AUTONOMOUS ON-BOARD CALIBRATION OF ATTITUDE SENSORS AND GYROS

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Abstract

This paper presents the state of the art and future prospects for autonomous real-time on-orbit calibration of gyros and attitude sensors. The current practice in ground-based calibration is presented briefly to contrast it with on-orbit calibration. The technical and economic benefits of on-orbit calibration are discussed. Various algorithms for on-orbit calibration are evaluated, including some that are already operating on board spacecraft. Because Redundant Inertial Measurement Units (RIMUs, which are IMUs that have more than three sense axes) are almost ubiquitous on spacecraft, special attention will be given to calibration of RIMUs. In addition, we discuss autonomous on board calibration and how it may be implemented.

1 Introduction

Attitude sensor and gyro calibration is generally critical to obtain accurate spacecraft attitude determination and fast and accurate slewing and targeting. Accurate gyro calibration is also needed to reduce attitude error when attitude sensor data is not available, for example during contingencies, trajectory control maneuvers or orbit adjusts, and during sensor occultation. Calibrated attitude sensors and gyros is needed for reliable measurement edit tests in an attitude determination filter. Calibration can be used for sensor performance trending and failure prediction, and for failure detection.

When a satellite is placed into operation, misaligned attitude sensors and uncalibrated gyros will cause large measurement residuals in the on-board attitude determination filter. A residual edit algorithm in the filter may edit all the attitude measurements, thus leading to divergence of the filter, or its residual edit threshold may be large enough to preclude residual editing but leave the filter vulnerable to highly erroneous measurements. On-board real-time calibration avoids this problem and permits rapid commissioning of a spacecraft.

Ground-based support for calibration is costly, time-consuming, and prone to error in planning and execution because it requires dedicated technical personnel and interaction with the spacecraft to perform calibration maneuvers, to collect and process a large amount of telemetry, and to upload and verify the calibration parameters. Telemetry is at a premium especially for deep space missions where the telemetry data rate is low. Ground-based calibration delays the commissioning of a spacecraft, and frequent ground calibration over a long mission duration increases the cost of ground support and reduces mission efficiency [1, 2]. On most missions, HST and Chandra for example, it is

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important to minimize interruption of the observation schedule and to maximize mission efficiency [1, 3]. By performing calibration in real time on board the spacecraft, telemetry bandwidth can be conserved, the cost of ground support can be significantly reduced, and mission performance and efficiency can be improved. Ground support can be reduced to simple automated monitoring and trend analysis.

Formation-flying spacecraft and constellations of spacecraft will benefit greatly from autonomous on-board real-time calibration: Not only is there a multiple of cost savings in ground operations due to the number of spacecraft in formation or in a constellation [1], there is also an improvement in performance because the formation attitude can be coordinated more accurately when the attitude sensors in each spacecraft are well calibrated.

A survey paper by LaVallee *et al.* [4] defines an autonomous system as one that "reacts to its external inputs and takes some action without human intervention". Hartley and Hughes [2] define an autonomous system as one that is "self-acting and self-regulating". This author would add that an autonomous system can react or adapt to changing external conditions, whereas LaVallee and Hughes might define this as an intelligent system [4].

Attitude determination and control requirements of future NASA spacecraft will demand greater performance, reliability, availability, and autonomy; and will demand reduced cost of procurement and operation and a shorter procurement cycle. Achieving these goals only through improvements in attitude and angular rate sensors is impractical, especially given the high cost and long development and procurement cycles of high performance hardware. On-board real-time calibration algorithms implemented in well designed COTS software are necessary to improve system performance.

The stated goal of the Flight Dynamics Analysis Branch (FDAB) at the NASA Goddard Space Flight Center is to perform calibration in real time on board the spacecraft. The following statement has been on the FDAB web site [5] for several years:

> "What is the future of ground attitude and sensor calibration estimation? The future is ultimately onboard the spacecraft, though this requires the development of algorithms suitable for onboard use and more sophisticated onboard computers. However, the development of each is only a matter of time. Currently, ground attitude and sensor calibration automation is being pursued. The ground has the high-powered computers to monitor the spacecraft attitude and sensor calibration autonomously. In conjunction with the development of these automation algorithms, onboard algorithms are being pursued for implementation onboard spacecraft once the hardware advances sufficiently."

The FDAB has made great strides in the last several years to improve ground-based automation to calibrate the attitude sensors on several missions, which has reduced costs and has improved mission efficiency and performance. This automated processing system called Multi-Mission Three-Axis Stabilized Spacecraft (MTASS) [1–3, 5, 6]. MTASS comprises gyro and alignment calibration software known as IRUCAL, ALICAL, and ALIQUEST, and various tools for magnetometer and fine sun sensor calibration, and software tools for processing Level 0 (raw) telemetry. Although significant progress has been made to automate ground-based calibration, ground-based calibration still presents a performance limitation (because it is non real-time) and cost liability.

1.1 Impediments to On-Board Real-Time Calibration

There have been several impediments to on-board real-time calibration becoming standard practice in both government and industry, although there have been successes:

Perception of Risk: Mission PIs are reluctant to accept risk or carry experimental hardware [2]. They adopt only proven state-of-the-art technology unless otherwise required to achieve their mission objective. Where requirements demand new technology, often it is requirements that are changed. Indeed short program schedules assume little technical, schedule, or cost risk, and therefore preclude research and development. There is also a reluctance within some organizations to adopt new and "unproven" methods due to the not-invented-here syndrome, lack of understanding of benefits, and lack of flight heritage. The still recent faster-better-cheaper era also increased the sensitivity to risk.

Development Cost: There is a large investment cost and risk to develop, test, and document real-time software. Cross-program support for research and development and for software products is difficult to achieve in many organizations.

Technical Challenges: Suitable real-time calibration algorithms are relatively new, particularly for a RIMU, and are computationally intensive. Calibration filters are often deemed to be potentially unstable or susceptible to divergence, particularly during long periods of autonomous operation [7]. Autonomous real-time operation presents additional challenges in algorithm and software design and operation, and in end-to-end system engineering [2].

Personnel: The development, integration, testing, and operation of calibration software requires specialized knowledge and experience to make it work correctly. Attitude sensor and gyro calibration has to be understood at the system, subsystem, and algorithm levels. Many spacecraft manufacturing companies, particularly small companies, cannot find or retain experienced attitude determination/calibration engineers, they may not have the resources to perform sufficient research and development, and they may not recover their investment costs. Therefore they have great difficulty in responding to more challenging attitude determination and calibration performance requirements.

1.2 Benefits of On-Board Real-Time Calibration

Technical benefits of on-orbit calibration include more precise calibration, ability to track parameter variations due to thermal variations, less recorder and telemetry data, minimal interruption of science observations, greater autonomy, and less ground support. A continuously-operating EKF-based calibration filter estimates attitude and calibation parameters, and it produces optimal (minimum variance) attitude estimates regardless of the attitude motions. The on-board calibration filter may be operated either continuously or intermittently, and it can provide optimal attitude estimates. Continuous on-board calibration also provides a means for fault detection and for attitude sensor and gyro performance trending. Intermittent calibration may be appropriate when slow age-induced variations in calibration parameters can be sufficiently calibrated with infrequent calibration maneuvers or normal attitude maneuvers. Intermittent calibration can be either on-demand as needed or scheduled at regular intervals in coordination with mission operations. Continuous on-board real-time calibration can track faster environmentally-induced parameter changes, particularly changes due to temperature variations, thereby giving optimal attitude and calibration parameter estimates at all times. Parameter tracking is achieved by modeling the calibration parameters as constants driven by white process noise. An ability to track temperature-induced parameter variations may allow less stringent thermal requirements, thereby reducing engineering design effort and cost, and possibly relaxing operational constraints. An EKF-based calibration filter can utilize mission attitude motions for calibration, possibly supplemented with calibration maneuvers when the mission attitude motions are not sufficiently persistently exciting.

Because the attitude sensors are always calibrated in an on-board real-time calibration filter (assuming a certain level of persistent excitation, i.e., maneuvering), the spacecraft can slew to a target faster and more accurately and require less time to converge onto the target, thereby reducing target acquisition time and increasing mission efficiency. In many systems, particularly imaging systems, attitude measurement data is telemetered to the ground for attitude determination and calibration processing. The attitude estimates are then used in processing of the image data. On-board real-time attitude determination/calibration can reduce the latency in transferring time-critical precise attitude estimates directly to end-users. Precise attitude can also be used to support on-board payload data processing, and precise (calibrated) attitude can be telemetered with the payload data [2]. The time to commission a spacecraft to full operating performance is reduced with on-board real-time calibration because attitude maneuvers and calibration can commence immediately after the spacecraft is placed on orbit, and the on-board filter can track the typically large variations in parameters that occur during the first several weeks or months of operation.

In this paper we focus on attitude sensor alignment calibration and gyro calibration. Calibration of magnetometers and Earth horizon sensors could be performed in real-time, but there doesn't seem to be a performance advantage. Real-time on-board focal plane distortion calibration may offer some performance advantages, but is not addressed in this paper. We also make a distinction between real-time on-board calibration versus near real-time ground-based calibration. Furthermore, on-board real-time calibration may be either semi-autonomous or fully autonomous.

2 Calibration Algorithms

Algorithms for calibration of attitude sensors and gyros were reviewed in a recent survey paper [15]. Sensor alignment calibration algorithms can be divided into two categories: attitude-independent and attitude-dependent. These categories can each be divided into batch least-squares and filtering or recursive least-squares methods. Gyro (or IMU) calibration can also be divided into batch least-squares and filtering or recursive least-squares methods, and may include attitude sensor alignment calibration.

Batch least-squares methods are not suitable for real-time calibration. Batch methods are generally suboptimal because process noise is usually omitted due to the difficulty of including it into the least-squares algorithm. Recursive least-squares is also suboptimal for the same reason. Extended Kalman Filters (EKF) are preferred for recursive state and parameter estimation because of their generality, but require proper initialization to ensure correct convergence.

2.1 Davenport, BICal, and Delta-Bias Methods

The main IMU calibration tool used by the Flight Dynamics Analysis Branch (FDAB) at the NASA Goddard Space Flight Center (GSFC) is the Davenport algorithm (IRUCAL), which is a batch least-squares method [8–10]. It has been used for more than 25 years to calibrate the gyros on many fabulous sciencecraft. The Delta-Bias and BICal algorithms have also been used to estimate gyro calibration parameters [11, 12]. Attitude sensor misalignments are estimated separately from the Davenport IRU calibration procedure using ALICAL and ALIQUEST.

The Davenport IRU calibration algorithm and the Delta-Bias, BICal, ALICAL, and ALIQUEST algorithms are all based on batch least-squares methods, which are not appropriate for on-board real-time calibration due to the large data storage and processing load required for a batch algorithm [1, p. 2], [6, p. 4]. The sequential Davenport IRU calibration algorithm [1, 3, 13] is an adaptation of the Davenport IRU calibration algorithm to incorporate prior calibration estimates, but is still a batch method. These batch least-squares calibration algorithms are not appropriate for on-board real-time calibration, and recursive versions are not appealing because they are suboptimal. A recursive formulation of the Davenport algorithm that resembles an Extended Kalman Filter (EKF) gyro calibration filter has also been developed [14].

2.2 EKF-Based Calibration Algorithms

Various EKFs for calibration were reviewed in a recent survey paper [15]. Although most of these have worked well in practice, some have not. For example, Hashmall [6, 11] reports serious difficulties with convergence of the EKF but does not offer enough information to evaluate the situation. Difficulties were also reported in [16, 17], which can be traced to over-parameterization and the use of the quaternion as a state in the filter. The calibration filter presented in [18] was a noble effort to develop a RIMU calibration filter, but has some notable deficiencies [15]. Unsubstantiated assertions that the EKF is susceptible to divergence have been made [7]. Such negative publicity has perhaps slowed the implementation of EKF-based calibration filters on board NASA spacecraft.

The feasibility of on-board real-time calibration using Extended Kalman Filters has been demonstrated on two NASA spacecraft. At the Jet Propulsion Laboratory, an on-board real-time inertial measurement unit (IMU) calibration was implemented in the Spitzer Space Telescope (SIRTF) [19, 20] and in Cassini [21, 22]. Calibration was initially performed every four days on Spitzer (though once per day was originally planned) [19] and is performed at least twice per year on Cassini using dedicated calibration maneuvers [22]. At present the calibration on Spitzer utilizes motions during science observations, and dedicated calibration maneuvers are no longer normally used. The IMU calibration model is the body-referenced parameterization discussed above. On Spitzer, only three of the four sense axes are used, but asymmetric scale factors are included in the calibration model. Attitude sensor and payload alignment calibration is performed separately from IMU calibration on Spitzer and Cassini. On Spitzer, the star tracker and payload sensor alignment calibration model comprises 27 parameters, which are estimated on board in real time by a Kalman filter [20].

The Draper Inertial Stellar Compass (ISC) is another example of on-board real-time calibration. The ISC integrates three MEMS gyros and the Draper APS star tracker with an Atmel TSC695F processor and a 27-state Kalman filter implemented with a square root (factorized) covariance [23–26]. The filter states comprise attitude, bias, symmetric scale factors, misalignments, and temperature coefficients for the bias and scale factors. The was flown aboard TacSat-2, which was launched on 16 December 2006 [23].

2.3 Calibration Maneuvers

The Davenport and Delta-Bias gyro calibration algorithms require a long inertial hold period and several piecewise-constant angular rate motions [6, 11, 12, 27]. The requirement for constant angular rates is inherent in the design of these calibration algorithms. Note that the use of constant angular rates can result in biased scale factor estimates because of scale factor nonlinearity. Long calibration intervals preclude tracking of faster variations in the calibration parameters. Long calibration intervals also reduce mission efficiency. Typical telemetry and maneuver durations required by the Davenport IRU calibration algorithm are 6 hours on Terra [11, p. 346], 11 orbits (not continuous) on EUVE [28], 9 hours on WIRE [11, p. 343], and 12 maneuvers over 2 days on Aqua [3].

These are extremely long durations compared to approximately 1 hour typical of an EKF-based calibration filter [29]. Unlike the Davenport algorithm, an EKF-based calibration filter does not require that the calibration maneuvers be of constant angular rate. The EKF-based calibration filter accepts arbitrary calibration maneuvers, subject only to spacecraft attitude constraints and conditions for identifiability of the parameters, and a long inertial hold period is not required. In some systems, the normal mission attitude motions may be sufficient to maintain convergence of the calibration parameters. In cases where the mission attitude motions are are not sufficient to maintain convergence of the parameters, the mission attitude motions can be supplemented with calibration maneuvers to ensure that the calibration parameters are sufficiently converged. Note, however, that the attitude estimation error is less sensitive to calibration parameter error in regions where the angular rate is small, so larger calibration error can be tolerated in those regions.

It was stated in [7] that long periods of zero or constant angular rate should not be processed in an EKF, claiming that there is little information content about the parameters and that correlations built up during a period of constant angular rate may cause instability of the EKF. Both of these claims are speculation, and in fact are false. A period of zero angular rate allows the covariance of the attitude and bias estimates to converge. Periods of attitude motions that are not persistently exciting, in particular zero or constant angular rates, will result in a slow growth of the parameter covariance in directions of small angular rate. This growth is due to the process noise on the parameters, which is generally very small. The parameter estimates may tend to drift as the covariance grows, but this drift is bounded by the covariance in a properly implemented filter. The EKF will be stable if the covariance is not allowed to grow beyond an upper limit. Practical limits in the standard deviation of error, as computed from the square root of the diagonal of the covariance matrix, are several degrees per hour for the gyro bias, 100 000 ppm for the gyros' scale factors, 3 degrees for the gyro axis misalignments, and 3 degrees for the attitude sensor misalignments. These limits will not be reached for a very long time with practical values for the parameter process noise, and the system can be designed to provide a calibration maneuver at appropriate intervals to maintain convergence of the calibration parameters. In regard to the second claim, correlations build up during a period of constant angular rate provide valuable information about certain linear combinations of parameters.

The angular rate used in the calibration maneuver should nearly uniformly span the range of angular rates expected during mission operations so that scale factor nonlinearity is averaged out over the rate range so that the scale factor estimate is not biased. The Davenport method requires piecewise-constant angular rates about each axis, so its scale factor estimate is biased by the scale factor nonlinearity at each angular rate. A large number of calibration maneuvers at various angular rates would be needed to reduce the effect of scale factor nonlinearity. (Scale factor nonlinearity can also be estimated in this way [15].) Except for the "persistent excitation" required of calibration maneuvers for any calibration method, the EKF does not place any other requirement on the calibration maneuver. Thus, a ramp-rate, sinusoidal, or other angular rate profile can be used for a calibration maneuver. Persistent excitation is the term used in system identification to mean that the input to a system makes the parameters distinguishable (or less precisely speaking, observable) at the outputs of the system.

3 On-Board Real-Time Calibration

Reliable and efficient real-time calibration software is required autonomous for on-board real-time calibration. A properly designed calibration filter can reliably estimate attitude and calibration parameters and run in real-time on present-day space qualified computers. The filter software should include features needed to support autonomy. Improved mission efficiency and performance can be achieved by optimizing calibration maneuvers. The optimization minimizes the parameter estimation error covariance with constraints on total control effort, attitude, angular rate, and angular acceleration. Also needed are metrics to measure how close a given calibration maneuver is to optimal.

Planning for calibration requires an understanding of when and how often calibration is required. This is influenced by hardware characteristics, environmental factors, performance requirements, and operational constraints. Planning is not completely deterministic, though a conservative assessment may be made regarding when and how often calibration should be performed. Calibration is generally performed more frequently in the weeks or months following orbit insertion, then less frequently once trends in the calibration parameters have been established. Efficient algorithms are needed for autonomous calibration planning and scheduling based on an optimal calibration maneuver or the calibration maneuver required to achieve a specified level of accuracy; predicted geometrical constraints on attitude; power, thermal, and communications constraints; physical constraints on agility of the spacecraft; the payload observation schedule; attitude performance; and historical calibration data. Calibration can be fully autonomous if calibration maneuver planning and scheduling can be performed on-board either on a fixed schedule or in coordination or conjunction with the science observation schedule. Semi-autonomous calibration is planned and scheduled in a ground-based system. Either way, the calibration maneuver planning algorithm has to incorporate the aforementioned constraints into its maneuver planning and scheduling algorithm.

Autonomous calibration may make use of on-board performance monitoring functions to determine when a calibration maneuver should be intiated. For example, targeting error may indicate a need for calibration. The calibration filter's estimation error covariance and measurement residuals can also be used to trigger or queue a calibration maneuver. Attitude motions are needed, of course, so that miscalibration is observable in the residuals. Sensor performance trending on-board can be used to plan calibration events. Although performance trending, failure prediction, and failure detection can be perfomed autonomously on-board a spacecraft, the same data should be telemetered to a ground-based system for historical recording and occasional oversight by an operator.

4 RADICAL™ COTS Calibration Software

Redundant Inertial Measurement Units (RIMUs) are IMUs that have more than three active sense axes [29]. A RIMU is used in attitude determination systems that demand high availability, reliability, redundancy, and accuracy. Attitude determination with a RIMU is more accurate than with a three-axis IMU. The redundancy also permits reliable and rapid fault detection. Furthermore, a RIMU possesses unique observability properties of the calibration parameters not found in three-axis IMUs [31–33]. The survey article [15] shows that RIMUs are almost ubiquitous on spacecraft. However, their characteristics have not been fully exploited in spacecraft attitude determination systems. Recent algorithm and software development will permit greater system performance and autonomy [29–32, 34, 35].

The commercially available RIMU Attitude Determination and Calibration (RADICAL™) filter [35] is a C language implementation of the RIMU calibration filter in [31] with several enhancements to support autonomous operation. The RADICAL™ software comprises core filter functions, a driver program, pre-processing functions, and Matlab support software for sensor simulation and for plotting and tabulating results. The core code is designed for autonomous on-board real-time operation. A wrapper code provides a user interface to the RADICAL™ core code for automated ground-based processing and for use as a desktop analysis and design tool. The core code includes an extended Kalman filter, several measurement error models, fault detection and self-monitoring logic, initialization for cold and warm start, sensor data interfaces and circular buffering, telemetry output in a choice of three different size but customizable packets, diagnostic output data, upload and download of default and active parameter tables, and a command interface. The core code also contains an algorithm and logic to support both intermittent and continuous calibration.

The RADICAL™ calibration algorithm is based on a physical-parameter model and the null-space measurement update [29]. The null-space measurement contains information that is not observable in the computed body angular rate and permits full observability of the calibration parameters. The full-order physical-parameter model also has other advantages in observability [31–33]. Process noise in the parameter model allows the calibration filter to track parameter variations and helps to ensure that the covariance does not become ill conditioned or singular.

The covariance matrix in a calibration filter can become ill conditioned during its initial convergence from a large initial covariance under high angular rate, and possibly when the process noise is small. Therefore UD-factorized covariance propagation and update algorithms are used in RADICAL™ to ensure numerical stability and accuracy, accuracy, and efficiency. The covariance matrix is never computed, except that certain elements of the covariance matrix are computed only for output and for convergence threshold tests. The factorized covariance algorithms are particularly important during the initial convergence of the parameters, especially under high angular rate about one axis, where the covariance matrix can become ill conditioned.

When operated intermittently, the initial state and covariance for one segment of data is the final state and covariance of the previous segment plus a covariance "bump", but with attitude and its covariance and cross-covariance being reset. A covariance "bump" can be applied at any time to permit selected parameters or attitude to reconverge, which is useful when hardware is power cycled or when there is a large thermal transient.

One feature of the RADICAL™ calibration filter is that it can process disjoint or interrupted telemetry streams. The attitude estimate, attitude covariance, and attitude cross-covariance are reset when there is a break in the gyro data. The parameter covariance remains intact (in UD factorized form). This is called a "warm-start" of the calibration filter. In addition, a covariance "bump" can be applied to model uncertainty due to a change in the parameters since the epoch of the previously processed telemetry stream. (A covariance bump can also be applied at any time during processing in RADICAL™.) A bump can also be applied to the attitude covariance. The covariance bump is simply a specified increase in the covariance of any estimated parameter or attitude. The covariance bump is applied upon a warm start and can be applied at any time upon command to permit selected parameters or attitude to reconverge, which is useful for example after a large thermal transient. The bump is applied directly to the UD factors of the covariance matrix to ensure numerical accuracy and stability and for computational efficiency. The importance of being able to process disjoint telemetry streams and applying the covariance bump is that the filter does not have to be reinitialized, and the filter is nearly converged when the prior converged estimates and their covariance are used to warm start the filter. Convergence problems are avoided when a prior estimate and a small prior covariance are used to warm-start the filter. A calibration maneuver can also be segmented to avoid constraints. The capability to process disjoint telemetry streams and to apply the covariance bump at any time supports autonomous on-board calibration. In addition, a shorter calibration maneuver may be sufficient to maintain convergence of the calibration parameters and their covariance. This is also beneficial during mission operations to reduce risk, to reduce interruption of science operations, and to reduce the volume of telemetry dedicated to calibration (in the case of ground-based calibration).

Simulation results in [36] and calibration results using MESSENGER telemetry data reported in [37–39] demonstrate the efficacy of the RIMU calibration filter and the utility of the RADICAL^{TM} calibration filter. Results in [39] demonstrate the RADICAL^{TM} filter's ability to process disjoint telemetry streams. Results from simulation and telemetry show that the RIMU calibration filter converges from large initial uncertainties of at least 3 degrees misalignment uncertainty, greater than 15000 ppm scale factor uncertainty, and 10 deg/hr bias uncertainty [15, 30, 37–39]. In practice, however, initial parameter uncertainties are much smaller. Attitude is initialized using attitude measurements and their covariance to avoid convergence problems. The RIMU calibration filter was used successfully in ground processing to calibrate the SIRU and the star trackers on MESSENGER [36–39].

5 Conclusion

The technology exists to perform on-board real-time calibration and has been demonstrated on two NASA spacecraft and in an experimental attitude determination system. We also have the capability to fully calibrate RIMUs and to take advantage of their unique benefit to performance and reliability. Reliable and efficient COTS calibration software for RIMU calibration is also available. It could be used on board a NASA mission today with traditional calibration maneuver planning and scheduling, and later integrated with an autonomy system.

Algorithms for optimizing calibration maneuvers subject to certain constraints are needed to maximize mission efficiency. Metrics are also needed to measure how close a given calibration maneuver is from optimal. These functions can then be integrated into an autonomy system.

References

[1] Sedlak, J., Welter, G., and Ottenstein, N., "Towards Automating Spacecraft Attitude Sensor Calibration", 54th International Astronautical Congress of the International Astronautical Federation, Bremen, Germany, 29–30 Sep 2003. 1, 2, 4

[2] Hartley, Jonathan B; Hughes, Peter M, "Automation of Satellite Operations: Experiences and Future Directions at NASA GSFC", Paper No. SO96.8.007, *Proceedings of the Third International Symposium on Space Mission Operations & Ground Data Systems for Space Mission Operations*, SpaceOps 96, Munich, Germany, Vol. 3, 16–20 Sep 1996, pp. 1262–1269. 1, 2, 3

[3] Sedlak J.; Hashmall, J.; "Automated Attitude Sensor Calibration: Progress and Plans", Paper No. AIAA-2004-4854, AIAA/AAS Astrodynamics Specialist Conference, Providence, RI, Aug 16–19, 2004. 2, 4, 5

[4] LaVallee, D. B.; Jacobsohn, J. F.; Olsen, C. D.; Schmoll, J.; "Autonomous Spacecraft Control An Industry Survey Update", Paper No. AIAA 2007-2871, AIAA Infotech Aerospace Conference and Exhibit, 7–10 May 2007, Rohnert Park, CA. Also: Paper No. AIAA-2006-7384, Space 2006, 19–21 Sep 2006, San Jose, CA. 2

[5] http://fdab.gsfc.nasa.gov/live/Tools/Attitude.asp?proxyid=0&xsection=2
http://fdab.gsfc.nasa.gov/live/Home/Tools_Attitude.html 2

[6] Hashmall, J. A.; Rowe; J.; Sedlak, J., "Spacecraft Attitude Sensor Calibration from On-Orbit Experience", 16th AIAA/IEEE Digital Avionics Systems Conference (DASC), 26–30 Oct 1997, Irvine, CA, Vol 2, pp. 8.4-1–8.4-8. 2, 4, 5

[7] Welter, G., *A Recursive Filter Approach to Onboard Gyro Calibration*, Computer Sciences Corporation, CSC-5569-04, Update 1: Aug 2003. 3, 4, 5

[8] Welter, G.; Boia, J.; Gakenheimer, M.; Kimmer, E.; Channell, D.; Hallock, L.; "Variations on the Davenport Gyroscope Calibration Algorithm", Proceedings of the 1996 Flight Mechanics/Estimation Theory Symposium, NASA Conference Publication 3333, NASA Goddard Space Flight Center, Greenbelt, Maryland, 14–16 May 1996, pp. 41–53. 4

[9] Davenport, P. B.; Welter, G. L., "Algorithm For In-Flight Gyroscope Calibration", Proceedings of the Flight Mechanics/Estimation Theory Symposium, NASA Conference Publication 3011, NASA Goddard Space Flight Center, Greenbelt, Maryland, 10–11 May 1988, pp. 114–127. 4

[10] Keat, J. E., *Gyro Calibration Analysis for the High Energy Astronomy Observatory-A (HEAO-A)*, Computer Sciences Corporation, CSC/TM-77/6082, Jun 1977. 4

[11] Hashmall, J. A.; Radomski, M.; Sedlak, J.; "On-Orbit Calibration of Satellite Gyroscopes", Paper No. AIAA-2000-4244, AIAA/AAS Astrodynamics Specialists Conference, Aug 2000. 4, 5

[12] Glickman, J.; Hashmall, J.; Natanson, G.; Sedlak, J.; Tracewell, D.; "Earth Observing System (EOS) Aqua Launch and Early Mission Attitude Support Experiences", Flight Mechanics Symposium, NASA/GSFC, 28–30 Oct 2003, NASA/CP-2003-212246. 4, 5

[13] Ketchum, E. A.; Lee, M. H., "A Gyroscope Calibration Analysis for the Gamma Ray Observatory (GRO)", *Flight Mechanics and Estimation Theory Symposium*, Greenbelt MD, 23–24 May 1989, NASA Conference Publication CP-3050, 1 Oct 1989, pp. 237–253. 4

[14] Natanson, G., "A Transition Matrix Approach to the Davenport Gyro Calibration Scheme", Paper No. AAS 98-334, AAS/GSFC 13th International Conference on Space Flight Dynamics, 11–15 May 1998, NASA-CP-1998-206858/VOL1, Vol. 1, pp. 373–397. 4

[15] Pittelkau, M. E., "Survey of Calibration Algorithms for Spacecraft Attitude Sensors and Gyros", Paper No. AAS 07-295, AAS/AIAA Astrodynamics Specialists Conference, Mackinac Island, MI, 19–23 Aug 2007, to appear in Advances in the Astronautical Sciences. 4, 6, 7, 8

[16] Deutschmann, J. K.; Bar-Itzhack I. Y., "Extended Kalman Filter for Attitude Estimation of the Earth Radiation Budget Satellite", NASA Conference Publication CP-3050, 1 Oct 1989, *Flight Mechanics and Estimation Theory Symposium*, Greenbelt MD, 23–24 May 1989, pp. 333–346. 4

[17] Deutschmann, J. K.; Bar-Itzhack I. Y.; Rokni, M., "Comparison and Testing of Extended Kalman Filters for Attitude Estimation of the Earth Radiation Budget Satellite", NASA Conference Publication CP-3102, 1 Dec 1990, *Flight Mechanics and Estimation Theory Symposium*, Greenbelt MD, 22–24 May 1990, pp. 233–253. 4

[18] Bar-Itzhack, I. Y.; Harman, R. R., "In-Space Calibration of a Skewed Gyro Quadruplet", *AIAA Journal of Guidance, Control, and Dynamics*, Vol. 25, No. 5, Sep–Oct 2002, pp. 852–859. 4

[19] Bayard, D.; "An Overview of the Pointing Control System for NASA's Space Infra-Red Telescope Facility (SIRTF)", Paper No. AIAA-2003-5832, AIAA Guidance, Navigation, and Control Conference and Exhibit, Austin, TX, 11–14 Aug 2003. 4

[20] Bayard D.; Kang, B.; "A High-Order Kalman Filter for Focal Plane Calibration of NASA's Space Infrared Telescope Facility (SIRTF)", Paper No. AIAA-2003-5824, AIAA Guidance, Navigation, and Control Conference and Exhibit, Austin, TX, 11–14 Aug 2003. 4, 5

[21] Wong, E. C.; Breckenridge, W. G.; "An Attitude Control Design for the Cassini Spacecraft", Paper No. AIAA-95-3274, Proceedings of the AIAA Guidance, Navigation, and Control Conference, Baltimore, MD, 7–10 Aug 1995, Part 2, pp. 931–945. 4

[22] Lee, A. Y.; Hanover, G.; "Cassini Spacecraft Attitude Control System Flight Performance", Paper No. AIAA 2005-6269, AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, California, 15–18 Aug 2005. 4

[23] Brady, T.; Buckley, S.; Leammukda, M.; "Space Validation of the Inertial Stellar Compass", 21st Annual Conference on Small Satellites, Logan, UT, 13–16 Aug 2007. 5

[24] Brady, T.; Buckley, S.; Tillier, C.; "Ground Validation of the Inertial Stellar Compass", Proceedings of the 2004 IEEE Aerospace Conference, 6–13 Mar 2004, Vol. 1, pp. 214–226. 5

[25] Brady, T.; Buckley, S.; Dennehy, C. J.; Gambino, J.; Maynard, A.; "The Inertial Stellar Compass: A Multi-function, Low Power, Attitude Determination Technology Breakthrough", Paper No. AAS 03-003, 26th AAS Guidance and Control Conference, Breckenridge, CO, 5–9 Feb 2003, in *Advances in the Astronautical Sciences, Guidance and Control 2003*, Vol. 113, pp. 39–56. 5

[26] Brady, T.; Tillier, C.; Brown, R.; Jimenez, A.; Kourepenis, A.; "The Inertial Stellar Compass: A New Direction in Spacecraft Attitude Determination", 16th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, 12–15 Aug 2002. 5

[27] Fink, D. R.; Chapman, K. B.; Davis, W. S.; Hashmall, J. A.; Shulman, S. E.; Underwood, S. C.; Zsoldos, J. M.; Harman, R. R.; "Experience Gained From Launch and Early Orbit Support of the Rossi X-Ray Timing Explorer (RXTE)", 1996 Flight Mechanics/Estimation Theory Symposium, NASA Goddard Space Flight Center, pp. 233–247. 5

[28] Hashmall, J.; Davis, W.; Harman, R.; "The Attitude Accuracy Consequences of On-Orbit Calibration of the Extreme Untraviolet Explorer Attitude Sensors by the Flight Dynamics Facility at Goddard Space Flight Center", Paper No. AAS 93-103, 1993 Spaceflight Mechanics Conference, in *Advances in the Astronautical Sciences*, Vol. 82, Part I, 1993, pp. 59–78. 5

[29] Pittelkau, M. E., "Calibration and Attitude Determination with Redundant Inertial Measurement Units", AIAA Journal of Guidance, Control, and Dynamics, Vol. 28, No. 3, May–Jun 2005. 5, 6, 7

[30] Pittelkau, M. E.; "Attitude Determination and Calibration with Redundant Inertial Measurement Units", Paper No. AAS 04-116, *AAS/AIAA Space Flight Mechanics Meeting*, 8–12 Feb 2004, Maui, HI, in *Advances in the Astronautical Sciences*, Vol. 119, Part I. 7, 8

[31] Pittelkau, M. E.; "Recent Advances in Calibration of Redundant Inertial Measurement Units", *Flight Mechanics Symposium*, NASA/GSFC, NASA/CP-2005-212789, 18–20 Oct 2005, [CD-ROM]. 7

[32] Pittelkau, M. E.; "Advances in Attitude Determination With Redundant Inertial Measurement Units", Paper

No. AAS 06-110, 2006 AAS/AIAA Spaceflight Mechanics Meeting, Tampa, FL, Jan 2006, *Advances in the Astronautical Sciences*, Vol. 124, Part 1, 2006, pp. 163–178. 7

[33] Pittelkau, M. E., "Observability and Calibration of a Redundant Inertial Measurement Unit (RIMU)", Paper No. AAS 05-105, *AAS/AIAA Space Flight Mechanics Meeting*, Copper Mountain, CO, 23–27 Jan 2005, in *Advances in the Astronautical Sciences*, Vol. 120, Part 1, 2005, pp. 71–84. 7

[34] Pittelkau, M. E.; "Cascaded and Decoupled RIMU Calibration Filters", *AAS Journal of the Astronautical Sciences*, Vol. 54, Nos. 3–4, Jul–Dec 2007. 7

[35] `http://www.acsinnovations.com/index_files/products.htm` 7

[36] Pittelkau, M. E., "MESSENGER Calibration", Technical Memorandum SRM-03-089, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 24 Dec 2003. 8

[37] Pittelkau, M., "MESSENGER Attitude Sensor Calibration", JHU Applied Physics Laboratory, Space Department, Memorandum SEG-04-060, Laurel, MD, 30 Sep 2004. 8

[38] OShaughnessy, D. J.; Vaughan, R. M.; Haley, D. R.; Hongxing S. Shapiro, "MESSENGER IMU Interface Timing Issues and In-Flight Calibration Results", Paper No. AAS 06-086, 29th Annual Aas Guidance And Control Conference, Breckenridge, Colorado, 4–8 Feb 2006. 8

[39] OShaughnessy, D.; Pittelkau, M. E., "Attitude Sensor and Gyro Calibration for MESSENGER", 20th International Symposium on Space Flight Dynamics, Annapolis, MD, 24–28 Sep 2007, NASA Conference Publication (number TBD). 8