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Autonomous Target Ranging Techniques

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Abstract — For the deep space asteroid mission, Bering, the main goal is the detection and tracking of Near Earth Objects (NEO's) and asteroids. One of the key science instruments is the 0.3m telescope used for imaging and tracking of the detected asteroid objects. For efficient use of the observation time of this telescope, a fast determination of the range to and the motion of the detected targets are important. This is needed in order to prepare the future observation strategy for each target, i.e. when is the closest approach where imaging will be optimal.

In order to quickly obtain such a determination two ranging strategies are presented. One is an improved laser ranger with an effective range with non-cooperative targets of at least 10.000km, demonstrated in ground tests. The accuracy of the laser ranging will be approximately 1m. The laser ranger may furthermore be used for trajectory determination of nano gravity probes, which will perform direct mass measurements of selected targets.

The other is triangulation from two spacecrafts. For this method it is important to distinguish between detection and tracking range, which will be different for Bering since different instruments are used for detection and tracking. Also, the baseline distance between the two spacecrafts will provide two different (close and far) scenarios of observation. The limiting range and the relative range accuracies of the triangulation method are discussed.

INTRODUCTION

One of the main goals of the Bering deep space mission, described in [1] - [5], is the autonomous detection, tracking and orbital element generation of Near Earth Objects (NEO's) and Asteroids. To achieve this, Bering consists of two highly autonomous spacecrafts equipped with a suite of instruments, the main of which is a small (0.3m) science telescope for observing and tracking selected targets. The telescope is equipped with a multi-band spectral imager and an external tip-tilt mirror, allowing target search and tracking without extensive spacecraft attitude maneuvers. An optimized laser ranger is also integrated in the optical system of the telescope.

The target detection, described in [4], is carried out by a number of star trackers, which together provide almost full sky coverage. The star trackers are micro-Advanced Stellar Compasses or μASC's, each equipped with up to four optical sensors heads (Camera Head Units or CHU's). Important for the subjects presented here is the fact that the telescope pointing can be determined with very high (sub arcsecond) accuracy using a CHU aligned with the telescope. The linking between the μASC and telescope is also described in [5].

One of the major achievements for such a mission is the possibility - with limited on-board resources e.g. a single telescope - to detect and classify autonomously and fast all the encountered objects and, in particular, to determine the orbital elements. This poses several challenges. On the one hand the aperture problem makes it impossible to distinguish between large-far-fast and small-close-slow objects without prolonged, dedicated tracking. On the other hand the use of the telescope precludes the allocation to such dedicated range-to-target tracking, since the telescope shall be focused on tracking the most interesting targets accessible at any given time. Thus a rapid distinction between the two classes of objects is needed to determine the future observation program of an object shortly after detection. A small object, say in the meter, class may be detected, ranged, spectrally classified and excluded from further science processing. This will allow the main telescope to focus on the more interesting objects in range. This process can be handled fully autonomously with a very high level of robustness.

Basically two solutions, which enable a rapid distinction between the two classes of objects, exist. First, a direct range measurement using a laser ranger. Second, a passive range measurement by triangulation. Each method has distinct advantages and limitations, which must be weighed against the specific mission requirements.

In addition to the rapid object class distinction, the laser ranger may be used together with nano-gravity-probes for direct mass estimations of selected target asteroids.

The following sections describe these methods.

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LASER RANGING

Laser ranging systems for space use developed until now, have mainly focused on two applications: Lunar and satellite ranging and planetary surface mapping. For the first application, the systems are ground-based, large and the power consumption is high. In addition the targets are mostly cooperative, i.e. carrying a reflector of some kind. The second application works with non-cooperative targets. These systems provide relatively short-range (approx 500km) good accuracy and are small enough to fly on a spacecraft. Both types of rangers have typical accuracies is in the cm to m range per shot. For an asteroid and NEO mapping mission like Bering the limiting range for non-cooperative targets must be increased to at least 10.000km in order to be useful.

Therefore, existing laser rangers fall in two main classes of "non-suitability":

a) Too big and too power hungry to be installed onboard a spacecraft.

b) Limiting range too short for the foreseen use.

At the Technical University of Denmark, the MIS (Measurement & Instrumentation Systems) Section has developed a laser ranging system that through optimization exhibit substantial advantages over similar designs used on spacecraft so far.

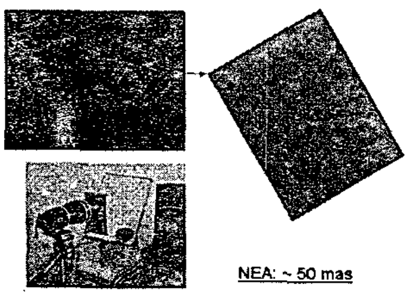

***Fig. 1:** A 250 mm telescope co-aligned with a CHU. Using the ASCfit algorithm, the attitude of the telescope was measures with a Noise Equivalent Angle (NEA) of 50 mas.*

Combining the laser ranger with a telescope and a star tracker, two major improvements are achieved. First, the telescope provide accurate beam pointing, thus minimizing the pulse widening from slant angles. Second, very small target spot sizes are achievable. The prototype design and preliminary performance tests of the laser ranger have been carried out and are described in the following.

Consider the situation depicted in figure 1, where a telescope and a CHU are pointed towards the same portion of the night-sky. After the telescope has been calibrated relative to the CHU as described in [5], the stars in the telescope field of view (FOV) are easily identified using e.g. the ASCfit SW package [6]. Since the stars in the telescope FOV are now identified, the actual pointing direction of the telescope can be calculated with very high accuracy by matching the stars observed by the telescope with a deeper catalog than the one used by the star tracker.

In theory the accuracy is improved with the ratio between the telescope focal length to the CHU focal length. In practice, the photon noise will limit the improvement. For the shown setup, we measured a pointing accuracy of 0.9" RMS the CHU, and 0.1" RMS for the telescope, i.e. an improvement of only 9 times despite of the focal length ratio was 12.5.

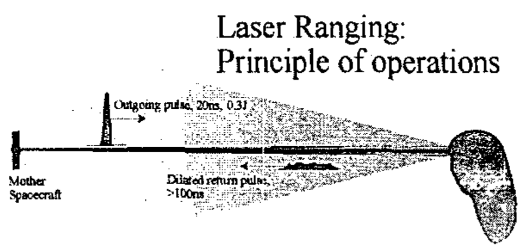

***Fig. 2:** The principle of operations of a laser ranger. The time of flight of a powerful laser pulse is measured from emission until its reflection form the target is received.*

Using the same philosophy, an μASC guided telescope can be utilized to increase the useful range of laser rangers substantially for small target applications. Consider a laser ranger that will have to hit relatively distant asteroid targets. With a typical target size in the range of 100m, the angle subtended at the limit of present space borne laser rangers of 500-1000km will only be 20-40 arc seconds. The basic problem using laser rangers at longer distances for smaller targets is that the beam has to be fairly divergent to ensure that the target is hit at all. Since laser rangers operate photon count limited at the far range, this problem sets an efficient limit on the achievable range.

However, if a telescope is guided by an μASC, to point at the asteroid, and the outgoing laser pulse is routed through the telescope, a very small beam divergence can be achieved due to the large exit beam size. The method has the additional benefit that the telescope entrance pupil is optimal for receiving the faint return beam. A further improvement comes from the precise detector masking that can be achieved because of the co-boresight alignment of the transmitter and receiver, by which the S/N of the receiver is dramatically increased.

Theoretical considerations regarding the number of photons, which can be detected, have been carried out using conservative worst-case approximations, e.g. NEO reflection properties (Lambertian surface, albedo of 0.15) and solar illumination conditions. These show that a S/N ratio of above 100 is achievable at distances as far as 40.000km.

The theoretical operational range of the above system is far superior to the existing space borne systems, as indicated in figure 3, where the expected signal to noise ratio for a 0.3m telescope system is shown.

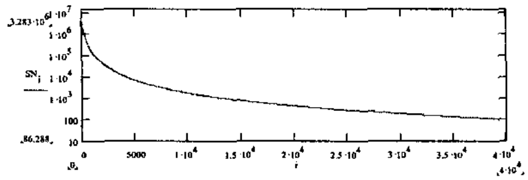

Fig. 3: Theoretical S/N ratio for the detected return pulse versus target distance.

To verify the operations of the above concept, a laboratory model, using a 1mJ laser pulse, and a 0.1m telescope was built [7]. Laboratory tests showed, that for the full system a 15.000km range is readily achievable.

The accuracy of the range measurement is basically dependent on the resolution of the measured travel-time. A resolution of 1ns is achievable leading to a range accuracy in the range of 0.3m.

The above range and accuracy is sufficient to discriminate between the two classes of objects mentioned in the introduction.. Also this accuracy is adequate to perform a course orbit determination of the observed target, which enables a later recognition of the target and, if possible, a tracking form Earth.

In addition to the rapid object class distinction, the laser ranger may be used for inter-spacecraft baseline measurements and in the processes of direct mass estimation of selected target asteroids as described below.

GRAVITY PROBES

For a number of interesting targets a direct measurement of the objects mass may be desirable. Such a measurement may be accomplished using nano gravity probes carrying corner-cube reflectors and weighing a few hundred grams. Onboard Bering, it is the plan to let these probes carry a miniature magnetometer as well. Such probes can reliably be ejected with appropriate speed towards the target asteroid where the gravitational pull of the asteroid will deflect the trajectory of the probe.

By continuous laser ranging and position determination of the probe, using the main telescope, the probe trajectory and hence the asteroid mass can be determined. Figure 4 shows the principle. The limiting factor in this determination is the accuracy with which the post encounter drift rate of the probe after deflection can be measured. Figure 5 shows the post encounter drift rate as a function of the relative velocity between asteroid and probe and the distance from the spacecraft and the probe. This is calculated assuming an impulse like deflection of the probe, which is a good assumption due to the relative high velocity between probe and target.

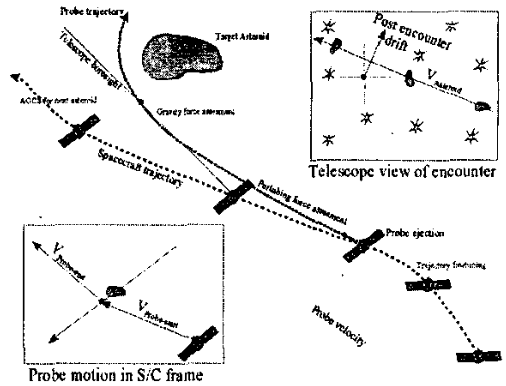

Fig. 4: Principle of mass estimation.

Angular drift-rates of 1-10mas/day will be observable when performing high accuracy astrometry on the images taken with the science telescope. The principle has been demonstrated on ground with the ASCfit software package fitting astronomical coordinates to images using catalog information [5], [6]. It is expected that the relative accuracy on images with close to identical star patterns will be better than 10mas RMS per measurement. With a measurement time of 100 sec, 1mas is achievable within minutes. Averaging over observations covering several hours will further increase the accuracy.

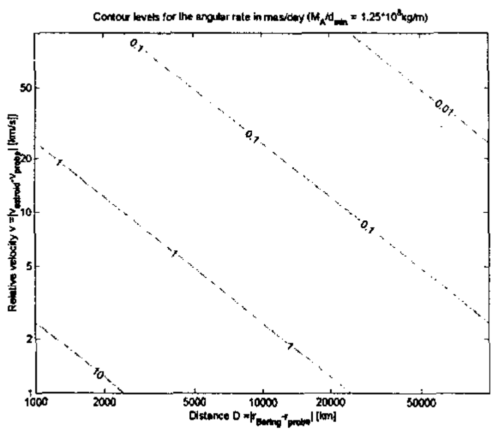

Fig. 5: Estimated post-encounter angular drift-rate.

Being able to fix the position of the probe to 10mas at a distance of 20.000km corresponds to a cross-line-of sight accuracy of 1m for the position of the probe relative to the Bering S/C. In the along line-of-sight a corresponding level of accuracy is expected from the laser ranger. Thus it will be possible to fix the probe position within a $1m^3$ error-box. Corresponding accuracy can be obtained for the asteroids that are luminous enough to be observed by the science telescope.

TRIANGULATION

The range measurement by triangulation can be done using a single spacecraft combined with Earth observations. However, Earth based observations impose severe limitations on range, size and position of the observable objects as well as harsh requirements to the available telescope time. Triangulation from two spacecrafts is far more versatile. Another benefit is, that the triangulation method basically only need the telescopes of the spacecrafts to be operating, wherefore this method also provide full redundancy to a large extent. Obviously, a number of tradeoffs have to be made between parameters such as detection volume, search time and range accuracy in order to obtain the optimum solution. These are all controlled by the inter spacecraft baseline length. The accuracy of the triangulation method is basically dependent on the accuracy of the direction-to-target measurement, which in turn depends of the target luminosity and proper motion. Finally, the accuracy also scales with length of the baseline.

For the triangulation it is important to note that the Bering spacecrafts will operate with two range scales. One scale is the detection range, which is the distance out to which the star trackers will be able to detect moving objects. This range depends on the magnitude and thus size of the target. The other is the tracking range, which is the distance out to which the science telescope will be able to track the targets once they have been found. This will also depend on the size of the target. The ratio of the detection to tracking range is approximately scales with the focal length ratio between the CHU and the telescope multiplied with a system dependant constant. For the planed Bering instrumentation this corresponds to a tracking to detection range ratio of t/d =25 times.

Two scenarios are possible for the triangulation from two spacecrafts: "close" and "far" formation flying. The two scenarios are depicted in figure 6.

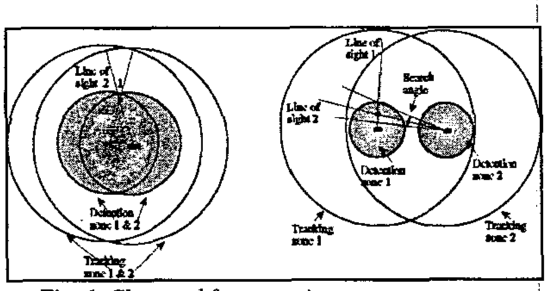

Fig. 6: Close and far scenarios.

The "close" scenario will feature a baseline of 10-20% of the detection radius of the individual spacecrafts thus ensuring a reliable simultaneous detection of targets by both spacecrafts and hence making a direct simultaneous triangulation with the science telescope possible at the first suitable opportunity. However such a formation will have a relatively limited detection volume.

Alternatively a "far" scenario will use detection from one of the Bering spacecrafts as basis for a search for the object being performed by the other S/C and visa versa. This search will be limited to the line of observation as determined by the S/C performing the detection. This approach will increase the detection volume, but will also imply an increase of the time being used by the telescope for the target search. Since the delta-V requirement to change between the two formation types is relatively small it could be considered to change between the two scenarios for dedicated observation campaigns.

The basic geometrical layout of the triangulation is depicted in figure 7. The observables are the baseline length (determined by laser or radio ranging) the inter S/C direction and the two measured directions to the target.

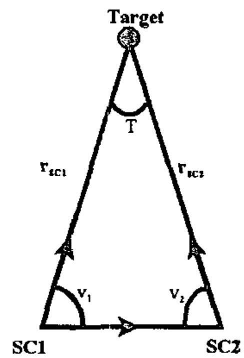

Fig. 7: Basic geometry for the triangulation.

Determining the angles v_1 and v_2 form the measured directions the basic equation of the ranges is:

$$\frac{\sin(T)}{b} = \frac{\sin(v_2)}{r_{SC1}} = \frac{\sin(v_1)}{r_{SC2}}$$

The range from SC1 to the target is thus

$$r_{SC1} = b\frac{\sin(v_2)}{\sin(T)}$$

Two parameters limit the maximum achievable range when using triangulation. The one is clearly the maximum tracking range of the telescope. However, since the star tracker has already detected the targets, this limitation never becomes active, as long as the triangulation is carried out relatively close to the initial detection point, i.e. before the relative motion deform the observation geometry too much. This is only a problem at the very "far" scenario, where the search time for the second S/C to move along the constraint line to also locate the target, may be too long.

Secondly, the target must be close enough that the difference in direction from the two S/C's to the target is observable. This scales with the baseline. Since the direction to the target can be determined with an accuracy of approximately 50mas, the ratio between the inter-spacecraft baseline and the distance to the target must be larger than:

$$\frac{b}{r} > a\tan\left(\frac{50*10^{-3}}{3600}\right) = 7.56*10^{-4}\,or$$

$$r < b*1257$$

For a typical baseline of 10.000 km this will correspond to an effective range of the triangulation of $12*10^6$ km. In this context it is worth noting, that the expected accuracy from directly measuring the distance to the other spacecraft using the laser ranger is 1m.

Since the maximum range is limited by the tracking range (t) and since the baseline (b) will be no smaller that 10% of the detection range (0.1d) maximum r/b is limited by

$$\frac{r}{b} < \frac{t}{0.1d} = 10\frac{t}{d}$$

This trivially fulfils the above restriction on r/b if t/d ratio is less than 125, which is indeed the case for Bering. It is noted that this limit on t/d increases as the baseline is increased.

ACHIEVABLE ACCURACY

The achievable accuracy intrinsically depends on the accuracy of the basic direction measurement and on the length of the baseline. For the geometry shown in figure 8 the accuracy in the range (along the line-of-sight) estimate as function of range, baseline and accuracy of target direction is:

$$\delta r_1 = r_2 \frac{\sin(\delta S_2)}{\sin(T)}$$

For the limiting range where T is small and $r_1 \approx r_2$, this reduces to:

$$\delta r_1 \approx r_1 \sin(\delta S_2)$$

For an angular accuracy of 50mas this corresponds to a relative accuracy of δr/r of $2.4*10^{-7}$ per sample. Again samples close in time may directly reduce this uncertainty with the square root of the number of samples.

The accuracy across the line of sight is determined by

$$\delta r_{1\perp} = r_1 * \tan(\delta S_1)$$

Which for small angle-uncertainties is basically the same as the along line-of-sight accuracy found above.

These accuracies are obviously not sufficient to generate reliable orbital elements, but far surpass the needs to ensure easy repetitions of observation, from Bering or from Earth.

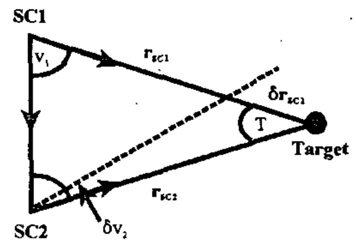

Fig. 8: Accuracy of the range estimate from triangulation.

CONCLUSIONS

For an autonomous deep space asteroid mission like Bering a fast ranging of the detected objects is necessary in order to determine the future observation strategy for the object. Two methods have been presented.

Firstly, the optimized laser ranger, which using the 0.3m science telescope and the μASC star tracker to obtain low beam divergence and highly accurate beam pointing, achieve a much increased effective range. Ground tests show reliable range detections out to 10.000km. The accuracy of such laser ranging is better that 1m.

The Laser ranger may also be used to follow nano gravity probes ejected form Bering to obtain direct mass estimates of selected targets.

Secondly, range determination by triangulation form the two Bering spacecraft have been evaluated with respect to the achievable maximum range and the associated rage accuracy. The controlling parameters for both are the baseline length and the accuracy of the pointing directions to the targets. It is found that maximum ranges up to $12*10^6$km are obtainable with relative accuracy better than $3*10^{-4}$.

The exact numbers will of cause depend on the final mission design, but the indications found here are very encouraging.

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