The Advancing State-of-the-art in Second Generation Star Trackers

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Abstract—Until recently, only first-generation charge coupled device (CCD) spacecraft star trackers have been available. These (rack a small nurnberofbright stars and are dependent on external processing for acquisition, calculation of corrections and transformation from CCD referenced to inertial referenced coordinates. Now, powerful microprocessors (> 10 million instructions per second (MIPS)) with a few Mbytes of memory have become available in space qualified grades and have enabled the next step in star tracker concepts: second-generation fully autonomous designs. These second-generation units are equipped with star catalogs covering the entire sky. Their microprocessors instantly perform acquisition by pattern recognition of the entire image, thus relating the output from the star tracker directly to the celestial sphere. Their output data can be used in the attitude control system of a spacecraft without intermediate data processing. This saves central processor load, memory capacity and integratation of thousands of line of source code. The use of a large number of stars in each data frame makes the attitude estimates more accurate and operation both smoother and more robust in comparison to first-generation star trackers.

TABLE OF CONTENTS

1. INTRODUCTION

It is vital for most space vehicles to know celestial referenced attitude from an onboard sensor. Attitude information is used to navigate, fire thrusters, to point antennas and experiments, etc. Usually, a quatemion or a direction cosine matrix is used to represent the attitude of the vehicle. These describe a rotation from an inertial space coordinate system to a coordinate system referenced to the attitude sensor. Successive coordinate rotations relate the attitude sensor coordinate system to the spacecraft body in pitch, yaw and roll.

A combination of magnetometers, star trackers, sun sensors, horizon sensors, or star scanners is used on both spin-stabilized and three-axis stabilized spacecraft for attitude determination [1]. Star trackers are best suited for three-axis stabilized applications. In most applications the output of the star tracker is used to update and correct drift in an inertial based reference system which provides high bandwidth attitude information. However, a 'gyroless' spacecraft can use a mathematical model for attitude information. The star tracker then updates the state vector in this model.

Figure 1 shows an example of rotating from inertial space to a vehicle. An inertial coordinate system can be defined as the X-axis towards the Vernal equinox, the Z-axis toward the North pole of the celestial sphere, and the Y-axis pointing opposite the cross product of the two vectors.

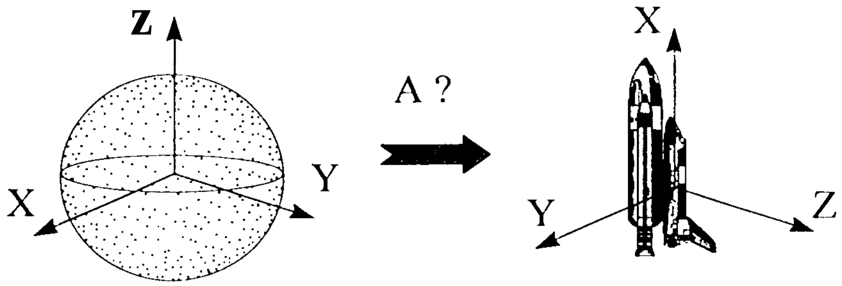

Figure 1. Rotation from the celestial sphere to a spacecraft referenced coordinate system.

2. First-Generation CCD Star Trackers

Attitude determination based on the use of CCD area array imaging sensors was pioneered in the early 1970s at JPL [2]. The sensing instrument consists of a CCD, associated optics, and dedicated electronics, Typically, two to six star images are detected in each data frame. The instrument then outputs the CCD coordinates of these bright spots which are then utilized in the satellite main computer or in later post processing of the data on ground. The attitude determination may require additional information such as the sun vector. Many commercial suppliers have implemented such star trackers [3–7]. They can be characterized as first-generation units. Figure 2 shows the early, Jet Propulsion Laboratory (JPL), high-accuracy, ASTROS design [8] with key parameters of it given in Table 1.

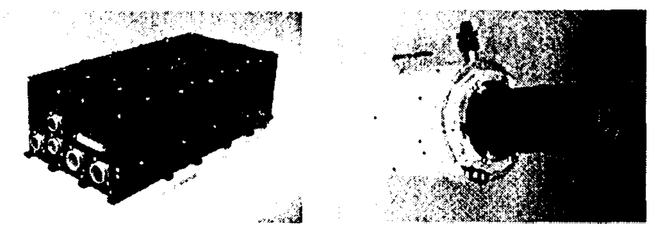

Figure 2. JPL ASTROS star tracker of 1985, processing electronics on the left, camera head on the right.

Table 1. ASTROS key parameters

Mass	41 kg
Power consumption	43 W
Field of View	2.2 x 3.3 degrees
Relative Accuracy	0.8 arcsec, 1 σ, 1 axis, per star
Number of stars tracked	1–3
Initial attitude acquisition	No
Update rate	6 Hz
Thermal electric cooler	Yes

The Lawrence Livermore National Laboratory, Clementine star tracker deserves special mention as an early autonomous design which helped pave the way for true second-generation units. It featured a small camera head of about 450 g mass with a power consumption of about 4.5 watts, a very wide field of view (FOV) of about 55 by 45 degrees, an innovative, spherically curved focal plane lens which was coupled to a Tompson CCD by a dual, field-flattening, fiber-optic plug system. [t relied on the use of an external tracker software system called Stellar Compass™ by its developer, Intelligent Decisions, Inc., which could track up to 10 stars from a small catalog of about 400 stars. Due to various factors, its accuracy and its sky coverage in roll angle were limited to the milliradian and 85°/0 ranges, respectively [9]. A successor model with improved performance characteristics is being manufactured by OCA Corp. of Garden Grove, California,

3. Second-Generation CCD Star Trackers

Within the last five years a new generation of star trackers has emerged. This recent development has been primarily facilitated by the availability of more powerful microprocessors (> 10 MIPS) and large memory (Mbytes) for spacecraft use. These are identified as second-generation units. This new generation of star trackers is different from the prior generation because:

- Star constellation pattern recognition is performed autonomously utilizing internal catalogs. The solution of the lost-in-space problem is inherent and no external processing nor additional attitude knowledge is needed for celestial pointing reference determination.
- Utilization of a large average number of stars (25 to 65) for each data frame significantly improves acquisition probabilities, accuracy, robustness, and continuity of operation over the whole sky. This is partially enabled by the use of small focal ratio (f/no) lenses in the range of f/0.7 to f/1. 1. This multi-star operation is supported by large internal catalogs in excess of 10,000 stars.
- All compensations, including light time effects, as they apply, are performed internally.
- Attitude quaternions referenced to inertial space are output directly without the intervention of external processing.

A significant advantage of a second-generation star tracker is the simplicity of its integration with its spacecraft. The tracker is completely stand-alone and autonomous. Only a very simple, low bandwidth data interface exists between the spacecraft main computer and its star tracker. The savings in spacecraft integration by not having the attitude control computer include star catalogs and all of the associated processing and correction algorithms (thousands of lines of source code) are significant, and can be a major fraction of the cost of the tracker, itself. Additionally, the lengthy experience gained during development and test flights helps to assure a high level of reliability and robust ness.

Figures 3 to 6 show four typical examples of second-generation star trackers [10,11] with key parameters of them given in Table 2. The first known orbital launch of a second-generation unit was that of the Advanced Stellar Compass (ASC) on the Ariane 5-02 on October 30, 1997.

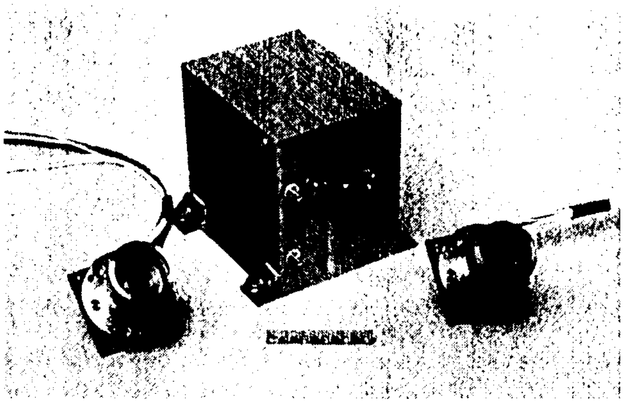

Figure 3. CHAMP ASC is used on the German CHAMP mission: a second-generation star tracker manufactured by the Technical University of Denmark, 1997. Data Processing Unit (DPU) is displayed with two separate camera heads.

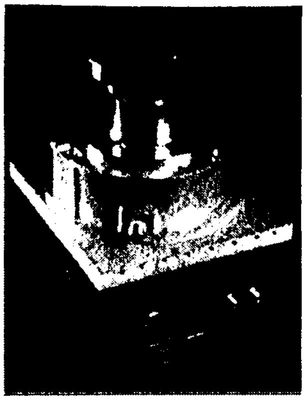

Figure 4. AST-201 is used on the JPL New Millennium Deep Space 1 and the Shuttle Radar Topography missions: a second-generation star tracker manufactured by Lockheed Martin Space and Missile Systems, 1997.

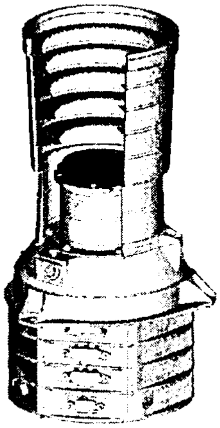

Figure 5. The SETIS star tracker being designed by Daimler-Benz Jena Optronik, Germany.

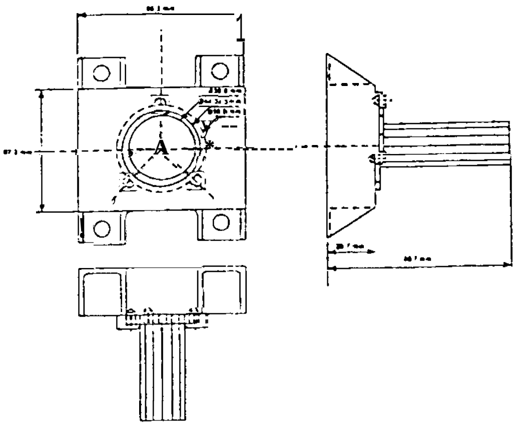

Figure 6. The CRI-15AS star tracker head being designed by Computer Resources International, Denmark.

Table 2. Second generation star tracker key parameters

	ASC	AST-201	CRI-15AS	SETIS
Mass (kg)	1	5 (including baffle)	3.5	3.9 (including baffle)
Power (W at 25°C)	7	14	10	12
Field of View (degrees)	19X 14	8.8 x 8.8	not specified	14.8 x 14.8
Error (arcsec, relative)	3	3	15 arcseconds (absolute, 3 sigma)	Bias <2.5 NEA <2.5 1,0s <1
Number of stars tracked	25-200	9-49	65 average	N/A
Initial attitude acquisition	Yes	Yes	Yes	Yes
Update rate	I-4 Hz	2-5 Hz	2–10 Hz	5 Hz
Thermal electrical cooler	No	Yes	No	Optional
Separate camera head/ processor	Yes	No	Yes	No

4. Initial Attitude Acquisition

The initial attitude acquisition, or pattern recognition of star constellations, is not a trivial matter. The problem is illustrated in Figure 7 where a second-generation star tracker images a small portion of the night sky (less than 1°/0) which it must identify. The image includes uncertainties in the magnitude and in the positions of the stars. Also, false objects may be present in the image (planets, other satellites, radiation, etc.). The star tracker is required to solve the problem in a few seconds.

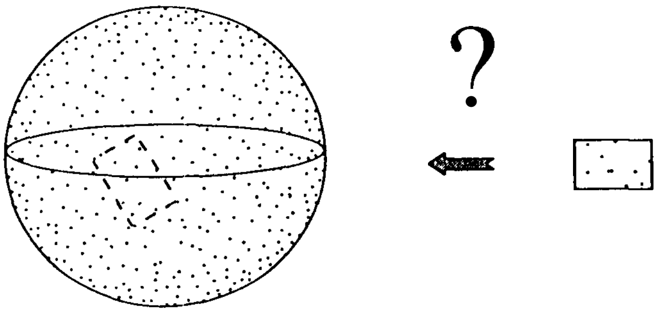

Figure 7. Performing pattern recognition of a star constellation.

The problem has been solved in various ways for second-generation units [12– 19]. In principle they all characterize stars relative to their nearest neighboring stars in the image and typically utilize distances, angles and/or brightness. Most algorithms utilize absolute measures in the images such as the angular distances between star images. However, some algorithms utilize characteristics such as relative brightnesses. The measured parameter values are then compared to those in a star catalog which covers the entire celestial sphere, and the correct stars are thus identified. Some algorithms are precompiled while others calculate parameter values from a raw star catalog. The later approach trades reduced memory size for speed. Usually, the algorithm will complete the pattern recognition in seconds with a success rate approaching 10OO/O. Star identification has been demonstrated down to an FOV size ofa few degrees.

5. Error Components

Typically, the errors of second generation star trackers are measured utilizing the real sky with a telescope drive [20–22]. Figure 8 shows the components of a star tracker error budget.

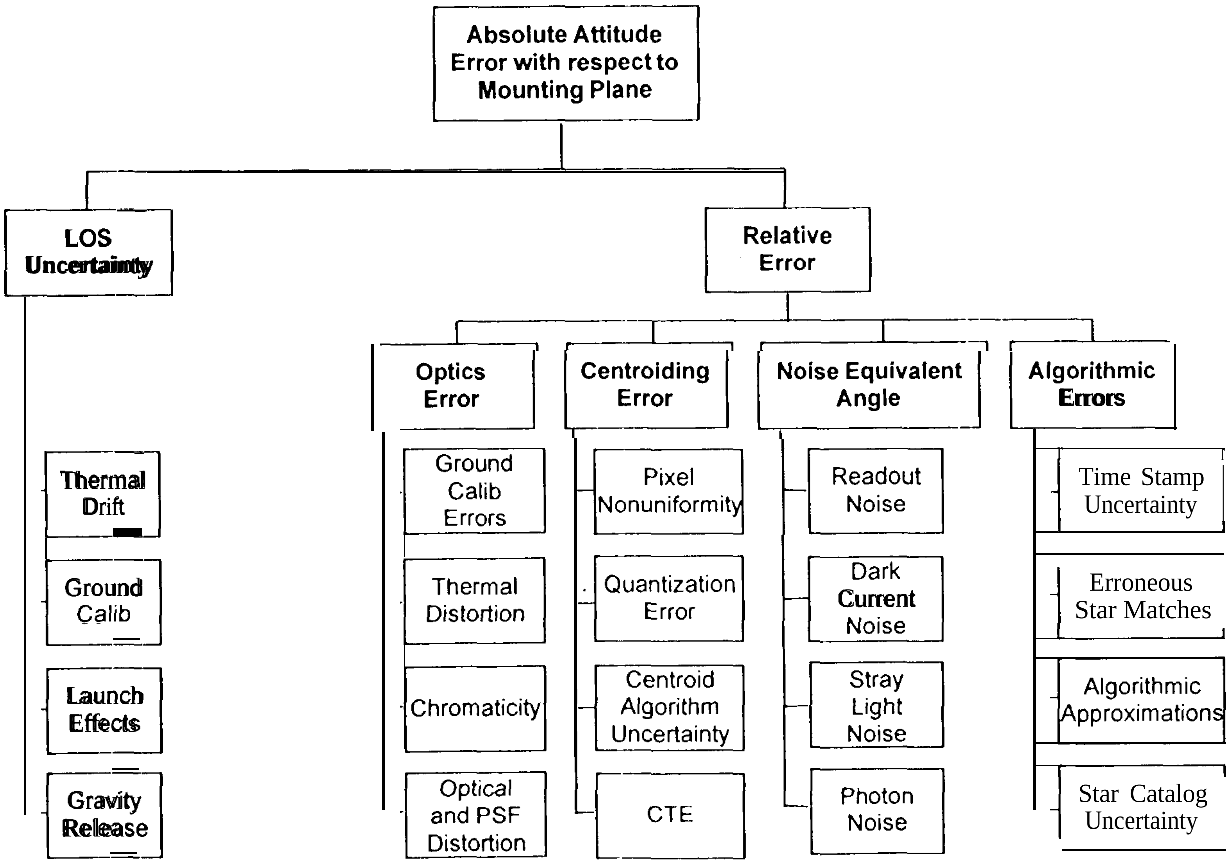

Figure 8. Star tracker attitude error budget components.

Absolute attitude error with respect to the mounting plane

"[’his is the overall error in the star tracker with respect to its mounting feet or plane.

LOS uncertainty

The line of sight (LOS) uncertainty is perhaps the most difficult uncertainty to measure. It consists of thermal drift, ground calibration residuals, launch effects and gravity release effects. Its initial value is measured in a laboratory with simulated stars which can be precisely referenced to the star tracker.

Relative accuracy

Relative accuracy is a measure of how accurately the star tracker can detect changes in attitude. This can be measured utilizing the real sky and the rotation of the Earth. The star tracker under test is mounted pointing near zenith to minim ize atmospheric perturbation. The night sky then drifts by at the sidereal rate. The declination will remain constant while the right ascension will change at the sidereal rate and the roll angle about the boresight will remain constant (assuming that the epoch of the star catalog is current and light time aberrations are applied). Often relative accuracy is referred to as star tracker accuracy. The components of the relative accuracy are noise equivalent angle, optics error, centroiding error and algorithmic errors.

Noise Equivalent Angle

The noise equivalent angle (NEA) represents the star tracker's ability to reproduce the same attitude when it is continuously presented with the same star image. Therefore, the NEA is a nonsystematic, or random error component. It is possible to measure the NEA utilizing astronomical observations. The tested tracker is mounted on a telescope. The telescope mount is then set to track a portion of the sky, and the star tracker outputs a constant attitude. The NEA is the standard deviation of the calculated attitudes. The NEA consists of the following items: readout noise, dark current noise, stray light noise and photon noise. It is primarily inversely proportional to the square root of the number of stars in the image.

Optical errors

Optical errors include ground calibration error, thermal distortion, and chromatic, optical distortion and point spread function (PSF) variations over the focal plane. They are primarily tangential in nature.

Centroiding error

Centroiding errors include pixel light sensitivity nonuniformity, quantization error, centroid algorithm uncertainty, and CCD charge transfer efficiency (CTE) effects.

Algorithmic errors

Algorithmic errors include time stamp, thresholding, and star catalog uncertainties, erroneous star matches, and algorithmic approximations.

6. Real sky measurements

The calculated declination angle of the ASC is shown in Figure 9 as measured at the University of Hawaii Mauna Kea observatories in July 1996 with a prototype Ørsted camera head.

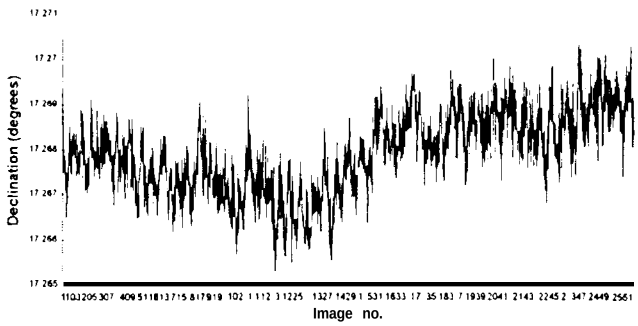

Figure 9. The declination angle measurements of the ASC.

It is observed that the relative accuracy of the star tracker is approximately 1.8 arcseconds, 1 σ, for the high frequency variations (image to image variations), whereas the slow long-term drift in the image (time frame of 0.5 hour) has an accuracy of approximate 3 arcseconds, 1 σ. Previously [22], the source of the slow variations has been attributed to observational artifacts, i.e. that the telescope was not mechanically stable, aligned properly, atmospheric effects, etc. The slow term variations were removed utilizing frequency domain filtering. However, to understand this effect more thoroughly, two identical star trackers were mounted co-foresighted (within a couple of degrees) on the telescope. If the slow term variations were due to observational artifacts, the two attitudes should be strongly correlated, whereas if the variation originates from the star tracker itself, the attitudes should not be correlated, The co-boresighted setup at the telescope is shown in Figure 10.

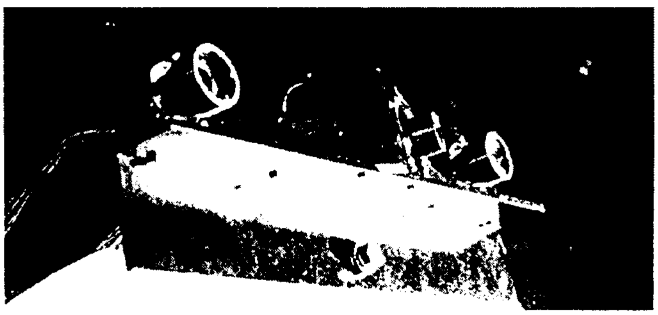

Figure 10. The co-foresighted CHAMP prototype star tracker heads mounted on the TMO telescope with an earlier Ørsted head in the center.

The declination and roll angles of the two star trackers about their foresights are shown in Figures 11 and 12 as measured at the Jet Propulsion Laboratory Table Mountain Observatory (TMO) facility in June 1997.

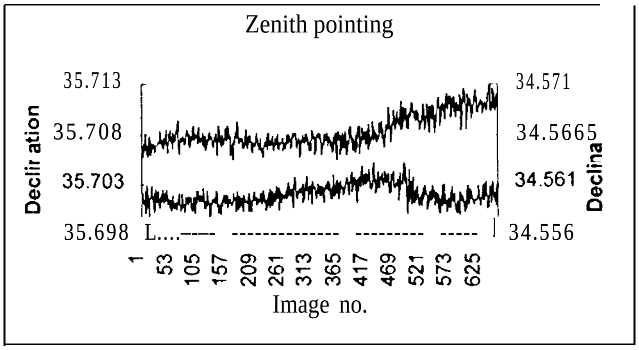

Figure 11. The declination angles of the attitude during zenith pointing of two co-foresighted star trackers.

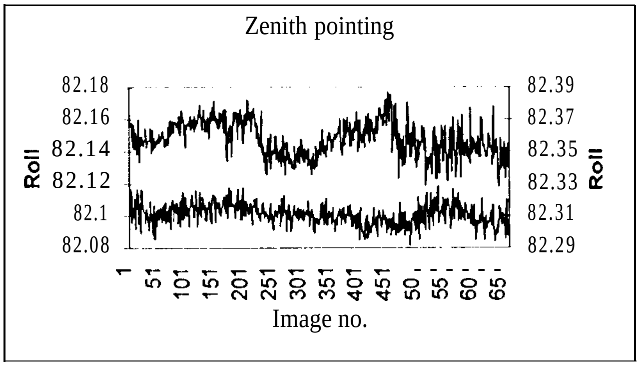

Figure 12. The roll angles of the attitude during zenith pointing of two co-boresighted star trackers.

It is observed that the attitudes from the two co-foresighted star trackers show some uncorrelated behavior. This implies one of two things:

1) The star trackers are not mounted rigidly with respect to each other.
2) The attitude drift is generated inside the star tracker, and has to be included in the relative error.

In order to investigate whether or not the cameras are mounted mechanical rigidly together, a series of sky tracking measurements was taken. If the construction is rigid, these measurements should be correlated. The result of the measurement series is shown in Figures 13–15.

It is observed in Figures 13-15 that the signals are generally correlated. Therefore, this indicates that the mount is mechanically stable, and that the errors shown in Figures 11-12 originate in the star tracker itself.

It generally should be emphasized that the algorithms used here to calculate the attitude are ***not*** the same as those used in the ASC from the Technical University of Denmark, but JPL software. The original ASC software can be expected to perform differently. As measured with the JPL generic software and star catalogs the pitch and yaw errors are in the range of 3 arcseconds (including long term variations) for the better performing star tracker rather than in the range of 1.8 arcseconds (image to image variations), 1σ,1 axis [11]. This is a topic for current investigation, refinement and future publication. Experience with other second-generation star trackers indicates that the causes of the larger long term variations can be minimized. Therefore, it is anticipated that refinements in the tracker will allow the long term variation to approach the value of the short term variation. One possible explanation is that errors and inaccuracies in the internal star catalog or algorithms occasionally correspond to stars with incorrect catalog entries and/or close star mergers. The atmospheric perturbation is also included in the accuracy measurements and its effects on operation could be significant.

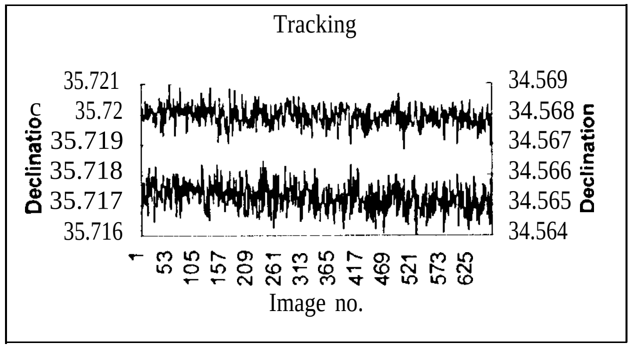

Figure 13. The declination angles of the attitude outputs during sky tracking of two co-boresighted star trackers.

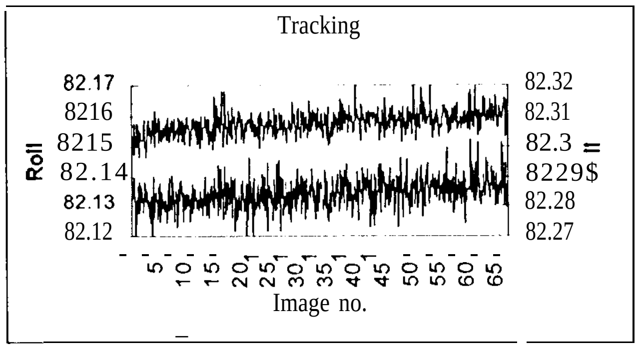

Figure 14. The roll angles of the attitude outputs during sky tracking of two co-foresighted star trackers.

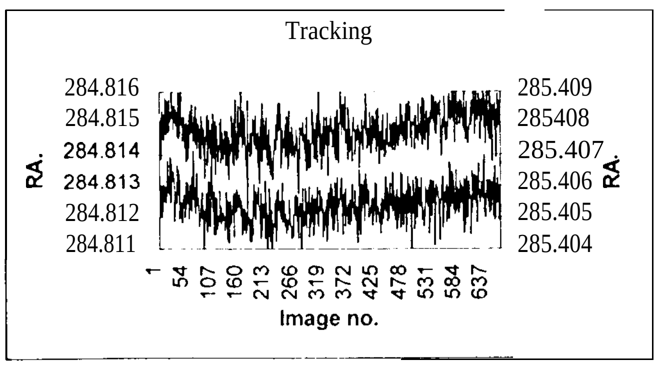

Figure 15. The right ascension angles (RA) attitude outputs during sky tracking of two co-foresighted star trackers.

7. Future Development of Star Trackers

Star trackers have undergone a significant evolution in the past five years; an even faster pace of evolution is anticipated in the next five years as a result of ongoing developments in sensors and microminiaturization.

All star trackers discussed herein are based on the mature CCD area array sensor technology. A competitive, new, sensor technology field has appeared: active pixel sensors (APS) [23-25]. APS advantages over CCDs include the potential for enhanced radiation resistance, a larger dynamic range without blooming, and control of individual pixel integration times. However, APS technology is not yet mature. Preliminary, real sky tests conducted at JPL [25] shows promising results in star tracker applications. An APS requires no special support integrated circuits (lC), since it is fabricated using standard CMOS technology. Therefore, supporting logic and parallel analog-to-digital (A/D) encoding can be integrated with it on a single piece of silicon. It also operates from a single 3.3- or 5-V power supply. These factors make it very compatible with microcontrollers and the eventual realization of a single IC star tracker whose mass and size are dominated by the optics and baffle. Such a high level of integration also promises great reductions in cost and a large increase in the number of applications.

The hardware demands for both present and future versions of a second generation star tracker can be generally summarized as follows:

- Small f/no optics
- 5--30 degree FOV
- Solid state, area array sensor
- 10–15 MIPS computer with A/D conversion
- Few Mbytes random addressable memory
- Few Mbytes FLASH memory
- Communications interface

Current state-elf-the-art microcontrollers designed for hand held devices [26-27] can meet all of the hardware requirements with 4 to 5 ICs for the entire star tracker, if an APS is utilized. Furthermore, the ICS can be stacked together in one package. It is believed that this existing technology can realize a second-generation star tracker weighing 200 grams and consuming 400 mW. The National Aeronautics and Space Administration (NASA) has funded a JPL Programmable Intelligent Microtracker (PIM) initiative at JPL which is working towards achieving this goal

The future combination of a second-generation camera head with a global position satellite (GPS) receiver for low Earth orbital applications is attractive for obtaining both precision position and pointing information. The GPS receiver is also a small instrument equipped with a powerful micro-computer. It is possible to combine these instruments so that they can utilize a common microcomputer. Once such a navigation instrument is developed, it would be very easy to integrate with a satellite and all navigation would be taken care of. Such a device is proposed for a JPL future space interferometer mission, but to be used with a local beacon, instead of the standard GPS system. It is also baselined for the GRACE mission.

In principle, a second-generation star tracker is a camera and a dedicated image processor. This combination has also many other applications in space, such as optical navigation, non-stellar object detection, space docking, formation flying, etc. [28]. One aspect of development is to investigate operation with the illuminated Earth or Moon in part of the FOV. This will significantly increase sky coverage for Earth orbiting applications, but with reduced accuracy.

8. Summary

Star trackers have been rapidly evolving over the last half decade. First-generation devices output only a few star positions in CCD coordinates, whereas recently developed, fully autonomous second-generation units output their attitude referenced directly to the celestial sphere, and with increased accuracy. The key components of accuracy and examples of how accuracy is measured at astronomical observatories have been covered. Finally, it is projected that future star trackers will be even smaller with the electronics integrated into a small number of very large scale ICS. Mass would be approximately 200 grams and power consumption 400 mW.

9. Acknowledgments

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11. BIOGRAPHIES

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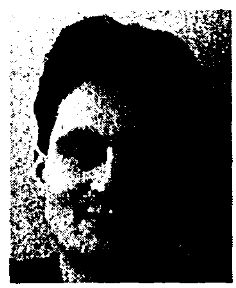

Dr. Carl Christian Liebe received his master of science degree in electrical engineering (1991) and his Ph.D. in imaging processing (1994) from the Department of Electro-physics, Technical University of Denmark. He was Research Assistant Professor at the Department of Automation, Technical University of Denmark 1995--1996 where he lectured in imaging processing and developed the star pattern acquisition algorithms and associated software for the Advanced Stellar Compass. Since January 1997, Dr. Liebe has been a member of the technical staff at the Jet Propulsion Laboratory, California Institute of I'ethnology, His current research interests are new technologies and applications for autonomous attitude deterrnination. He has authored/co-authored more than 20 papers.