# The Elusive Human Maximum Altitude Record

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As of this writing in 2009, the highest Earth altitudes ever achieved by humans were clearly logged during Apollo missions to the Moon. Not so obvious are factors conferring the maximum human altitude record on Apollo 13's crew. Reconstructions of as-flown Apollo mission trajectories are used to confirm, and possibly refine, this record. These reconstructions are based on officially archived data available to present-day researchers in Apollo mission reports.

#### I. Nomenclature

d =	center-to-center	distance	between	Earth	and	Moon
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- H = height above the Moon's mean surface radius of 1737.53 km
- h = geodetic altitude above an Earth surface ellipsoid with equatorial radius 6378.136 km and flattening factor 0.003352813 approximating mean sea level
- $\Delta v_D$  = magnitude of vector difference between reconstructed spacecraft velocity and that inferred from corresponding NASA Apollo Trajectory (NAT) elements at a coasted trajectory segment's initial "departure" epoch
- $\psi$  = heading angle of inertial velocity projected into the local horizontal plane.

### **II.** Introduction

During circumlunar flight, each Apollo crew<sup>†</sup> logged a local maximum h as their spacecraft flew over the Moon's farside hemisphere hidden from Earth. With respect to the Moon, these farside trajectories are confined to a relatively narrow H envelope near +100 km. A notable farside H outlier is the Apollo 13 mission because it never achieved lunar orbit. Following mission abort en route to the Moon, the Apollo 13 spacecraft flew recorded history's first gravity-assist trajectory, using a lunar flyby to initiate Earth return with minimal propellant consumption. This Earth "free return" trajectory was achieved post-abort by targeting an unusually high farside pericynthion with H = +252.4 km ([1], p. 4–5, PDF p. 30).

If the Moon maintained a near-circular orbit with constant d to  $\sim 100$  km precision, Apollo 13's single farside pass would unquestionably qualify as the human maximum h record. But the Moon's geocentric orbit is far from circular and subject to perturbations such that it is not even a closed ellipse from one month to the next. Averaged over time, the Moon's mean apogee and mean perigee differ by 42,200 km ([2], Table 15.9). Consequently, a farside H achieved during an Apollo lunar mission is only a secondary factor influencing maximum h in that timeframe.

Nevertheless, as illustrated in Figure  $1^{\ddagger}$ , Apollo 13 was in the Moon's vicinity almost precisely when the Moon was at its April apogee in year 1970. Primarily for this reason, Apollo 13 is associated with the maximum human altitude record, a feat documented as follows ([4], p. 369).

The 1992 *Guinness Book of World Records*, page 118, states that Apollo 13 holds the record for the farthest distance traveled from Earth: 248,655 statute miles [400,171 km] at 01:21 British

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<sup>&</sup>lt;sup>†</sup> These crews flew on Apollo 8 and Apollo 10 through Apollo 17. No other Apollo missions reached the Moon's vicinity.

<sup>&</sup>lt;sup>‡</sup> Figure 1 utilizes precision d values from the Jet Propulsion Laboratory's (JPL's) *Horizons* ephemeris system [3], together with event times obtained from [4]. Similar plots covering other Apollo mission dates appear subsequently in this paper and possess the same data pedigree.

Daylight Time 15 April 1970 at 158 miles [254 km] above the Moon, the equivalent of 216,075 nmi at 00:21 GMT<sup>§</sup> 15 April 1970 (19:21 EST, 14 April) at an altitude of 137 nmi.

To assess this claim, precision trajectory reconstruction is conducted and documented by this paper for Apollo 13 and any competing missions whose circumlunar operations were conducted with the Moon near its apogee. An Apollo trajectory reconstruction technique has been documented and applied to the Apollo 13 mission [5]. This process, based on as-flown NASA Apollo Trajectory (NAT) elements, is invoked as necessary in mission-specific sections of this paper to reconstruct relevant portions of Apollo trajectories.

In general, a reconstructed trajectory is coasted from a specific set of "departure" NAT elements to a set of "arrival" NAT elements while accounting for gravitational accelerations from the Sun, Earth, and Moon on the spacecraft. Although a reconstructed coast preserves departure and arrival positions to 1 km precision, generally small (ideally, zero) departure velocity dispersions are imposed by this preservation with respect to the original NAT departure elements. The degree of deviation between reconstructed and NAT-inferred velocity at departure is quantified by  $\Delta v_{D}$ . Each trajectory reconstruction is post-processed to determine the time at which spacecraft geocentric radial velocity is zero above the lunar farside. At these times, h is assumed to be at a maximum for the farside pass in progress<sup>\*\*</sup>.



Figure 1: d Variations Circa Apollo 13's Circumlunar Operations (red line)

<sup>&</sup>lt;sup>§</sup> Coordinated Universal Time (UTC) was not generally available prior to 1972 but is adopted for use throughout this paper. Since time *coordination* is chiefly an issue associated with accurate current time broadcast and reception, the difference between Universal Time (UT) and UTC in this paper's historic context is insignificant. These time scales are also equivalent to Greenwich Mean Time (GMT).

<sup>&</sup>lt;sup>\*\*</sup> Strictly speaking, the "zero radial velocity" criterion fails to precisely account for Earth's oblate figure, but the consequences of this simplification are negligible. At lunar distances, errors arising from this criterion are small to the degree they are dwarfed by lunar ephemeris errors and Earth terrain variations. Furthermore, the value of h computed at a zero radial velocity condition *does* fully account for an oblate spheroid Earth surface.

#### III. Apollo 13 Altitude Assessment

From claims documented in [4] and substantiated by Figure 1, Apollo 13 certainly warrants trajectory reconstruction during its single lunar farside pass. This reconstruction also supports comparison to and possible refinement of the maximum human altitude record cited by [4]. A trajectory segment reconstructed as follows spans the period of interest ([1], p. 4-3, PDF p. 28).

Departure on 14 April 1970 at 104/08:43:17.7 UTC, Midcourse Correction 3 (MCC-3) cutoff

 $\Delta v_D = 1.006 \text{ m/s}$ 

Arrival on 15 April 1970 at 105/02:40:39.0 UTC, Pericynthion +2 hrs (PC+2) ignition

When the reconstructed trajectory is post-processed, its pericynthion H = +264.4 km is encountered on 15 April 1970 at 105/00:34:12.850 UTC. This reconstruction is 12.0 km higher and 16 sec later than corresponding pericynthion values appearing in [1]. Maximum h = +400,046.0 km is obtained from the reconstructed segment on 15 April 1970 at 105/00:34:13.663 UTC. This reconstruction is 125 km lower and 13 min later than the maximum human altitude record cited in [4].

### IV. Apollo 8 Altitude Assessment

Figure 2 indicates Apollo 8 was not in the Moon's vicinity at any time near lunar apogee. The period of circumlunar operations is demarcated in Figure 2 as extending from the green vertical line at Lunar Orbit Insertion (LOI) to the red vertical line at Trans-Earth Injection (TEI). Consequently, no Apollo 8 trajectory reconstruction is warranted because this mission cannot compete with the maximum human altitude record already quantified for Apollo 13.



Figure 2: d Variations Circa Apollo 8's Circumlunar Operations (LOI to TEI)

#### V. Apollo 10 Altitude Assessment

Figure 3 indicates Apollo 10 was near the Moon shortly after May's lunar apogee in year 1969. The period of circumlunar operations is demarcated in Figure 3 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, Apollo 10 trajectory reconstruction in the LOI timeframe is warranted.



Figure 3: d Variations Circa Apollo 10's Circumlunar Operations (LOI to TEI)

A trajectory segment reconstructed as follows can be coasted through the LOI burn arc assuming the hyperbolic trajectory prior to LOI ignition. This reconstruction is supported by NAT elements obtained from [6], p. 6-9, PDF p. 50.

Departure on 19 May 1969 at 139/19:22:03.9 UTC, MCC-1 cutoff

 $\Delta v_D = 0.068 \text{ m/s}$ 

Arrival on 21 May 1969 at 141/20:44:54.0 UTC, LOI ignition

When the reconstructed trajectory is post-processed, its maximum h = +399,805.1 km is obtained on 21 May 1969 at 141/20:49:45.366 UTC. This reconstruction is 240.9 km lower than the maximum human altitude record documented in Section III.

Because the foregoing maximum h is obtained 291.4 sec after LOI ignition, an equally relevant coasted trajectory segment can be reconstructed as follows for the elliptic lunar orbit after LOI cutoff. This reconstruction is also supported by NAT elements obtained from [6], p. 6-9, PDF p. 50.

Departure on 21 May 1969 at 141/20:50:50.1 UTC, LOI cutoff

 $\Delta v_{\rm D} = 9.010 \text{ m/s}$ 

Arrival on 22 May 1969 at 142/01:14:08.1 UTC, circularization ignition

Post-processing this reconstruction leads to a maximum h = +399,807.0 km on 21 May 1969 at 141/20:49:44.502 UTC, effectively the same result as obtained with the pre-LOI reconstruction.

### VI. Apollo 11 Altitude Assessment

Figure 4 indicates Apollo 11 was not in the Moon's vicinity at any time near lunar apogee. The period of circumlunar operations is demarcated in Figure 4 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, no Apollo 11 trajectory reconstruction is warranted because this mission cannot compete with the maximum human altitude record already quantified for Apollo 13.



Figure 4: d Variations Circa Apollo 11's Circumlunar Operations (LOI to TEI)

### VII. Apollo 12 Altitude Assessment

Figure 5 indicates Apollo 12 was not in the Moon's vicinity at any time near lunar apogee. The period of circumlunar operations is demarcated in Figure 5 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, no Apollo 12 trajectory reconstruction is warranted because this mission cannot compete with the maximum human altitude record already quantified for Apollo 13.



Figure 5: d Variations Circa Apollo 12's Circumlunar Operations (LOI to TEI)

### VIII. Apollo 14 Altitude Assessment

Figure 6 indicates Apollo 14 was not in the Moon's vicinity at any time near lunar apogee. The period of circumlunar operations is demarcated in Figure 6 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, no Apollo 14 trajectory reconstruction is warranted because this mission cannot compete with the maximum human altitude record already quantified for Apollo 13.



Figure 6: d Variations Circa Apollo 14's Circumlunar Operations (LOI to TEI)

### IX. Apollo 15 Altitude Assessment

Figure 7 indicates Apollo 15 was near the Moon shortly after July's lunar apogee in year 1971. The period of circumlunar operations is demarcated in Figure 7 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, Apollo 15 trajectory reconstruction in the LOI timeframe is warranted.



Figure 7: d Variations Circa Apollo 15's Circumlunar Operations (LOI to TEI)

A trajectory segment reconstructed from  $[7]^{\dagger\dagger}$  as follows can be coasted through the LOI burn arc assuming the hyperbolic trajectory prior to LOI ignition.

Departure on 29 July 1971 at 210/15:40:47.1 UTC, Scientific Instrument Module bay door jettison

 $\Delta v_D = 0.399 \text{ m/s}$ 

Arrival on 29 July 1971 at 210/20:05:46.7 UTC, LOI ignition

When the reconstructed trajectory is post-processed, its maximum h = +398,401.0 km is obtained on 29 July 1971 at 210/20:09:09.353 UTC. This reconstruction is 1645.0 km lower than the maximum human altitude record documented in Section III.

Because the foregoing maximum h is obtained 202.7 sec after LOI ignition, an equally relevant coasted trajectory segment can be reconstructed as follows for the elliptic lunar orbit after LOI cutoff. This reconstruction is also supported by NAT elements obtained from [7].

Departure on 29 July 1971 at 210/20:12:25.1 UTC, LOI cutoff  $\Delta v_D = 5.641$  m/s Arrival on 30 July 1971 at 211/00:13:49.1 UTC, Descent Orbit Insertion (DOI) ignition

<sup>&</sup>lt;sup>††</sup> This Table 3-III of Apollo 15 NAT elements is missing from various scanned versions of the "Apollo 15 Mission Report" and must be downloaded as a dedicated image file from the Apollo Lunar Surface Journal website.

Post-processing this reconstruction leads to a maximum h = +398,403.9 km on 29 July 1971 at 210/20:08:30.089 UTC, effectively the same result as obtained with the pre-LOI reconstruction.

#### X. Apollo 16 Altitude Assessment

Figure 8 indicates Apollo 16 was near the Moon shortly before late April's lunar apogee in year 1972. The period of circumlunar operations is demarcated in Figure 8 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, Apollo 16 trajectory reconstruction in the TEI timeframe is warranted.



Figure 8: d Variations Circa Apollo 16's Circumlunar Operations (LOI to TEI)

A trajectory segment reconstructed from [8] (p. 3-4, PDF p. 17) as follows can be coasted in the TEI timeframe by assuming the elliptic trajectory following subsatellite deploy.

Departure on 24 April 1972 at 115/21:56:09 UTC, subsatellite deploy

 $\Delta v_{\rm D} = 1.084 \text{ m/s}$ 

Arrival on 25 April 1972 at 116/02:15:33 UTC, TEI ignition

When the reconstructed trajectory is post-processed, its maximum h = +398,008.7 km is obtained on 25 April 1972 at 116/02:12:32.508 UTC. This reconstruction is 2037.3 km lower than the maximum human altitude record documented in Section III. Reconstructed maximum h occurs 180.492 sec before TEI ignition. Consequently, no post-TEI trajectory reconstruction is warranted.

With regard to the foregoing reconstruction and others performed for Apollo 16 using Moon-centered NAT elements from [8], additional remarks are warranted. Of specific interest in this Apollo 16 context is the NAT element  $\psi$  relating selenocentric velocity direction in the local horizontal plane. The  $\psi$  pedigree documented in [5] adopts a *geocentric* true north celestial pole reference regardless of whether NAT elements are Moon-centered or Earth-centered. This pedigree is consistent with NAT elements obtained from [1] (Apollo 13), [6] (Apollo 10), and [7] (Apollo 15). In contrast, Apollo 16 Moon-centered NAT elements obtained from [8] evidently adopt a *selenocentric* true north celestial pole  $\psi$  reference. In benign cases, failure to recognize this deviation will have no

effect on trajectory reconstruction results because  $\psi$  is not directly related to departure or arrival position. Even in these cases, however, interpreting a departure Moon-centered  $\psi$  from [8] as having a geocentric true north celestial pole reference will generally produce an associated trajectory reconstruction  $\Delta v_D$  value on the order of *hundreds* of m/s.

### XI. Apollo 17 Altitude Assessment

Figure 9 indicates Apollo 17 was not in the Moon's vicinity at any time near lunar apogee. The period of circumlunar operations is demarcated in Figure 9 as extending from the green vertical line at LOI to the red vertical line at TEI. Consequently, no Apollo 17 trajectory reconstruction is warranted because this mission cannot compete with the maximum human altitude record already quantified for Apollo 13.



Figure 9: d Variations Circa Apollo 17's Circumlunar Operations (LOI to TEI)

## XII. Conclusion

The geocentric lunar ephemeris employed by this paper to assess h from trajectory reconstructions has position errors with respect to [3] generally less than 10 km in magnitude. To at least this precision, Table 1 summarizes maximum geodetic altitudes documented by this paper. Apollo 10 and Apollo 15 data in Table 1 are an average of pre-LOI and post-LOI trajectory reconstruction assessment results because maximum h occurs during the LOI burn arc.

Mission	Maximum h (km)	UTC
Apollo 13	+400,046	15 April 1970 at 105/00:34:14
Apollo 10	+399,806	21 May 1969 at 141/20:49:45
Apollo 15	+398,402	29 July 1971 at 210/20:08:50
Apollo 16	+398,009	25 April 1972 at 116/02:12:33

Table 1: Maximum Geodetic Altitudes Achieved By Apollo Missions Flown Near Lunar Apogee

Some 40 years after humans attained the Table 1 altitudes, exceeding them to establish new records remains an elusive prospect for at least another decade. In addition to quantifying the current human altitude record, an account of this record's pedigree has been provided by documenting multiple pertinent trajectory reconstructions associated with Table 1 data. These reconstructions critically depend on cited Apollo mission reports containing complete NAT element sets. These publications are among the few remaining officially archived sources of as-flown Apollo trajectory data. With respect to Apollo 16-specific Moon-centered NAT elements, a previously unknown deviation in convention from other missions has been discovered and documented.

### References

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