CONSIDERATIONS OF INERTIAL AND OTHER NAVIGATION SYSTEMS AS THEY FULFILL THE EXACTING REQUIREMENTS OF AERIAL SURVEY

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BACKGROUND

It was the summer of 1972 when I received my introduction to the rigors of aerial survey navigation and precise pattern flight path guidance. As an applied mathematician/physicist, I was assigned the task of reprogramming the digital computer of the Litton Aero Products LTN-51 Inertial Navigation System (INS) for the automatic guidance of U. S. Coast Guard aircraft through the three standard search and rescue patterns. The INS was electrically coupled to the aircraft autopilot and, without pilot intervention, automatically flew the aircraft through the preprogrammed patterns. This was the first application of digital computer techniques for precision automatic aircraft guidance to become commercially available to the survey industry.

Through the intervening years my association with the industry has evolved through most all disciplines of remote sensing wherein aircraft are used as the platform. Aerial photography, infrared, magnetics, radiometrics and gravity, to name the most prevalent. Most all classes of aircraft were employed: single engine Cessnas, Sikorsky helicopters, Bandeirantes, Citations, Learjets, C-130's and high altitude RB-57's. Virtually all altitudes and aircraft velocities, from 30 meters through 20,000, and from 30 Kts through 500. Very few aircraft platform requirements discussed in this Congress have escaped attention. This work culminated in the developments of the Litton ITGS (Inertial Track Guidance System) and PICS (Photogrammetric Integrated Control System) which were presented to the 1980 Hamburg Congress.

Why Inertial?

My work in precision guidance used inertial navigation as the position sensor because my employer at that time was Litton Aero Products, who is a leading inertial systems manufacturer. They were one of the few equipment manufacturers to have the foresight to fund progress in this area. There are other beneficial positioning systems available which could have been used. The reader will note the generic references in ITGS and PICS: "Track Guidance System"; "Integrated Control System". These terms denote mission orientation rather than reflecting the type of positioning system employed. The techniques developed in each of these systems can utilize any applicable positioning system. They were mechanized in inertial systems because of Litton's willingness to participate and invest in the aerial survey discipline.

Mission Orientation

Throughout the years of aerial survey, many electronic navigation systems have been used to assist the aircrew. Most systems were standard systems developed for normal air transport then adapted by the individual survey operators to meet their needs. It is unfortunate that most manufacturers failed to see the necessity of tailoring the operational characteristics of their products to the needs of survey aircraft crews. The procedures of aerial survey are foreign to the typical avionics producer whose dominant marketplace requires navigation and guidance only from one airport to another. The exacting minute-to-minute positioning of survey aircraft requires displays and procedures which must be specifically created to this end. Traditional airline or military navigation systems cannot be directly applied to survey aircraft. Regardless which position sensor system is employed, the guidance algorithms, sequence logic and procedures must be mechanized so that the unique aspects of the survey mission are considered. Indeed, the ITGS/PICS concepts are mandatory if full utility is to be realized from any navigation system.

REPRESENTATIVE NAVIGATION AIDS AND THEIR CHARACTERISTICS

The aerial survey operator is constantly inundated with advertising, magazine articles, Congress papers and salesmen claiming that a particular navigation system is the best. Different manufacturers will capitalize on a specific attribute, totally ignoring deficiencies. Typical criteria include low cost, high accuracy, ease of installation and operation, widest utility, increased productivity. An operator must have a full time navigation systems specialist to ferret out the truths from the myths. This of course is a luxury which only the largest organizations can afford, so the majority of operators has experienced disappointment when system performances could not meet survey requirements.

Most operators have either purchased or experimented with one or more of the available navigation systems. Degrees of success have been varied; however, the purchaser has generally not been willing to discuss deficiencies of his selected system. It is human nature not to broadcast a very expensive mistake. This lack of operator dialog has perpetuated myths and misunderstandings regarding individual system capabilities.

It is beyond the scope of this paper to provide detailed descriptions of each type of navigation system. It is assumed that the reader has some knowledge of the principles of these systems. The material presented relates system characteristics to the requirements of aerial survey. Personal observations of attributes and deficiencies are reflected.

Inertial Navigation Systems

Inertial Navigation Systems have three basic attributes for the survey operator. They are self contained requiring no external aids; their positional and velocity error propagation is continuous and systematic rather than random as in radio systems; and, survey instrument attitude information (pitch, roll, and yaw) is continuously available. The system is referred to as the Cadillac of navigation systems, having prices in the $100,000 to $300,000 USD range.

The basic problem areas of inertial systems include weight, power requirements and warmup time, and uncertainty of drift characteristics on a given flight. Inertial systems have an installed weight of approximately 75 kilograms including DC/AC inverters and installation hardware. This can be problematic to operators using smaller aircraft.

The INS requires that a ground power unit be available at each airport used by the operator. This is necessary to provide the large amount of power used during the 15-30 minute initialization and system alignment phase which precedes each survey flight. The logistics of providing this power can be difficult at remote airports.

INS drift errors, expressed in nautical miles per hour, are smooth and continuous. This is the strong attribute of INS. The specification for these errors is statistically derived and for most commercial systems is 1.3 nautical miles per hour C.E.P. The problem is that this is an average, and while one flight may experience 0.1 nm/hr of error, the next may have 2.0 nm/hr. A false sense of security produced by the former leaves the operator unprepared for the latter. This large flight-to-flight deviation of error characteristics has been a constant source of frustration to aircrews. Newer, better calibrated equipment is becoming available, thus reducing the uncertainty on a given mission. Laser gyro strapdown systems are producing more consistent error profiles than are the electro-mechanical systems now in service. However, inertial systems will always present the operator with a distribution of error propagations which must be compensated to maintain flight line specifications.

Inertial systems would have had very limited use in the survey industry had it not been for the ITGS/PICS system concept. The mission oriented procedures allow the crew to compensate for INS inaccuracies and work with the system. The ability to update INS position to visual ground references has made it a viable means of survey navigation for most specifications.

Omega/VLF Navigation Systems

Omega/VLF systems have been attractive to operators because of their comparatively low cost and ease of use. Systems vary in price from $25,000 to $80,000 USD, significantly lower than most others. Most systems require inputs from compass and true airspeed systems, and this can double total system costs. Weights vary from 20-40 Kg including installation hardware and some systems can use existing radio antennas. Omegas operate in latitude/longitude coordinates in the same manner as INS.

The absolute positional accuracy of Omega/VLF systems is inadequate for aerial survey navigation. These systems rely upon a magnetic anomaly map of the world to compute position for normal transport aircraft. At best, to date, the combination of error sources has produced an error triangle, one nautical mile on a side. This depends upon the specific global location in which the navigation system is being operated. The observed errors have been as great as six nautical miles. However, this is a "bounded" error. That is, the error does not increase as a function of operating time. In newer systems, the random error is quite stable as a function of time, depending upon time of day, and has been known to fluctuate as little as 100-200 meters. This is true for stationary receivers; however, for survey aircraft, the dynamics create a different situation.

Omega/VLF systems produce a refreshed position each ten seconds. This refresh rate is established by the system specification and cannot be improved. Traveling at aircraft velocities a receiver will experience significant errors due to the time delays inherent to this rate. A seven hundred meter error lag in the direction of flight is common. This lag combined with receiver filtering algorithms creates problems during the line-to-line turn maneuver. The system must "catch up" with actual aircraft position in the crosstrack direction during acquisition of the new line. Therefore the survey lines must be extended for several minutes of flight to allow the system to stabilize in the crosstrack driection. This non-productive time required for accurate line capture can be a significant percentage of the total mission.

The Omega along track position will always lag that of the aircraft; however, for most surveys this is not a severe requirement. Maintenance of crosstrack position on the line, providing accurate line separations takes precedence.

No Omega systems have the visual position updating capability of the ITGS/PICS concept. If this were available, despite the required survey line extensions, the stability and relative accuracy of Omega systems would afford the operator a viable source of navigation and guidance offering advantages both in cost and long term accuracy.

<u>Doppler Navigation Systems</u>

Doppler systems have long been the standard navigator for survey operators. Being self-contained, they require no ground aids and can be used in the most remote areas. The most accurate of these systems are voluminous and heavy. They require precise installation and a high accuracy compass heading input to achieve their performance specifications. When an installation is complete, total costs accumulated can exceed those for inertial systems.

Performance characteristics are similar to inertial systems in that Doppler velocities are integrated along the aircraft heading vector to achieve a latitude/longitude position. Because there is only one integration, fluctuations in Doppler accuracies are less than inertial, and system errors are dependent upon heading and sensed velocity accuracies. The errors are not bounded and do accumulate as a function of flight time.

Doppler, relying upon the reflection of radio frequency waves from the earth's surface, has difficulties when over smooth water surfaces because of the geometry of reflection (away from the aircraft) and over moving water currents, where the current speed is included in the

Doppler sensed aircraft speed. Most high accuracy Doppler systems are of high weight and complexity, causing operational and logistical problems.

While Doppler systems have long been used in aerial survey, no manufacturers have seen the need for operational procedures dedicated to the execution of survey missions. The survey operator must create his own procedures to comply with the basic enroute guidance capabilities of commercially available systems.

Loran C Navigation Systems

Developed by the U. S. Coast Guard, many have thought Loran C to be the answer to aerial survey navigation problems. The advertised accuracies range from 20-100 meters bounded error with no line-of-sight requirement. The range for a given chain of transmitter stations can be over 1,000 nautical miles. Loran C does not have worldwide coverage. Most of North America, Europe, the Mediteranean area and South East Asia are covered, but the rest of the world is not. Loran C is affected by local magnetic anomalies, and there is no compensation in commercially available navigation equipment, although these have minimal effect for most survey applications.

Loran C has response problems similar to Omega/VLF. The system, in order to achieve its high accuracy, requires significant filtering of radio positional information. This requires the same long line extensions to allow the filtered position to stabilize prior to entering the survey area. Thus, extra time must be spent in the line-to-line turns where no production is effected.

The repeatability of Loran C is its greatest asset. Time after time, 20 meters is the maximum deviation experienced. Therefore, the institution of visual position updating procedures would make the system an attractive navigation tool. The cost for non-productive turns would be overshadowed by increased productivity in the survey area.

Microwave Positioning Systems

The previous systems discussed require no survey area ground logistics for their operation. Microwave transponder positioning systems require the precise pre-operation positioning of ground based transmitter/receivers in a network which uniquely provides coverage for the area to be surveyed. While these gigahertz frequency range systems must have line-of-sight communications with the survey aircraft, they offer positional accuracies of five meters or better. The inherent position updates are of such high rates and accuracies that the commercially available systems present no problem to positional stability during line-to-line turns.

Each microwave ground transponder has a usable range of approximately seventy kilometers. Since proper triangulation between at least three such stations must be maintained to achieve the specified accuracy, the survey area allowed by three given stations is quite small. Therefore, a network of stations can be established for large areas, and individual stations are selected for navigation at any given point in the survey.

The greatest drawback to this type of system is the positioning of the ground transponder stations. The system is only as accurate as the operator's ability to ascertain precise station coordinates. In many cases existing maps are inadequate and satellite fixes requiring days of monitoring are required. Ground stations must be so located as to provide proper triangulation with neighboring stations or navigation accuracies will deteriorate. These stations must be located on prominences such as mountain peaks lest line-of-sight communication with the survey aircraft be lost. Some countries require federal permission to operate these systems. In some situations the logistics of preparing for a survey outweigh the survey itself by several orders of magnitude.

There are surveys, such as airborne gravity, where the precise positioning only afforded by microwave systems is mandatory. Many organizations have experimented with them in geophysical exploration wherein survey areas were of limited expanse. Very little has been done with this class system in aerial photography, since mission accuracy requirements do not warrant the site preparation expense.

Suppliers of microwave positioning systems are the only system suppliers who have addressed the problems of the aerial survey industry by applying ITGS concepts to the guidance equations and operational procedures. This is because of the very nature of microwave systems; all customers have unique applications requirements. Knowing precise position is only half the requirement. That capability which makes one supplier better than the next is the ability of the user to directly apply the system toward satisfaction of his mission requirements. The leaders in this discipline have advanced application of ITGS/PICS concepts addressing the specific needs of the aerial survey industry.

Satellite Navigation Systems

We have, for years, been patiently waiting for the general, worldwide availability of the Navstar Global Positioning System (GPS). Soon it will become a reality. By the time of our next Congress in 1988, there should be sufficient satellites in orbit to afford this general utilization. However, until then the aerial survey industry will have to continue being patient. Avionics manufacturers in the U.S. are spending millions of private dollars on the development of commercial GPS navigation systems. The U.S. Government has held competitions and four companies were selected to receive government funded development programs. There is a total commitment in the United States for GPS development and deployment. The preliminary reports of navigation system performance using the current eight satellites are promising to the aerial survey industry, at minimum.

GPS has two modes of operation. The military mode has accuracies which are classified by the U.S. Government; however, requiring special receiving equipment, it is unavailable to the general public. The general use mode is advertised to have accuracies in the range of Loran C, 20-100 meters. Recent tests, however, have demonstrated accuracies significantly better than anticipated, on the order of 5-15 meters. Recognizing that GPS provides three axis (X,Y,Z) positional information, the impact of introduction of this system to the survey industry will be monumental and revolutionary. Many tricks and navigation techniques commonly practiced by aerial survey operators will become obsolete. Everyone will have access to the same absolute positional accuracy and at an affordable price.

That which will be required and which will be difficult to achieve is a survey mission guidance and control operational procedure imbedded in any of the systems made commercially available by manufacturers. GPS is so new and will be so much in demand that suppliers' production capacities will be saturated by the general marketplace to the neglect of special markets like aerial survey.

Discussion

The above descriptions demonstrate the fact that all systems, present and future, have limitations when applied to aerial survey. These limitations will persist and not be addressed until an ITGS/PICS concept is applied. Unfortunately, the aerial survey marketplace is not sufficient enticement to induce a given manufacturer to offer capital investment toward such concepts. The payoff for one company's share of the market just doesn't exist.

The answer is to imbed the aerial survey procedures in a separate management computer capable of working with any of these systems. Each of the above systems provides digital output buses containing all the information required by the management computer. These buses are sufficiently standardized, both in hardware and format characteristics, that interface would be straightforward. The navigation systems then would be simply sensors inputting appropriate data to the computer which would satisfy the mission requirements unique to aerial survey. Thereby one or two manufacturers could directly address the needs in a manner profitable to them and cost effective to the survey industry.

AERIAL SURVEY REQUIREMENTS

Mission requirements for a management computer include the ability to address the complexities of navigation, guidance and operational difficulties in a manner which increases productivity while reducing required crew capability and workload. The requirements most often encountered are discussed.

Navigation References

The topographic map has long been considered absolute reference for evaluation of survey mission performance. Comparing tracking camera pictures with map features has been the accepted technique for geophysical survey positioning, and maps are used against actual photographs in photography missions. All electronic navigation systems use either latitude/longitude or universal transverse mercador coordinate systems which very often are in disagreement with the map projections. These variances range from a few meters upward to kilometers depending upon the local situation.

There will be no discussion as to the relative merits or arguments of map errors versus navigation system errors. It suffices to say that these discrepancies do exist. The point is that in most surveys the maps, with their associated errors, are used as reference for performance evaluation, and any navigation system must be able to adapt to this fact. This is true for present systems, and will be true for satellite systems so long as maps are used as reference. Visual updating techniques must be available to aircrews for effective performance.

Many techniques have been experimented with to achieve this visual update. In the ITGS/PICS, no fewer than five independent methods were made available to translate the observed positional errors into changes in latitude/ longitude coordinates. Each technique had its limitations and the manner in which their uses could be intermixed very often produced situations where errors compounded rather than cancelled each other. The flight crew was faced with the dilemma of determining which procedures had been helpful and which were detrimental to positioning accuracies, very often an impossible task.

An updating procedure which permits the aircrew to reorient the navigation system in accordance with the planned survey grid lines as represented on the topographic map reference is required. It must allow position updating at any point within or outside the survey area, and must not require aircrew knowledge of latitute/longitude coordinate information during the survey mission. The procedures of ITGS/PICS were a first step toward this goal.

Guidance Functions

The basic purpose of a survey guidance system is to provide direction to the aircrew for maintence of the aircraft on the survey flight lines at all times. This requires translating flight lines as drawn on the map into mathematical expressions to be operated upon in the guidance computer. The traditional technique of representing individual lines by pairs of latitude/longitudes has limitations and irreparable inaccuracies unless adjusted and fine tuned in the guidance computer. Just as the aircraft position updates must be referenced to map and terrain correlations, the mathematical representation of flight lines, their positions and direction, must be adjusted to agree with the map references. The aircrew must have the ability to easily make these adjustments during flight. Certainly they have the ability to visually determine the aircraft position and the desired flight path from map/terrain evaluation. They cannot be expected to mathematically isolate navigation position errors from survey line position and direction errors and relate them to the guidance computer. Such capability must be imbedded in the computer itself.

Operational Capabilities

The concept of a mission oriented system implies that procedures are available to address the operational difficulties encountered during execution of the mission. The ITGS/PICS represents a first step toward this end. While many of the procedures and crew interfaces are cumbersome and not human engineered, that system has addressed the operational peculiarities of aerial survey missions to a degree unsurpassed in the industry by allowing for:

- Automatic enroute guidance to the survey flight line
- Mission interruption and re-entry
- Specific selection of flight lines
- Inflight alterations of mission plans
- Reflight of survey lines
- Fine tuning of aircraft autopilot offsets
- Extending flight lines beyond programmed survey area
- Individual flight line interruption and re-entry
- Optimum guidance through line-to-line turns
- Either rhumbline or great circle guidance
- Aircrew annunciation of warnings and errors
- Display of information meaningful to survey missions
- Automatic guidance on return to the airport

The next generation system would provide this information and more. Streamlining of operator/machine interfaces to provide a user friendly environment is of greatest importance. The ability to monitor and control survey instruments along with aircraft positioning from a single crew station could reduce crew size. This requires a true survey mission management system.

SURVEY MISSION MANAGEMENT SYSTEM

Development of the ITGS/PICS was the result of over seven years experience in the aerial survey discipline. Many flight hours were consumed observing the mission peculiarities and the corrective procedures employed by various survey crews. After compiling volumes of observations, it became clear that there is significant commonalty to all survey missions. The procedural variations were dominantly required by the restrictions of the particular navigation system being used, not so much due to mission requirements. There can be a survey mission management system universally applicable to survey flight operations.

Tools for creating the second generation system are available now. Technological advances in the utility of microprocessors (low cost, high reliability, ease of programming, ease of electronic interfacing) allow creation of a management system capable of performing as the command center for all airborne survey activities. Military and commercial aircraft avionics industries have employed this philosophy for some time.

Tactical military aircraft have target tracking and fire control computers separate from navigation systems. Transport aircraft are evolving toward performance management systems which consider all aspects of powered flight (airframe characteristics, engine parameters, loading, altitude and mission profiles). The navigation "system" is being relegated to the status of position "sensor" and is just one of many subsystem inputs to the management system. The system provides commands to the aircraft autopilot and engine controls and allows easy programming, monitoring, and operational use by the flight crews. Modified to specific functions, this same concept can be applied to survey mission management.

The digital computer world today presents all the building blocks necessary for such a system. There are standard modules for computer processors, memory, displays, and digital and analog interfaces. The languages offered in these computers allow ease of reprogramming for special situations. In fact, the software programs can be so modularized as to allow the user to create functions required for his specific task with little training. The hardware is reliable and most packaging is adequate for airborne use.

Dr. R. Audi of São Paulo, Brasil presented his paper "Practical Results with the Inertial Navigation System -- PICS of the Litton Aero Products, as Obtained by Terrafoto S.A." to the 1980 Hamburg congress. In it he provided a quantitative analysis of the benefits derived from the ITGS/PICS mission oriented concept. Those to be expected from a centralized management system are even more dramatic.

The complex systems being fielded today, the more exacting flight path specifications and the escalating cost of aerial survey operations state the message clearly. Survey mission management systems are required for improved productivity. It now remains for industry to supply this capability. However, the initiative must come as a collective voice from the aerial survey community.