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Development of a GPS-Aided Motion Measurement, Pointing, and Stabilization System for a Synthetic Aperture Radar

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Biography

Mr. Fellerhoff is a Senior Member of the Technical Staff at Sandia National Laboratories in Albuquerque, New Mexico. He has both a BSEE and a MSEE from the University of New Mexico. His interests include GPS/inertial navigation technology and applications in the fields of radar pointing and motion measurements systems.

Mr. Kohler is a Distinguished Member of the Technical Staff at Sandia. He has a BSME from Rice University and MSME from Cal Tech. His interests include the application of control systems technology to the fields of inertial measurement and gyro stabilization.

Abstract

An advanced Synthetic Aperture Radar Motion Compensation System has been developed by Sandia National Laboratories (SNL). The system includes a miniaturized high accuracy ring laser gyro inertial measurement unit, a three axis gimbal pointing and stabilization assembly, a differential Global Positioning System (GPS) navigation aiding system, and a pilot guidance system. The system provides several improvements over previous SNL motion compensation systems and is capable of antenna stabilization to less than 0.01 degrees RMS and absolute position measurement to less than 5.0 meters RMS. These accuracies have been demonstrated in recent flight testing aboard a DHC-6-300 "Twin Otter" aircraft.

Introduction

During the last several years, synthetic aperture radars (SARs) have been developed by Sandia National Laboratories (SNL) and flight tested aboard the SNL SAR Applications Testbed, a DHC-6-300 "Twin Otter" platform. The most recent version of the testbed includes state-of-the-art features including a miniaturized RLG and GPS-aided navigation. In this paper, details of the design and operation of the SNL SAR Motion Measurement System (SNL-MMS) are presented.

SAR Motion Compensation Overview

A Synthetic Aperture Radar is an airborne imaging radar which produces a two dimensional image of terrain and objects broadside to the aircraft's flight path. This imaging geometry is illustrated in Figure 1.

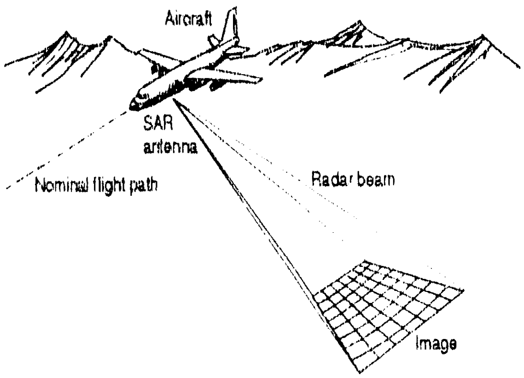

Figure 1: SAR Imaging Geometry

During the image formation process, any translational motion of the aircraft which is a deviation from a nominal straight line trajectory will de-focus the image. Rotational motion of the aircraft does not effect image focusing as the antenna is mounted on a rotationally stable three axis gimbal set which isolates the antenna from aircraft rotational motion. In order to produce a correctly focused image, the radar signal must be compensated for translational deviation from straight-line flight path.

This motion compensation consists of two phases: first, rotationally stabilizing the SAR antenna and measuring the deviation from straight-line flight, and second, compensating the radar signal for this translational motion. The SNL-MMS described in this paper performs the first of these functions, antenna stabilization and translational motion measurement. The actual compensation of the radar signal is not described in this paper.

The heart of the SNL-MMS is a recently developed miniaturized ring-laser gyro IMU. Designated RLGA (Ring Laser Gyro Assembly), the IMU is a joint development between SNL and the Space and Strategic Systems Group of Honeywell, Inc. It is attached to the three-axis antenna-pointing gimbal assembly near the antenna phase center and provides the measurements needed for aircraft navigation and guidance, SAR motion measurement, and antenna gyro stabilization.

The functions of the SNL-MMS can be categorized into four major areas:

- *Antenna Stabilization*
- *Navigation Functions*
- *Motion Measurement Calculations*
- *Aircraft Guidance*

Each of these functions is described in the following section. These functions are implemented in a SANDAC (Sandia Airborne Computer), a multiprocessor MC68020-based flight computer. SANDAC was designed by SNL and is produced by Honeywell. A SANDAC coprocessor module containing an AT&T DSP32C digital signal processor performs the required high-speed gimbal control calculations.

SNL-MCS Description

Antenna Stabilization

The RLGA IMU, the SAR antenna, and the radar low-noise amplifier (LNA) are supported by a three-axis gimbal assembly, shown in Figure 3.

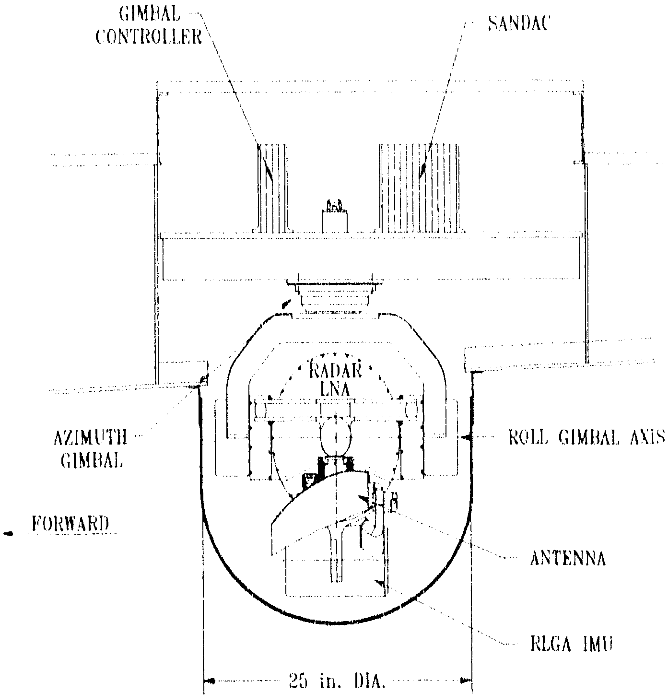

Figure 3: Gimbal Assembly

The IMU accuracy is categorized in the 1 nm/hr class. It utilizes Honeywell GG-1320 gyros and Sundstrand QA-1200 accelerometers. Volume is 186 cubic inches (5.0 in. dia. X 9.5 in. long), and weighs approximately 12 lbs. Figure 4 is a cutaway drawing of the IMU.

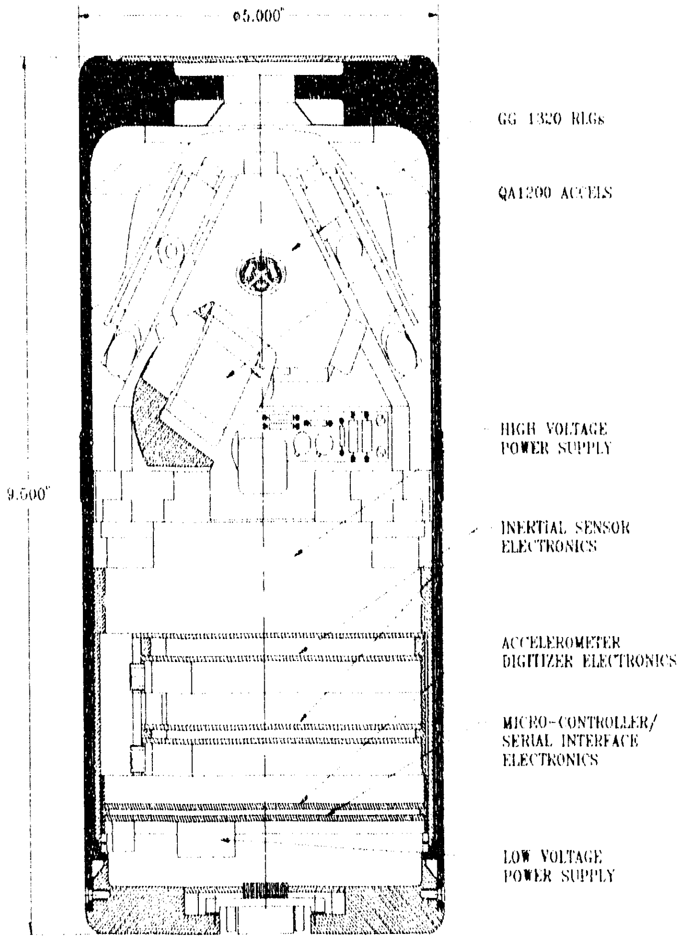

Figure 4: RLGA IMU

Each gimbal axis is driven by a DC torque motor and employs a synchro-resolver as a gimbal angle transducer. The multimode gimbal control strategy uses filtered gyro data from the RLGA (via SANDAC), supervisory commands from the SANDAC, and gimbal angle measurements as inputs to the gimbal control calculations. The interface electronics between the SANDAC and the gimbal assembly includes PWM drives for the motors and 16-bit resolver-to-digital converters for digitizing the synchro-resolver outputs. The gimbal controller software, which runs in the SANDAC DSP32C coprocessor, is written mainly in "C" language, with some assembly-level subroutines for utility functions. The control outputs are voltage commands to the PWM electronics, and are updated at a 1024 Hz rate. Coefficients for the controller algorithm were generated via MATLAB ™ optimal control system design features. Non-linear simulations were performed to validate the controller algorithms. During flight testing, the measured gimbal control errors (pointing errors) were less than 0.01 degrees RMS.

Navigation Function

The navigation information is supplied by the RLGA IMU with differential GPS (Global Position System) aiding. The IMU navigation calculations and GPS Kalman filter calculations are performed in the SANDAC. The RLGA provides short term high frequency motion measurement capability, and the GPS system provides long term error stability.

The differential GPS operation, illustrated in Figure 5, requires the use of two GPS receivers, one aboard the aircraft (slave receiver) and a second on the ground (master receiver) at a precisely known location. Both units receive position and velocity updates from the same set of satellites, but the master receiver's a priori knowledge of its position and velocity enable it to compute a correction to the GPS-indicated position and velocity. This correction is then transmitted to the aircraft and applied by the slave GPS receiver to produce an aided navigation solution.

The differentially corrected position and velocity outputs of the slave GPS receiver are used as measurement inputs into a Kalman filter to estimate and correct for the errors in the RLGA IMU and navigation equations. The Kalman filter consists of ten error states: latitude, longitude, altitude, north velocity, east velocity, vertical velocity, north tilt, east tilt, azimuth, and vertical acceleration. The horizontal position, velocity, and tilt errors of the navigator are corrected for in an open-loop configuration. The vertical channel errors are compensated by either an open-loop estimation of the baro-aided RLGA vertical channel, or with a closed loop compensation where RLGA's vertical channel is stabilized with the GPS Kalman filter altitude estimate.

The differential GPS (two receiver) approach has the advantage of greater accuracy than is attainable with one receiver. The disadvantage is that the system must be operated within a 50 Km radius of the master receiver. The slave receiver can also be used in an autonomous mode (no ground receiver) if differential accuracies are not required.

Km radius of operation.

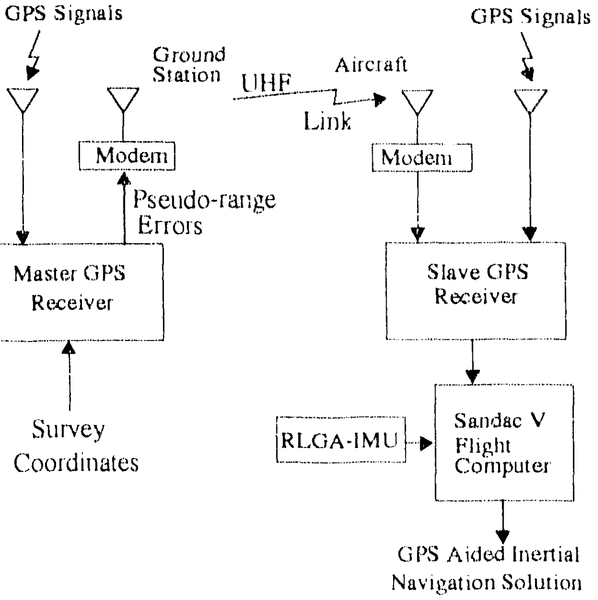

Figure 5: Differential GPS System

SAR motion measurement calculations

As mentioned earlier, producing well focused SAR images requires the measurement of the antenna translational motion during the image formation process.

Many previous motion compensation systems utilize an IMU which is physically located in the aircraft, not on the antenna. It was determined that, for many of these earlier systems, high frequency antenna motion due to structural resonances excited by the aircraft engines was not being measured by the IMU located inside the aircraft. This high frequency motion can cause degraded image focussing. For this reason the SNL-MMS utilizes an IMU mounted on the same surface as the antenna. This is made possible by the small size and weight of the RLGA.

The speed of the IMU nav calculation is 512 Hz, which is a significant increase over conventional IMU implementations. This faster speed allows higher frequency antenna motion to be measured and also reduces data latency. The faster IMU navigation calculations were made possible by adding processor modules to the SANDAC flight computer.

The SANDAC software configuration is illustrated in Figure 6. Each block in the figure corresponds to software executing in one 68020 processor module. Also shown is the DSP32 processor module executing the gimbal stabilization software. Thus the SANDAC flight computer consists of eight 68020 processor modules and one DSP32 digital signal processor module, executing more than 150,000 lines of "C" and assembly code.

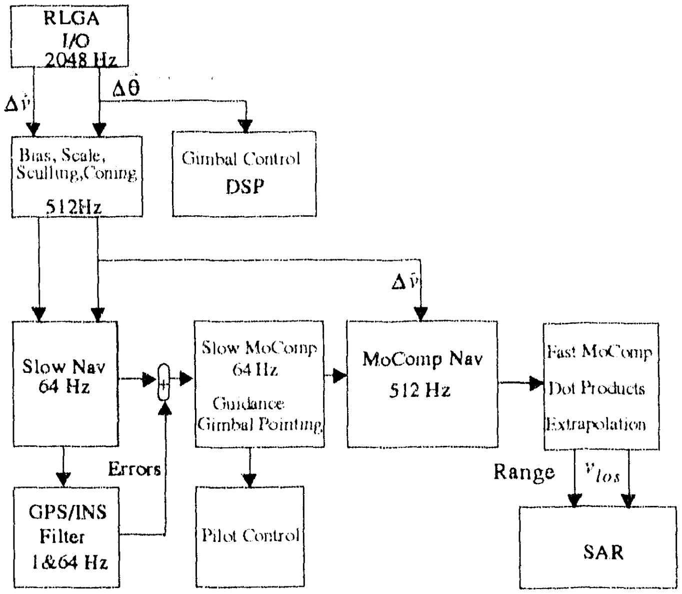

Figure 6: SNL-MMS Software Configuration

Aircraft Guidance

The final function of the SAR motion measurement system is an aircraft waypoint guidance system which directs the pilot to fly precise trajectories. These precise trajectories greatly facilitate the imaging of objects of interest at known locations. The pilots are directed to fly these precise trajectories through the use of a video monitor located in the cockpit. Figure 7 illustrates the pilot display.

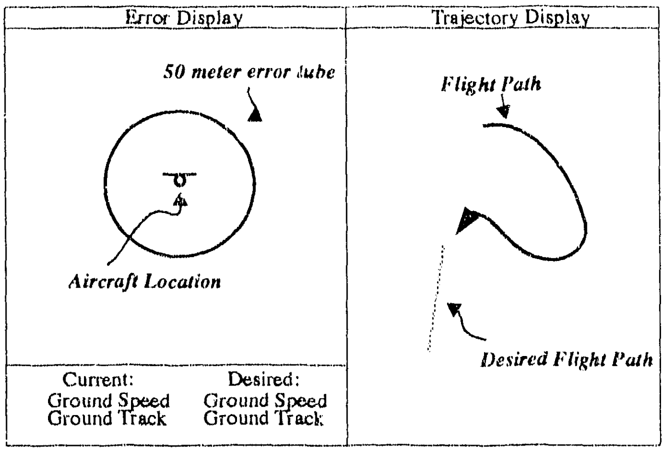

Figure 7: Pilot Guidance Display

The monitor display is divided into three areas, a trajectory display, an error display, and a text display. The trajectory display shows the aircraft's horizontal flight path as well as the desired horizontal flight path. The error display shows the aircraft position relative to a 50 meter error tube connecting any two desired waypoints. Thus the pilot simply flies the aircraft so as to keep the indicated aircraft position near the center of the 50 meter tube.

This guidance system has been very successful in flight testing and has allowed imaging in more complex trajectories, including a circular trajectory.

Flight Test Results

Flight testing of the SNL-MMS was performed during May-November, 1991. The set of flight test results which follow were taken from a flight test conducted July 3, 1991, and represent a typical set of results. Figure 8 shows the flight trajectory for this flight. The circular trajectories mentioned above are evident in this figure.

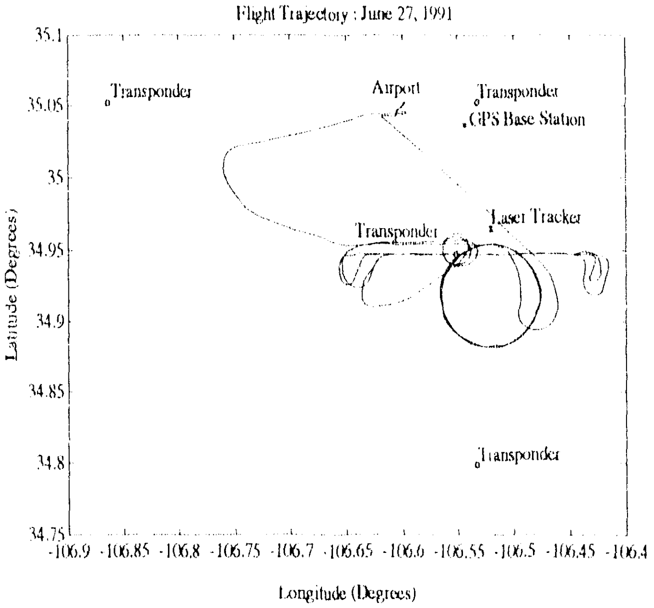

Figure 8: Flight Trajectory

The flight was scored by a Cubic CR-100 ranging transponder system which provides highly accurate aircraft position and velocity for comparison with the SNL-MMS outputs. Figure 9 shows the RLGA velocity errors (no GPS aiding) for this flight. These velocity errors are typical for a 1 nm/hr IMU.

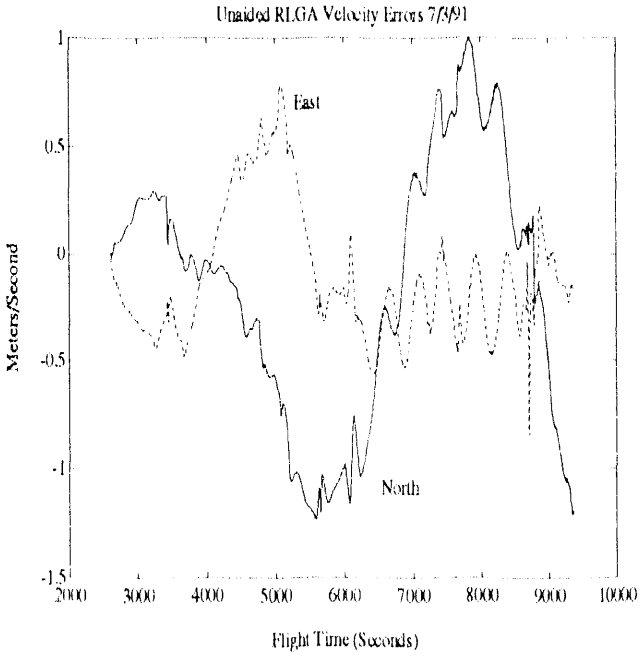

Figure 9: RLGA Velocity Errors

Figure 10 shows the velocity error when the system is aided by GPS. Only the north velocity error is shown, but the results are similar for the east and vertical channels.

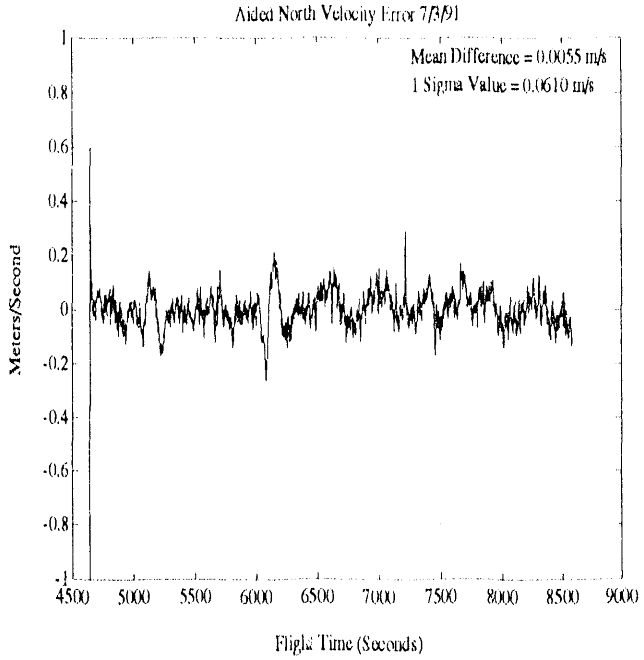

Figure 10: Aided North Velocity Error

Figure 11 shows the position error with GPS aiding

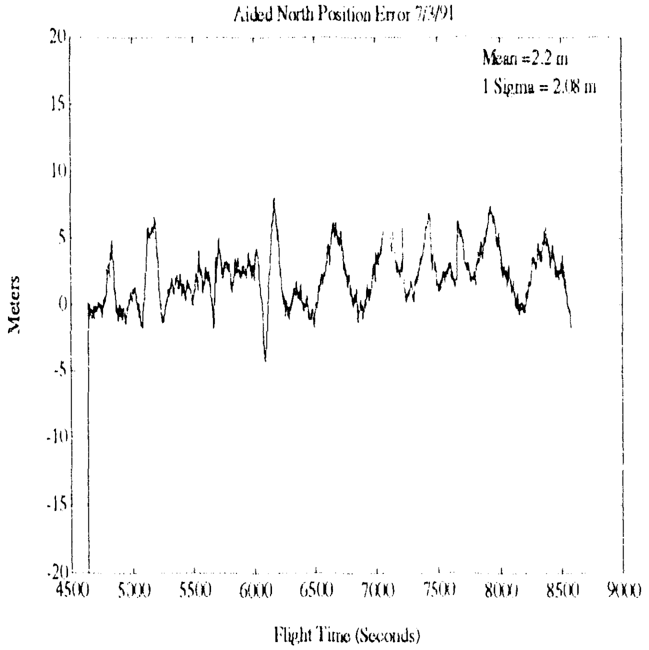

Figure 11: Aided North Position Error

Figure 12 shows the GPS estimates of the RLGA attitude. Attitude error correction improves both antenna pointing accuracy and antenna motion measurement accuracy. The antenna stabilization accuracy is illustrated in Figure

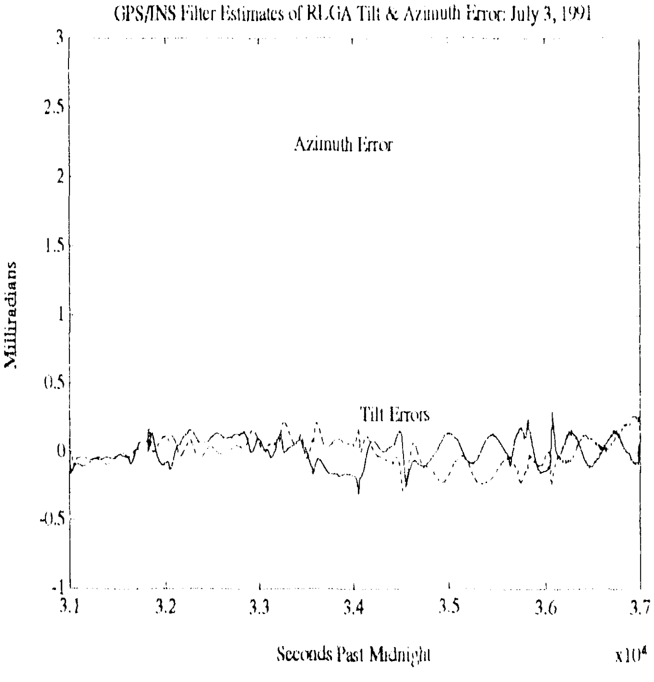

Figure 12: RLGA Attitude Errors

13, which shows the RLGA heading angle during an imaging pass. The heading angle affects the antenna azimuth pointing. Also shown in Figure 13 is the azimuth gimbal angle, which accounts for aircraft heading variation of the imaging pass. Thus even is the presence of large aircraft heading variation the RMS value of the RLGA heading for this imaging pass is less than 0.01 deg, and similar performance is obtained from the pitch and roll axis.

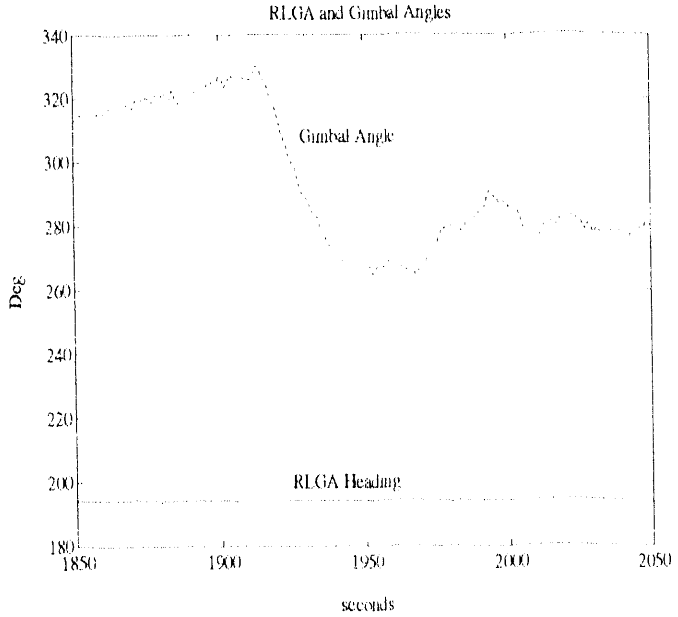

Figure 13: Antenna Stabilization

Conclusions

Sandia National Laboratories has developed an advanced Synthetic Aperture Radar Motion Measurement System. Flight testing has confirmed that the system meets the accuracy required for well focused image formation. The system includes several state-of-the-art components including a miniaturized high accuracy ring laser gyro inertial measurement unit, a three axis gimbal pointing and stabilization assembly, a differential GPS navigation aiding system, a pilot guidance system, and a multi-processor flight computer.

Acknowledgment

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References

T. Owen and R. Wardlaw, "Evaluating the Velocity Accuracy of an Integrated GPS/INS System: Flight Test Results", Proceedings of the Institute of Navigation National Technical Meeting, San Diego, CA, 1992, pp. 13-22.

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