

Final
CL03-1831

Acquisition, Tracking, and Pointing using Earth Thermal Images for Deep Space Optical Communications

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Abstract - The feasibility of using long wavelength Earth thermal (infrared) images for telescope tracking/pointing applications for both Deep Space Free-Space Optical Communications has been investigated and is reported here. The advantage of this technology rests on using full Earth images in this band, which yield more accurate estimates of geometric centroids than that of Earth images in the visible band. Another major advantage is that these images are nearly independent of Earth phase angle. The results of the study show that at a Mars range, with currently available sensors, a noise equivalent angle of 10 to 150 nanoradians and a bias error of better than 80 nanoradians can be obtained. This enables precise pointing of the optical communications beam for high data rate links.

INTRODUCTION

The use of Earth image tracking in the visible band to accurately point the optical communication downlink signal beam to the receiver telescope on the Earth's surface has been investigated for more than a decade. The major limitations with this concept have been a) a low signal level at high Earth phase angles and b) a large albedo variation due to Earth atmospheric changes [1, 2]. This report demonstrates that with the use of Earth tracking in the thermal band, the above problems are significantly mitigated. With thermal images, a full Earth image can be maintained even for high phase angles. Low albedo variations of thermal images are shown due to the relatively slow thermal changes of the Earth surfaces compared with rapid changes of reflectivity of the Earth surface for visible wavelengths. As a clear example from two imagers on the Mars Odyssey Spacecraft, the entire (full) Earth thermal image was successfully taken whereas the visible light image shows the thin crescent Earth viewed from Odyssey's perspective (figure 1).

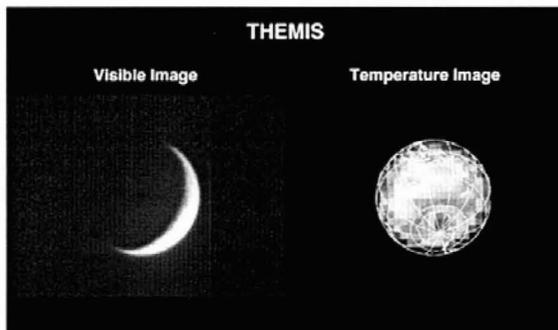


Figure 1. Visible and Thermal Earth Image from Mars Odyssey spacecraft.

The basic concept is to use a long wavelength infrared (LWIR) sensor to collect images of the Earth. The Earth image serves as the reference to the communications tracking and pointing system. Tracking on the earth closes the pointing loop in this 'beacon-less' approach. The location of the Earth receiver is determined by i) computing the earth's centroid location from the image and ii) calculating the receiver location relative to the center of the earth based on time information and an on-board model. Any error in this determination is known as the bias error.

The work reported here has focused on validation of the tracking/pointing accuracy using the measured Earth thermal images and emissivity variations. For the wide range of albedo variations, simulations have been used to estimate the impact to the centroid accuracy. Investigation of available infrared detectors has been made to assess the readiness of the detector technology. The estimated pointing accuracy has been compared with the required pointing accuracy for optical communications.

RANDOM ERROR

Random error, or noise equivalent error (NEA), is mainly governed by the Signal-to-Noise Ratio (SNR). Therefore, accurate estimation of total signal at the detector and the system noise is the critical step. The steps taken here for NEA estimation are: wavelength selection, estimation of available signal, background noise, and LWIR detector characteristics. The former two subjects provide an estimation of the signal and the latter two subjects address the noise level. Wavelength is selected based on maximum available signal and least effect from emissivity variations. Once a certain wavelength band is determined, available signal level can be estimated. Sources of possible background noise

include solar straylight in the selected wavelength band. Detector noise is largely dependent upon specific detector material and manufacturing process/design. The objective of trade-off among these parameters is to maximize the SNR, thus minimizing the NEA.

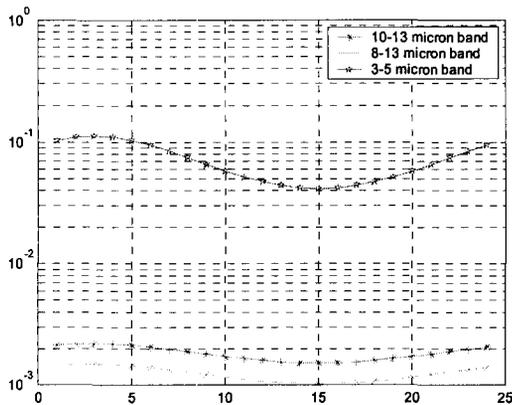


Figure 2. NEA (pixel) vs. Phase Angle. Energy from 3 bands considered for inertial sensor assisted tracking update rate (10 Hz) using the worst-case scenario system parameters.

The NEA is estimated using the derived photon radiant intensity values and typical system parameters (e.g. centroid window of 9x9, 30 cm aperture). There are two classes of parameters: one that is design value such as aperture size and detector full well, the other is mission dependent, such as range and centroid window size (governed by beacon spot size). For two tracking scenarios, optical only tracking and inertial sensor assisted tracking, beacon update rates of 10 Hz and 1 kHz were used to represent the required update rates. For inertial sensor assisted tracking, the NEA is very small on the order of 10 nrad for 8-13 um bands (Figure 2). For 3-5 um band, the NEA is up to 1 urad. With trade-offs on detector full well and aperture size, this can be reduced to 70 nrad. For optical tracking only, the worst-case estimate of NEA is more than 1 urad. With the trade-offs on the detector full well and the aperture size, NEA of better than 100 nrad can be achieved. In summary, the bands of 8-13 and 10-13 um can provide adequate centroiding NEA for optical communication in both optical only and inertial sensor assisted tracking with some trade-offs.

BIAS ERROR

It is expected that the bias error depends more on the knowledge of the earth model than on the particular Earth centroiding approach (there are different

techniques under each approach). To determine the center of the Earth we looked at three approaches a) edge detection, b) centroid determination with bias offset and c) maximum likelihood matching. All three approaches have bias error close to the bias error budget of 100 nrad for optical communications. The distance between the Earth and Mars was assumed as 0.5 AU, or the Earth image of 6 pixels wide. Depending on the trade-offs on the optics design such as Field-of-View (FOV) and the telescope size, it can be met. For example, 5 urad pixel, instead of 10 urad pixel, gives 80 nrad bias error from the maximum likelihood method. Additionally, if the distance becomes 1 AU, the bias error from edge detection method will be 118 nrad.

SUMMARY

The resulting centroiding error (NEA and bias error) shows that the 8-13 micrometer wavelength band can meet optical pointing requirements while 3-5 micrometer band is not sufficient for optical communication requirements. The 8-13 um band is more attractive due to a) higher signal availability, and b) a lower emissivity variation. The obvious advantage over visible band is the ability to detect the perimeter of Earth with low emissivity variation such that the potential centroiding error can be reduced. This solves a major problem that visible image tracking was not able to solve (albedo variation and partially reflected Earth image). Another benefit is a simplified centroiding algorithm due to the symmetry of the Earth shape. This concept is also applicable beyond Mars distance as long as sufficient signal is received. Trade-offs such as larger aperture size and lower detector noise can extend the operating range.

ACKNOWLEDGEMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

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