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SATELLITE ATTITUDE DETERMINATION USING A CCD STAR CAMERA

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ABSTRACT

The star tracker experiment will demonstrate accurate, near real time, autonomous satellite attitude determination using a state-of-the-art charge-coupled-device star camera. The experiment will fly on a NASA spacecraft, designed to carry and support experimental payloads, and launched for a 40-hour mission from the space shuttle, and then retrieved for return to earth. The new camera and attitude software represent a significant step towards spacecraft autonomy. The experiment design and algorithm are discussed, along with a brief description of the data analysis plans. Features needed to improve the system to support a mapping application are also discussed.

INTRODUCTION

Photogrammetrists using satellite imagery for mapping must obtain the position and orientation of the camera for each image. This is normally done manually by using ground control points (Ref. 1). Even though the equations to calculate the position and orientation are not that difficult, it is time consuming to calculate them for each set of images. This method tends to add errors because it uses maps and other sources to find the control points. The satellite's position can be determined by ground tracking data and the time an image was taken. If a system provided real-time attitude and position for each image then to a degree, errors in triangulation would be controlled.

The mapping community has been considering use of star cameras for mapping applications for a number of years. For example, the Apollo missions used a film-based star camera for post-flight attitude determination in order to interpret photographs taken during the mission. USAETL has been involved in star camera studies since 1973 and has funded research on algorithms to determine satellite attitude from star camera data (Ref. 2). This paper describes an experiment which is an outgrowth of those early studies. The experiment will use a camera with state-of-the-art technology and achieve higher accuracy than previous star cameras.

In January 1985, the Vice Chief of Staff of the Army tasked the U.S. Army to identify candidate Army shuttle experiments. In response to this request USAETL proposed the star tracker experiment (START). In June 1986, the DOD Tri-Service review board approved the START experiment to be manifested on the space shuttle. This paper describes the experiment.

SATELLITE ATTITUDE

Determination of spacecraft's attitude is a fundamental problem in the operation of almost every satellite, including mapping satellites, during at least a portion of the mission. Attitude knowledge may be required so that booms, antennae or solar panels can be deployed when the spacecraft is in the proper orientation. In other satellites, attitude information may be required throughout the mission to properly interpret data from sensors or cameras on the spacecraft.

Spacecraft attitude is usually given as a set of three angles that describe successive rotations about three orthogonal vehicle axes to orient the spacecraft relative to a frame of reference. The orientation is usually referenced to an inertial coordinate system. In other situations the orientation may be referenced to a local coordinate system, usually defined by the local vertical (from nadir to the satellite), the orbit normal and the perpendicular to these two.

There are various methods for sensing the spacecraft attitude. Typical sensors include horizon scanners, digital solar aspect sensors, magnetometers, and star trackers or cameras. Information from sensors must be combined with knowledge about the parameter being measured so that the attitude can be determined. Star trackers are the most sophisticated and accurate of these sensors. The primary disadvantages of star trackers are cost, size and the complexity needed for high accuracy. New types of star trackers that are being developed will partially overcome these problems and, at the same time, achieve higher accuracy. These trackers are actually star cameras and use a charge-coupled-device (CCD) or a charge-injection-device (CID) to detect starlight (Ref. 3). They take a "snapshot" of the sky, giving locations of a number of stars in the field of view simultaneously, rather than being limited to viewing only one star at a time as in conventional trackers.

The experiment described in this paper will use one of these new star cameras and a computer to determine satellite attitude in near real time (within several seconds after the star data are obtained). Figure 1 shows an artist's concept of the experiment but with two cameras, rather than the single camera configuration.

In the remainder of this paper we will describe the
experiment and the major components. In the last section
we will discuss the implications for the future and how
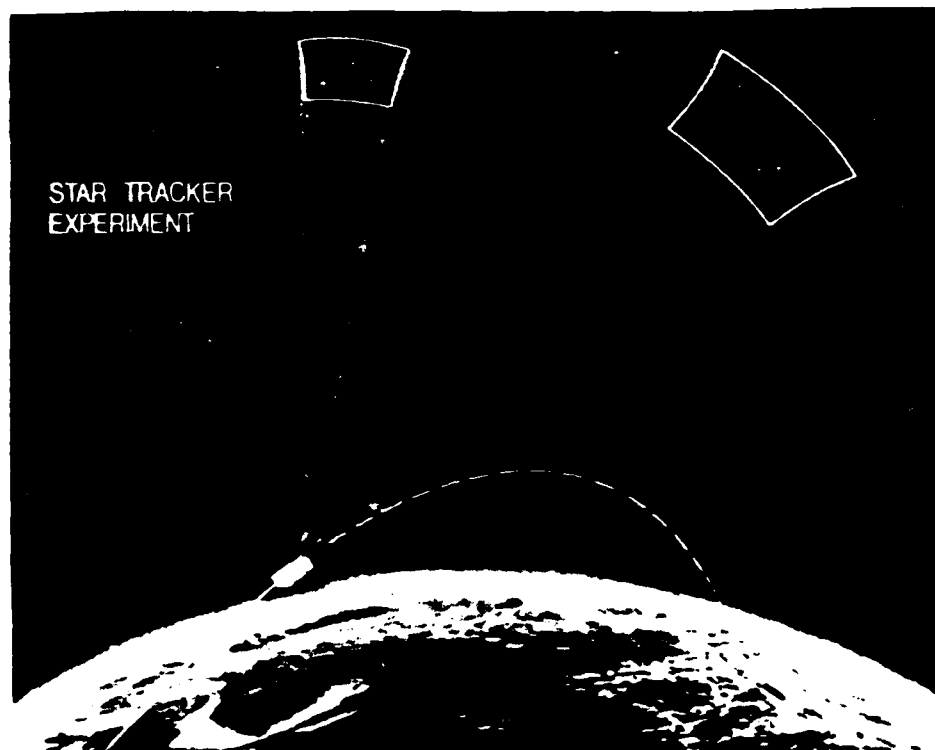satellite attitude determination can be improved.

Figure 1. Artist's conception of the star tracker
experiment. The figure shows two cameras; one will be
flown on the demonstration flight. The field of view is
about 7 X 9 degrees.

EXPERIMENT OVERVIEW

The START experiment consists of a star camera and its
electronics, a flight computer, and mechanical struc-
ture, all mounted to a NASA Spartan spacecraft. Figure
2 shows the experiment package attached to the Spartan
spacecraft. Figure 3 is a drawing of the experiment
package with major components identified. Three main
objectives were set for the experiment. These are:

   1. Demonstrate near real time, autonomous attitude
   determination.

   2. Collect star camera data for a variety of
   conditions to serve as a database for further
   attitude algorithm development.

   3. Evaluate the CCD star camera for attitude
   determination accuracy.

After a brief discussion of the Spartan spacecraft and
its relationship to the experiment, we will discuss
these objectives in more detail throughout the remainder
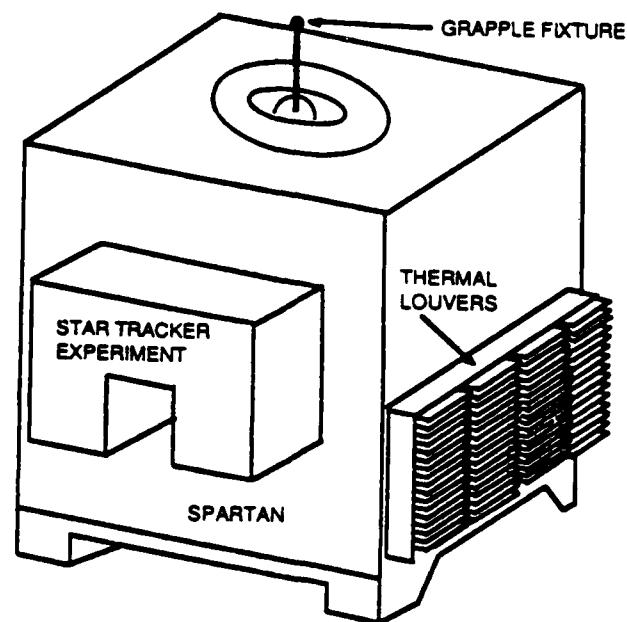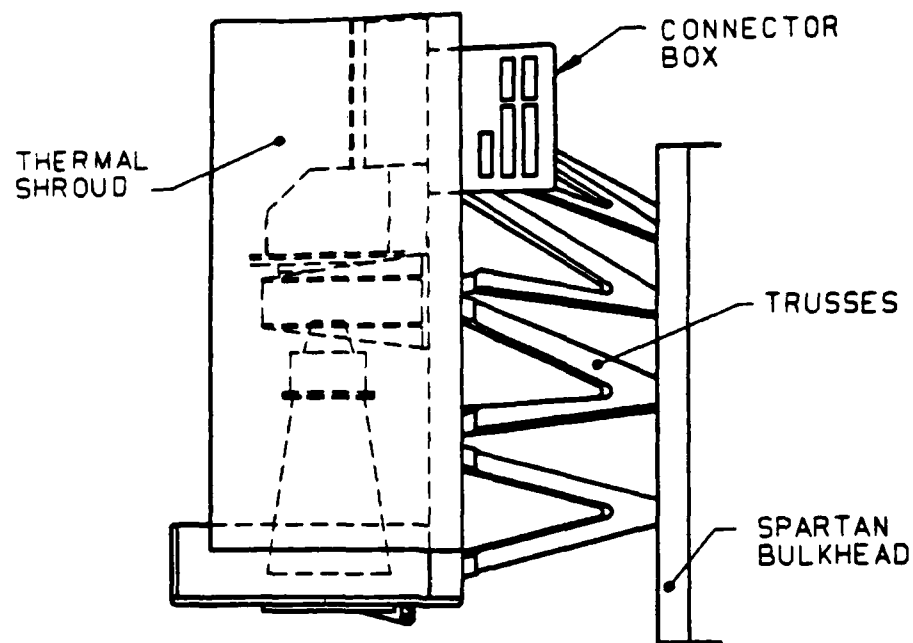of the paper.

Figure 2. The star tracker experiment will be attached to the Spartan. The Spartan provides power, attitude control and the data storage on a tape recorder.
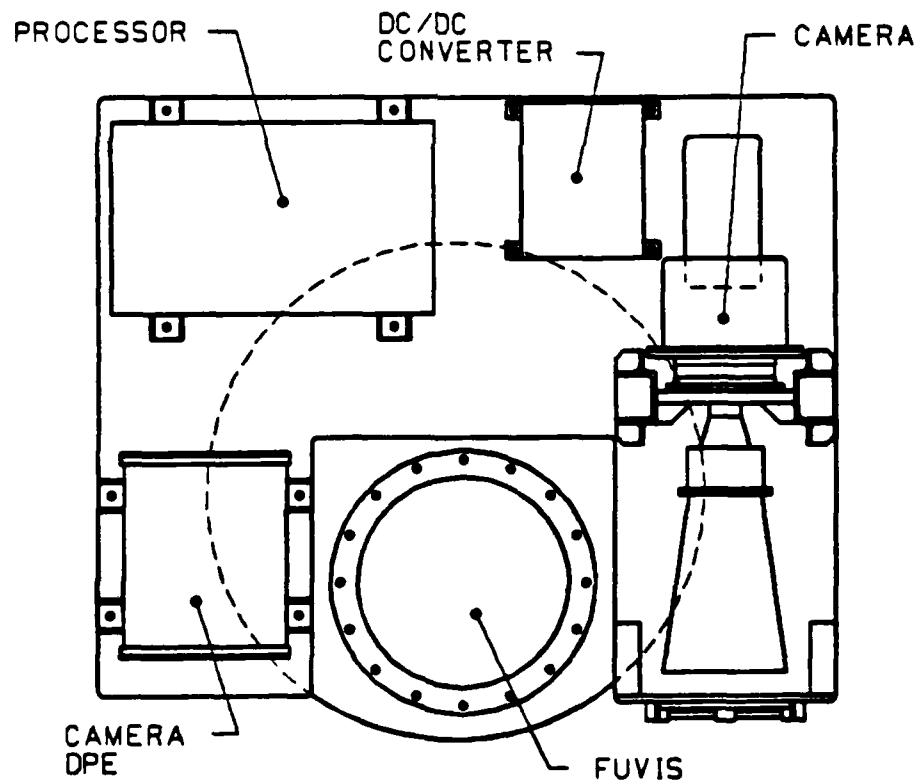
Spartan Spacecraft

Initially the START experiment was to be a Get Away Special (GAS) experiment. Upon investigation the possibility of using the Spartan vehicle (Ref. 4), USAETL decided to reconfigure the START experiment for the Spartan. The Spartan vehicle for this test is built by NASA Goddard Space Flight Center and funded by the U.S. Air Force. The Spartan is a cost-effective and simple way to test scientific equipment and retrieve the equipment after the test. There will be another experiment on this Spartan flight, the Far Ultraviolet Imaging Spectrograph (FUVIS). The 40 hours will be shared between the two experiments.

Spartan's source of transportation is the Space Shuttle. The Spartan is deployed and retrieved by the shuttle's remote manipulator system. It has a preprogrammed 40-hour mission; there is no real-time intervention once Spartan is deployed. During the 40-hour mission, attitude control, power, and data recording are provided for the experiment by Spartan. For the START experiment, this means having the ability to test the camera performance in various modes of Spartan operation (sluing or staring). By having the recording device onboard, the START experiment will collect data for later analysis to determine the

CONNECTOR BOX

THERMAL SHROUD

TRUSSES

SPARTAN BULKHEAD

SIDE VIEW

PROCESSOR

DC/DC CONVERTER

CAMERA

CAMERA DPE

FUVIS

PLAN VIEW

(THERMAL SHROUD REMOVED)

Figure 3.   This figure shows two views of the star tracker experiment.

accuracy of the camera and the precision of the
algorithms. These data will provide a source for
changes to the hardware as well as the software for
future experiments. In addition to being programmed to
point the camera in many different directions, Spartan
will be programmed to slue at different rates to test
the attitude accuracy dependence on this parameter and
to point close to bright sources such as the sun, earth
and moon.

The CCD Star Camera

The heart of the START experiment hardware is the star
camera. This camera, built by Perkin-Elmer Corporation,
employs a CCD on which a 7 X 9 degree portion of the sky
is imaged. The optical system was designed to spread
each star image over several light-sensitive elements or
pixels. This permits the star image centroid to be
determined to a fraction of a pixel. The camera
processor electronics performs this task and also
corrects known systematic errors. Various camera
parameters can be controlled by the host computer, in
this case the START experiment flight processor. Up to
five star images per camera frame are processed in this
way and the coordinates and inten- sities are passed to
the START flight processor.

If a CCD camera is to be flown in space for the type of
applications which require precise attitude, its per-
formance in space must be characterized. Then it can be
used without uncertainty or risk. Analysis of flight
data from this mission may lead to new camera designs or
restrictions in its use for follow-on missions.

To fully explore the performance of the tracker, we must
test it in a variety of conditions. Basically, we must
know how accurate the star positions are as a function
of the angle from bright objects and vehicle slue
rates. The Spartan vehicle will be programmed to
exercise the camera in various modes.

Attitude Determination

The START objective to demonstrate near real time
autonomous attitude determination will be performed by
software in the START flight processor. While most of
the camera data will be passed to the Spartan without
further processing, some of the frames will be processed
on board to determine attitude. Conceptually, the
software attempts to identify measured stars and match
the camera picture with a simulated picture using stars
from a catalog in computer memory. By matching the two
views, we can determine the camera attitude. Accuracy
in two axes is expected to be about 1-2 arcseconds while
accuracy in the third axis (rotations about the line of
sight) will be less accurate (approximately 20-40 arc-
seconds) because of the limited field of view. The
attitude determination process proceeds through a number
of steps. First, a group of stars is retrieved from the

on-board star catalog using an initial estimate of the attitude. Second, measured stars are matched with the subset of catalog stars by comparing the angle between pairs of measured stars with angles between pairs of catalog stars. Third, when a match is made between a measured and catalog pair, the initial attitude estimate is adjusted, via least-squares, so that the catalog pair of stars, when mathematically projected on the focal plane, lies over the measured pair. Fourth, a search is made for other catalog stars that would lie close to other measured stars when projected. If other matches are found, the probability of an incorrect attitude is essentially zero and the attitude is uniquely determined. Finally, another least-squares adjustment of the attitude is made using all the matched stars to more accurately determine the attitude.

The flight software will also contain routines to estimate the Spartan vehicle rate. In its simplest form, this requires saving previous attitude determination results and computing finite differences. The rate estimate is used to propagate the previous attitude estimate to the time of the next camera frame. This will aid in the catalog search and possibly reduce the number of iterations needed for the least-squares.

We have described the attitude determination as being autonomous. When the experiment is initially powered, the host satellite must send a rough estimate of the camera direction. However, once the flight software has successfully found the spacecraft attitude for the first frame, it should be able to continue finding matches for subsequent frames, provided the software operates quickly and the vehicle doesn't move too rapidly. For this experiment, pointing aids will also be sent following any periods of prolonged earth pointing. These aids would not be required if, for example, there were another camera in a different orientation or some other sensor to help out during periods with no camera data.

Autonomous attitude systems are important because they enable satellites to maneuver independently from ground control in a closed-loop systems, and they free the control centers from having to process all the data. In addition, the rate estimates, using this type of camera, can be quite accurate and, therefore, eliminate the need for gyros in some applications (Ref 5). This application would require faster processing than is possible for this experiment.

Post Mission Data Analysis

The data analysis task will be a major undertaking. The analysis of the camera accuracy will be complicated because there won't be another reference which has equal or greater accuarcy. Therefore, we must infer the

accuracy from internal errors and errors from frame to frame. The internal accuracy can be estimated by examination of the statistics of angles between pairs of stars from the same data frame. This method is independent of errors in the camera orientation and external errors.

We will process all of the data after the mission, not just the small percentage actually processed on board. This will permit us to examine data for various effects such as random noise and systematic camera errors. In general, we will process all of the frames of data in much the same manner as the frames are processed on board. However, we can adjust several parameters or weighting factors in the least-squares reduction, and include such things as calibration factors if any are indicated. Errors in pointing will be inferred by examination of successive frames of data and possibly by correlating the attitude results with the Spartan record of attitude control, which is also on the tape recording.

Design Tradeoffs

There were a number of tradeoffs in the design of the experiment. Several of these are discussed in this section.

Star position uncertainty is about 0.5 arcsecond and effectively sets the limit for attitude accuracy that can be achieved with star cameras. In a CCD star camera, a star image centroid can be located, relative to its neighbors, to about 1/50 to 1/100 of a pixel, depending on the image profile and other design criteria. Since we are evaluating the camera performance and don't want the star position uncertainties to be a significant source of error, we have chosen to make the field of view of the camera somewhat large. This also implies that the star catalog doesn't have to contain stars that are very faint but will still contain enough stars to match with measured stars. The larger format we selected is also about the same as the FOV size of the standard NASA star trackers (which are not as accurate but are in wide use). The star catalog for START will contain approximately 6000 stars although only about 3300 would be required to give five stars per field of view if the real distribution were uniform.

All of the camera data will be sent to Spartan for storage during the mission. The attitude determination task will be a background task, using time that's available when data are not being sent to Spartan. We expect to be able to process about one camera frame every 10 seconds. A higher processing rate would be possible on a dedicated processor or in situations which didn't require saving all of the data. Faster processing would also reduce the need to propagate the attitude and improve the rate estimate. Follow-on systems will likely improve on this.

FUTURE EFFORTS

There are a number of improvements that can be incor-
porated in future system concepts and experiments. We
discuss the most obvious of these in this section.

One obvious and necessary improvement would be the
inclusion of a second camera mounted at a right angle or
at some large angle with respect to the first. As
mentioned earlier, the rotation about the camera
boresight is poorly determined in a single-camera
system. The uncertainty in this angle would be reduced
to the 1-2 arcsecond level by use of a second camera.
Two cameras would also provide a measure of the
variation in the interlock angles between the cameras.

Another improvement is to include a dedicated processor
for attitude computations or relaxing the requirement to
save all of the data. This would give not only more
attitude information but also better rate estimates with
closer spaced data points.

We chose to have a larger field of view to limit the
catalog size and to minimize the errors caused by the
catalog uncertainities. However, to get the best
accuracy, a smaller field of view is better, at least
until the catalog errors dominate. Except for the
catalog errors, we should be able to extrapolate, to a
certain degree, the results of our experiment to a
smaller field of view.

Finally, an ideal system must include a positioning
system as well as an attitude system. The global
positioning system (GPS) is an obvious choice but other
techniques, such as laser ranging, could also be used
(see figure 4) to support autonomous location of image
points or targets.

SUMMARY

This paper describes an experiment to demonstrate
autonomous satellite attitude determination using a CCD
camera. The experiment will collect data for evaluating
the camera performance after the mission and for
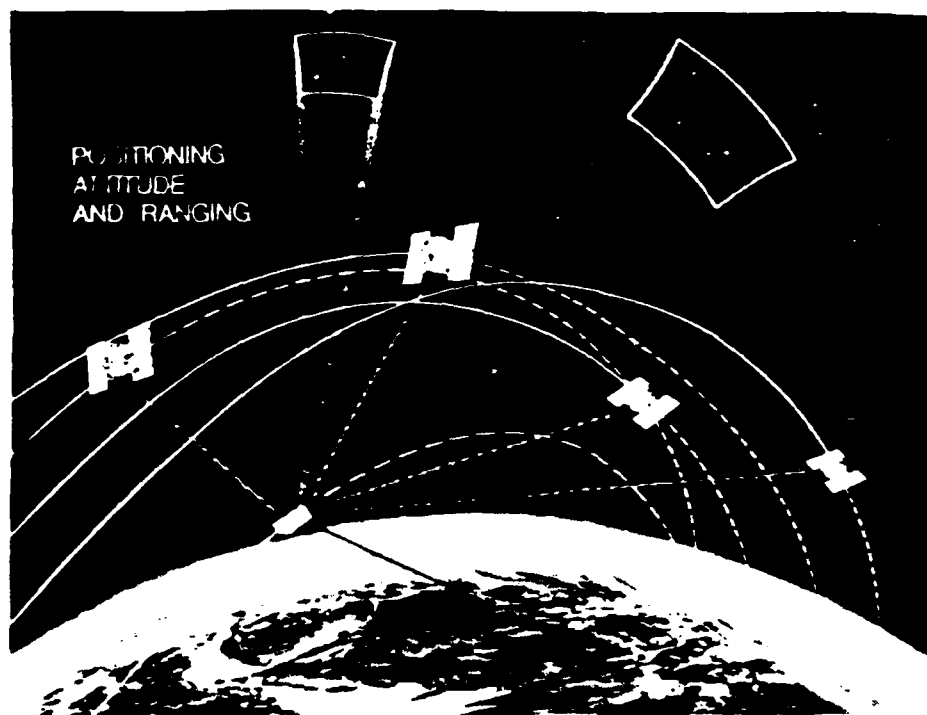refinement of attitude determination algorithms and
hardware.

Figure 4. Artist's conception of a future system
employing star cameras for attitude determination, GPS
receivers for positioning and laser for ranging.

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