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Design of Solar Sail Trajectories with Applications to Lunar South Pole Coverage

M. T. Ozimek,* D. J. Grebow,* and K. C. Howell†
Purdue University, West Lafayette, Indiana 47907-2045

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Potential orbits for continuous surveillance of the lunar south pole with just one spacecraft and a solar sail are investigated. Displaced periodic orbits are first computed in the Earth–moon restricted three-body problem, using Hermite–Simpson and seventh-degree Gauss–Lobatto collocation schemes. The schemes are easily adapted to include path constraints favorable for lunar south pole coverage. The methods are robust, generating a control history and a nearby solution with little information required for an initial guess. Five solutions of interest are identified and, using collocation, transitioned to the full ephemeris model (including the actual sun-to-spacecraft line and lunar librations). Of the options investigated, orbits near the Earth–moon L_2 point yield the best coverage results. Propellant-free transfers from a geosynchronous transfer orbit to the coverage orbits are also computed. A steering law is discussed and refined by the collocation methods. The study indicates that solar sails remain an option for constant lunar south pole coverage.

Nomenclature

a = altitude from the lunar south pole
$\boldsymbol{a}$ = sail acceleration vector
$\boldsymbol{DF}$ = Jacobian matrix
E = two-body energy with respect to Earth
$\boldsymbol{F}$ = full constraint vector
$\boldsymbol{g}_i$ = path constraint vector
H = two-body angular momentum with respect to Earth
h_k = general node states and/or control constraint
$\boldsymbol{\kappa}$ = characteristic acceleration
$\boldsymbol{l}$ = sun-to-spacecraft unit vector
n = number of nodes
$\boldsymbol{R}$, $\boldsymbol{V}$ = position and velocity vectors, Earth mean equator of J2000 inertial frame
$\boldsymbol{r}$, $\boldsymbol{v}$ = position and velocity vectors, Earth–moon rotating frame
T_i = segment time
t = time
U = potential function
$\boldsymbol{u}$ = control variable vector
$\boldsymbol{X}$ = total design variable vector
$\boldsymbol{x}$ = state variable vector
α = sail pitch angle
$\boldsymbol{\Delta}_i$ = defect vector
δ = sail clock angle
ϕ = elevation angle from the lunar south pole
ψ_i = control-magnitude constraint
ω_s = angular rate of sun, Earth–moon rotating frame

I. Introduction

COMMUNICATIONS satellites are an important component of long-duration autonomous surveillance and manned exploration of the lunar south pole. Generally, studies have been focused on deployment of at least two spacecraft for complete coverage. One solution approach involves constellations of primarily low-altitude elliptically inclined lunar orbits, for which the Earth gravity and lunar spherical harmonics are included as perturbations to a predominately two-body problem. By averaging, the variations in orbital eccentricity, argument of periapsis, and inclination are eliminated, resulting in the well-known frozen orbits [1]. According to Ely [2], a lunar constellation of three spacecraft can be assembled in which two vehicles are always in view from the lunar surface for the polar regions. Additional long-term numerical simulations confirm that constant coverage can be achieved with two spacecraft in similar low-altitude elliptically inclined lunar orbits [3]. Alternatively, the problem might be approached from a multibody investigation of libration-point orbits. For example, Grebow et al. [4] demonstrated that constant communications can be achieved with two spacecraft in many different combinations of Earth–moon libration-point orbits. Low-thrust transfers to these orbits were later computed by Howell and Ozimek [5]. These two approaches (namely, frozen orbits and multibody orbits) were later compared by Hamera et al. [6]. Grebow et al. [4] also proposed adapting the north and south Earth pole-sitter concept from NASA's Living with a Star program to the moon for possible south pole architectures [4,7]. In fact, NASA engineers have previously considered the use of solar sails for constant surveillance of the atmosphere over the north and south poles of the Earth [8]. If such solar sail orbits exist near the lunar south pole, then only one spacecraft would be necessary to maintain continuous coverage.

The concept of practical solar sailing was introduced as early as the 1920s, according to the writings of the Soviet pioneer Tsiolkovsky and his colleague Tsander, as described in [9]. Following a proposal by Garwin of IBM Watson Laboratory at Columbia University in 1958, who coined the term *solar sailing*, more detailed studies of solar sailing ensued in the later 1950s and the 1960s. Aided in part by mission applications envisioned by prominent science-fiction authors [10], serious investigations have continued. In 1967, Vonbun [11] proposed an interesting and relevant mission concept using low-thrust propulsion, not for transporting a spacecraft, but to maintain a stationary position at the Earth–moon L_2 point. From 1976–1978, NASA initiated the first major mission design study incorporating a solar sail to rendezvous with Halley's comet. In 1991, Forward [12] proposed *statites* that would employ solar radiation pressure to levitate in non-Keplerian trajectories. Forward also proposed *polestats* (i.e., statites that hover above the polar regions of the Earth). These applications resemble Vonbun's [11] hummingbird concept, but rely specifically on a solar sail for propulsion. Solar sails were also previously identified as one of five technological capabilities under consideration in NASA's Millennium Space Technology 9 (ST-9) mission. Proposals for ST-9 have included solar sails that produce

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*Ph.D. Candidate, School of Aeronautics and Astronautics, Armstrong Hall of Engineering, 701 West Stadium Avenue. Student Member AIAA.

†Hsu Lo Professor, School of Aeronautics and Astronautics, Armstrong Hall of Engineering, 701 West Stadium Avenue. Associate Fellow AIAA.