TRAJECTORY DESIGN FROM GTO TO NEAR-EQUATORIAL LUNAR ORBIT FOR THE DARK AGES RADIO EXPLORER (DARE) SPACECRAFT

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The trajectory design for the Dark Ages Radio Explorer (DARE) mission concept involves dropping the DARE spacecraft off in a generalized geosynchronous transfer orbit (GTO) as a secondary payload. From GTO, the spacecraft is then required to enter a near-equatorial lunar orbit that is stable (i.e., no station-keeping maneuvers are required) and yields the required number of cumulative hours (1,000) for science measurements while in the lunar farside radio quiet cone over a span of three years. Preliminary and expected results of the corresponding trajectory design are presented herein.

PRELIMINARY AND EXPECTED RESULTS

The goal of the proposed paper is to show that the Dark Ages Radio Explorer (DARE) spacecraft can ride as a secondary payload to geosynchronous transfer orbit (GTO) and reach the required near-equatorial circular science orbit around the Moon. The DARE mission is currently in the concept development phase with partners including NASA Ames Research Center (ARC), the University of Colorado Boulder, and Ball Aerospace and Technologies Corporation. The reason why the DARE spacecraft will plan to enter lunar orbit is so that it can observe away from the Moon's surface into the Dark Ages while in a unique radio-quite zone shielded from noise and other interference. Preliminary details and expected results are presented herein.

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Radio-Quiet Region Definition

The concept of a radio-quiet region has a significant role for radio astronomy. The interferences that man made radio-emissions create in our environment yield huge challenges for the observation of determined frequency spectrums. A high resolution is needed to address important challenges in the fields of astrophysics and cosmology. Several studies have characterized and defined the existence of a place in the solar system that is free of radio interference from any local source; Maccone et al.[1, 2] stipulated in various publications the characteristics of a radio-quiet zone located on the farside of the Moon. This region is extended above the surface, forming a cone that is free of major interferences on its interior. It is this lunar farside cone that is of interest to the DARE spacecraft, which will look at frequencies in the 40-120 MHz range and will thus need to be shielded from any noise in this range in order to study the 21 cm signal and resolve the turning points during the Dark Ages[3].

This location is very unique in the Solar System since the Moon acts as a shield not only from the emissions that come from Earth but also from the Sun. Radio-emissions from potential solar bursts and other solar activity can be a serious threat for DARE's required science observation. It was also necessary to account for emissions from the GEO belt and diffraction effects produced by the spherical shape of the Moon during wave propagation. Figure 1 shows a representation of two separate radio quiet cones calculated by considering the emissions from both the Sun and the Earth. As it appears in the image, the full radio quiet region is located only within the intersection between these two cones. It is only when the DARE spacecraft is located in this radio-quiet region that science observation are permitted.

After the geometric and physical calculation of the cone shapes, the Analytical Graphics Inc. (AGI) Systems Tool Kit (STK) was used to generate a computer based model that calculated the time that the spacecraft was in the radio-quiet region. DARE orbital dynamics were performing high-fidelity propagation of the lunar orbit. Specifically, the STK model utilized a High Precision Orbit Propagator (HPOP) based on the LP150Q lunar gravity model. In order to improve the accuracy, the order and degree chosen were both 70, with the addition of third body perturbations from the Earth and the Sun as well as solar radiation pressure. The movement of the radio quiet cones at every time during the simulations was computed by an external propagator. A set of rotating coordinates was used to account for Earth and Sun orbital movement and to locate the apex of both cones to be shielded at any time from their respective parent bodies.

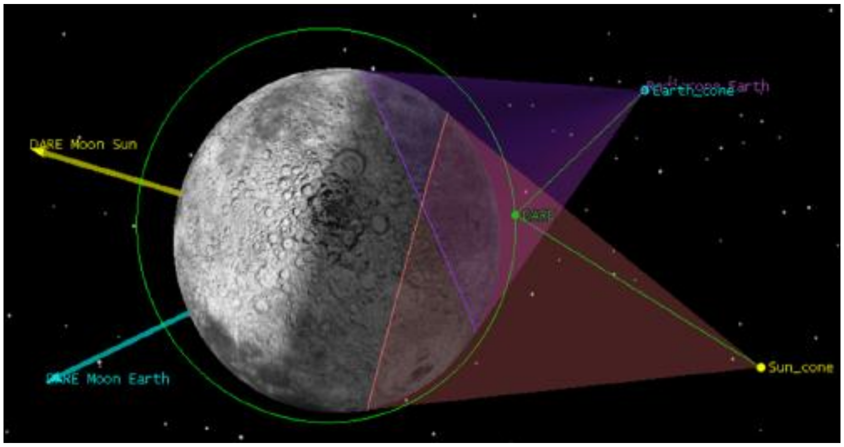

Figure 1. Radio-Quiet Region shown as intersection between Earth and Sun cones on Lunar Farside.

Lunar Orbit Altitude and Inclination

In 2005, Ramanan & Adimurthy[4] studied the impact of inclination on the orbital lifetime of low altitude lunar orbits. In our study we were able to characterize equivalent inclination windows that create instability in the spacecraft orbit. These unstable windows are located above regions of large mass concentrations (or mascons) within the Moon's crust, seen in Fig. 2 which plots the minimum perilune altitude of a 200 km circular orbit after two years of high-fidelity propagation for all lunar orbit inclination values.

The DARE mission requires the spacecraft to obtain a total integration time of at least 1,000 hours (plus contingency) in the radio-quiet region while maintaining a minimum perilune altitude above 40 km throughout a three year science mission duration. In addition, the orbit has to be reached with the limited spacecraft ΔV budget as a secondary payload orbiting the Earth significantly inclined to the lunar equatorial plane. An extensive study was performed to calculate an orbit that could provide the required science time while complying with stability and ΔV requirements for the DARE spacecraft. The study showed that an orbit of 125 km at inclinations between 24.5 and 28 degrees comply with the requirements of maintaining at least a 40 km minimum perilune altitude and obtaining at least 1,000 hours (plus contingency) in the radio-quiet region for all values of right ascension of the ascending node (RAAN). Evidence to support this statement is found in Fig. 3a and 3b.

Retrograde lunar orbits are also analyzed in Fig. 3c and 3d. Although these orbits were only analyzed for 2.5 year of science duration (not the nominal three years), it is quite clear that such orbits are far less stable than their posigrade counterparts. As it stands, no retrograde inclinations are acceptable for DARE's science orbit, but a small acceptable inclination range around 153 degrees may be acceptable after extending the analysis to three years. For simplicity, this study will focus on acceptable posigrade inclinations between 24.5 and 28 degrees, with 26 degrees designated as the nominal science orbit inclination for discussion purposes.

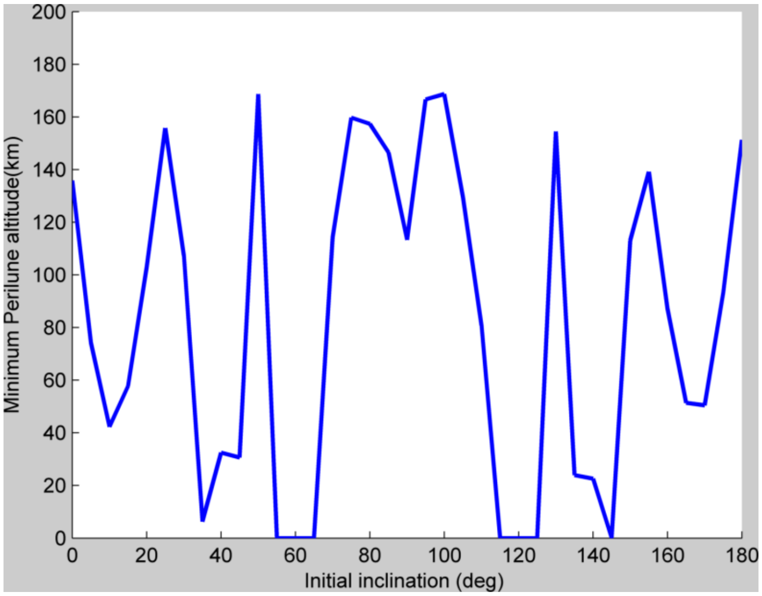

Figure 2. Minimum Perilune Altitude vs. Lunar Orbit Inclination for an initially circular lunar orbit at 200 km altitude with RAAN set to zero.

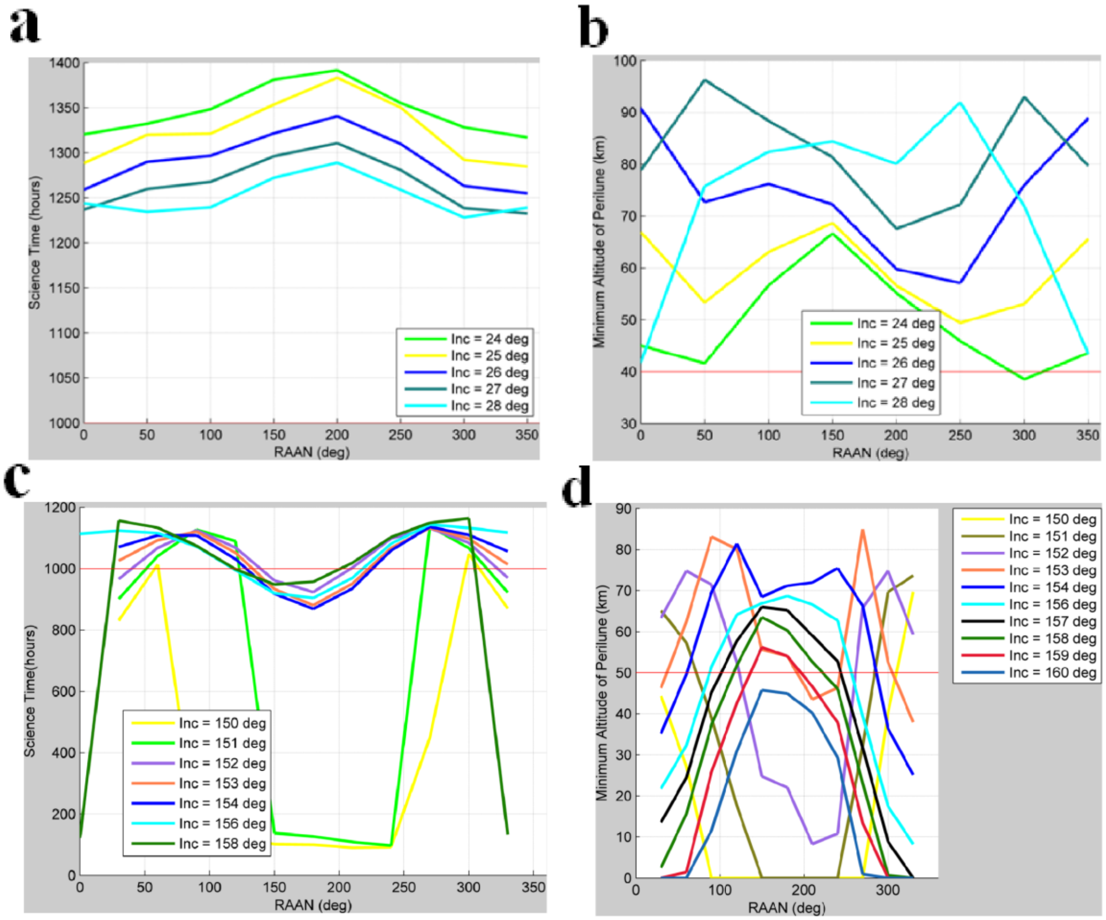

Figure 3. Orbit Inclination and Stability with regard to time spent in the Radio-Quiet Region.

Nominal Trajectory Design and Analysis

The orientation of the initial orbit (GTO) must be discussed before designing the nominal trajectory. Qauntus et al.[5] support the use of the Ariane V launch vehicle since its standard launch times for possible GTO payload are seen in Fig. 4a, with a favorable perigee located in Earth's shadow after launch. Additionally, the local launch times of historical launches to GEO (via GTO) are seen in Fig. 4b, with two clusters of data forming near local times of midnight and 6pm. The latter is equivalent to 10pm or 11pm UTC (depending on the time of year) and thus 10:30pm UTC is chosen as the baseline launch time for the DARE spacecraft. (It is of note that a preliminary analysis has been performed for a launch at any time of a single day, with results indicating higher total ΔV requirements upon initial lunar encounter.)

Fortunately, having the orbit perigee in Earth's shadow allows the apogee to be located in a favorable Sun-Earth WSB quadrant with regard to returning to the Moon[6, 7]. Working with a spacecraft ΔV capability of 1,655 m/s, Sun-Earth WSB transfers from GTO to the Moon were computed for every day in a launch period from April 1 to October 1, 2020. The ΔV breakdown is seen in Fig. 5, where most values are below the current 1,655 m/s limit.

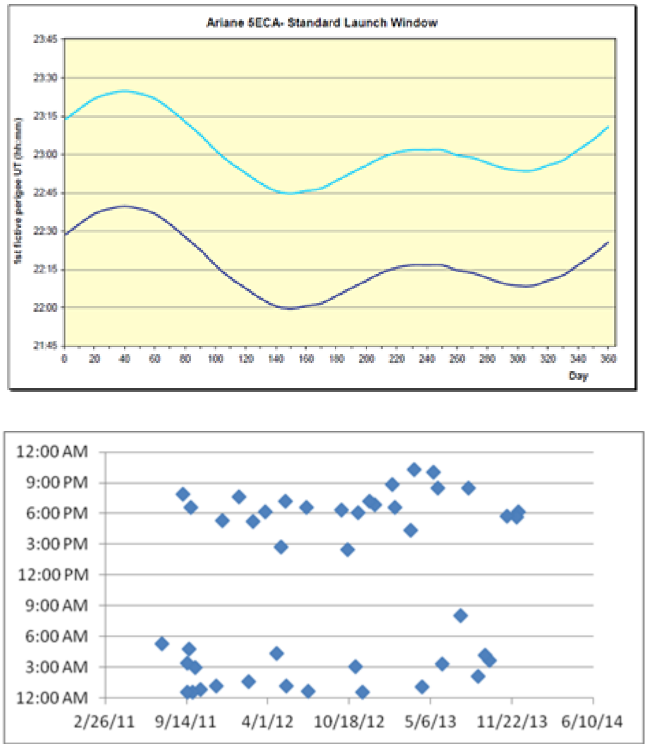

Figure 4. Local Launch Time of Payloads to GEO (via GTO) from mid-2011 to early 2014.

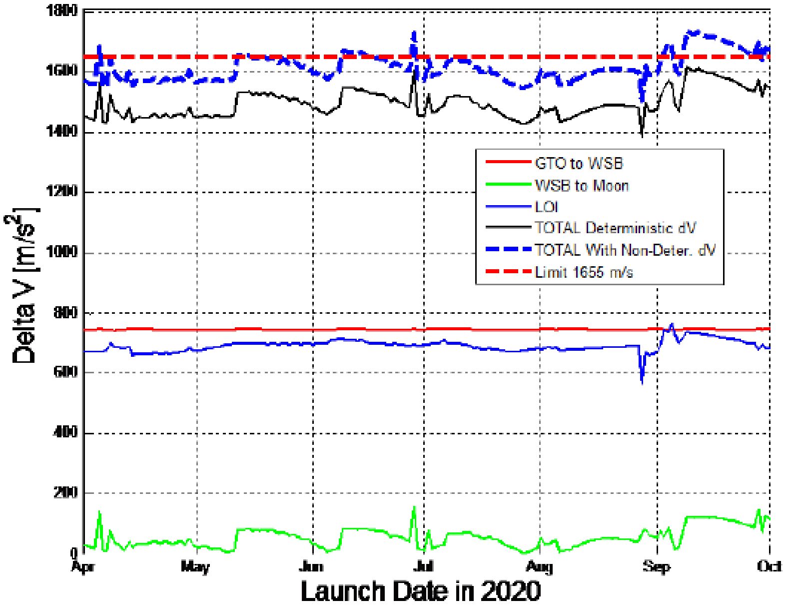

Figure 5. Breakdown of ΔV for Launch Dates between April 1 and October 1, 2020.

Unfortunately, many lunar return trajectories approach the Moon in orbit planes significantly inclined to the lunar equatorial plane (Fig. 6). Since the declination of the arrival asymptote (DAA) at the Moon is as high as about 75 deg (in magnitude), the lunar encounter is used as a flyby opportunity to change the orbital plane (not perform LOI) to allow the inclination range of 24.5 to 28 degrees to be achieved within the DARE spacecraft's ΔV budget. To demonstrate this design element, a lunar return case with |DAA| = 67 degrees is selected from Fig. 5, since the arrival at the Moon is nearly the steepest (i.e., |DAA| is close to the maximum 75 deg and thus requires the largest plane change to achieve an acceptable science orbit). For this case, launch occurs on May 8, 2020, where the spacecraft is dropped off in GTO (Fig. 7a, A). After incrementally raising apogee to escape the Van Allen radiation belts and phase with the Moon, the spacecraft would travel to an apogee (Fig. 7a, B) near the Sun-Earth WSB (1.4 million km from Earth in this case) and perform a maneuver ΔV of 30 m/s to target a 3,900 km altitude flyby "under" the lunar south pole on August 26, 2020 (Fig. 7a, C). Once in an acceptable orbital plane, the DARE spacecraft would wait in a 3:2 lunar resonance orbit and perform the LOI maneuver on October 16, 2020 (Fig. 7a, D and 7b). The total deterministic ΔV for this case is 1,512 m/s (1,632 m/s total, which is currently 23 m/s below the 1,655 m/s limit), with the primary cost of the lunar flyby being the approximate two months of duration (i.e., not ΔV).

In the proposed paper it will be shown that for any of the considered GTO cases, at most one lunar flyby is needed to target the acceptable inclination range within the ΔV budget of the DARE spacecraft.

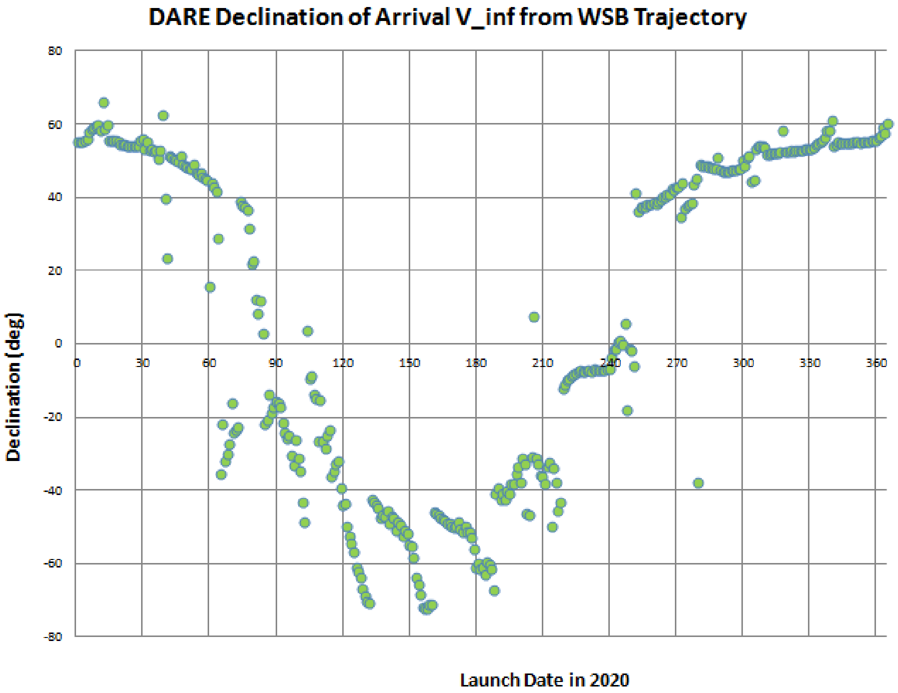

Figure 6. Declination of the Arrival Asymptote upon initial Lunar Encounter.

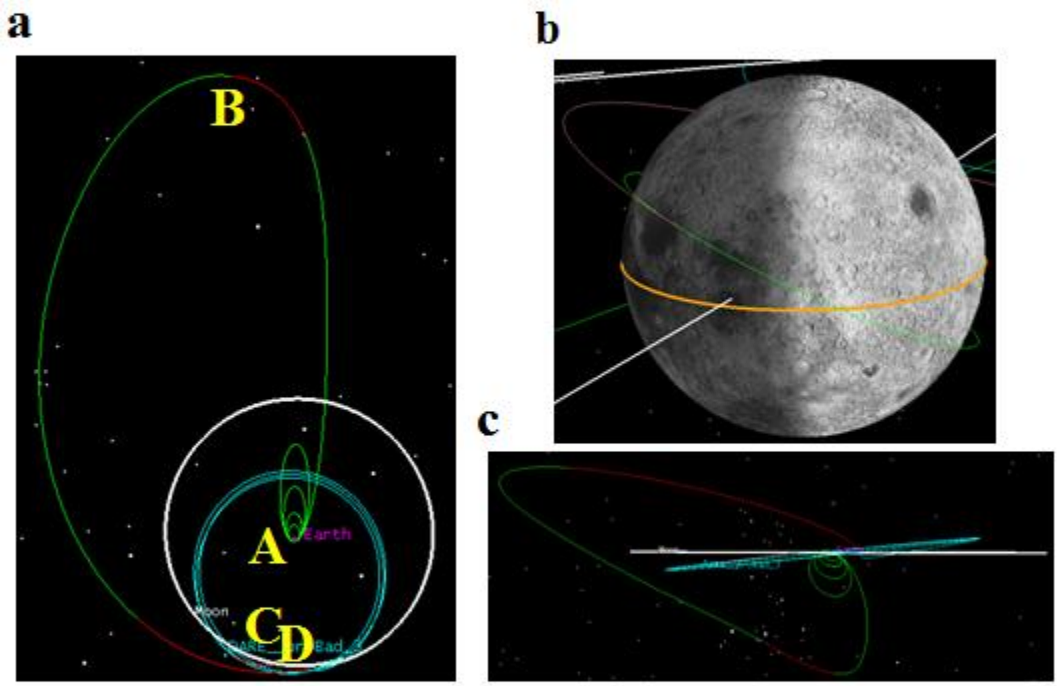

Figure 7. Nominal Trajectory Design from Launch to Lunar Orbit. Lunar flyby design element demonstrated on case with |DAA| = 67 deg. Trajectory shown in Earth-centered, Earth inertial frames with view normal to (a) and edge-on (c) the lunar orbit plane. View of LOI and first science orbit (26 deg inclination and 125 km altitude) in a Moon-centered, Moon inertial frame (b).

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