A MICROMECHANICAL INS/GPS SYSTEM FOR SMALL SATELLITES

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Abstract

The cost and complexity of large satellite space missions continue to escalate. To reduce costs, more attention is being directed toward small lightweight satellites where future demand is expected to grow dramatically. Specifically, micromechanical inertial systems and microstrip GPS antennas incorporating flip-chip bonding, ASIC, and MCM technologies will be required.

Traditional microsatellite pointing systems do not employ active control. Many systems allow the satellite to point coarsely using gravity gradient, then attempt to maintain the image on the focal plane with fast-steering mirrors. Draper's approach is to actively control the line-of-sight pointing by utilizing on-board attitude determination with micromechanical inertial sensors and reaction wheel control actuators.

Draper has developed commercial and tactical-grade micromechanical inertial sensors. The small size, low weight, and low cost of these gyroscopes and accelerometers enable systems previously impractical because of size and cost. Evolving micromechanical inertial sensors can be applied to closed-loop, active control of small satellites for microradian precision-pointing missions.

An inertial reference feedback control loop can be used to determine attitude and line-of-sight jitter to provide error information to the controller for correction. At low frequencies, the error signal is provided by GPS. At higher frequencies, feedback is provided by the micromechanical gyros. This blending of sensors provides wide-band sensing from dc to operational frequencies.

First-order simulation has shown that the performance of existing micromechanical gyros, with integrated GPS, is feasible for a pointing mission of 10 microradians of jitter stability and ~1 milliradian absolute error, for a satellite with 1 meter antenna separation. Improved performance micromechanical sensors currently under development will be suitable for a range of micro-nano-satellite applications.

1. Introduction

The cost and complexity of conducting space missions with individual, highly integrated, large satellites continue to escalate. To reduce costs, more effort and attention is being directed toward small, light-weight satellites where future demand is expected to grow dramatically. During the past few years significant effort has been made to develop the "smaller, better, faster" approach being embraced by the aerospace industry as a means to prepare for space missions of the future. Recent advances in silicon microfabrication technology have led to the development of low cost micromechanical inertial sensors. The small size, low weight, and low cost attributes of these sensors permit on-board insertion of gyroscopes and accelerometers for space applications previously considered impractical because of size and cost considerations.

A micro-nanoclass spacecraft with a precision pointing requirement is a unique design challenge for the hardware, instrument, and payload designers. This class of satellite is an ideal application for micromechanical gyros to provide the inertial reference information needed to perform image motion compensation for stabilization and the reduction of image smear in an extremely small and light weight package.

Existing microsatellite pointing systems do not employ active control to improve pointing performance. Some systems allow the bus to point coarsely, then attempt to maintain the image on the focal plane with fast-steering mirrors. GPS alone will not provide sufficient accuracy. However, line-of-sight pointing can be controlled by on-board attitude determination from micromechanical inertial sensing, coupled with GPS, and closed-loop error correction and attitude control actuators. Others have not undertaken this approach since traditional inertial reference systems are significantly heavier and larger than the micromechanical package, and could consume a significant fraction of the mass budget for an entire micro-class satellite.

The concept described herein consists of a three axis stabilized system using on-board GPS, next-generation micromechanical inertial instruments, small reaction wheels for attitude control, and miniaturized phased array antennas for line-of-sight communications. The basic structure will be advanced graphite-epoxy composite materials. Material fabrication is kept cost effective by using simple shapes and optimizing the overall configuration. Body-fixed solar cells, as well as batteries, are used. This flexibility permits selection and adjustment of the center of gravity coincident with the center-of-pressure to minimize rotational torques due to atmospheric drag.

The feasibility of a micromechanical gyro to provide sufficient performance to accomplish a pointing mission has been analyzed for a bandwidth of 0.1 Hz, based on estimated external and induced disturbance frequencies. From a first-order simulation, it was determined that the performance of existing micromechanical gyros with integrated GPS is capable of providing pointing jitter stability better than 10 microradians and absolute pointing error of approximately 1 milliradian, for a satellite with 1 meter antenna separation (i.e., 1m baseline). This result is encouraging and gives credence to the overall concept and approach. For a satellite with ~100 mm baseline, pointing accuracy will be degraded by more than a factor of 10 unless more accurate micromechanical instruments are used.

2. Pointing Scenario

A typical pointing scenario assumes that the satellite will process GPS-derived attitude measurements (and perhaps attitude-rate) and gyro-derived attitude rate measurements while in orbit to establish estimates of gyro drift bias and scale factor (SF). Satellite maneuvers can be used to separate the error components due to bias and SF. Accelerometer measurements can be used to provide delta velocity in cases where the satellite may require orbit changes.

The satellite is pitched forward from a nominal nadir-pointing attitude to some new attitude, and then pitched in reverse during imaging to reduce the transverse velocity of the line-of-sight at the surface of the earth. Without this counter motion, the satellite velocity over an integration period will result in too much blur of the picture. The amount by which the satellite must be initially pitched forward in preparation for the imaging slew depends upon the amount of time required to settle out initial pitch slew transients once the imaging slew begins. The time requirement, in turn, depends upon the controller bandwidth. A higher controller bandwidth will result in transients subsiding quicker but will result in a greater response to sensor noise. A 0.03 Hz controller bandwidth requires an initial attitude of a least 60° of the nadir and a 0.1 Hz controller bandwidth requires less than 30° in order to satisfy the requirement that the additional drift (i.e., in addition to the nominal drift due to satellite motion) over an integration period should not exceed the equivalent of 1 pixel motion.

During this large angular rotation in a short period of time there will likely be several changes of GPS satellites and, possibly, a large variation of attitude precision. Therefore, attitude measurements from GPS will be effectively suppressed during the imaging slew and attitude inputs to the controller will rely essentially upon calibrated gyro measurements. Calibration of the gyros depends upon the effectiveness of the integrated GPS/gyro filter.

If gyro calibration is not sufficiently accurate, it may be necessary to pause at the end of the preparatory pitch-forward maneuver to regain the required absolute attitude accuracy by again processing GPS attitude measurements at the new pitch attitude. If this angle is large, a second set of GPS antennas might have to be used to obtain satisfactory satellite visibility. On the other hand, if the angle is small, as required for the 0.1 Hz controller, a single set of antennas may suffice for both the nadir and off-nadir satellite attitudes.

Table 1 shows the component requirements for a conceptual imaging mission with an absolute pointing requirement of 1 mrad and a jitter requirement of 0.5 microradian, for a satellite baseline of 1 meter.

Table 1. Component Requirements

Function	Requirements	
Attitude Control System	Jitter	0.5 microradian over 14 ms integration
	Slew Rate	0.75°/s
	Absolute	1 milliradian (1σ)
Inertial Sensor*	Angle Random Walk	0.1 deg√hr
	Bias Drift	4 deg/hr (1σ) over 10 minutes
	Scale Factor	1000 ppm (1σ)
Control Actuators	On-board Disturbance	Negligible between 0.01 - 50 Hz 0.0001 N-m at any single freq. between 50 to 500 Hz

***Calibrated integrated system performance.**

3. INS/GPS Role

Miniature INS/GPS systems are currently under development at Draper. The system typically contains a Micromechanical Inertial Measurement Unit (MMIMU) comprising three orthogonal micromechanical accelerometer instruments and three orthogonal micromechanical gyro instruments with individual conditioning electronics and high-resolution digital output quantizers. The system also contains a GPS receiver as well as a guidance and navigation processor. This entire system is miniaturized further using low power mixed signal CMOS ASICs, high-performance bump bonding techniques, shared/multiplexed electronics functions and advanced high-density packaging. A single clock, voltage reference, A/D converter, and DSP are used to service the micromechanical INS/GPS system, resulting in a compact, low-power, multisensor, multi-axis system. The complete INS/GPS system occupies less volume than a hockey puck. Power dissipation is minimized both through the use of low power CMOS and also by using power conserving sleep modes.

As new fabrication technologies reduce the size of the electronic assemblies in GPS receivers and other portable communications equipment, the antenna and battery become limiting factors in determining the minimum size of the overall receiver package. Miniaturized GPS microstrip antennas, fabricated on high-dielectric (k≥80) constant ceramic substrates, are being developed at Draper. These permit significant reduction in size compared to antennas fabricated on common low-dielectric substrates. New analytical models that are unique in their application to both antenna design and test are required.

GPS Role

GPS provides position with accuracy on the order of a few meters, and provides a highly reliable technique for providing attitude using interferometry techniques. Attitude determination using GPS is based on a simple geometric principle: two distinct points uniquely define a line and three noncolinear points define a plane. Treating GPS antennas with known relative positions as the noncolinear points, the orientation of the plane in which they reside can be determined, as well as the orientation of the antennas within the plane. This is achieved by using the differences in phase of the incoming GPS carrier signal between the antennas, hence the term "GPS interferometry".

The ability to determine the translational and rotation state of a satellite is dependent on the number of GPS satellites in view and the resulting measurement geometry. Since the GPS system was designed for "Earth-bound" users, the GPS satellite radiation signal is directed toward Earth. Satellites at altitudes up to approximately 1000 km will generally find 10 or more satellites "in view". At higher altitude, the user may be outside the main radiation beam of some GPS satellites. At altitudes above roughly 3000 km, the number "in view" may frequently drop below 4. Although 4 satellites in view is generally considered the minimum set to solve for both the three components of position and the use clock bias, studies have shown that acquisition of a single GPS satellite can be adequate to maintain orbit accuracy. Thus, satellites in either high altitude or highly elliptic orbits can maintain accurate position information.

The determination of attitude using GPS is based upon the carrier phase difference between two antenna tracking the same satellite. Figure 1 illustrates the basic measurement geometry. The angle θ is determined by knowing the baseline (**b**) in body axis and measuring the GPS signal delay (**Δr**). Thus, θ can be determined as follows:

$$\theta = \cos^{-1}(\Delta r/b)$$

Extending this to three axes using more than one baseline allows complete determination of vehicle attitude.

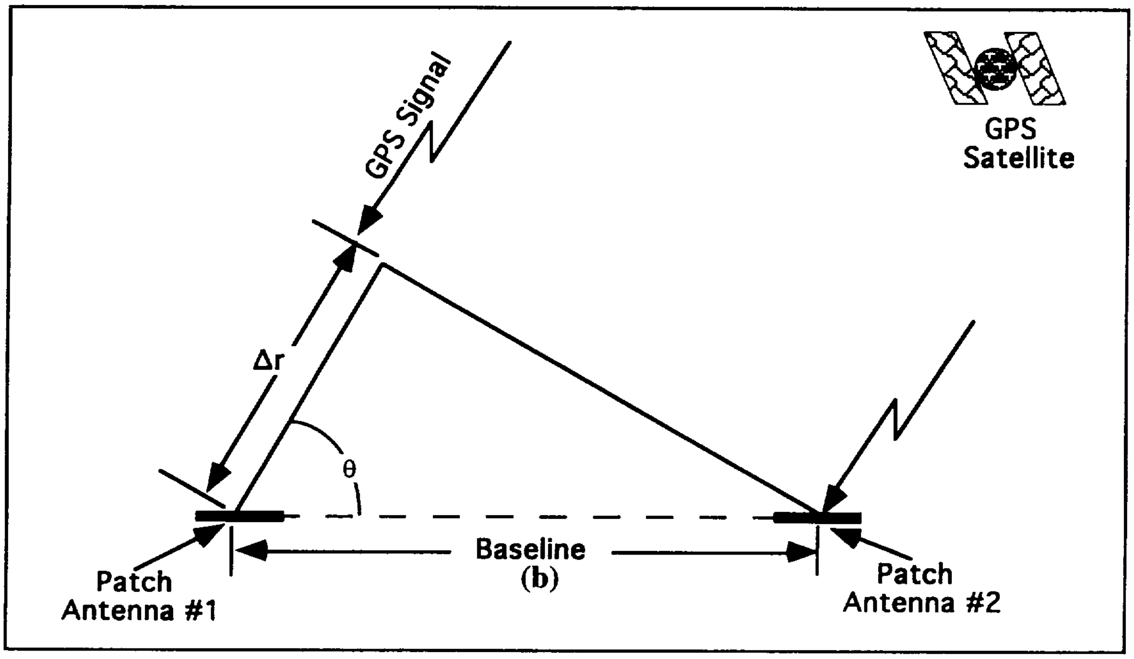

Figure 1. GPS Interferometry

One example of this technique is the GPS Attitude and Navigation Experiment (GANE), which will test a GPS interferometer intended for International Space Station Alpha (ISSA). It is currently scheduled to fly onboard the Shuttle in April, 1996. Mounted on a 1.5m by 3m platform in the cargo bay will be a four-antenna interferometer, along with an Inertial Reference Unit (IRU) for attitude verification. The requirements for this stand-alone GPS interferometer are to estimate the station's attitude to within 0.3 deg (3σ) per axis and attitude rates to within 0.01 deg/s (3σ) per axis at 0.5 Hz.

Micromechanical IMU Role

In a small satellite, the micro-mechanical IMU data can be blended optimally with the GPS data, thereby taking advantage of the IMU's ability to measure high-frequency dynamics and the GPS's ability to bound the error growth due to gyro drift.

A small satellite should have attitude determination capability at any orientation in space. The ability to determine attitude from a "cold start" without any prior knowledge is also important. Furthermore, the ability to measure rotation rates will be crucial to achieving stable conditions at any desired attitude. The micromechanical IMU can play a major role in alleviating these problems.

The ability to instantaneously measure via GPS all components of vehicle attitude can place severe requirements on spacecraft geometry and antenna mounting to ensure observability. Antennas must be mounted such that both antennas making up a baseline can observe the same satellite without masking problems. Furthermore, this condition must be met for more than one baseline and satellite. Using the micromechanical IMU (or gyro package) as a reference permits us to bridge small gaps in interferometer coverage in both a spatial and temporal sense. This can reduce the number of antennas required and mitigate problems arising from field-of-view masking due to factors such as solar arrays or other instrumentation.

Two other key roles for the IMU are control feedback for both rotational and translational maneuvers. First, attitude pointing and stabilization requires high-speed, low-noise measurements for effective control. GPS measurements alone (without an IMU) will be too noisy for effective attitude control if antenna baselines are short. Second, translational maneuvers can be provided with instant 3-axis measurement of Δv maneuvers via the IMU to perform orbit placement or adjustment. GPS has the ability to measure velocity changes very precisely via carrier tracking, and therefore could be used in place of the IMU accelerometers. Use of the IMU is more straightforward and eliminates antenna masking and satellite observability concerns.

4. INS/GPS Subsystem Integration

Figure 2 describes the satellite INS/GPS subsystem in which the flight processor navigation blends the INS/GPS data to determine translational and rotational state. Alternately, INS data could be supplied to the receiver for optimal estimation, or a cascaded design could be used. In this option, the GPS and INS data are blended at the translational/rotational state level.

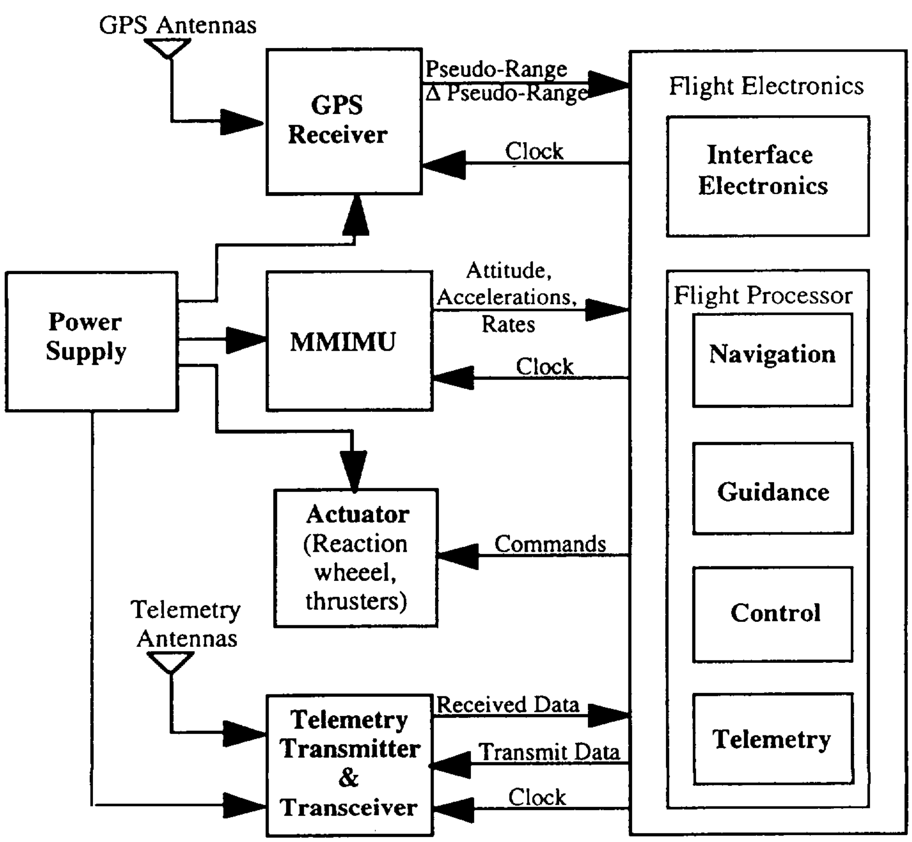

Figure 2. INS/GPS Subsystem

5. Micromechanical IMU

Draper Laboratory has been developing micromachined silicon gyroscopes and accelerometers since 1984. Micromachining uses process technology developed by the integrated circuit industry to fabricate tiny sensors and actuators. Very small-size and low-cost instruments have been microfabricated at Draper from single-crystal silicon anodically bonded to a glass substrate (dissolved wafer process). These instruments are described in more detail in the references.

These sensors are extremely rugged, and easy to fabricate. The gyro senses the Coriolis acceleration of the proof masses operating as a double-ended tuning fork. Sense and drive are electrostatic. The present units demonstrate 0.5°/s bias stability over a temperature range of -40 to +85°C without thermal compensation or control; stability at room temperature is <30°/h; angle random walk is 0.3°/√h. The accelerometer is a pendulous seesaw. At room temperature, bias stability is 1 milli g and velocity random walk is 0.05 m/s/√h.

The next evolution of these sensors is in progress towards goals of 1°/hr gyro bias stability, 0.1% scale factor error, and 100 μg accelerometer bias stability. These performance goals are sufficient for several micro-nano-satellite applicatons, including the pointing scenario described in Section 2.

6. Microminiature Electronics

The micromechanical sensors are of extremely small size, with each sensor occupying an area of less than 4 square millimeters. It is therefore consistent with the applications for these small sensors to develop mating electronics which are of minimum size, power, and cost.

Draper has developed multi-chip modules (MCMs) and mixed-signal application-specific integrated circuits (ASICs). Both technologies are necessary for the implementation of micromechanical (MEMs) systems. Flip-chip (or bump) bonding is required for alignment accuracy between sensors and to fiducials (reference lines and edges or surfaces of circuit board upon which components are mounted). Presently, the optimal in small size, low power and low production cost can be achieved using mixed-signal CMOS ASICs. A first-iteration of the rate-gyroscope electronics has been designed and implemented on a single mixed-signal CMOS ASIC. The gyroscope sensor, ASIC, and supporting components are placed in a one inch square flat-package as shown in Figure 3. Total power dissipation for the gyroscope ASIC is a small fraction of a watt.

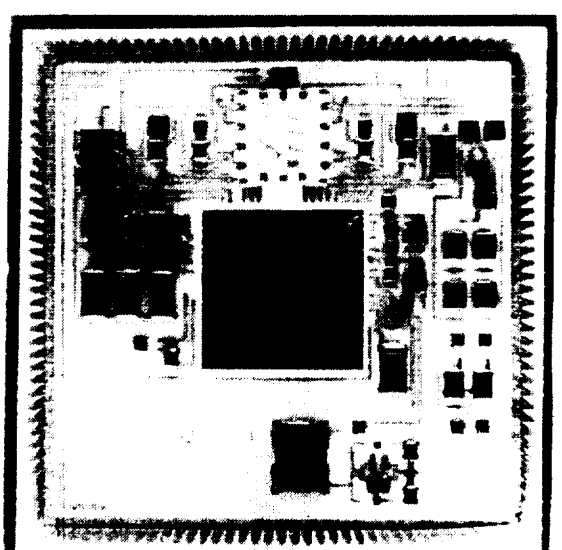

Figure 3. 1 inch by 1 inch Gyro and ASIC Package

Draper has developed a mixed-signal ASIC which will support a number of micromechanical accelerometer designs ranging from micro-g accelerations to guided munitions applications requiring measurement of 100,000 g accelerations. The accelerometer ASIC includes a high resolution digital output as well as continuous automatic self-test.

Electronics to support an entire inertial measurement unit can be placed on a single ASIC. In conjunction with the efforts toward increased miniaturization, are efforts toward improved performance and lower power. Near term goals are to develop a wide-bandwidth DC-coupled miniature gyroscope instrument with <10 degree/hour bias error and 0.1% scale-factor error which uses a fraction of the power of the present ASIC.

7. INS/GPS Accuracy

Figure 4 shows how the integrated INS/GPS system improves absolute pointing accuracy for a 1 meter baseline satellite. The GPS attitude errors are highly dependent on multipath environments. As sampling time increases, the integrated system reaches the calibrated performance of the inertial sensors.

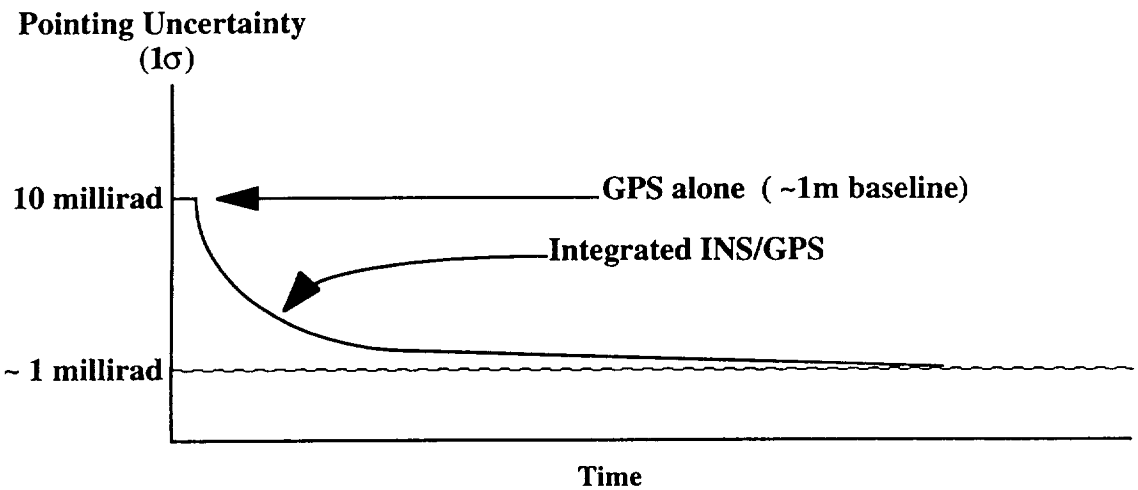

Figure 4. Pointing Accuracy with Integrated INS/GPS

The attitude accuracy potential using GPS is dependent on many factors. A very small satellite on the order of 0.5m or less can present a special challenge due to short measurement baselines, but small size can also mitigate problems from vehicle structural flexibility and carrier wave ambiguity. Major error sources in the GPS observed attitude solution are discussed below; areas where the micromechanical IMU can alleviate these problems are identified.

Receiver Noise

The calculation of the incoming signal's phase angle is subject to error induced by the hardware itself. The phase error depends on the receiver design quality, as well as the vehicle dynamics. If the satellite dynamics are minimal, the risk of losing carrier lock is minimal and narrow-band tracking loops can be used to extract very accurate phase difference measurements.

The biases from the frequency standard and receiver hardware cancel in differencing these measurements. Thus phase difference measurements should be corrupted by less than a millimeter after passing through the RF switch at the receiver's front end. One millimeter is ~2° of tracking error. If we assume an antenna baseline of 1 meter, then the angular uncertainty introduced by a 1 mm tracking error at each end of the baseline is roughly 0.08° (about 3 mrad). If we halve the baseline, this contribution to the overall error will double. Fortunately we can use the micromechanical IMU as a stable reference over which many GPS phase-difference measurements can be averaged. This filtering process allows the receiver noise to be significantly reduced.

Vehicle Flexibility

Knowledge of the spacecraft attitude can only be as good as that of the baseline vectors, for it is these vectors which define the orientation. A trade-off exists in choosing the baseline length. One might expect that greater angular resolution would be obtained with longer baselines, but more integer ambiguity and unaccounted vehicle flexing between the antennas might negate that benefit. An acknowledgment that the baselines are subject to flexures is therefore required for realistic attitude determination. One source of flexure would be thermal stresses experienced by the craft when passing in and out of eclipse. The effect of the flexure can be to change the baseline length, as well as its direction. The latter result may not be easily differentiated from a change in vehicle attitude. On a small satellite, this should not be a problem unless the antennas are mounted on flexible appendages. If the configuration of the satellite makes this a particularly severe problem, the inclusion of a micromechanical attitude reference at each of the antennas could measure the relative rotational dynamics, and calibrate thermal bending as the satellite moves in and out of eclipse.

Line Bias

The line bias over a baseline results from the difference in electrical path lengths from each antenna to the receiver. This "bias" may not be constant, however, since the effective path lengths may change with thermal variations, similar to the baseline variations previously mentioned. Minimizing the error can be accomplished by keeping the path lengths as short and as symmetrical as possible, and by configuring the vehicle such that the cabling is subject to small temperature gradients. Fortunately, the phenomenon affecting the path delay to one antenna should be similar to that affecting the path delay to another; the changes in path delay are therefore mitigated somewhat. The line bias can be eliminated by utilizing the between-satellite double difference observable.

Multipath

Multipath is the undesired reflection of the incoming GPS signal from the antenna's surroundings. The antenna may receive both the direct and reflected signal, or could conceivably receive only the reflected one. Since the reflected signal travels a different path, its phase is shifted from the direct signal. The signal reflected then appears as an additive bias to the primary transmission. For small baselines on a spacecraft, the multipath error experienced by each antenna could have a common component.

Multipath error can be diminished by various techniques. A low-multipath environment is most desirable; antennas, therefore, should obviously not be placed near multipath sources. If the satellite has a simple shape without appendages (such as a sphere or cylinder), then small patch antennas on the surface will not experience multipath problems. A suitable choice of coating on the mounting surface can also reduce reflectivity. The antenna gain pattern can be appropriately shaped to mask out signals entering from directions of suspected multipath sources. Calibration of the repeatable part of multipath is another alternative. The only source of multipath in a spacecraft application is the spacecraft itself. A wave front from a given direction will reflect off vehicle surfaces in a repeatable way, provided the reflectivity does not change and there are no moving parts in the viewing antenna. The multipath can then, in theory, be calibrated out as function of incidence direction, and whatever error remains is characterized as receiver noise. It may be possible to perform this calibration in orbit using the micromechanical IMU as an alternate attitude reference. Using the IMU as an independent attitude reference, severe multipath conditions can easily be detected and edited out of the blended GPS/INS solution.

Antenna Phase Center Variations

Another error source is the asymmetry of the antenna gain pattern. This asymmetry can cause significant differences in phase based on the signal's incidence direction, resulting in an apparent migration of the phase center. Two antennas of the same make can have similar gain patterns, and the error can be small if the two are similarly oriented with respect to the incoming signal. But if the signal arrives from two different antenna-relative directions caused by, say, the antennas being canted away from each other, the error in differencing the two phases can be significant. This area should receive special attention on a small satellite since short baselines increase the sensitivity. Again, the micromechanical IMU can aid an inflight calibration process. By changing satellite attitude over a short timeframe such that gyro drift is not a concern, the GPS line-of-sight with respect to the satellite will change. Using the IMU as a reference, this phenomena can be measured and calibrated, within the limitations of receiver noise, etc. Both phase center movement and multipath effects would be contained in the observable.

Dilution of Precision

The attitude solution is also compromised by the GPS satellite geometry, itself. For translational state solutions, the familiar Geometric Dilution of Precision (GDOP) figure-of-merit is used to assess the impact of satellite geometry on position and time determination. A smaller GDOP corresponds to a greater volume of the poly-hedron formed by connecting the vertices of the unit vectors from the user to each GPS satellite. For attitude determination, the best resolution occurs when the line of sight is perpendicular to the baseline vector. An alternate figure of merit, Attitude Dilution of Precision (ADOP), is therefore required to rate the effect of satellite geometry on the attitude solution. Proper antenna placement can help minimize this concern.

Integer Ambiguity and Cycle Slip

Obviously, the GPS receiver cannot distinguish one cycle of the carrier signal from any other. Thus, for baselines longer than half of a wavelength (L1 carrier wavelength = 19 cm), an ambiguity in the integer number of cycles between the two antennas exists. Translating the phase difference, Δf, into the range difference, Δr, and ultimately solving for the relative positions of the antennas requires resolution of this integer ambiguity. For small satellites with short baselines this should not be a problem. Furthermore, the micromechanical IMU can easily aid in the detection of any cycle slip occurrences.

Antenna

At a minimum, 3 antennas are necessary to solve for the vehicle attitude. A single baseline between two antennas observing phase difference measurements from a single GPS satellite can determine one component of vehicle attitude. A second GPS satellite observed over the same baseline, can completely resolve the direction of the baseline (i.e., two components of attitude). Ideally, the two GPS satellites should be nearly orthogonal to obtain maximum precision. However, rotation about the baseline is not observable, thus requiring a second baseline (3rd antenna) to completely resolve three-axis attitude.

8. Summary

This paper presents a compilation of technologies, hardware, and control methodology that may contribute to future micro-nanoclass space applications. Draper's development of commercial and tactical-grade micromechanical inertial sensors spearheads this effort. The work outlined here addresses a fairly precise pointing challenge and proposes a solution using micromechanical gyros, integrated with GPS, and active control.

Among the emerging opportunities for micromechanical inertial sensor insertion is the application to closed loop, active control. These instruments combined with a GPS receiver, provide complete inertial navigation for attitude control and precision pointing applications.

Recent advances in silicon microfabrication technology have led to the development of low cost, tactical performance grade, micromechanical inertial sensors. The inherent small size, low weight, and low cost of these sensors permit on-board insertion of gyroscopes and accelerometers for inertial instrument application previously impractical because of size and cost considerations.

The micromechanical sensors under development at Draper Laboratory are of extremely small size, with each sensor occupying an area of less than 4 square millimeter. Mating electronics consistent with the applications for these small sensors are being developed for minimum size, power, and cost. Miniaturized GPS microstrip antennas, fabricated on high-dielectric (k≥80) constant ceramic substrates, are being developed at Draper. These permit significant reduction in size compared to antennas fabricated on common low-dielectric substrates.

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