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ScienceDirect

Advances in Space Research 57 (2016) 1515–1527

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Optical tracking of deep-space spacecraft in Halo L2 orbits and beyond: The Gaia mission as a pilot case ☆

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Received 17 July 2015; received in revised form 3 December 2015; accepted 5 January 2016
Available online 12 January 2016

Abstract

We tackle the problem of accurate optical tracking of distant man-made probes, on Halo orbit around the Earth–Sun libration point L2 and beyond, along interplanetary transfers. The improved performance of on-target tracking, especially when observing with small-class telescopes is assessed providing a general estimate of the expected S/N ratio in spacecraft detection. The on-going GAIA mission is taken as a pilot case for our analysis, reporting on fresh literature and original optical photometry and astrometric results.

The probe has been located, along its projected nominal path, with quite high precision, within $0.13_{\pm 0.09}$ arcsec, or $0.9_{\pm 0.6}$ km. Spacecraft color appears to be red, with $(V - R_c) = 1.1_{\pm 0.2}$ and a bolometric correction to the R_c band of $(\mathrm{Bol} - R_c) = -1.1_{\pm 0.2}$. The apparent magnitude, $R_c = 20.8_{\pm 0.2}$, is much fainter than originally expected. These features lead to suggest a lower limit for the Bond albedo $\alpha = 0.11_{\pm 0.05}$ and confirm that incident Sun light is strongly reddened by GAIA through its on-board MLI blankets covering the solar shield.

Relying on the GAIA figures, we found that VLT-class telescopes could yet be able to probe distant spacecraft heading Mars, up to 30 million km away, while a broader optical coverage of the forthcoming missions to Venus and Mars could be envisaged, providing to deal with space vehicles of minimum effective area $\mathcal{A} \geqslant 10^6$ cm^2. In addition to L2 surveys, 2 m-class telescopes could also effectively flank standard radar-ranging techniques in deep-space probe tracking along Earth's gravity-assist maneuvers for interplanetary missions.

Keywords: Space vehicles; Techniques: high angular resolution; Astrometry and celestial mechanics; Techniques: photometric

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1. Introduction

The exploitation of the Sun–Earth Lagrangian points, especially L1 and L2, along the Sun–Earth direction (Farquhar and Kamel, 1973; Nariai, 1975; Rawal, 1991; Farquhar et al., 2002) has been an extraordinary challenge for space exploration in the recent years. For their particular position, some $1.5 10^6$ km away, on opposite sides of Earth and therefore well beyond the Moon, both locations are ideal lookouts for astrophysical observatories aimed at studying the Sun (L1) and the deep Universe (L2), far from any anthropic contamination. The L2 point, in particular, has been hosting a number of important astrophysical missions, starting with the WMAP, PLANCK and HERSCHEL probes, and currently continuing with the GAIA mission, aimed at performing an exhaustive census of the Milky Way stellar population (de Bruijne, 2012; Cacciari, 2015). Following GAIA, other major space facilities are planned to be located in a so-called Halo L2 orbit in the forthcoming years. These include the James-Webb Space Telescope (JWST; Gardner et al., 2006), the EUCLID cosmological

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☆ Based on observations collected at the Cassini Telescope of the Loiano Observatory, Italy.

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http://dx.doi.org/10.1016/j.asr.2016.01.003

probe (Laureijs et al., 2010), and the Athena X-ray observatory (Barret et al., 2013).

Optical ground tracking is yet of recognized importance for any L2 mission. For the co-rotating orbit to be maintained within its nominal figures, in fact, we need to carefully check spacecraft during its course along a complex Lissajous trajectory, as seen from Earth (e.g. Bray and Gouclas, 1967; Zagouras and Markellos, 1985;Liu et al., 2007; Kolemen et al., 2012; Dutt and Sharma, 2011; Qiao et al., 2014). This is also of special interest for any space observatory (like Gaia, or the next Jwst) as its absolute inertial position is required with exquisite precision to allow, for instance, a confident measure of astronomical parallaxes of distant stars with the on-board instruments. In this regard, radar-ranging techniques may actually provide a better measurement of spacecraft distance and radial velocity (Imbriale, 2003), but telescope observations, from their side, take advantage of a superior angular resolution, providing in principle more accurate astrometry and finer proper motion estimates (Altmann et al., 2011).

Compared to the observation of near-Earth satellites, however, optical tracking of distant probes, in L2 and on route to even farther interplanetary distances, has to deal with much fainter target magnitudes, a drawback that urges a substantial improvement in terms of telescope skills and especially of observing techniques to effectively assess our deep-space situational awareness (e.g. Mooney et al., 2006; Ruprecht et al., 2014; Woods et al., 2014).

In this contribution we want therefore to briefly assess some technical issues (Section 2) dealing with accurate ground tracking of deep-space probes at optical wavelength, taking fresh observations of the Gaia spacecraft (Section 3) as a pilot case for tuning up our theoretical analysis. The relevant photometric figures for Gaia will constrain the required telescope performance, for the optical observations to consistently complement standard radar-tracking techniques as in the forthcoming space missions to Mars and other planets of the solar system (Section 4). Our conclusions will be briefly stressed in Section 5.

2. Apparent magnitude of distant spacecraft

Depending on its physical properties, a satellite under solar illumination reflects a fraction α (the so-called Bond albedo) of the incident flux. The remaining fraction of the input energy is retained and heats the body up to an equilibrium temperature that leads to a balance between the absorbed and re-emitted flux. At Earth's heliocentric distance, this temperature cannot exceed 120 °C (e.g. Gilmore, 2002), so that thermal emission of spacecraft in the terrestrial neighborhood (and beyond) is only relevant at mid/far-infrared wavelength.

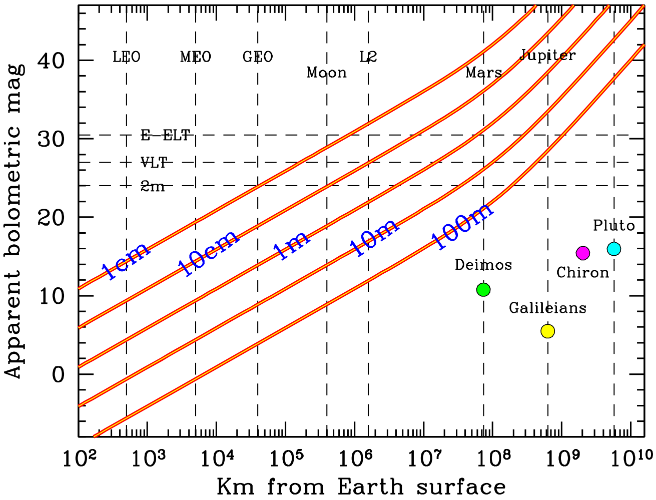

Fig. 1. The apparent bolometric magnitude for man-made spacecraft at increasing distance from Earth, according to Eq. (2). Probe scale-size is labeled along each curve. The altitude of LEO (set to 500 km), MEO (5000 km) and GEO terrestrial orbits is marked, together with a few small bodies in the Solar System and their reference interplanetary distances at Earth's opposition. The limiting magnitude reached by a 2 m mid-class telescope, the 8 m ESO VLT and the forthcoming 40 m E-ELT telescope, when observing distant Sun-type stars, is also sketched on the plot.

If a probe offers a cross-section s^2 to Sun's light, being s its reference scale-size, and if we assume the illuminated body to reflect isotropically, then the apparent bolometric magnitude of a spacecraft placed at a distance d from Earth's surface (at Sun's opposition)[1] simply scales as the ratio of the incident solar flux at Earth and at the spacecraft distance, so that

$$m_{\rm bol} - m_\odot^{\rm bol} = -2.5 \log \left[\left(\frac{D_\odot}{D_\odot + d} \right)^2 \left(\frac{s^2}{4\pi d^2} \right) \right], \tag{1}$$

where $D_\odot = 1.49\,10^{13}$ cm is the astronomical unit (AU) and $m_\odot^{\rm bol} = -26.85$ is the apparent bolometric magnitude of the Sun, as seen from Earth (e.g. Karttunen et al., 1996). With the relevant substitutions, and expressing the spacecraft distance $u = d/D_\odot$ in AU, Eq. (1) takes the form:

$$m_{\rm bol} = -5 \log s + 5 \log[u\,(1+u)] + k, \tag{2}$$

where the numerical constant is

$$k = 2.5 \log(4\pi D_\odot^2) + m_\odot^{\rm bol} = 41.77, \tag{3}$$

providing the satellite scale-size s is set in cm.

In Fig. 1 we report an illustrative summary of the expected bolometric magnitude for distant man-made probes of different characteristic size, compared with a few small planetary bodies. Just as a guideline, the limiting magnitude as for observing Sun-type stars, reached by mid-class (2 m aperture) and new-generation telescopes (i.e. the ESO 8 m VLT and the forthcoming 40 m E-ELT) is also marked on the plot.

As a fraction $(1-\alpha)$ of the incident solar flux is "diverted" into the infrared, to convert the bolometric figures to other broad-band *optical* magnitudes, say for

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[1] Although, strictly speaking, d is a topocentric distance, to all extent, for a distant spacecraft in L2 and beyond, it basically coincides with the geocentric distance, as well.