Minnesat: GPS Attitude Determination Experiments Onboard a Nanosatellite

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ABSTRACT

This paper presents an overview of the attitude determination experiments onboard the University of Minnesota nanosatellite, Minnesat. Minnesat is designed as a test bed for conducting ultra-short baseline GPS attitude determination experiments in Earth orbit. The primary scientific mission of the Minnesat project is to design, develop, and validate an ultra-short baseline GPS attitude determination (AD) system. Minnesat is equipped with a set of sensors to support two independent AD systems that are referred to as the Primary AD System and the GPS AD System. The Primary AD System blends measurements of a three-axis magnetometer to estimate Minnesat's attitude. The GPS AD System blends measurements of inertial sensors with differential carrier phase GPS measurements to estimate Minnesat's attitude. The Primary AD System is used as a truth source to validate the GPS AD System.

INTRODUCTION

Attitude refers to a vehicle's angular orientation in space. The attitude of a vehicle can be defined by specifying the relative orientation of two reference frames. For spacecraft guidance, navigation, and control applications in Earth orbit, the two reference frames typically used are a vehicle fixed body frame and a navigation frame with known orientation. The navigation frame generally refers to an inertial frame, an Earth-fixed frame, or a local vertical local horizontal frame and its selection depends on the application. Attitude determination (AD) systems are used to estimate the orientation of a vehicle or, more specifically, to estimate the relative orientation of the two reference frames.

An AD system consists of a set of sensors to measure the vehicle's attitude and a filter that blends the sensor measurements to estimate the vehicle's attitude. The attitude sensors typically used in spacecraft AD systems include inertial sensors, star trackers, Sun sensors, and horizon sensors. The selection of an attitude sensor depends on several factors including its size, mass, power consumption, and performance characteristics. Nanosatellites are a class of miniature satellites that have severe restrictions on size, mass, and available power. These restrictions effectively become restrictions on attitude sensors and, thus, limit the selection of attitude sensors that can be used for nanosatellite AD systems.

Recently, the Global Positioning System (GPS) has been used to estimate the attitude of vehicles in aerospace applications. AD systems designed using GPS require multiple GPS sensors onboard the vehicle. A GPS sensor consists of an antenna to measure the signal carrier broadcast by GPS satellites and a receiver to collect and process the signals measured by the antenna. The size, mass, and power consumption of a typical GPS sensor satisfy the restrictions of a nanosatellite. Therefore, GPS sensors have the potential to be used as attitude sensors for nanosatellite AD systems.

GPS AD systems use carrier phase measurements from multiple antennas separated by distances referred to as baselines.¹ The performance of GPS AD systems depends on several factors including the relative distance between antennas. These antennas are arranged in configurations where the lengths of the baselines are at least several integer cycles longer than the wavelength (~19 cm) of the GPS signal carrier. These antenna baseline lengths are selected to mitigate the effect of measurement errors of a GPS sensor.

GPS sensor measurement errors include both uncorrelated and correlated components.² The uncorrelated errors refer to wide band noise. These errors are due to thermal noise in the signal channel and the GPS receiver. The correlated errors refer to the phase delay of the GPS antenna. The effect of the phase delay becomes more significant as the antenna baseline lengths approach the wavelength of the GPS signal carrier. Current GPS AD systems do not incorporate models of the antenna correlated errors. Therefore, the performance of these AD systems depends on the antenna baseline lengths and whether the phase delay contributes significantly to the measurement errors of the GPS signal carrier.

Current GPS AD systems are used on aerospace vehicles much larger than nanosatellites. These AD systems require the vehicles to support antenna baselines longer than the dimensions of nanosatellites and aerospace vehicles of similar size. However, if accurate models of the antenna correlated errors can be developed and incorporated into GPS AD systems, then these AD systems could estimate attitude using shorter antenna baselines. Furthermore, these AD systems could be used for applications where shorter antenna baselines are necessary.

The University of Minnesota Small Satellite Program is currently designing a nanosatellite called Minnesat. Minnesat is the University of Minnesota's entry into the AFRL, AIAA, & AFOSR University Nanosat-4 competition. The scientific mission of the Minnesat project is to design and evaluate the performance of an ultrashort baseline GPS AD system. The objectives of this mission are to investigate the hardware modifications required for operation of GPS sensors using ultra-short baselines in Earth orbit; to design and validate models for the antenna correlated errors; to design and validate the algorithms required to mechanize an attitude filter for the ultra-short baseline GPS AD system; and to evaluate the accuracy of the attitude estimates computed by the attitude filter. The Minnesat project is a student managed and operated project and, thus, the cost of components is an important design constraint for every system. Therefore, inexpensive, commercial-off-the-shelf components are used throughout the design of Minnesat.

This paper presents an overview of Minnesat's scientific mission and is organized as follows. First, we describe the fundamentals of GPS attitude determination. This description is limited to top-level details and the technical details will be presented in a following paper. Second, we describe the GPS antenna configuration supported by Minnesat's frame. Third, we briefly describe Minnesat's systems and operation. Fourth, we describe the Kalman filters designed to estimate Minnesat's attitude.

GPS ATTITUDE DETERMINATION FUNDAMENTALS

The attitude of a vehicle can be computed by considering three fixed non-collinear points on the vehicle. In general, three non-collinear points in space define a plane. If the positions of these three points are known in the vehicle's body frame, then the orientation of this plane can be uniquely defined in this body frame. Furthermore, if the positions of these three points are known in the navigation frame, then the orientation of this plane and body frame can be computed relative to the navigation frame.

GPS AD systems make use of this principle to estimate a vehicle's attitude in the following manner. Three non-collinear GPS antennas are mounted on the structure of a vehicle such that their positions are always known in the vehicle's body frame. Therefore, these three antennas define three fixed baselines and a fixed plane in the vehicle's body frame. The positions of the antennas are measured using GPS carrier phase signals and their relative positions are estimated using differential carrier phase GPS (CDGPS) techniques. These differential carrier phase measurements (dCPMs) are used to estimate the orientation of the fixed plane and, thus, the vehicle's body frame relative to the navigation frame.

CDGPS techniques are based on subtracting the carrier phase measurements of two antennas that are tracking common GPS satellites. These dCPMs provide an estimate of the phase difference between GPS signals measured by the two antennas. This phase difference provides an estimate of the relative position, or delta range, of the two antennas along the line-of-sight (LOS) vector from the antenna baseline to a GPS satellite (Figure 1). There exists a geometric relationship between the antenna baseline vector, the LOS vector, and the delta range. If the two antennas are tracking four common GPS satellites, then this geometric relationship can be used to determine the direction of the antenna baseline vector. Α second antenna baseline is required to resolve the rotational ambiguity in the direction of the first antenna baseline vector. The third antenna baseline is redundant because only two antenna baselines are required to determine attitude.



Figure 1. GPS Antenna Baseline Geometry

The dCPMs of an antenna baseline are corrupted by several errors that must be calibrated before the attitude filter can use these measurements to compute estimates of a vehicle's attitude. These measurement errors include integer ambiguities, line bias, multipath noise, and antenna phase delay.³ The advantage of using dCPMs is that they eliminate common mode errors of the carrier phase measurements. These first three error sources have been the subject of intense recent research. The fourth error source is the subject of research for the Minnesat project. The resolution of these errors is referred to as the calibration procedure for the dCPMs.

Integer ambiguity refers to the whole number of signal carrier cycles that exist in the dCPMs. The range of the integer ambiguity space depends on the length of the antenna baseline and the wavelength of the GPS signal carrier. The L1 GPS signal carrier has a frequency of 1575.42 MHz corresponding to a wavelength of 19.03 cm. Therefore, as the length of the antenna baseline increases, the range of the integer ambiguity space increases and the time required to resolve the integer ambiguity for dCPMs increases as well. The integer ambiguity must be resolved for each GPS satellite tracked by the two antennas that form the baseline.

Line bias refers to the time delay a measured GPS signal experiences between the antenna and its corresponding receiver. The line bias is generally assumed to be slowly time varying and is dependent on several factors including temperature. The line bias is independent of the GPS satellite constellation and the attitude of the vehicle. Multipath noise refers to GPS signals measured from reflective surfaces around the GPS antenna.

The phase delay refers to delays that result from the misalignment of the geometric centroid of the antenna and the phase measurement center. This delay depends on the LOS vector from the antenna baseline to the GPS satellite and on the size of the antenna. This delay becomes more significant as the length of the antenna baseline approaches the wavelength of the GPS signal carrier. This delay is time varying because the LOS vector depends on the position of the GPS satellite and the attitude of the vehicle. This delay can be resolved by generating an *a priori* lookup table that lists estimates of the phase delay for the azimuth and elevation angles of an arbitrary LOS vector.⁴ The azimuth angle of the LOS vector ranges from 0° to 360° . The elevation angle of the LOS vector ranges from 0° to 90° . In summary, the calibration procedure for dCPMs requires resolution of the integer ambiguities, resolution of the line bias, and adjustment for the phase delay using a lookup table.

Current GPS AD systems use long antenna baselines where the baseline lengths are several integer cycles longer than the wavelength of the L1 GPS signal carrier. The advantages of using long antenna baselines as compared to short antenna baselines are that the measurement errors introduced by thermal noise and differential phase delay are negligible. Therefore, AD systems that do not account for these measurement errors are more accurate. The disadvantages of using long antenna baselines as compared to short antenna baselines are as follows. First, the range of the integer ambiguity space increases so that more time is required to resolve the integer ambiguities and calibrate the dCPMs. Second, the size of the vehicle must support the long antenna baselines. Nanosatellites, and aerospace vehicles of similar size, do not have sufficient rigid surface area to support long antenna baselines. It is possible to mount antennas on extendable booms from the However, antennas mounted on nanosatellite. these booms are subject to the vibrational modes of the boom that would add an additional error source to the dCPMs and would affect the accuracy of the attitude estimates.

GPS ANTENNA CONFIGURATION

The University of Minnesota nanosatellite, Minnesat, is designed as a test bed for conducting ultra-short baseline GPS attitude determination experiments in Earth orbit. Minnesat's frame supports a GPS antenna configuration that is designed to ensure that at least two antenna baselines are available for attitude determination regardless of its orientation or orbital position. The guidelines of the University Nanosat-4 competition constrain the physical dimensions of Minnesat to fit within a physical envelope defined by a circular cylinder of diameter 48 cm and height 48 cm and to weight less than 30 kg.

Minnesat has an axisymmetric hexagonal frame with a circumscribed radius of 22.5 cm and with a height of 45 cm. One GPS antenna is mounted at the center of each side of the frame for a total of eight GPS antennas onboard Minnesat. Figure 2 shows a schematic of Minnesat. The GPS antennas are represented by light colored boxes at the center of each side of the satellite. Solar cells are represented by dark blue boxes on each side of the satellite. The design trade-offs for the frame design and antenna configuration are influenced by several factors including the number of antenna baselines available for attitude determination; the antenna baseline redundancy in the event of GPS sensor failure; the additional volume, mass, power, and cost required to support one GPS sensor; and the available surface area for placement of GPS antennas and solar cells.



Figure 2. Minnesat Schematic

This GPS antenna configuration supports twenty eight possible antenna baselines. However, antennas located on opposite sides of the frame can not form a baseline for attitude determination. For example, Figure 3 shows that antennas mounted on sides 3 and 6 of the frame will not have common visible GPS satellites. Figure 4 shows that this antenna configuration supports twenty four antenna baselines for attitude determination. Antennas located on sides 1 and 8 of the frame can form baselines with antennas





located on adjacent sides of the frame for a total of six baselines each. Antennas located on sides 2 through 6 of the frame can form baselines with any antenna except those located on opposite sides of the frame. This antenna configuration supports three baseline lengths: 19.5 cm, 31.8 cm, and 33.8 cm. For the L1 GPS signal carrier, the integer ambiguities of dCPMs for these three antenna baselines are -1, 0, and 1, only. Table 1 summarizes the available antenna baselines for attitude determination. A red \times indicates that the baseline formed using these antennas can not be used for attitude determination.



Figure 4. GPS Antenna Baselines

GPS	1	2	3	4	5	6	7	8
Sensor								
1	×	31.8 cm	×					
2	31.8 cm	×	19.5 cm	33.8 cm	×	33.8 cm	19.5 cm	31.8 cm
3	31.8 cm	19.5 cm	×	19.5 cm	33.8 cm	×	33.8 cm	31.8 cm
4	31.8 cm	33.8 cm	19.5 cm	×	19.5 cm	33.8 cm	×	31.8 cm
5	31.8 cm	×	33.8 cm	19.5 cm	×	19.5 cm	33.8 cm	31.8 cm
6	31.8 cm	33.8 cm	×	33.8 cm	19.5 cm	×	19.5 cm	31.8 cm
7	31.8 cm	19.5 cm	33.8 cm	×	33.8 cm	19.5 cm	×	31.8 cm
8	×	31.8 cm	×					

Table 1. GPS Antenna Baseline Lengths

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20th Annual AIAA/USU Conference on Small Satellites Minnesat's GPS antenna configuration is selected to ensure that more than two baselines are available for the GPS AD system regardless of Minnesat's orientation or orbital position. Therefore, Minnesat does not require an attitude control actuators control system and to continuously point the satellite so that the same two antenna baselines are used for attitude determination. Furthermore, onboard CPU processing time, mass, and power do not have to be allocated to an attitude control system and control actuators. It should be noted that the moments of inertia are selected to ensure that Minnesat is dynamically stable.

MINNESAT MISSION OVERVIEW

Minnesat is equipped with multiple sensors and components to support two real-time AD systems and a real-time navigation system (Figure 5). The two AD systems are referred to as the Primary AD System and the GPS AD System.



Figure 5. Mission Overview

The Primary AD System (Figure 6) consists of rate gyros, a three-axis magnetometer, a magnetometer calibration procedure, and an extended Kalman filter (EKF). The EKF blends measurements of the rate gyros with calibrated magnetometer measurements to compute real-time estimates of Minnesat's attitude. The GPS AD System (Figure 7) consists of rate gyros, multiple GPS sensors, the dCPM calibration procedure, and an EKF. The EKF blends measurements of the rate gyros with calibrated dCPMs to compute real-time estimates of Minnesat's attitude. The rate gyros are used to increase the filter bandwidth for both AD systems as compared to using the magnetometer or GPS sensors individually.

The attitude estimates computed using the Primary AD System are used to establish a baseline for filter performance. The performance of the GPS AD System can then be evaluated by comparing its attitude estimates to the baseline filter performance. It should be noted that the visible GPS satellite constellation depends on time and Minnesat's orbital position. The effect of the visible GPS satellite constellation on the accuracy of the dCPMs can be quantified through the attitude dilution of precision (ADOP). Therefore, the performance of the GPS AD System is also evaluated as a function of ADOP.

The Navigation System (Figure 8) uses the GPS navigation messages to estimate Minnesat's current orbital position, to predict Minnesat's orbit, and to estimate the orbital positions of the GPS satellite constellation. Minnesat's orbital position is used by the Primary AD System to estimate the local Earth magnetic field vector for its EKF. Minnesat's predicted orbit is used to estimate when ground communication is possible with Minnesat's Ground Station System located in Minneapolis. The orbital positions of the GPS satellite constellation are used by the GPS AD System to estimate the LOS vector from an antenna baseline to a visible GPS satellite.

Minnesat transmits both attitude and navigation data to the Ground Station System during ground communication windows. The attitude and navigation data consists of sensor measurements, selected data from the GPS navigation messages, the Navigation System position data, the Primary AD System calibration and attitude filter data, and the GPS AD System calibration and attitude filter data. These data sets are time stamped, compressed, and stored in onboard archival memory in the form of data packets. These data packets are then sequentially transmitted to the Ground Station System for processing.











Figure 8. Navigation System

KALMAN FILTER DESIGN

An AD system consists of a set of sensors to measure the vehicle's motion, dynamic models of the vehicle's motion, models of the sensor characteristics, and a filter that blends the sensor measurements using the models to estimate the vehicle's attitude. In general, sensor measurements are corrupted by errors such as bias and wide band noise. These errors are time varying and can fluctuate due to factors such as temperature variations and mechanical vibrations. Furthermore, the sensors can be misaligned from their intended orientation due to manufacturing errors or mounting errors. Therefore, the attitude filter requires models of the sensor errors to accurately estimate attitude.

In these attitude determination experiments, EKFs are designed to blend rate gyro measurements with either magnetometer or dCPMs to estimate Minnesat's attitude in the presence of sensor errors (Figure 9). Rate gyros are high bandwidth sensors and can be used to estimate the attitude of a vehicle performing rapid maneuvers. However, rate gyro measurements are subject to bias and wide band noise and the attitude estimates computed using these measurements result in unbounded errors.⁵

Magnetometers and GPS sensors are low bandwidth sensors and can not be used to estimate the attitude of a vehicle performing rapid These sensor measurements are maneuvers. independent of the rate gyro measurements and measurement errors. Therefore, the magnetometer and GPS sensor measurements can be used to estimate the rate gyro bias and bound the gyrobased attitude estimation errors. The Kalman filter is used to blend the measurements from these sensors to compute more accurate attitude estimates as compared to using the sensors individually. The magnetometer and GPS sensors can be thought of as part of an aiding system for the gyro-based attitude estimates.

The general design of the EKFs for both the Primary AD System and the GPS AD System is shown in Figure 10. The Kalman filter blends measurements from multiple sensors to compute



Figure 9. Complementary/Kalman Filter



Figure 10. EKF Design

estimates of the state mean vector and the state covariance matrix using a time update and a measurement update.⁶ The time update involves propagating estimates of the state mean vector and state covariance matrix using the rate gyro measurements. The state vector is defined from the dynamic models selected to describe the vehicle's attitude motion. The measurement update involves computing posterior estimates of the state mean vector and state covariance matrix using the aiding system sensor measurements. The measurement update uses a measurement model to relate the aiding system sensor measurements to the state mean vector and state covariance matrix. The time update can be considered as a gyro-based AD system. The measurement update can be considered as a gyro-free AD system.

The EKFs of the Primary AD System and GPS AD System use the same dynamic and covariance models for the time update. The vehicle dynamic models include Euler's equations and quaternion based attitude kinematic equations.⁷ Rate gyro measurements are used to propagate the dynamic and covariance models. Therefore, the time update rate occurs at the rate gyro sampling frequency. A rate gyro error model is incorporated into the time update so that the rate gyro bias can be estimated by the aiding system and the attitude errors computed by the gyro-based AD system can be bounded.

The EKFs of the Primary AD System and GPS AD System use different measurement models for the measurement update. The Primary AD System uses a three-axis magnetometer to provide one vector measurement of attitude. The measurement model is designed based on a vector matching algorithm that solves Wahba's problem.^{8,9} The measurement update rate occurs at the magnetometer sampling frequency. The GPS AD System uses the calibrated dCPMs to provide at least two vector measurements of attitude. The measurement model is designed based on the LOS vector from an antenna baseline to a GPS satellite. The measurement update rate occurs at the GPS sensor sampling frequency.

In summary, the rate gyro measurements are used in both EKF designs to increase the bandwidth of the gyro-free AD systems, to smooth the attitude solution in between measurement updates, and to provide attitude measurements in the event of aiding system sensor unavailability or failure. The aiding system is used to estimate the rate gyro bias and bound the attitude errors computed by the gyrobased AD system. Euler's equations are included in the dynamic model of the time update to act as a dynamic constraint on the vehicle's attitude model in the event of attitude sensor unavailability or failure.

The attitude estimates computed by the EKF of the Primary AD System are considered the true attitude of Minnesat. Both AD systems use the same rate gyro measurements so that the time update rates for both EKFs are the same. The magnetometer and GPS sensor measurements are synchronized so that the measurement update rates for both EKFs are the same. The performance of the GPS AD System is evaluated by comparing the estimates of the state mean vector and state covariance matrix for both AD systems.

SUMMARY

The University of Minnesota nanosatellite, Minnesat, is designed to perform ultra-short baseline GPS attitude determination experiments in low Earth orbit. This paper has described the design of both the Primary Attitude Determination System and the GPS Attitude Determination System that will be tested onboard Minnesat. The intent of the University of Minnesota Small Satellite Program is to complete the design and development of Minnesat by March 2007.

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