AN INTEGRATED GPS FLIGHT MANAGEMENT SYSTEM

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ABSTRACT:

The high operating costs associated with using aircraft for remote sensing applications are well known. Many of the contributing factors that determine hourly flight time expenses must be borne, however, others can be significantly reduced. Highly efficient aircraft navigation utilizing the NAVSTAR Global Positioning System (GPS), in conjunction with commercially available digital map databases, can dramatically increase productivity. This paper will detail a state-of-the-art flight management system being currently used by the National Oceanic and Atmospheric Administration's (NOAA) Photogrammetry Branch in support of their Coastal Mapping Program. The system described not only enhances daily aircrew flight operational considerations, but is equally beneficial to mission planning and event inventory.

KEY WORDS: Global Positioning System (GPS), Geographic Information System (GIS), Flight Management, Photogrammetry.

1. OPERATIONAL PARAMETERS

Prior to detailing the operation and physical criteria that comprise the NOAA Global Positioning System Flight Management System, a thorough discussion of the system's evolution is required. This system was initially developed to modernize the NOAA Photogrammetry Branch's Flight Operations Section. As a Mission and Aircraft Commander having flown and coordinated numerous Coastal Mapping Projects, it was evident to me, that the effort involved in collecting aerial photography had significant inefficiencies. As the system was designed, however, it became increasing apparent that it would be very beneficial to the Photogrammetry Branch's Planning and Support Sections as well.

NOAA's Coastal Mapping Program involves the cyclic collection of controlled geodetic coastal aerial photography. Primarily, this photography is used to define the legal shoreline represented on the NOAA Nautical Chart series. This controlled small scale (1:50,000) strip photography is collected and used to aerotriangulate important objects throughout the numerous photographs within the planned mission area. Black & white infrared photography is also collected over the same geographic area during specific stages of tide. This photography is used to supply the accurate depiction of the mean lower low and mean high water lines on the nautical chart.

To collect this small scale photography efficiently, a Cessna Citation II Fanjet is used as the camera platform. This aircraft has proven to be ideally suited for this mission and was selected for the following reasons:

- o High altitude capability; service ceiling 43,000 feet.
- o Moderate cabin size; allowing dual camera operation.
- o Fanjet power; fuel efficiency at both low and high altitudes.
- o "Straight" wing; provides excellent handling characteristics and field length requirements.
- o Endurance; 5 hours at cruise performance.
- o Reliability; excellent safety and mechanical record.
- o Weight; heavy enough to provide good stability.

The Citation is operated by two pilots, one aerial photographer, and is equipped with two large format (23x23 cm) - 152mm focal length - metric mapping cameras. In addition to eliminating mission down-time due to a camera failure, dual cameras increase productivity by providing the ability to capture two different film emulsions simultaneously. This particular configuration has worked well, providing quick response throughout the United States and its territories.

Most coastal mapping missions are flown at 1:50,000 scale (25,000 feet above ground level using 152mm focal length camera cones) in ideal atmospheric conditions. Standard operating procedures dictate that flight line photographs be completely free of clouds (and cloud shadows) with horizontal visibility requirements of 12 miles minimum. The weather conditions necessary under these specifications occur rather infrequently. Additionally, the integral requirements that this ideal weather has to occur during daylight hours, at specific sun angles, <u>and</u> during certain stages of tide, makes data collection all the more difficult. Weeks can pass waiting for all of these parameters to come together at many coastal locations throughout the U.S. Conventional photographic flight line coverage for aerotriangulation requires 60% end-lap between successive exposures and minimally 15% side-lap between adjacent strips.

Prior to the GPS Flight Management System, flight line navigation was accomplished using a camera navigation site (a "bomb" site with limited forward looking capability) in conjunction with cluttered, cryptic-looking flight maps. The flight maps were simply cut-up 1:500,000 scale VFR aeronautical sectional charts, with numbered, straight, inked lines, drawn to indicate where photographic coverage was desired. The flight lines were drawn so that adjacent strips would have a minimum of 30% side-lap, hopefully, to accommodate flight line mis-navigation. With unstable winds aloft even a 100% safety factor is not sufficient to prevent rejected strips of photography.

2. OPERATIONAL UNCERTAINTIES

Of particular concern to the mission commander is the uncertainty associated with collecting photographic imagery. A particularly frustrating and expensive ordeal, is to wait weeks (for ideal weather) to re-shoot rejected imagery. The major sources of photogrammetric aerial uncertainty revolve around:

- Imagery exposure and processing
- Atmospheric visibility
- Weather
- Existence of ground targets?
- Flight line mis-navigation

2.1 <u>Imagery Exposure and Processing</u>

Film processing mistakes (film processed to the wrong gamma, under and over exposure, etc.), are going to happen. To limit the frequency of these mistakes, NOAA's photogrammetric missions operate with professional photographers at all times.

2.2 Atmospheric Visibility

Frankly, this should be relatively easy for a pilot to determine, however, there have been times when adequate atmospheric conditions were field reported, yet the photography rejected due to poor resolution. Surprisingly, some photography captured under marginal atmospheric conditions looked great on film! The trick here is not so much the horizontal visibility looking out the aircraft window, but rather the actual visibility looking through the drift site. One must think like a camera, to "see" like a camera.

2.3 Weather

Mother nature can humble the most arrogant of men. Depending on the mission location, cloud cover can change dramatically during a short period of time. There have been many productive days that were forecast to be wet and miserable. One must take the weather as it comes, however, one must not give up hope at noon. Over the years it has been found that a key to successfully dealing with weather for aerial photography is to locate the mission as close to the work ground (no matter how unsavory) as possible. If located close enough, looking skyward will yield the weather at all times, thus freeing the crew from having to depend hourly on the weather "experts".

2.4 Ground Targets

Because aerotriangulation requires exposure station control, some ground control will no doubt always be necessary. Photo panels must be set in open areas with excellent visibility to all quadrants of the sky. They also must be routinely checked because of vandalism, wind damage, and other hazards. From five miles high, panels are almost never visible to the human eye. If panels are not film visible, re-flights are most often required to constrain models for aerotriangulation.

2.5 Flight Line Navigation Errors

The most controllable yet irritating uncertainty is flight line mis-navigation. The costs associated with operating any photogrammetric aircraft are significant. The extent of which is directly proportional to the amount of time the aircraft has it's landing gear retracted. To refly a previously flown photographic strip for whatever reason amounts to triple jeopardy; air time, film costs, and per diem. Photographic flight line navigation using a photo-nav site is inherently inaccurate. I say this for three key reasons, 1) the longitudinal lubber line of the navigation site shifts instantaneously in relationship to ground reference with any change in aircraft direction, 2) this shift is directly proportional to the aircraft altitude, i.e. the higher the altitude, the greater the horizontal shift, 3) navigating with a photo-nav site involves lowering one's head to one's knees and looking down while simultaneously being jolted by air currents; this is not the recommended treatment for vertigo. The point here is that someone is less likely to sense an aircraft attitude change (bank and direction) with one's head lowered, concentrating on ground objects observed through a set of magnified lenses.

Flight line mis-navigation generates three major photogrammetric problems:

- Ground control not captured; targets being outside the limits of the photographs.
- Inadequate coverage; "holidays" between adjacent strips of photography.
- Unrectifiable models; gross changes in aircraft attitude between consecutive or adjacent photos.

These problems occur to varying degrees and are not always readily apparent to the aircraft navigator. As a result, the extent of these problems are not immediately known or field correctable in a timely manner. Usually the imagery has to be developed, inspected, plotted, and ground control identified before the photographic strip is declared a success. This process will take several working days; some of which will invariably be weather perfect for corrective, replacement photography. The desire to overcome this "time delay" and substantial costs associated with flying corrective photography was the incentive to design a photogrammetric navigational solution.

3. AIRCRAFT NAVIGATION

Various aircraft navigation systems have been implemented since the vintage "bomb-site" was introduced. VHF Omni-directional Range (VOR), Long Range Navigation (LORAN), Tactical Air Navigation (TACAN), and Distance Measuring Equipment (DME) are routinely used by most aircraft today. Singularly, none of these navigational aids can be used for highly accurate remote sensing purposes. LORAN comes the closest to meeting the photogrammetrist's demands, however, its accuracy is location dependent, and its range is altitude dependent. Until recently, the best solution was a combination of several different components, each system complimenting the other.

The NAVSTAR Global Positioning System may prove to be the practical solution to the accurate positioning dilemma. Because GPS is space-based, many of the reception and terrain problems associated with other navigation systems are eliminated. Although the GPS satellite constellation in not complete, nor declared operational, 3-dimensional positioning throughout the U.S. is prevalent. The accuracy of the GPS Standard Positioning Service is variable, however, up to now, the accuracies achieved have been consistently better than that of the other previously mentioned systems.

4. KINEMATIC PHOTOGRAMMETRY

For several years, NOAA's Photogrammetry Branch has been actively involved in various GPS related ideas and experiments. Initially, the GPS receivers used, were borrowed, wherever and whenever available. As the GPS satellite constellation grew, so too did the Branch's expertise using this system. Soon GPS equipment manufacturers provided an easy way to mark or "time-tag" (in micro-seconds) special events. Kinematic photogrammetry developed out of the ability to time tag the camera shutter's center-of-opening pulse to the GPS receiver. Techniques for post processing the carrier-phase GPS signal have demonstrated that the aircraft's antenna position can be resolved to within 10 centimeters (Lapine, 1990).

Recently, NOAA has completed several camera calibration experiments using various manufacturer's GPS receivers. Eventually, the Branch was able to procure its own Trimble 4000 SST 16-channel geodetic GPS receivers. The Branch's first practical carrier-phase kinematic photogrammetric mission was accomplished in October 1990 in Pamlico Sound, North Carolina. Every mission since has been accomplished using kinematic GPS. When a system to merge GPS with a Geographical Information System (GIS) for vehicular tracking became commercially available, it was realized that this technology could be used to reduce mission costs significantly and increase productivity.

5. MERGING GPS WITH GIS

At the time (1990 - 1991), although several impressive GIS map bases were commercially available, most lacked a GPS/GIS combination that (for a reasonable price) would adequately track the high dynamics of an aircraft. Most companies' GPS/GIS systems were based on 3 channel GPS "card" receivers. These systems are fine for car, truck, and boat operators, but because of their update rate, it was not clear that these would accurately track an aircraft traveling at 100 -

200 meters per second. Besides, the aircraft was already equipped with a 16-channel GPS receiver, all it needed was a friendlier way to display positional information.

The DeLorme Mapping Company of Freeport, Maine produces a GPS/GIS moving map display called XMAPPRO which has graphic integrity and is extremely user flexible. The GIS is CD-ROM based, works under Microsoft's WINDOWS, and the data is arranged to maximize fast retrieval and display. XMAPPRO's features are too numerous to describe in detail, however, for this application its key attributes are:

- Street level detail throughout the U.S.
- Precise measurement with latitude - longitude control.
- Friendly interactive presentation.
- Ability to quickly change map scales and detail.
- Create and save overlays to the geographic database.
- Ability to import and display other database files.
- High quality printout of any generated map.

After consulting with Mr. David DeLorme (president of DeLorme Mapping), he indicated that merging a Trimble 4000 SST GPS receiver with his GIS would present a minimal amount of re-configuration, and that DeLorme Mapping would be willing to support additional photogrammetric related customized features. Knowing the capabilities of both the Trimble 4000 SST GPS receivers and XMAPPRO, a customized system was designed and an integrated GPS flight management system emerged.

6. THE INTEGRATED GPS FLIGHT MANAGEMENT SYSTEM

The system consists of a luggable 486-33 MHz IBM compatible computer, a Wild RC-20 metric mapping camera, a Trimble 4000 SST GPS receiver, connecting hardware, and associated peripherals. The self-contained computer includes a 10 inch VGA color monitor, a 3.5 inch floppy disk drive, a 200 megabyte hard drive, a CD-ROM reader, mouse, keyboard, and an internal modem. The GPS receiver drives the "moving map" system by transmitting two messages to the computer's GIS. The position calculation, and the navigation calculation message are received every second to update the aircraft's position within the GIS.

The position calculation message contains the pseudo-range position (latitude/longitude), date, GPS time, position dilution of precision (PDOP), and other satellite information. In addition, the navigation calculation message contains the height (altitude above ellipsoid), horizontal velocity, vertical velocity, and flight line way point information.

An aircraft icon on the computer display represents the geographic position of the plane's GPS antenna in relation to the GIS package. Each second this position is up-dated, along with the aircraft's speed and ground track. Likewise, the aircraft icon rotates as its azimuth changes. XMAPPRO software senses icon movement as it approaches the edge of the VGA display, and automatically relocates the aircraft icon in the center of the monitor as additional digital geographic data is filled in.

Geographic flight line end-point coordinates (latitude/longitude) are pre-loaded as way points into the GPS receiver. These way points are called up on the receiver as specific photographic flight lines are flown. The receiver's navigation message passes to the computer way point range, bearing, and cross-track information. This information allows the navigator to accurately track the desired flight line. With a little concentration, cross-track errors of 50 meters (relative to GPS positional accuracy) or less can easily be obtained.

Each camera exposure is annotated on the GIS by the shutter pulsing the on board computer. This annotation creates a square overlay on the GIS. This square delineates the approximate geographic area covered by each exposure event. The dimensions of the squares are variable, depending on the photographic scale, and are manually entered by the operator. The squares generated by the GIS are approximations primarily because 1) the exposure event is assumed to be level with the ground, and 2) the square is centered on the last GPS pseudo-range position of the aircraft. Depending on the circumstances, additional camera exposure station information could be fed to the computer. For NOAA's purposes (typically small scale photography) these limitations do not significantly degrade the outstanding benefits derived from this feature. As the squares are systematically accumulated, the navigator can visually see the area of photogrammetric coverage. Each strip of squares are saved as a GIS photo overlay file and can be viewed or computer manipulated at any time.

Specific GPS message output can be imprinted and linked to the GIS system. By synchronizing the camera clock with GPS time, and attaching GPS time messages to the square overlays, each photograph can be cross-referenced to an overlay square in the GIS. Another very informative feature involves linking the icon's color with certain ranges of PDOP. This visually alerts the navigator to weakening satellite geometry. Numerous customizations are possible and easily accomplished with XMAPPRO software.

All three previously mentioned flight line navigation problems (ground control, "holidays", and exposure rotational angles) are virtually eliminated when using this system. Using hand-held GPS receivers, ground control pseudo-range positions can be overlaid on XMAPPRO as soon as control panels are placed. The aircraft navigator will know instantly whether or not the panels are covered by the "squares" as photography is collected. "Holidays" between adjacent strips of photography can be visualized by simultaneously displaying two or more photo overlay files on the computer's monitor. Field photographic rectification cannot be completely guaranteed; however, using GPS, photogrammetric model rotational problems due to aircraft navigation are greatly reduced. This is assured because GPS provides accurate numerical navigation information every second. As a result, aircraft course corrections using GPS are more frequent, but of a much smaller magnitude.

Perhaps the greatest benefit from using this system is eliminating the photograph collection evaluation "time delay" problems. Aircraft field personnel now have the information necessary to make accurate photographic collection decisions in real time. It is estimated that by using this system, the Branch's mission related overhead will be reduced by as much as 20%.

7. ADDITIONAL IMPACT

The Photogrammetry Branch's Planning and Support Sections are equally affected by implementing this technology. Mission planning is now accomplished using a computer and XMAPPRO. Gone are the days of numerous confusing paper flight maps. Planning now supplies the flight crew a single floppy disk containing all flight line overlay files and way point positions for an entire project.

In the field, in addition to a daily progress report, the mission transmits (via modem) all photographic flight line overlay files as soon as photography is secured. The Planning Section receives the exposure locations, time, and geographic limits of each photo often before the roll of film is completely exposed!

The Photogrammetry Branch's Support Section is primarily responsible for the complete inventory and commercial sale of all secured photography. Presently, over 3800 rolls of photography are archived from supported coastal mapping missions. This inventory increases by approximately 100 rolls (some 12,500 photographs) per year. In the past this inventory was manually compiled and cross-referenced. At each step of this tedious photo plotting and positioning process the chance of human error was present.

With the advent of the flight management system, a computer and GPS receiver replaces this undesirable and inefficient task. XMAPPRO has made it possible for the Support Section to inventory all further photography on a convenient and powerful GIS database. The impact to this Section's efficiency and subsequent public response is still peaking.

8. CONCLUSIONS

As photogrammetric mission costs continue to climb, a system similar to the one described will be common place throughout the remote sensing community. The potential for customizing software and hardware for particular photogrammetric configurations is limited only by one's imagination. The GPS flight management system described has been operational for only a few months. In this amount of time it is too early to quantify the total impact that the system will have on the NOAA Photogrammetry Branch. However, early indications have verified and exceeded design expectations.

Many potential problems were anticipated concerning the ability of the hardware components to stand-up and operate normally in an aircraft environment. Computers are notoriously finicky instruments and CD-ROM readers are known to be sensitive. So far, none of these problems have materialized. The most difficult problem encountered so far has been controlling the computer's mouse in turbulent air. A solution to this is being addressed.

9. REFERENCES

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