Star Tracker Based ATP System Conceptual Design and Pointing Accuracy Estimation

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ABSTRACT

A star tracker based beaconless (a.k.a. non-cooperative beacon) acquisition, tracking and pointing concept for precisely pointing an optical communication beam is presented as an innovative approach to extend the range of high bandwidth (> 100 Mbps) deep space optical communication links throughout the solar system and to remove the need for a ground based high power laser as a beacon source. The basic approach for executing the ATP functions involves the use of stars as the reference sources from which the attitude knowledge is obtained and combined with high bandwidth gyroscopes for propagating the pointing knowledge to the beam pointing mechanism. Details of the conceptual design are presented including selection of an orthogonal telescope configuration and the introduction of an optical metering scheme to reduce misalignment error. Also, estimates are presented that demonstrate that aiming of the communications beam to the Earth based receive terminal can be achieved with a total system pointing accuracy of better than 850 nanoradians (3 sigma) from anywhere in the solar system.

Keywords: Acquisition, tracking, and pointing system; Deep-space optical communications; Star tracker

1. INTRODUCTION

The current baseline for the flight terminal pointing system of a deep space optical communication link relies on the use of a ground based laser for acquisition, tracking and pointing[1]. A limiting factor to this ATP concept is the requirement for very high power laser beacon sources at the earth ground station that must also be accurately pointed to the spacecraft through the atmosphere[2]. And even with the current highest power lasers, the range is now limited to ~ 3 AU. This is caused by the rapid drop off in power as the laser power decreases in a $1/r^2$ rate. In order to extend the range of high bandwidth optical communication links throughout the solar system, precision pointing systems based on non-cooperative beacon sources are being investigated and developed.

The goals of this development are a system that achieves precise pointing of the communications laser beam, utilizes non-cooperative beacon sources and enables communication to 40 AU. The pointing precision required is less than 1 microradian to enable communication rates in the 100's of Mbps. This tight pointing is necessary to reduce the transmit signal allocation for pointing loss. For example, a 1 urad (3 sigma) pointing accuracy results in 0.9 dB of pointing loss for a diffraction limited 30 cm aperture with a 1064 nm downlink transmitter wavelength. A simple doubling of the pointing accuracy to 2 urad significantly increases the pointing loss to 3.9 dB. The use of non-cooperative beacons (e.g. celestial sources) eliminates the need for a high power uplink laser from the earth receive terminal. This has the effect of reducing the complexity, operations and cost of the ground system. Furthermore it eliminates the need to deal with the effects of uplink pointing jitter caused by atmospheric scintillations. And by using non-cooperative beacon sources a single solution to the ATP architecture can be provided for optical communication links throughout the solar system.

Three non-cooperative beacon tracking concepts have to date been proposed. The first uses the sun scatter from the earth in the visible spectrum; the second relies on using the infrared energy emission from the earth in the 8 to 13 micron band and the third is based on using stars as the beacon source. Major drawbacks of the visible earth concept are its high sensitivity to albedo variations[3] and its strong phase dependence[4]. The thermal earth tracking concept shows

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promise to overcome both of these issues and yet have sufficient signal for precise tracking[5]. The star tracker has distinct advantages over both of these concepts such as range independence; inherit mature star tracker technology, and high link availability (no Sun-Probe-Earth angle dependence and stars everywhere)[6].

This paper presents recent results in the development of the star tracker based optical communications terminal. The star tracker based concept is presented with the layout of the system. Results are presented from analysis that were performed to determine the best mounting configuration of the star tracker relative to the optical comm terminal based on stray light susceptibility, volume, weight and misalignment error. Also presented is the design of the optical metering scheme introduced to reduce the misalignment bias error. This is followed by a presentation of the details in estimating the total pointing error including knowledge jitter, knowledge bias, misalignment error and vibration residual errors.

2. CONCEPTUAL DESIGN

2.1. Configuration of Star Tracker and Optical Comm Telescope

The technical approach of the star tracker based acquisition, tracking and pointing (ATP) system is to acquire and track on stars to obtain precise attitude knowledge and to propagate that knowledge to the optical beam pointing mechanism with the use of low noise high bandwidth gyroscopes. High accuracy star trackers are used to provide absolute reference information that is merged in an attitude estimator with information from the high bandwidth inertial sensors (e.g. gyro) that provide relative attitude knowledge and information from the navigation ground system that provides position information of the spacecraft and the target. The attitude estimator merges the data to provide a filtered attitude estimate and with the position data determines the pointing direction which it then uses to command the pointing mechanism (typically a fine steering mirror).

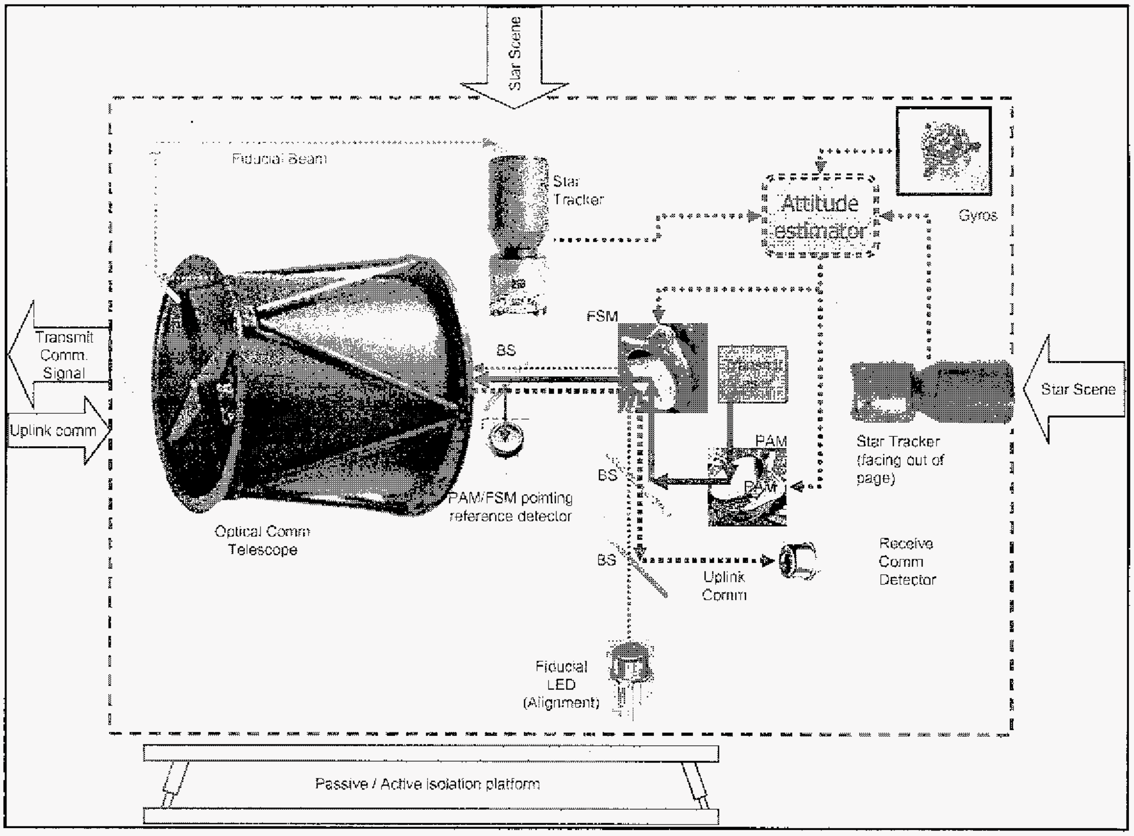

Figure 1. Star Tracker based Optical Comm Terminal Layout in the Orthogonal Configuration. Absolute attitude information from two 8 cm star trackers are combined with relative attitude from gyroscopes to estimate accurate pointing direction of the optical communication beam pointing mechanism for aiming to the earth based receiver

The conceptual design consists of two star trackers that are both mounted in an orthogonal direction with the line of sight of the optical communications terminal, see Figure 1, and orthogonally oriented to each other. (The star tracker on the right side of the figure is facing out of the page.) An optical metering system using a fiducial beam was introduced to reduce the misalignment bias between the line of sight of the downlink and the star tracker. The point ahead mirror (PAM) is introduced to deal with angle differences between the optical line of sight and the intended pointing direction which could be up to 100's of micro-radians. The spacecraft micro-vibrations are compensated using a combination of passive/active isolation and a fast steering mirror (FSM) stabilization control loop. The FSM is also used to maintain the uplink communications signal on the receive detector. It was found necessary to utilize two star trackers to deal with the fact that star trackers have good precision in the pitch and yaw axis, but have degraded performance in the roll direction.

2.2. Mounting Configuration Trades

Three configurations for mounting the star trackers relative to the optical communications telescope line-of-sight were considered and analyzed for stray light susceptibility, volume, weight and misalignment error. These configurations were termed the antipodal, the orthogonal and the co-boresighted. The antipodal configuration mounts the star trackers in an opposite direction as the optical comm telescope as shown in Figure 2. The orthogonal configuration has the optical comm terminal and the two star trackers all mounted in an orthogonal direction to each other, see Figure 3. The co-boresighted configuration has the star tracker either sharing the aperture with the optical comm telescope or mounted in the same line of sight. It was determined that except for the co-boresighted configuration it was necessary to introduce two star trackers in order to have high precision in the pitch and yaw attitude of the optical comm terminal line of sight. This decision was made to deal with the inherent reduced attitude accuracy performance of star trackers in the roll direction.

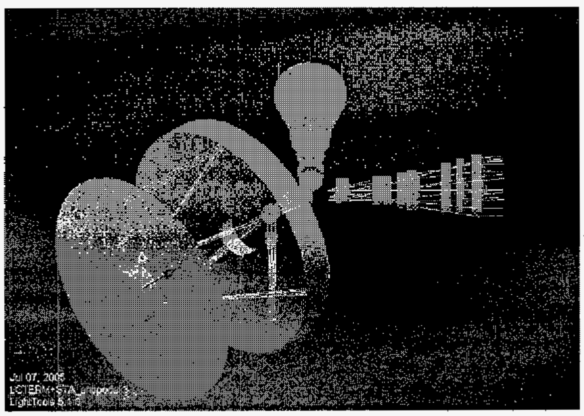

Figure 2. Antipodal configuration of a 30 cm optical comm terminal with two 8 cm star trackers.

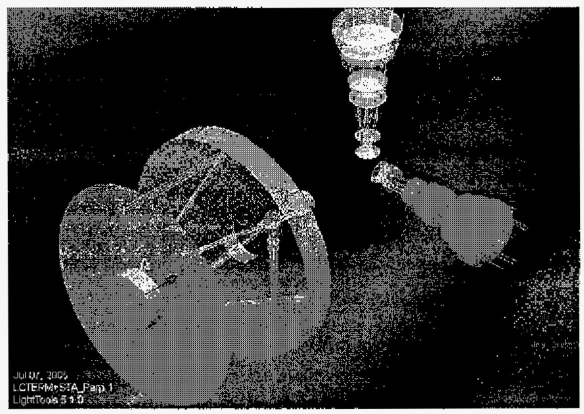

Figure 3. Orthogonal configuration of a 30 cm optical comm terminal with two 8 cm star trackers.

The stray light susceptibility into the star tracker is negligible for the antipodal and orthogonal configurations but can be quite significant for the co-boresighted configuration. This is because the optical comm terminal line of sight is always in the direction of earth and therefore the antipodal star trackers are facing away from earth scatter and away from sun stray light for even low sun-probe-earth (SPE) angles. One concern is that during the terminal's orbit of a planet, the antipodal and orthogonal configuration need to be rotated to ensure that both trackers do not have the planet in their field of view (FOV). On the other hand, the co-boresighted configuration has stray light influences dependent on the SPE angle and the performance of the star tracker will be highly reduced at low angles. Since the system desired is one that is capable of link ranges up to 40 AU, where SPE angles are but a few degrees, the co-boresighted configuration is deemed unsatisfactory.

The volume of the antipodal configuration was found to be 15.5 % higher than that of the orthogonal. The volume is 86080 cm^3 for the antipodal and 74560 cm^3 for the orthogonal. The orthogonal configuration provides a more compact solution. Different materials were considered to estimate the weight. The materials that were analyzed were graphite epoxy composite (GrEp) and silicon carbide (SiC) for the telescopes (telecom and star trackers). While for the interface bench joining the telescopes the materials considered were GrEp and ultra-low expansion glass (ULE). When the telescopes and the bench/interface were made of GrEp the antipodal configuration weight was 18.08 kg while the orthogonal configuration weight was 19.57 kg. When the telescopes were made out of SiC and the bench/interface was made of ULE, the weights increased slightly to 19.62 kg for the antipodal and 20.98 kg for the orthogonal. In summary the antipodal was lighter than the orthogonal by about 7 %.

The misalignment bias between the optical comm telescope line of sight and the star tracker was also analyzed for the materials and configurations mentioned above. It was found that even with very low thermal of expansion materials the misalignment error was in range of 1.5 - 2.2 urad. This level of misalignment was deemed unacceptable for getting to a sub-microradian pointing accuracy and therefore an optical metering scheme was investigated.

2.3. Optical Metering Scheme

Optical metering was found to be necessary to reduce the misalignment bias between the line-of-sight of the optical telescope and that of the star tracker to the levels necessary to obtain a total sub-microradian pointing accuracy. The optical metering scheme devised to reference the 30 cm optical comm terminal with the 8 cm star trackers is shown pictorially in Figure 4. It consists of a lateral transfer hollow retro-reflector (LTHR), a hollow penta-retro-reflector (HPR) and a set of fiducial lights. The fiducial light beam (from a set of light emitting diodes) originates in an optical channel of the 30 cm comm telescope and is guided to the edge of the secondary and the primary in order to enter the LTHR which then directs the beam to the HPR above the star tracker. The beam is then reflected onto the focal plane array of the star tracker. The residual error of this metering system depends on the stability of the retro-reflectors and the jitter of the star tracker. The misalignment bias error estimated for the optical metering scheme is 136 nrad.

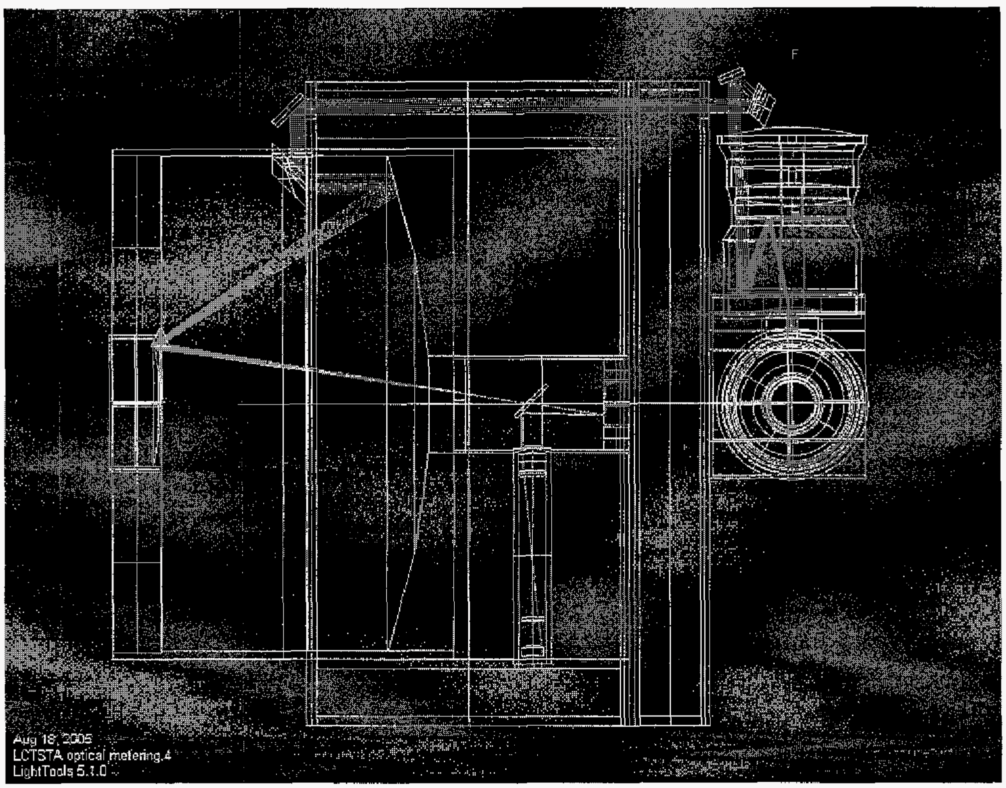

Figure 4. Drawing shows the optical metering path coupling the 30 cm optical com terminal with the 8 cm star trackers.

3. TOTAL POINTING ACCURACY

3.1. Total Pointing Estimate Summary

The total pointing accuracy of the system was estimated to be 842 nanoradians (3 sigma, radial) for the star tracker based optical communication terminal. The pointing error components are summarized in Table 1. The system uses the orthogonal mounting configuration (as presented above) including the telecom telescope, two star trackers, gyroscopes and optical metering between the telescopes. The dominant error terms in the system are the residual jitter and the misalignment bias. For estimating the residual jitter, two different micro-vibration compensation approaches were considered and compared in the table. The first approach uses a Disturbance Free Platform (DFP) as an isolation stage between the telescopes and the spacecraft[7]. The second uses a combination of a passive isolator hexapod with an optical inertial reference unit that provides a stabilized optical beam on a quad detector for high frequency tracking and stabilization. The optical beam is used to track out the spacecraft jitter using a fast steering mirror[1]. The DFP option yields better performance due to its ability to offer over 60 dB of isolation across a broad frequency band from 0.1 to 100 Hz. The misalignment bias error is due to the optical metering components under a thermal load as expected during a Mars occultation. The details of each of the error terms are discussed in the following paragraphs.

Table 1. The estimated total pointing accuracy for the star tracker based optical comm terminal is 842 nanoradians (radial, 3 sigma) using the Disturbance Free Platform for vibration isolation and 1182 nanoradians when using an optical IRU that provides a stabilized optical beam on a quad detector for vibration compensation with a fine steering mirror. Both systems provide microradian level precision in the pointing accuracy of the optical comm beam.

Error Components	Error [with DFP] (nanorad)	Error [optical IRU] (nanorad)	Rationale/comments
Random Errors:			
Knowledge Jitter (Star Tracker + Gyro)	67	67	Star tracker with 2 Hz update rate and 0.5 urad/frame accuracy; 30 sec averaging window
Uncompensated micro-vibrations	100	200	MTO MLT vibration spec.;
FSM Noise	40	40	400 nrad FSM spec with 10X optical magnification
PAM/FSM reference detector	75	75	1 pW; 01 sec integration
Total Random Error, single-axis	147	227	1 sigma
Quasi-static Errors:			
Knowledge Bias (Star Tracker + Gyro)	65	65	Gyro drift dominated; 30 sec averaging window;
Mis-alignment	136	136	Using fiducial lights for optical metering
Ephemeris	28	28	10 km ephemeris uncertainty of earth; 2.4 AU
Total Quasi-static error, single-axis	153	153	
Total Pointing Accuracy, radial	842	1182	3 sigma (quasi-static + 3*random)

3.2. Knowledge Jitter

To estimate the attitude knowledge jitter from the combination of star trackers and gyroscopes an analytical model was built[8]. This model propagates the star tracker attitude measurements with the gyroscopes and uses an iterative averaging process to improve the accuracy of the combined update. The estimated knowledge jitter improvement as a function of the averaging process (averaging window) is plotted in Figure 5 for two levels of gyro angle random walk (6E-5 deg/√Hour and 1.7E-5 deg/√Hour). The averaging window is the 'running window' that averages the star tracker samples within the window size. A star tracker with a 0.5 urad/frame accuracy and a 2 Hz update rate is used in this plot. (This level of performance for a star tracker has now been demonstrated in a flight mission[9].) By averaging over a 30 sec window and using the 1.7E-5 deg/√Hr gyro it can be seen that the attitude knowledge jitter is better than 70 nrad. This combination of sensors gives very low attitude knowledge accuracy. The jitter can be reduced further with larger averaging window size, but this will increase the knowledge bias error as the gyro drift term grows.

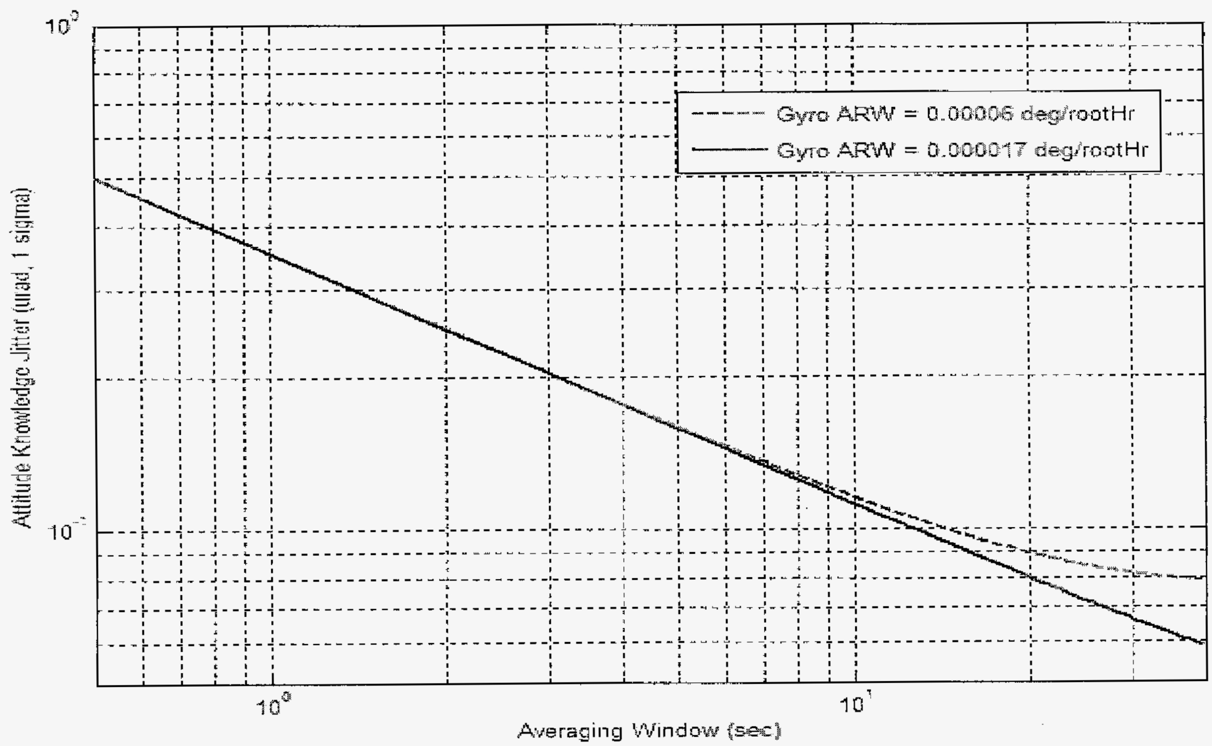

Figure 5. Attitude knowledge jitter from star tracker and gyro combination as a function of the averaging window size. Better than 70 nrad knowledge accuracy can be obtained by having an averaging window of 30 seconds with a gyro having an ARW of 1.7E-5 deg/√Hour. A star tracker with 0.5 urad/frame accuracy and an update rate of 2 Hz is used.

3.3. Knowledge Bias

The knowledge bias depends on the star tracker bias error sources such as pixel non-uniformity, spatial quantization, and accuracy. It also depends on the gyroscope variance and drift error. Furthermore, the bias error depends on the window time used in the iterative averaging process that is used to reduce the knowledge jitter. In general, it is found that the bias error is dominated by the gyro drift. Figure 6 shows the competing effect between the attitude knowledge jitter and bias error. With increasing averaging window size, more samples are averaged thereby reducing the jitter error, but the bias error linearly increases due to the increase in gyro drift. Because the total error from the star tracker/gyroscope combination is the bias plus three times the jitter, an optimal value for the total is found around an averaging window size of 30 to 40 seconds. This estimate was done with a 2 Hz update rate star tracker having a 0.5 urad/frame accuracy combined with a gyro having 1.7E-5 ARW and a 50 Hz update rate.

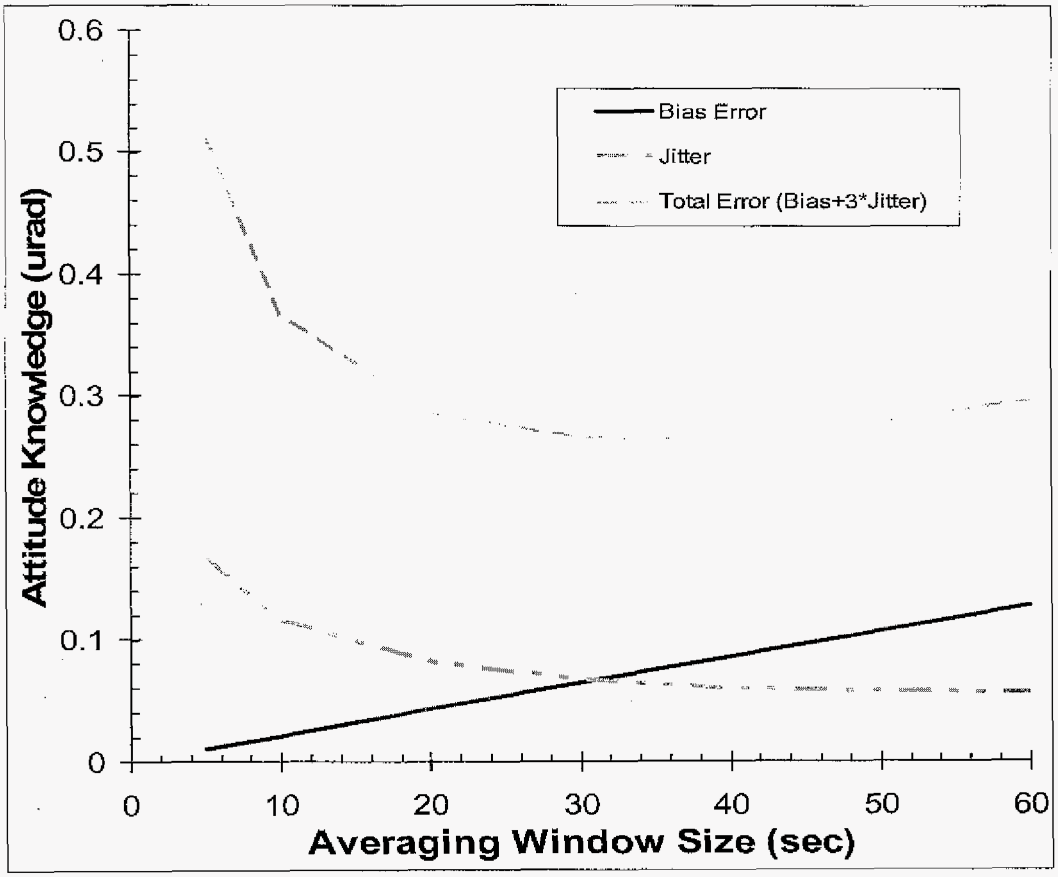

Figure 6. Attitude knowledge errors (bias, jitter and total) from the star tracker and gyro combination as a function of the averaging window size. There is an optimal averaging window time that minimizes the total attitude knowledge error. This occurs when the averaging time is increased to reduce the jitter before the drift of the gyro dominates the bias. This optimal averaging window size is found to be in the 30 to 40 sec range yielding a bias error of ~ 70 nrad and a jitter of ~ 70 nrad.

3.4. Misalignment Bias

The misalignment bias between the 30 cm optical comm telescope line of sight and the two 8 cm star trackers line of sight was also analyzed for the configurations and materials mentioned above. The analysis included thermo-elastic computations of the rigid body misalignments of each of the optical elements (tips, de-centers and de-spaces, also referred to as thermal bending).

This analysis was done to determine if the misalignment error would be low enough without needing to introduce an active referencing/metering technique. The thermal conditions for the analysis assumed that the system was orbiting Mars with a 90 minute orbit and would have thermal shielding, small make-up patch-heaters and radiators. The resulting thermal change during the eclipsing of the terminal was a 5 degree Celsius thermal soak with a 0.01 degree C gradient, where these changes would occur, in a worst case, over about 2.5 hours. With the telescopes and bench/interface made from GrEp it was found that the misalignment bias was 4329 nrad for the antipodal configuration and 6902 nrad for the orthogonal, see Table 2. More thermally stable materials were introduced to reduce this bias error. It was found that with the telescopes made of SiC and the bench/interface made of ULE, the misalignment reduced to 1484 nrad for the antipodal and 2205 nrad for the orthogonal. This level of misalignment was deemed unacceptable for getting to a sub-microradian pointing accuracy and therefore an optical metering scheme was investigated.

The residual error of the metering system consists of the root sum square of the errors due to the thermo-mechanical stability of the retro-reflectors and the noise equivalent angle measurement error of the star tracker. For the same thermal conditions as mentioned above and the orthogonal configuration with SiC telescopes and ULE bench/interface, the stability of the retro-reflectors was calculated to be 90 nrad. The NEA using a 592 nm HP LED with an output radiance of 4.82 $W/cm^2/sr$ upon the star tracker sensor was estimated at 48 nrad. This yielded a total misalignment bias for the optical metering scheme of 136 nrad.

Table 2. Thermo-mechanical misalignment bias error for various configurations and materials. It was found necessary to introduce an optical metering scheme to reduce the misalignment bias error to levels that would enable sub-microradian pointing. Analysis conditions include a thermal soak of 5 degree C and a 0.01 degree C gradient.

Configuration (Star Tracker & Lasercom Material)/(Interface Bench Material)	**Star Tracker Internal Stability (nanoradians)**	**Star Tracker to Lasercom Bench/Interface (nanoradians)**	**Lasercom Internal Stability (nanoradians)**	**Total Bias Error (nanoradians)**
Antipodal (GrEp/GrEp)	1679	1304	1346	4329
Orthogonal (GrEp/GrEp)	1679	3878	1346	6902
Antipodal (ULE/SiC)	321	1413	321	1484
Orthogonal (ULE/SiC	321	1562	321	2205
	Star Tracker Retro Stability	Measurement Error	Lasercom Retro Stability	Total Bias Error
Optically Metered Orthogonal (ULE/SiC)	90	48	90	136

3.5. Vibration Compensation

Three vibration compensation architectures were investigated to reduce the micro-vibrations due to the spacecraft navigation and control system. All three approaches blend the star tracker/gyro absolute attitude information with high bandwidth stabilization and control loops. The first approach uses passive isolation interfaces and high bandwidth angle sensors that sense the vibrations and command a fast steering mirror to stabilize the transmit optical beam. The second approach utilizes an optical inertial reference unit (e.g. MIRU[10]) that provides a stable reference optical beam that travels thru the optical comm channel. This beam is tracked at a high bandwidth with a quad detector and the outgoing transmit beam is stabilized with a fast steering mirror. The third approach uses an isolation platform with a very broad frequency response. This isolation platform is also known as the Disturbance Free Platform [[11]] and has over 60 dB of isolation from 0.1 to 100 Hz. The uncompensated micro-vibration estimate was performed for many spacecraft vibration power spectral densities (PSD's). The spacecraft vibration specifications considered were those for the Relay Mirror Experiment S/C, Olympus S/C, Landsat, Motorola, HRDLS, Bosch and the Mars Telecom Orbiter S/C (baselined for the Mars Lasercom Terminal). An update rate of 10 Hz is assumed for commanding the DFP. The results are shown in Table 3. It can be seen that due to the DFP's broad bandwidth and high level of isolation, the residual jitter is significantly reduced for all of these vibration spectra.

Table 3. Residual jitter and uncompensated jitter for the Star tracker based Optical comm terminal for a variety of spacecraft platforms utilizing the Disturbance Free Platform for vibration isolation.

Spacecraft	Uncompensated Jitter (urad) [no DFP]	Residual Jitter (urad) [with 10 Hz update rate to DFP]
RME	0.6	< 0.01
Olympus	12.46	< 0.01
Landsat	13.68	0.01
Motorola	21.43	0.02
HRLDS	28.49	0.03
Bosch	84.68	0.08
MTO MLT	107	0.10

SUMMARY

The conceptual design of the Star Tracker based Optical Communications terminal was presented. Analysis demonstrated that the orthogonal mounting configuration offered 15 % lower volume and 7 % higher mass than the antipodal configuration. Both of these configurations offered very low stray light susceptibility. An optical metering scheme was shown to be necessary in order to reduce the misalignment error between the star tracker line of sight and the optical comm telescope line of sight sufficiently to enable sub-microradian pointing accuracies. The misalignment error was reduced from 2200 nrad without metering to 136 nrad with metering.

The total pointing accuracy of the system was demonstrated to be 842 nanoradians. A detailed error budget was presented that included the knowledge jitter, the knowledge bias error, the misalignment error and the residual jitter. The major sources of error were shown to be the residual jitter error and the misalignment bias error. Analysis of each of the major error sources was presented to demonstrate feasibility. The specifications of the sensors used in the analysis were taken from demonstrated technology that are at a high technology readiness level and in some cases the sensors have already been used in flight missions.

ACKNOWLEDGEMENTS

The work described was performed at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

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