - CV 340 SYSTEM

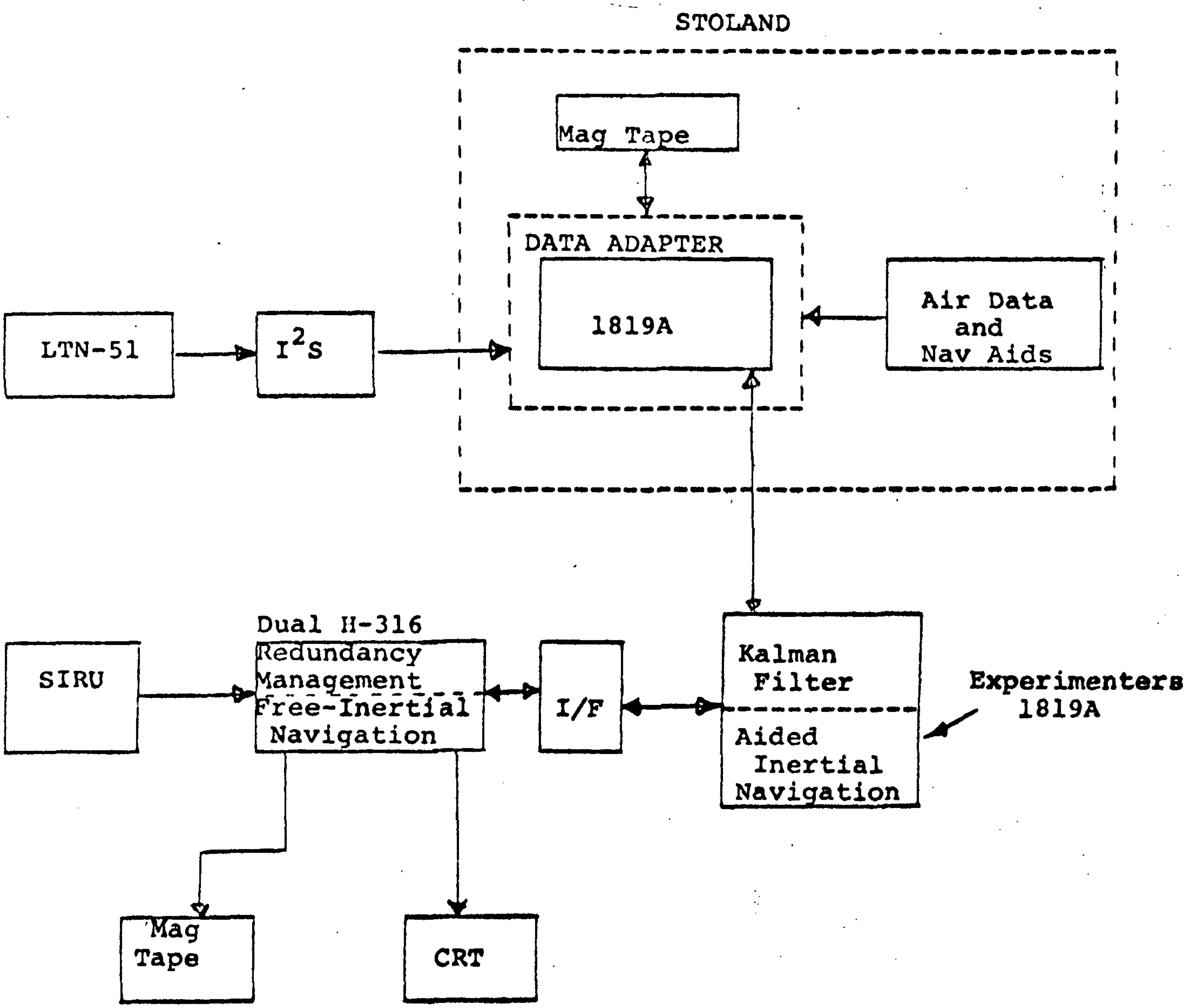


Fig. 4 - STOLAND SYSTEM (TWO 1819A's)

3) Flight tests of the improved system to verify achievement of predicted performance and demonstrate the system's utility as a reference system.

Objective B. - This objective is now being pursued by NASA/MSC (reference 18 indicates that they are proceeding full speed down the KFAI path to provide integrated navigation from the beginning to the end of the SSV mission) and can therefore be dropped as an Ames goal.

Objective C. - This objective came into being originally in the form of one of the STOL Operating Experiments (Experiment XIV-4, reference 19). The only progress to date on this objective is a heritage from Objective B; namely, the software which has been coded for the 1819A computer. Work on this objective will require funding for AMA to complete the development of this software, modify our simulation program, and construct an efficient IBM 360/67 data analysis program. Attempting to do this in house is impractical because we do not have sufficient manpower to do the job on an effective time scale. Some of the specific problems in this application were identified in the earlier discussion of objective C.

Objective D. - This objective was established as a means for carrying out an evaluation of the MIT Strapdown Inertial Reference Unit (MIT/SIRU). The plan for this evaluation, as described in reference 17, calls for putting together avionics systems on board the CV340 and C8 aircraft which could be as shown in Figures 3 and 4 (although other configurations are possible). The required modifications of on board software have already been described. Modification of the simulation program is also required to incorporate a model of the MIT/SIRU system, and also modification of the data analysis program called for under objectice C to facilitate evaluation of SIRU performance. Thus, objective D is only a relatively modest extension of objectives A and C.

It should be emphasized, in concluding this overview of future work, that as an immediate result of fulfilling the objectives stated above, we will have produced on board the CV340 a highly accurate and versatile system which could be used as a real time precision reference for a variety of applications. For instance, we have proposed using this system in the evaluation program for SIRU. The accuracy of the system is possible because of the availability of ACPRS data on board the CV340, and the versatility results from the sophisticated input/output computer routines constructed to support the experimental work. Developing such a reference system was not originally an objective of the Ames aided inertial work. However, since it is now available, we strongly recommend that it be put to use. For example, the system could play a very useful role in the dynamic calibration of the new Ames radar tracking system and the MODILS installation at Crows Landing.

Among the organizations which should be interested in this system is the FAA, which recently issued an RFP (reference 20) for the procurement of 21 flight inspection aircraft equipped for the evaluation of VOR/TACAN and ILS installations. The avionics onboard each aircraft will include an INS with provision for updating via DME R-NAV computations and visual position fixes. This is a rather conventional approach, understandable in view of the immediate need for these aircraft. It is of interest to note that when presently planned work on the CV340 has been completed we will have on this aircraft a capability, not just for isolated position fix updating, but for continuous updating (i.e., "aiding") via the Kalman filter algorithm. In addition, for aiding purposes (to establish a precision reference trajectory in real time) than the scheme described in reference 20.

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