

# Capabilities of Furlable Solar Sails for Asteroid Proximity Operations

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Missions have been proposed in which a spacecraft equipped with a large furlable solar sail transfers to a main-belt asteroid using the fully deployed sail for propulsion and then performs an inspection mission at the asteroid with the sail fully stowed. This paper examines ways in which the partially deployed sail could instead be used to maneuver the spacecraft while in the vicinity of the asteroid, with the goal of improving the science observations that could be made. Methods are presented for quantifying the performance that can be obtained by taking advantage of the freedom to select the active sail area for two types of hovering problems: one in which the spacecraft is to maintain a fixed position in the rotating sun–asteroid frame and the other in which it is to maintain a fixed position relative to a landmark on the rotating asteroid surface. In both of these problems, the ability to adjust the active sail area greatly expands the range of locations at which the spacecraft can satisfy the specified hover conditions.

## Nomenclature

$A$	= solar sail area, $m^2$
$A(r), B(r), C(r)$	= acceleration component scalings in the heliostationary flight problem, $1/s^2$
$a, e, i, \Omega, \omega, M_o$	= classical elements of solar sail orbit about an asteroid, various units
$\mathbf{a}_g, \mathbf{a}_{des}, \mathbf{a}_{sail}$	= gravitational, desired, and solar sail acceleration vectors, $m/s^2$
$a_{max}$	= maximum achievable solar sail acceleration, $m/s^2$
$a_R, a_S, a_W$	= solar sail acceleration components expressed in the $RSW$ orbital frame, $m/s^2$
$a_{sail}$	= magnitude of solar radiation pressure acceleration on the sail, $m/s^2$
$m$	= solar sail spacecraft mass, kg
$n$	= solar sail orbit mean motion, $rad/s$
$p$	= solar radiation pressure, $N/m^2$
$p_E$	= solar radiation pressure in the vicinity of the Earth, $4.56 \times 10^{-6} N/m^2$
$q_{bc}$	= variation-of-parameters influence coefficient for variable $b$ from acceleration component $c$ , various units
$R_{AU}$	= distance of the asteroid from the sun, astronomical units
$r_{ast}$	= asteroid radius, m
$r_L$	= asteroid $L_1/L_2$ libration point radius, m
$r_{pole}$	= radius lower limit on the polar segment of the heliostationary flight solution, m
$r_{sync}$	= asteroid synchronous orbit, or resonance, radius, m

$r_1, r_2$	= lower and upper limits on solution radii for the heliostationary flight problem, m
$\hat{s}$	= unit vector directed from the sun to the asteroid, dimensionless
$u$	= solar sail orbit argument of latitude, rad
$x, y, z$	= relative orbital position components expressed in the $RSW$ orbital frame, m
$x_1, x_2$	= modified asteroid libration point radii for the solar sail, m
$\alpha$	= angle between sail normal and sun line (i.e., sail cone angle), rad
$\gamma$	= solar sail viewing angle of the illuminated asteroid hemisphere, rad
$\delta_1, \delta_2$	= measures of difficulty for the body-fixed hovering problem, $m^3/s^2$
$\lambda$	= latitude of sail target point on the asteroid, rad
$\theta$	= asteroid longitude, rad
$\eta$	= solar sail efficiency factor, dimensionless
$\mu_{ast}$	= gravitational parameter of the asteroid, $m^3/s^2$
$\nu$	= solar sail orbit mean true anomaly, rad
$\varphi$	= solar latitude, perpendicular angle between the sun line and equatorial plane of the asteroid, rad
$\psi$	= solar sail clock angle, rad
$\omega_{ast}$	= rotation rate of the asteroid, $rad/s$

## Introduction

THE NASA Autonomous Nano-Technology Swarm (ANTS) concept [1,2] is based on the use of swarms of very small spacecraft (nominally 1 kg picosatellites) equipped with large segmented solar sails [3] (nominally with a fully exposed area of  $100 m^2$ ). One key mission that has been proposed for ANTS is the Prospecting Asteroid Mission. The high area-to-mass ratio of these designs leads to flight times from Earth to the main belt [4] on the order of 2.5 years, with these trajectories well defined from previous studies. However, how best to exploit the solar force that acts on the sail once the spacecraft is operating in the vicinity of an asteroid is not so clear. This question served as motivation for the work that is described in this paper.

Three possible goals will be considered, the first being general orbital adjustments. These would occur, for instance, if the spacecraft were to be transferred from an equatorial to a polar orbit or if the orbit were to be circularized. It is shown that a spacecraft such as ANTS would be capable of very rapid orbit changes of this type.

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