JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 46, No. 5, September–October 2009

Review of Options for Autonomous Cislunar Navigation

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DOI: 10.2514/1.42819

During the early days of spaceflight, and especially during the Apollo program, significant advances were made in developing methods for navigation in cislunar space. Since then, new technologies and new data processing methods have been created that enable navigation options that were not available during the Apollo era. There are also new requirements associated with NASA's Constellation Program and the Orion spacecraft. Therefore, as NASA prepares to return to the moon, it is instructive to review the options, both new and old, available for cislunar navigation. By comparing the sometimes forgotten techniques used in the early days with the familiar techniques used on modern spacecraft, it is possible to make a more informed selection of the best navigation solutions for future missions to the moon.

Nomenclature

a = orbit semimajor axis, km
b = measurement bias
c = speed of light, km/s
d_a = apparent diameter, rad
E = eccentric anomaly, rad
e = orbit eccentricity
f = flux
h_{star} = apparent lunar altitude of reference star, km
I = ionosphere delay, km
m = apparent magnitude
$\mathbf{n}_{\text{star}}$ = unit vector in direction of reference star (no error sources)
$\hat{\mathbf{n}}_{\text{star}}$ = unit vector in direction of reference star (with error sources)
PR = pseudorange, km
R = geometric range, km
R_p = radius of planet/moon, km
$\mathbf{r}$ = position vector of spacecraft, km
$\mathbf{r}_{\text{SF}}$ = position vector to surface feature, km
T = troposphere delay, km
$\mathbf{T}$ = rotation matrix
t_{SC} = time of arrival of pulse from pulsar at spacecraft, s
t_{SSB} = time of arrival of pulse from pulsar at solar system barycenter, s
δR_p = error in radius of planet, km
ϵ = measurement error
η = error (vector) in knowledge of the location of a surface feature, km
ν = true anomaly, rad
ξ = angular measurement between a surface feature and a reference star, rad
ρ = range, km
τ = error in the measured time of arrival of pulse from pulsar at spacecraft, s
τ_{SSB} = error in the predicted time of arrival of pulse from pulsar at spacecraft, s
φ = angle between lunar periapsis and projection of antistar direction, rad

I. Introduction

THE increased interest in the moon as a target for robotic and human exploration gives rise to a need for precise orbit determination in cislunar space. The cislunar transfer phase is critical for many mission types and scenarios. For example, precise position knowledge is necessary for a crewed return from the moon due to entry, descent, and landing (EDL) requirements that constrain the spacecraft's position, velocity, and attitude at entry interface [1].

During operations in low Earth orbit (LEO), the data required for navigation may be obtained through traditional spacecraft navigation methods, such as an onboard Global Positioning System (GPS) receiver or radiometric tracking. As the distance between the spacecraft and Earth increases, some of the methods used in LEO become problematic due to design (e.g., GPS signals are designed to transmit toward the Earth) and/or poor geometry. To address this difficulty, past spacecraft operating in cislunar space (e.g., Ranger [2], Lunar Prospector [3], and Apollo [4]) have employed a combination of inertial measurements and inertial state updates from ground tracking. Traditionally, three-axis accelerometers and gyros are used to propagate the state (dead reckoning) between inertial state updates provided from an external source. Between these updates, the integrated solution will drift. The difficulty here lies primarily with the accelerometers and the associated estimate of the spacecraft position; the gyros may be inertially updated using onboard star trackers.

Consider the navigation system for NASA's Orion vehicle [5], the spacecraft expected to return humans to the moon, as a motivating example. For this type of mission, the traditional ground tracking approach (radiometric tracking with up-linked state estimates) is no longer adequate due to the desire for the Orion vehicle to be capable of an autonomous lunar return [6]. Because external updates are required to prevent the dead reckoning state estimate from drifting too far from the true state, autonomous cislunar navigation requires the vehicle to be capable of onboard inertial navigation updates.

The objective of the present research is to investigate navigation solutions that would enable a spacecraft to autonomously navigate in cislunar space. Specifically, the focus is on navigation in the cislunar regime, not in LEO or in low lunar orbit (LLO). Throughout the following discussion, the phrase "autonomous navigation" refers to navigation without contact with Earth. In the case of the Orion example, such a system would permit the safe autonomous return of the Orion vehicle from the moon in the event of a communication system failure.

Note that many of the navigation techniques presented here are not new. What is new, however, are some of the considerations related to implementation in the cislunar regime and the presentation of all of

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Presented as Paper 7265 at the AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, HI, 18–21 August 2008; received 17 December 2008; revision received 3 June 2009; accepted for publication 14 June 2009.

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