Earth's Pseudo-Moon 2016 HO_3

Discovered on 27 April 2016 by the Pan-STARRS 1 asteroid survey telescope on Haleakala (Maui, Hawaii), near-Earth object (NEO) 2016 HO_3 is currently the best example of a natural interplanetary object in protracted proximity to Earth. According to the report at http://www.jpl.nasa.gov/news/news.php?feature=6537, 2016 HO_3's geocentric motion is a series of loops extending for centuries into the future, bringing it no closer than 38 lunar distances (LD) or 14 million km from Earth and no farther than 100 LD or 39 million km from Earth.

The NEO Human Space Flight Accessible Targets Study (NHATS) website at http://neo.jpl.nasa.gov/nhats/ maintains a database for the most accessible NEOs. Among the metrics in this database is n, the number of NHATS-compliant roundtrip missions that can be flown to a particular NEO from Earth. Thanks to its persistent Earth proximity, 2016 HO_3 has the second largest n = 3,181,683 (as of 17 June 2016) in the NHATS database, exceeded only by 2000 SG_{344}'s n = 3,302,718 (as of 17 June 2016). On the accessibility downside, 2016 HO_3's ecliptic inclination of 7.77° (2000 SG_{344} has 0.11° inclination) and absence of really close Earth approaches render its mission dataset far from the least demanding among NHATS-compliant NEOs. As computed by NHATS on 17 June 2016, the sum of change-in-velocity magnitudes (Δv) associated with a 2016 HO_3 mission is never less than 6.276 km/s. In contrast, 2000 SG_{344} has a minimal Δv = 3.556 km/s. Contrasts between NHATS-compliant missions to 2016 HO_3 and 2000 SG_{344} are apparent in Figures 1 and 2, respectively.

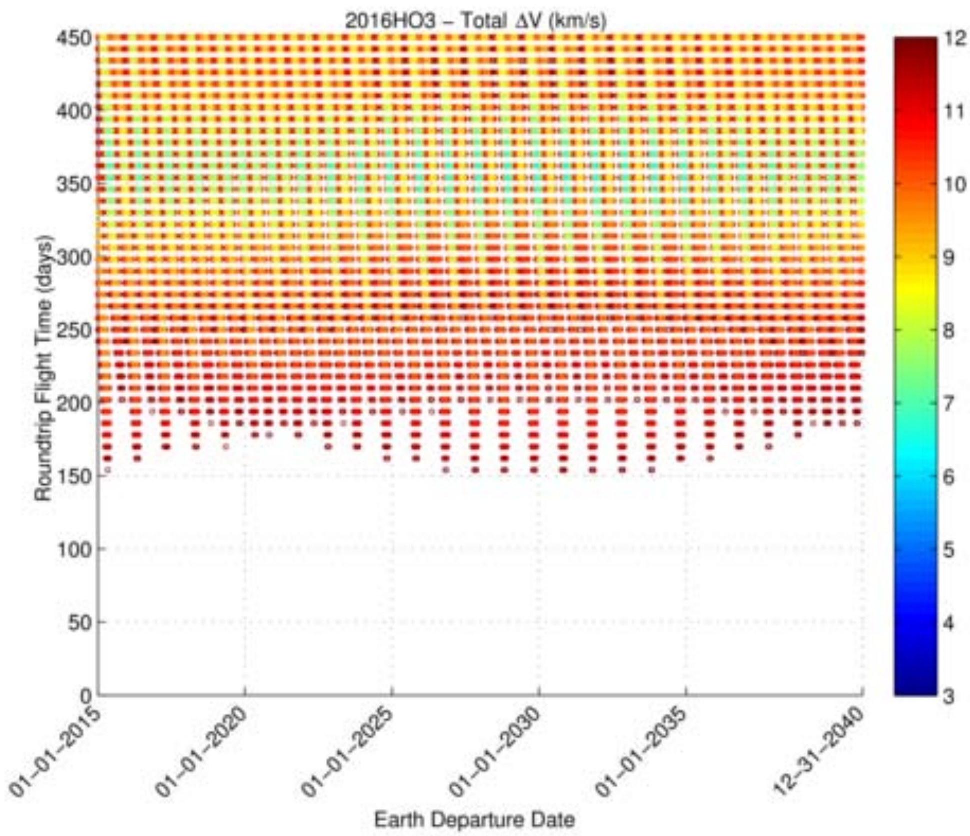

Figure 1 (ref. NHATS website). Color-coded Δv is illustrated for all NHATS-compliant missions to 2016 HO_3. Note minimal deep blue Δv is absent, but NHATS-compliant missions can be flown during any Earth departure year from 2015 through 2040.

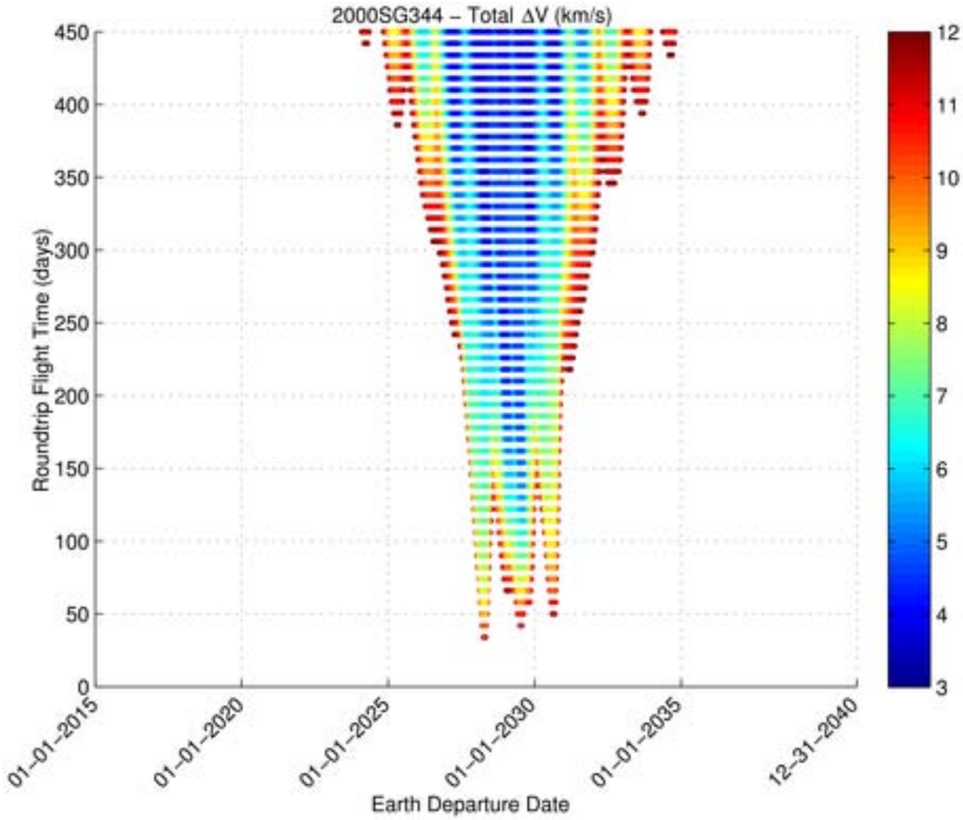

Figure 2 (ref. NHATS website). Color-coded *Δv* is illustrated for all NHATS-compliant missions to 2000 SG_{344}. Note the profusion of minimal deep blue *Δv* missions circa Earth departure year 2030. Because 2000 SG_{344} does not remain in Earth's vicinity, however, no NHATS-compliant missions are computed in most years from 2015 through 2040.

The previously cited report simultaneously visualizes 2016 HO_3 heliocentric and geocentric motion over many years in a time-lapse video. This dual-origin illustration can be confusing even to experts, particularly when static snapshots of the video are displayed (ref. http://www.jpl.nasa.gov/images/asteroid/20160615/asteroid20160615.jpg). Subsequent visualizations in this paper will each be tied to a single origin in an attempt to impart a clear description of 2016 HO_3 motion in three dimensions. These visualizations utilize the JPL#10 ephemeris for 2016 HO_3 as posted on the JPL *Horizons* server (accessible at http://ssd.jpl.nasa.gov/?horizons). Note this ephemeris was updated circa 22 June 2016.

Figure 3 is a visualization of Earth and 2016 HO_3 heliocentric inertial motion during most of year 2016 from a viewpoint 45° north of Earth's orbit plane, the ecliptic[1]. This perspective enables viewing dotted projection lines of 2016 HO_3 position onto the ecliptic plane and obtaining insight with regard to this NEO's heliocentric angular rate versus Earth's. Early in June, 2016 HO_3 crosses from above to below the ecliptic plane (descending node), and it passes inside Earth's orbit trailing our planet by about 25 million km as July begins. Thereafter, 2016

[1] Latitude with respect to the ecliptic is "north" in the hemisphere containing Earth's north celestial pole.

HO_3 catches up and passes Earth. In mid-November, 2016 HO_3 reaches its ascending node on the ecliptic plane, and it passes outside Earth's orbit in mid-December about 35 million km ahead of our planet.

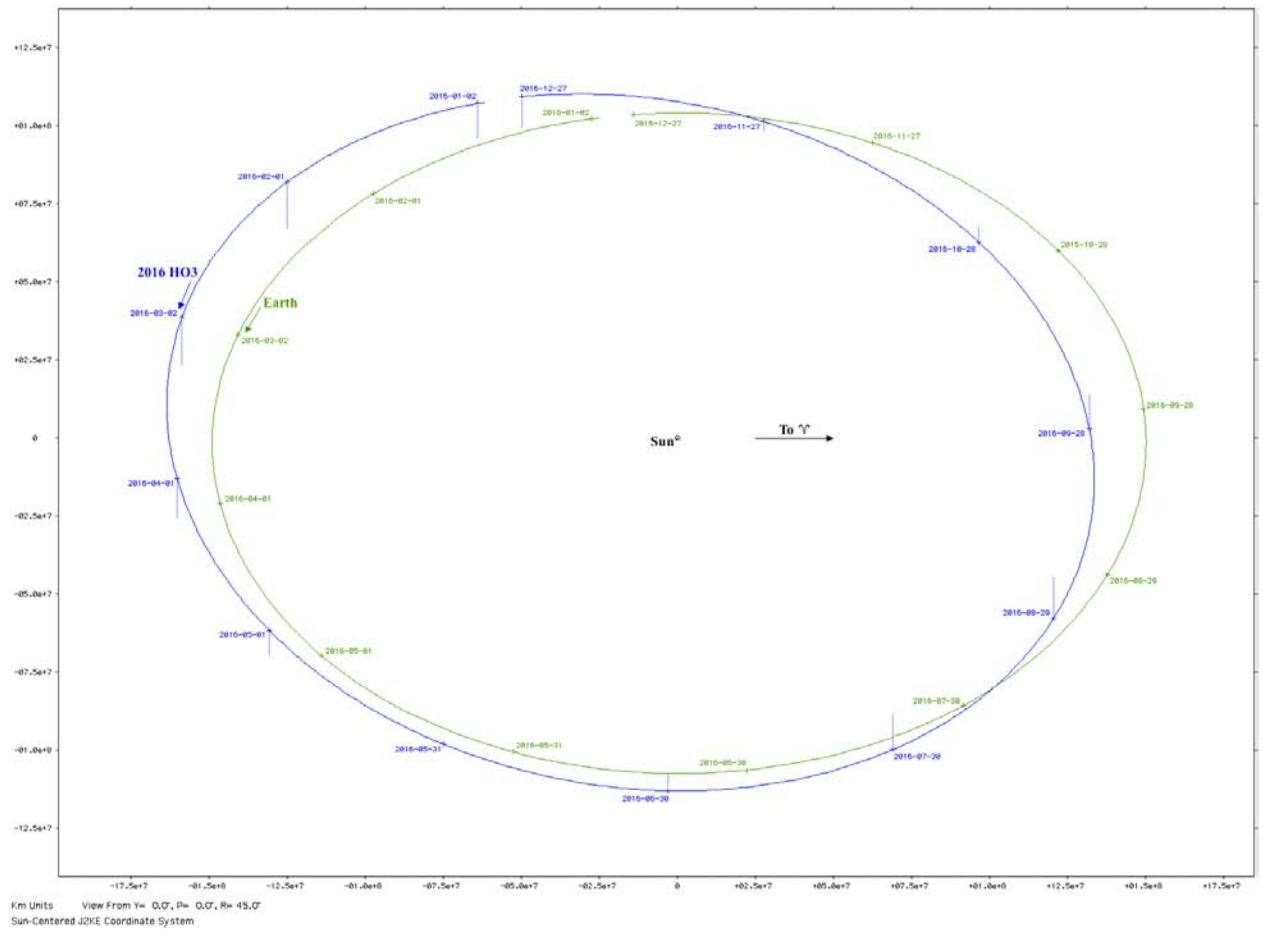

Figure 3. Heliocentric inertial motion of Earth (green) and 2016 HO_3 (blue) during most of year 2016 is viewed from ecliptic latitude 45° N; longitude 270° (the direction to zero ecliptic longitude is the first point of Aries, where the ecliptic's ascending node on Earth's equatorial plane is located, as indicated by the arrow annotated "To ♈"). Each "+" position marker is annotated with the corresponding 00:00 UT date in YYYY-MM-DD format, and dotted lines emanating from 2016 HO_3 markers are projections onto the ecliptic plane.

Geocentric motion of 2016 HO_3 throughout year 2016 is plotted in Figure 4. The Local Vertical Curvilinear (LVC) coordinate system used for this plot rotates in inertial space with the Sun-Earth line. Although the horizontal LVC axis passing through the Earth origin would appear as a straight line if plotted in Figure 4, its geometry is a heliocentric arc whose radius is Earth's heliocentric distance at any point in time. The vertical LVC axis thereby measures 2016 HO_3's heliocentric distance with respect to Earth's heliocentric distance (either exterior to Earth and upward in Figure 4, or interior to Earth and downward in Figure 4) regardless of the distance by which 2016 HO_3 leads or trails Earth in a heliocentric sense.

An apparent inconsistency between Figures 3 and 4 arises when attempts are made to estimate the date on which 2016 HO_3 passes through the Sun-Earth line. For example, 2016 HO_3 appears to pass between the Earth and Sun shortly after 28 September in Figure 3, but the corresponding geometry in Figure 4 appears to arise about 2 weeks before 28 September. The Figure 4 estimate is correct because its viewpoint is orthogonal to the ecliptic, whereas Figure 3's perspective is not.

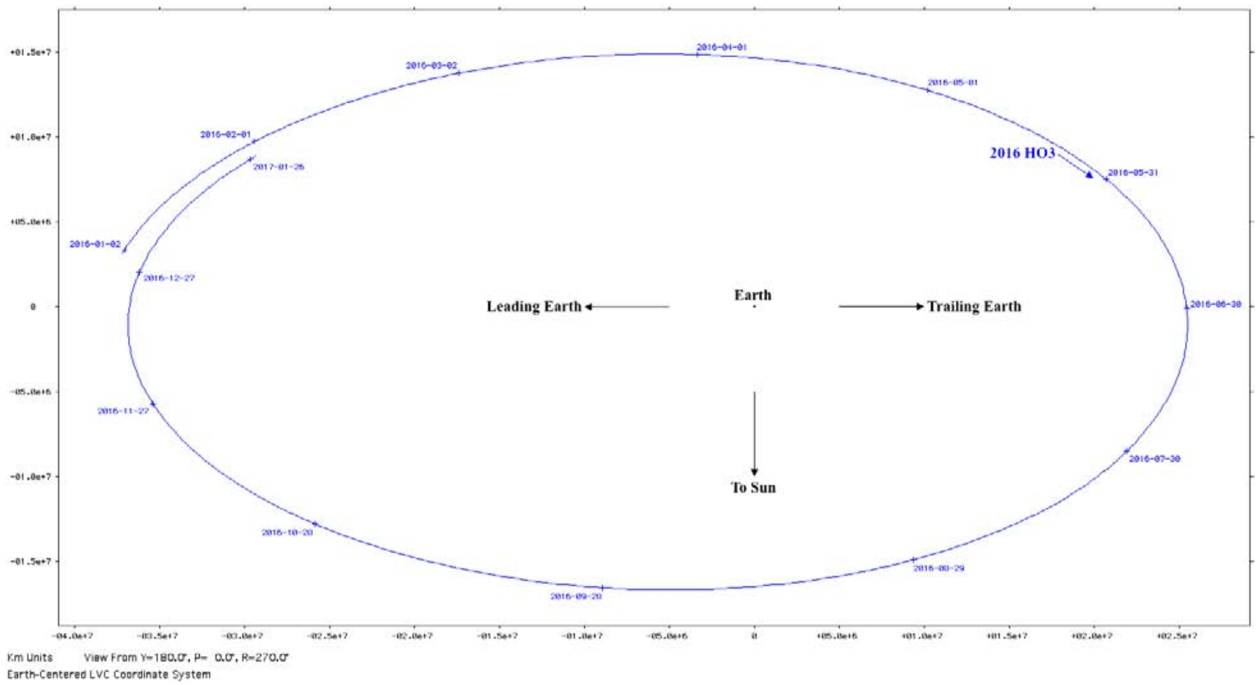

Figure 4. Geocentric motion of 2016 HO_3 is plotted throughout year 2016 in the Local Vertical Curvilinear (LVC) coordinate system rotating with the Sun-Earth line. Viewpoint is from the north ecliptic pole.

Clockwise motion in Figure 4 suggests 2016 HO_3 occupies a distant retrograde orbit (DRO) in the Sun-Earth system. Although this may be a useful visualization concept, it is dynamically incorrect. A Sun-Earth DRO would entail motion interior to or near the weak stability boundary between Earth's gravitational region of dominance and interplanetary space. Horizontal and vertical scales in Figure 4 are annotated at 5 million km increments. Earth's gravitational region of dominance, approximated by a sphere about 2 million km in diameter, would be spanned by the "Earth" annotation in Figure 4. Clockwise motion in Figure 4 is but a natural consequence of two prograde heliocentric orbits having nearly equal periods. One (the Earth) is nearly circular, while the other (2016 HO_3) has appreciable eccentricity (0.104 on 29.0 July 2016 UT). Another characteristic of DROs in the Sun-Earth system is they encompass Earth when plotted over an orbit period in an inertial coordinate system. Inspection of Figure 3 indicates this is not the case for 2016 HO_3 in year 2016. This NEO always lies in geocentric directions greater than 180° from ♈. Because of 2016 HO_3's protracted proximity to Earth and the two bodies' nearly equal heliocentric orbit periods, 2016 HO_3 is termed a pseudo-moon of Earth in this paper.

Intriguing asymmetries are apparent in Figure 4. By virtue of its heliocentric orbit eccentricity, 2016 HO_3 drifts farther interior to Earth's heliocentric distance than exterior to it, but it also spends more time exterior to Earth than interior to it. These radial displacements tend to offset each other and produce a 2016 HO_3 heliocentric orbit period very near Earth's. How do orbit periods of Earth and 2016 HO_3 compare? Figure 5 plots osculating heliocentric orbit period for Earth and 2016 HO_3 as computed by the *Horizons* server throughout year 2016. Regular variations in Earth's orbit period are due to its motion about the Earth-Moon barycenter, so this dynamical point's osculating heliocentric orbit period is also plotted in Figure 5. Since 2016 HO_3's orbit period is consistently greater than Earth's during year 2016, it clearly belongs to the Apollo orbit group of NEOs[2] in the near-term.

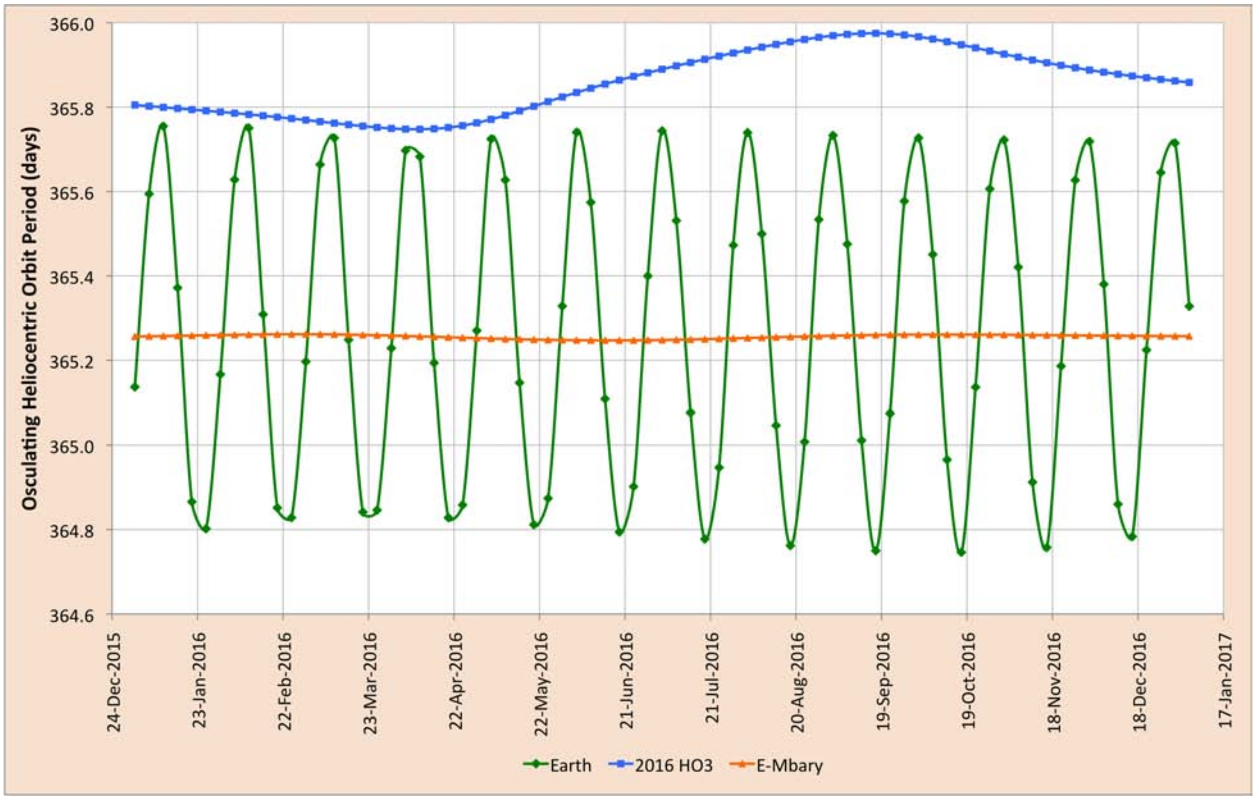

Figure 5. Osculating heliocentric orbit periods for Earth (green), 2016 HO_3 (blue), and the Earth-Moon barycenter (orange) are plotted throughout year 2016 at 5-day intervals.

Initial and final 2016 HO_3 CLV positions in Figure 4 confirm this NEO's Apollo pedigree. Although Figure 4 clearly shows 2016 HO_3 to be predominantly leading Earth during year 2016, it exhibits a net loss in that lead due to its longer heliocentric orbit period per Figure 5. Does this trend continue? Figures 6 and 7 indicate 2016 HO_3 is predominantly trailing Earth in year 2026, continuing to fall behind but at a reduced rate compared to that in year 2016. Furthermore, Earth perturbations are slowly changing 2016 HO_3's heliocentric orbit. By approaching Earth more closely from behind during years circa 2016, predominant gravitational tugs from ahead increase 2016 HO_3's orbit period to exceed that of Earth's. But those tugs are revered in year 2026. By year 2036, Figures 8 and 9 show 2016 HO_3's osculating heliocentric orbit period is consistently less than Earth's, making it a member of the Aten orbit group. In year 2036, 2016 HO_3 is predominantly trailing Earth, but the trend in Figure 8 is toward reduced trailing distance.

[2] See http://neo.jpl.nasa.gov/neo/groups.html for precise definitions of NEO orbit groups.

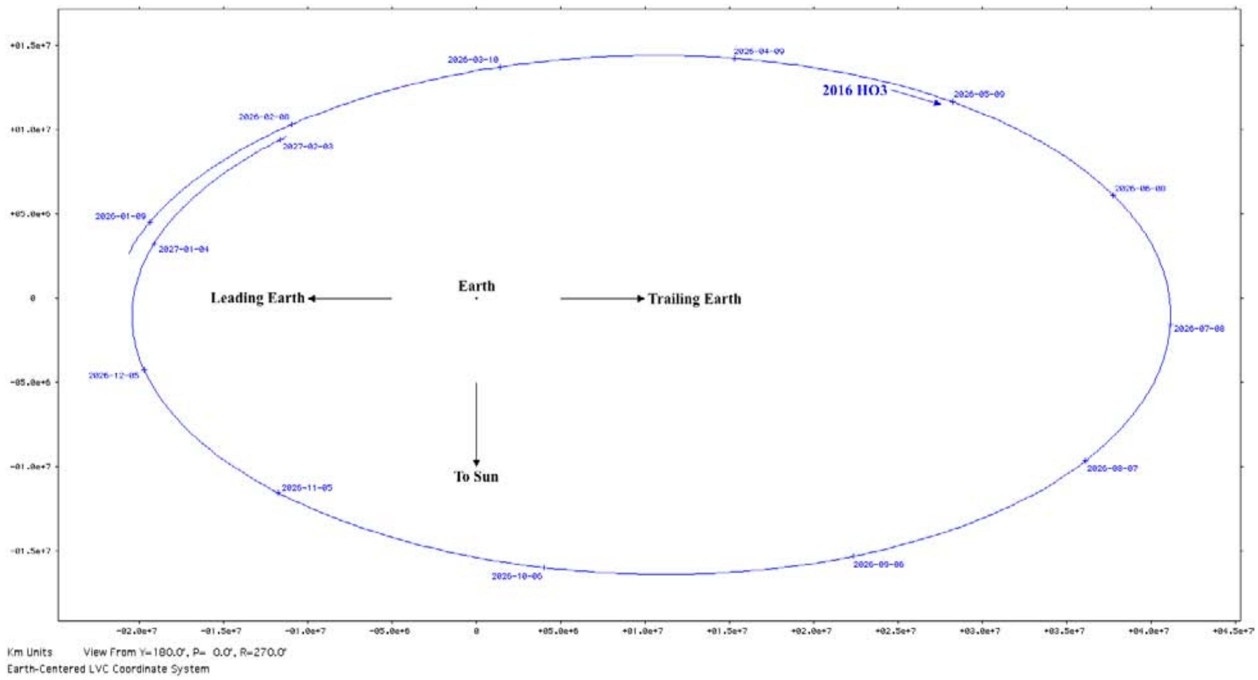

Figure 6. Geocentric motion of 2016 HO_3 is plotted throughout year 2026 in the LVC coordinate system rotating with the Sun-Earth line. Viewpoint is from the north ecliptic pole.

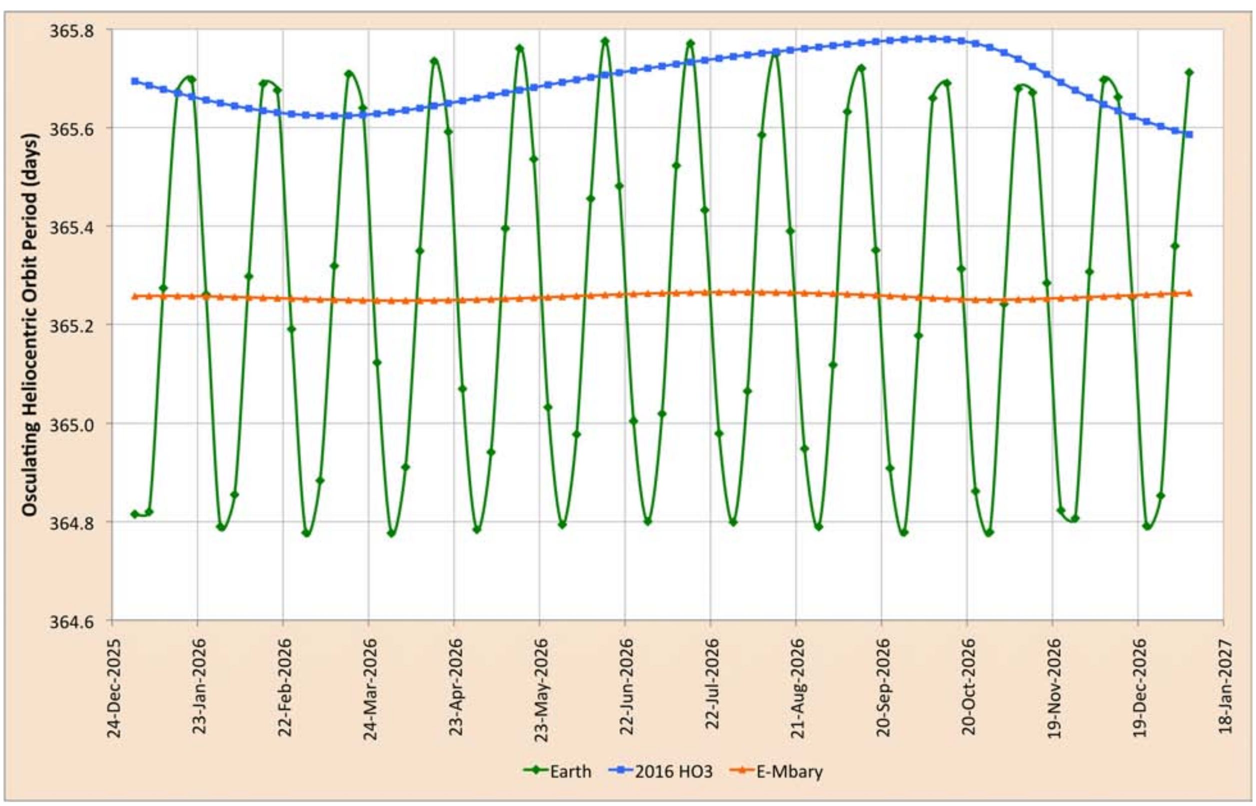

Figure 7. Osculating heliocentric orbit periods for Earth (green), 2016 HO_3 (blue), and the Earth-Moon barycenter (orange) are plotted throughout year 2026 at 5-day intervals.

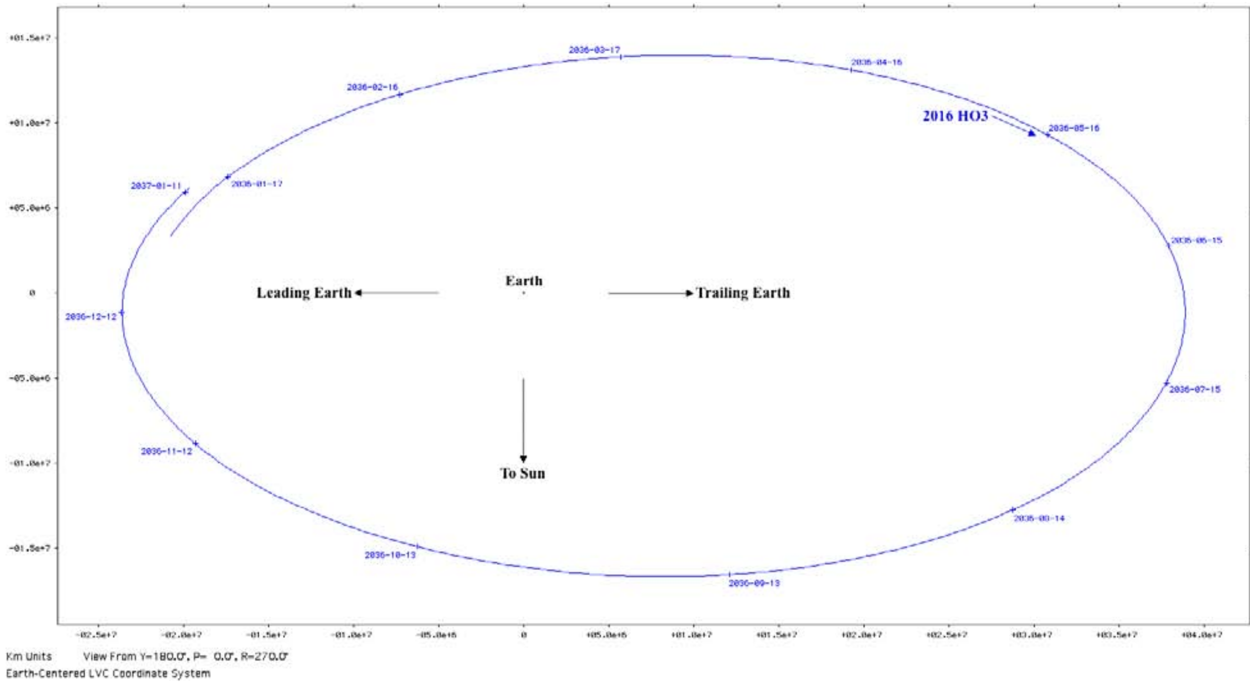

Figure 8. Geocentric motion of 2016 HO_3 is plotted throughout year 2036 in the LVC coordinate system rotating with the Sun-Earth line. Viewpoint is from the north ecliptic pole.

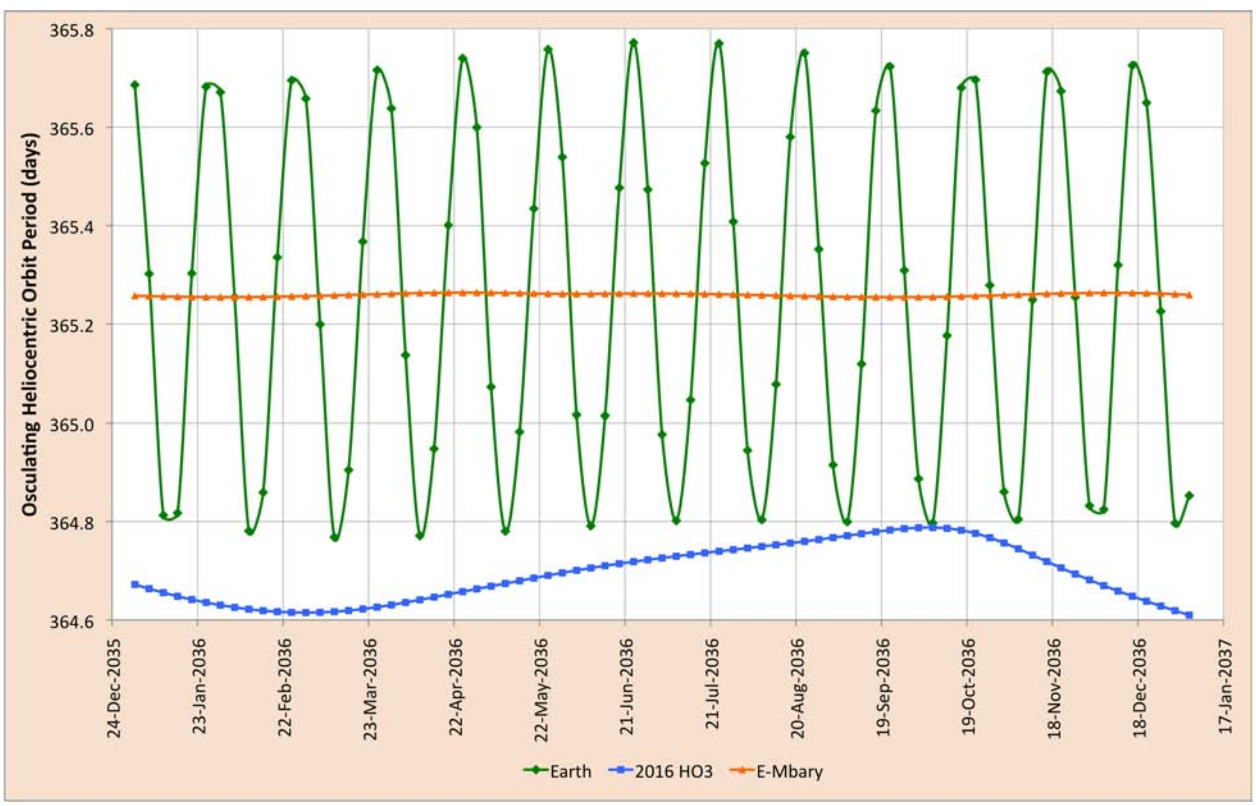

Figure 9. Osculating heliocentric orbit periods for Earth (green), 2016 HO_3 (blue), and the Earth-Moon barycenter (orange) are plotted throughout year 2036 at 5-day intervals.

Figure 10 plots variations in osculating heliocentric orbit period for 2016 HO_3 and the Earth-Moon barycenter over a 100-year time span at 15-day intervals. At this larger time scale, relatively minor annual variations in 2016 HO_3 orbit period are seen to be superimposed on a larger sinusoidal variation about ±0.7 days in amplitude and requiring around 40 years to play out. All the orbit periods plotted in Figure 8 average 365.280 days for 2016 HO_3 and 365.257 days for the Earth-Moon barycenter. These averaged periods correlate to 0.0063% and leave little doubt that Earth gravity plays a major role in 2016 HO_3's dual identity as an Apollo and an Aten.

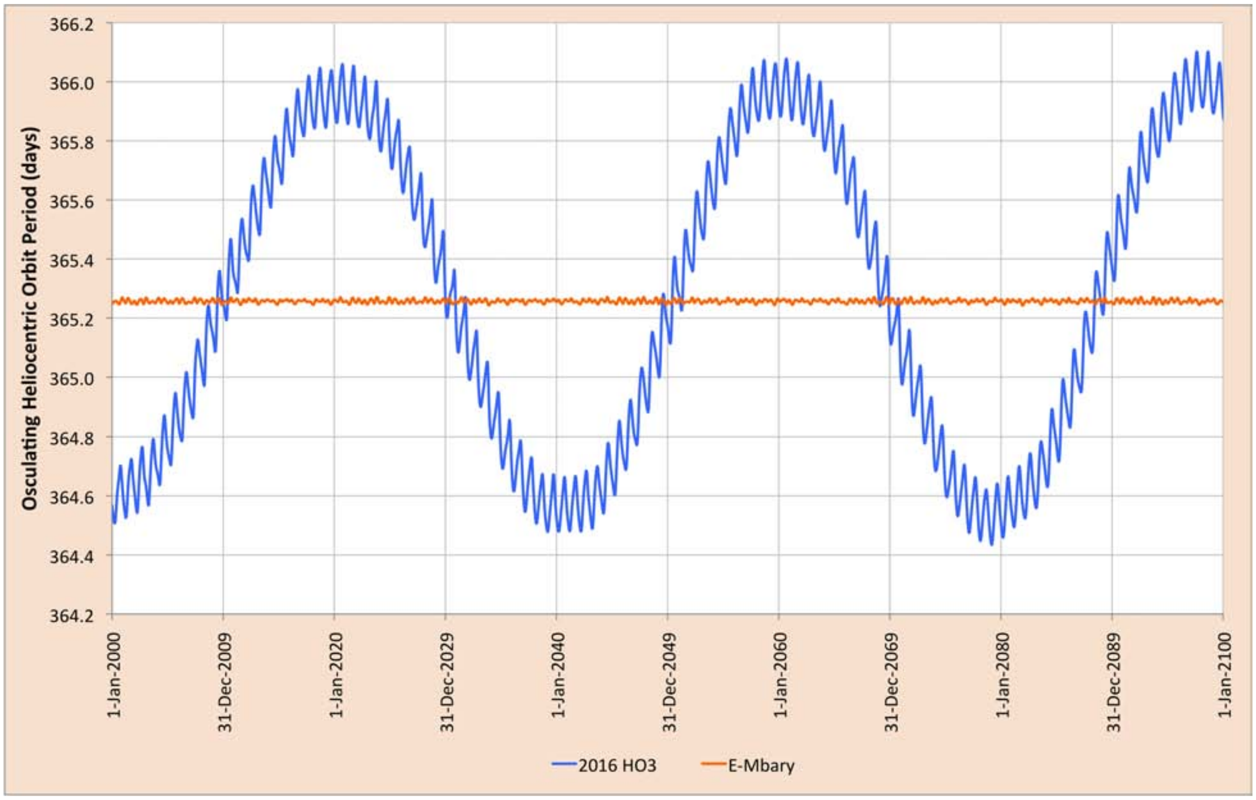

Figure 10. Osculating heliocentric orbit periods for 2016 HO_3 (blue) and the Earth-Moon barycenter (orange) are plotted throughout the 21st century.

Figure 10 serves as a guide to appropriate time intervals in which geocentric 2016 HO_3 motion spanning a full cycle of period variations can be plotted. Figure 11 displays such a plot beginning and ending with the first two minima in Figure 10's 2016 40-year HO_3 period variations cycle. Positions are plotted at 15-day intervals in Figure 11. These LVC positions are annotated with leading Earth January dates in YYYY-MM-DD format at 5-year intervals.

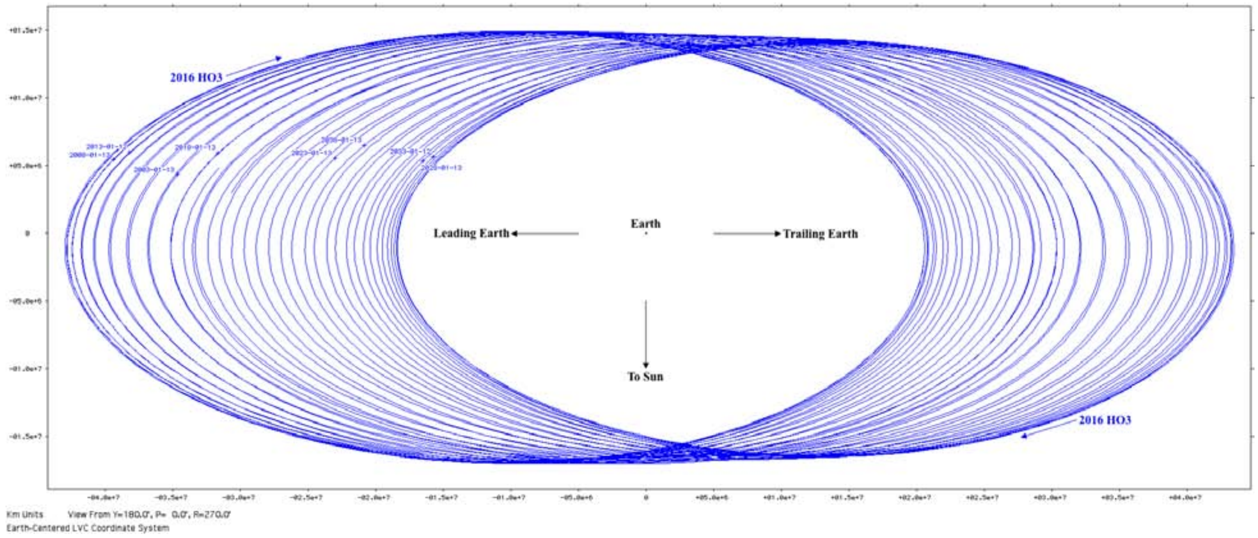

Figure 11. Geocentric motion of 2016 HO_3 is plotted from year 2000 to year 2043 in the LVC coordinate system rotating with the Sun-Earth line. Viewpoint is from the north ecliptic pole.

Figure 11 date annotations confirm extreme leading Earth and trailing Earth conditions arise when 2016 HO_3's orbit period most closely matches that of the Earth-Moon barycenter in Figure 10. For example, the leading Earth extremum falling between years 2008 and 2013 from date annotations in Figure 11 corresponds to period-matching conditions circa year 2010 in Figure 10. Prior to year 2010, 2016 HO_3 has been an Aten with relatively short orbit period, and that condition progressively contributes to predominantly leading Earth geocentric motion in Figure 11. But a leading Earth bias tends to encounter closer Earth approaches and stronger Earth gravity perturbations with 2016 HO_3 in a trailing Earth position. Those perturbations in turn increase 2016 HO_3's orbit period such that it becomes an Apollo and begins falling progressively farther behind Earth after year 2010. Further research will be required to determine if this period cycling over decades of time or other, possibly non-gravitational, dynamics will trigger 2016 HO_3's departure from Earth's vicinity. Until such a departure, 2016 HO_3 will remain a distant Earth pseudo-moon, perhaps for centuries.

In a quest for other examples of 2016 HO_3's Earth-driven period cycling as illustrated by Figure 10, the JPL Small Bodies Database was searched for all objects having heliocentric orbit period between 364.2 days and 366.2 days as of 22 June 2016. This scan identifies 18 objects. Of these candidates, only (164207) 2004 GU_9 appears to undergo period cycling keeping it in Earth's vicinity throughout the 21st century. Per Figure 12, a (164207) 2004 GU_9 period cycle requires about 68 years to play out. This substantially longer cycle with respect to 2016 HO_3's 40 years may be due to (164207) 2004 GU_9's higher ecliptic inclination, 13.65° as of 2.0 June 2010 UT. A geocentric LVC plot of (164207) 2004 GU_9 motion from year 2001 to year 2069 appears in Figure 13 using *Horizons* ephemeris JPL#51. Note Figure 13's scale is two times larger than Figure 11's.

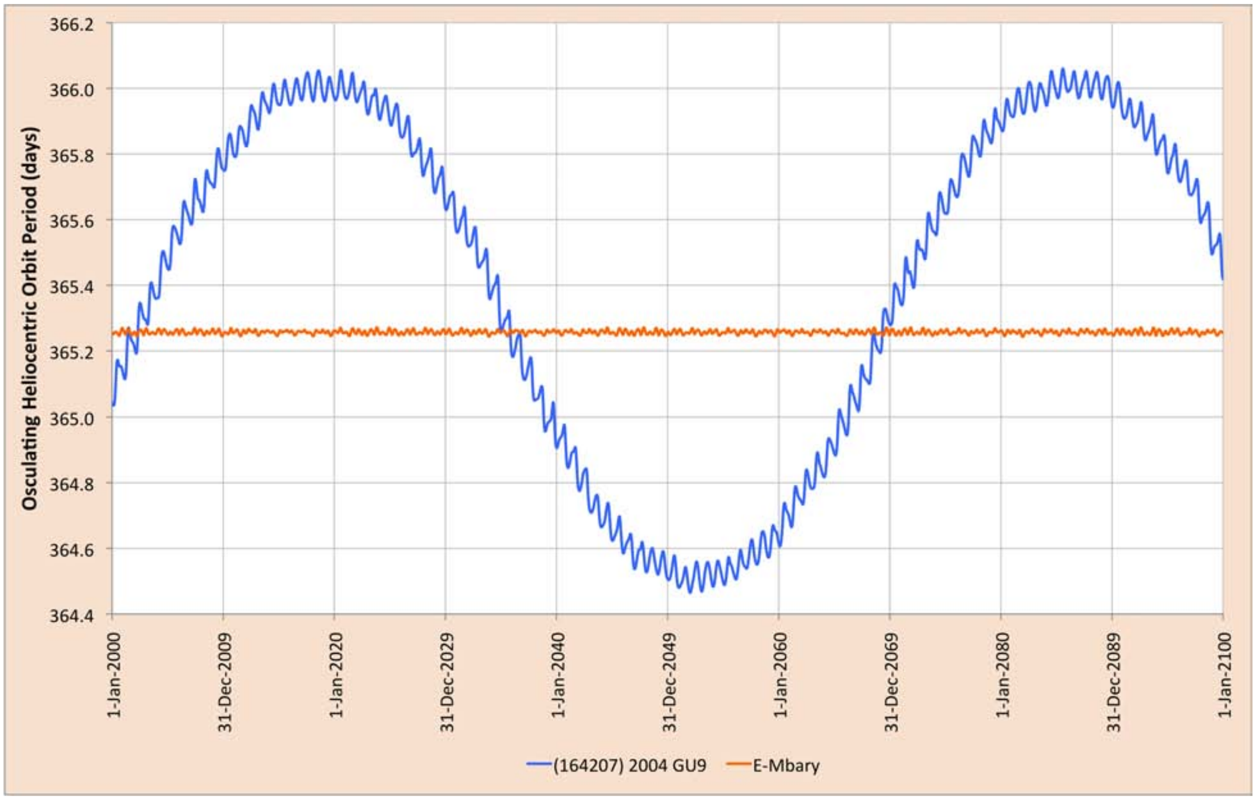

Figure 12. Osculating heliocentric orbit periods for (164207) 2004 GU_9 (blue) and the Earth-Moon barycenter (orange) are plotted throughout the 21st century.

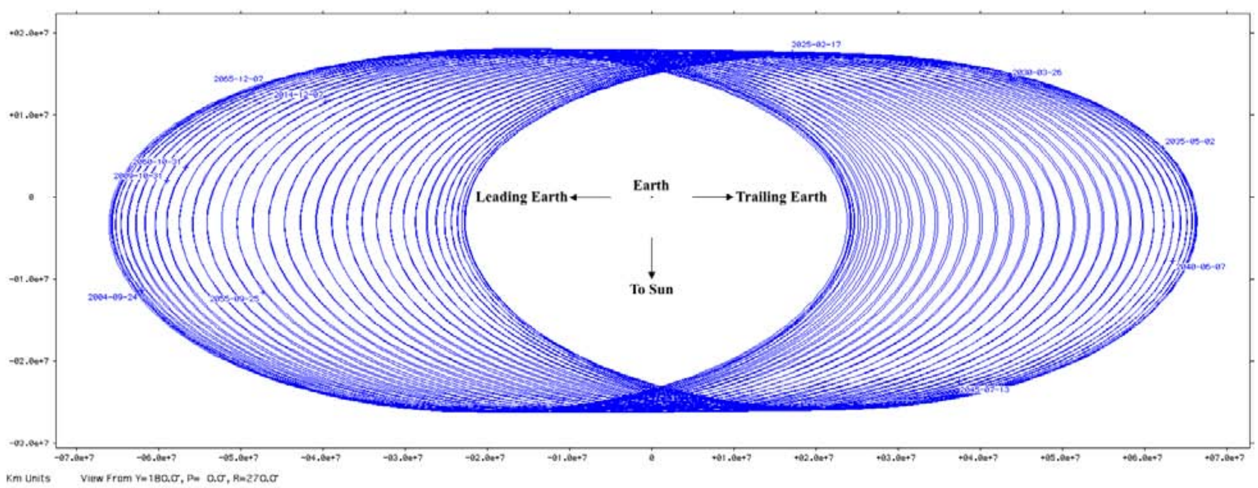

Figure 13. Geocentric motion of (164207) 2004 GU_9 is plotted from year 2001 to year 2069 in the LVC coordinate system rotating with the Sun-Earth line. Viewpoint is from the north ecliptic pole.

At lower ecliptic inclination (0.79° on 21.0 February 2013 UT) and eccentricity (0.085 on 21.0 February 2013 UT), dual identity as an Aten and an Apollo manifests itself as a "horseshoe" orbit for NEO 2013 BS_{45} (ref. the article on pp. 20-26 of the AIAA-Houston Section's *Horizons* newsletter for March/April 2013, accessible at http://www.aiaahouston.org/Horizons/Horizons_2013_03_and_04_high_resolution.pdf). In a horseshoe orbit, the Sun-Earth line is never crossed, but the NEO otherwise circulates around Earth's entire heliocentric orbit. The 2013 BS_{45} horseshoe orbit requires about 160 years to fully play out. During the Apollo-to-Aten turnaround of the horseshoe orbit in year 2013, Earth approaches to within 1.9 million km made 2013 BS_{45}'s discovery possible. Those approaches are 7 times closer than 2016 HO_3 ever comes to Earth in the 21st century. Consequently, Earth gravity perturbations working to produce Apollo/Aten transitions for 2016 HO_3 are much more subtle than near the 2013 BS_{45} horseshoe orbit's turnaround points.

In a closing note, orbit determination for 2016 HO_3 had reached a degree of stability warranting assignment of a permanent catalog number circa 21 June 2016. This NEO is now officially called (469219) 2016 HO_3.