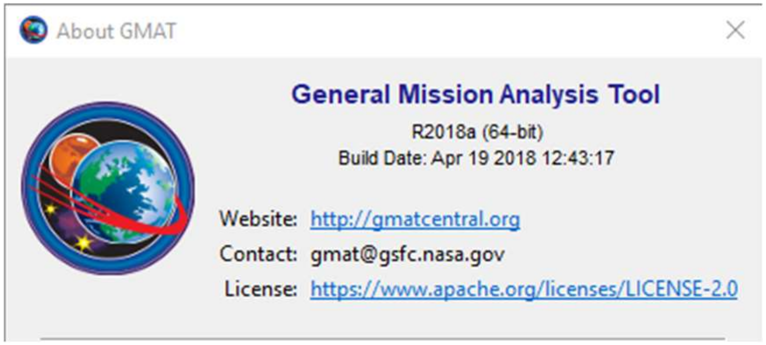
Simulating the Apollo 11 LM Ascent Stage Orbit

Searching for the Eagle

Introduction

- Neil Armstrong and Buzz Aldrin landed the Apollo 11 Lunar Module "Eagle" on the Moon in July 1969
- The next day they lifted off in the Eagle ascent stage and rejoined Mike Collins in "Columbia" for the trip back to Earth
- The ascent stage was jettisoned in lunar orbit on July 21st. No one knows what became of the Eagle
- I reconstructed the original orbit, and then simulated the stage, to narrow the search for an impact crater
- What I find is that the orbit is quasi-stable
- The Eagle might still have wings!

Simulation Environment



https://sourceforge.net/projects/gmat/

- Using GMAT R2018a
- Using a GRAIL gravity model
  - Accurately models “lumpy” Lunar gravity
- Some customization of output and other paths may be required for your setup
- Moon gravity models are publicly available:

https://pds-geosciences.wustl.edu/grail/grail-l-lgrs-5-rdr-v1/grail_1001/shadr/

Sources for the Orbit of Eagle

- The Apollo 11 Mission Report, Trajectory Parameters, Table 7-II
  - https://history.nasa.gov/alsj/a11/A11_MissionReport.pdf
- This "Lunar Gravity Models" paper, from 1970, with tables of Apollo orbit data
  - https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19700028128.pdf
- Mission Transcripts
  - https://history.nasa.gov/afj/ap11fj/20day6-reboard-lmjett.html
- Mission Control Audio
  - apolloinrealtime.org/11/?t=129:59:40&ch=1

Time Conversions

- Using a spreadsheet one can convert Mission Elapsed Times to UTC
- You need the UTC times for GMAT

Event	UTC	Mission Elapsed Time
Launch	7/16/1969 13:32:00.00	0:00:00.00
Undocking	7/20/1969 17:44:00.00	100:12:00.00
Docking	7/21/1969 21:35:00.00	128:03:00.00
A11 Ascent Stage Jettison	7/21/1969 23:41:31.20	130:09:31.20

Orbit Parameters from Mission Report

TABLE 7-II.- TRAJECTORY PARAMETERS

Event	Ref. body	Time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude, miles	Space-fixed velocity, ft/sec	Space-fixed flight-path angle, deg	Space-fixed heading angle, deg E of N
Docking	Moon	128:03:00.0	1.18N	67.31E	60.6	5 341.5	0.16	-87.63
Ascent stage jettison	Moon	130:09:31.2	1.10N	41.85E	61.6	5 335.9	0.15	-97.81
Final separation								
Ignition	Moon	130:30:01.0	0.08N	20.19W	62.7	5 330.1	-0.05	-52.86
Cutoff	Moon	130:30:08.1	0.19N	20.58W	62.7	5 326.9	-0.02	-52.73

position	GLD100(m)	SLDEM2015+LOLA(m)	lon	lat
0.044	-1927.319901	-1929.164092	23.472844	0.674123
0.048	-1927.471304	-1929.497111	23.472976	0.674122
0.052	-1927.49359	-1929.830003	23.473108	0.674121

Landing site 2 altitude is 1.929 km below the mean radius of the Moon which is 1738 km

Altitude	Perpendicular distance from the reference body to the point of orbit intersect, ft or miles; altitude above the lunar surface is referenced to Landing Site 2
Space-fixed velocity	Magnitude of the inertial velocity vector referenced to the body-centered, inertial reference coordinate system, ft/sec
Space-fixed flight-path angle	Flight-path angle measured positive upward from the body-centered, local horizontal plane to the inertial velocity vector, deg
Space-fixed heading angle	Angle of the projection of the inertial velocity vector onto the local body-centered, horizontal plane, measured positive eastward from north, deg

Problem with Mission Report Values

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Can't be right!!!

- The "Heading" value in the table cannot be right. Apollo 11's orbit hugged the Lunar equator, so this angle must be close to -90 degrees
- To correct this value I used the orbit data from the 1970 "Lunar Gravity Models" paper.

“Lunar Gravity Models” Orbit Data Table

ARC 5 APOLLO 11

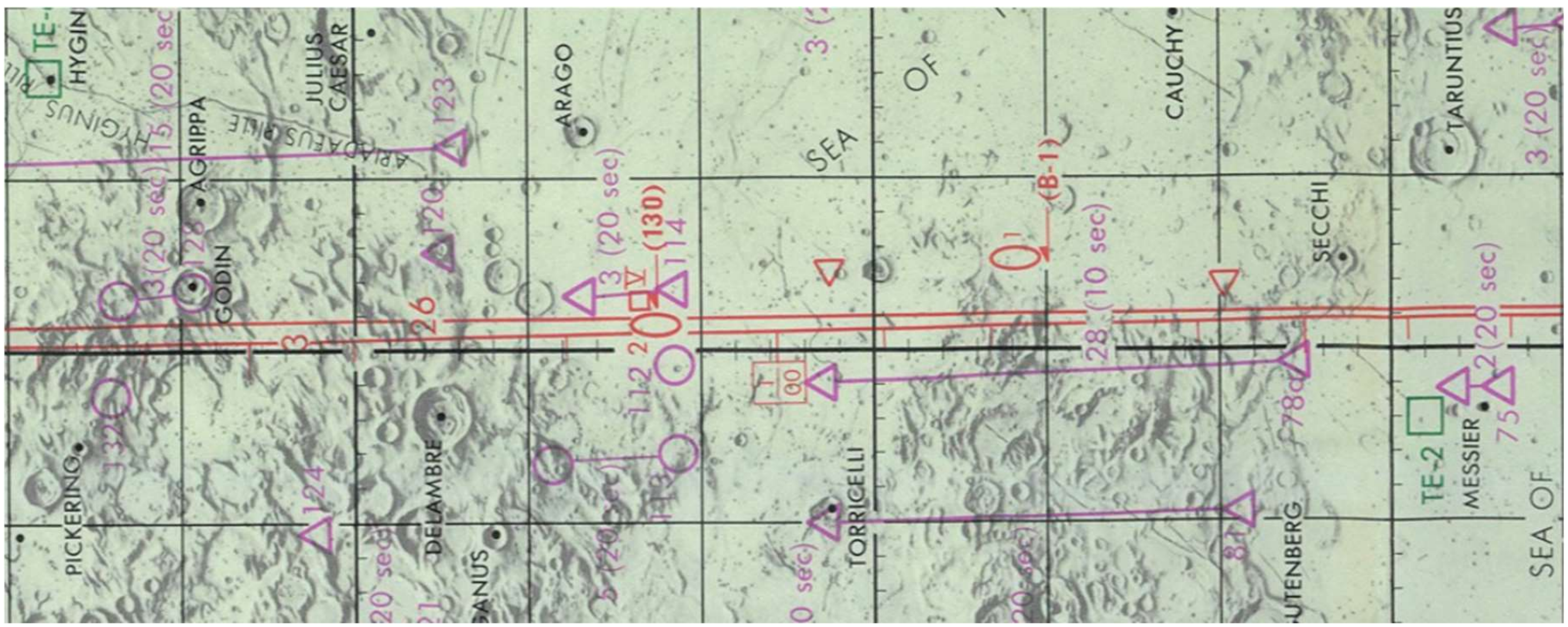
TIME(MJD)	a(M.R.)	e	i(DEG.)	ω(DEG.)	N(DEG.)	M(DEG.)
40422.8718940	1.06231331	.0039640	178.5915	269.9769	163.2371	0.0
40422.9548903	1.06236750	.0037580	178.5875	271.7263	162.1272	0.0
40423.0379747	1.06234978	.0035680	178.5897	276.4500	163.5866	0.0
40423.1216486	1.06226403	.0034620	178.6448	284.7647	166.0358	0.0
40423.2046242	1.06232822	.0033250	178.6532	288.3690	165.3336	0.0
40423.2885118	1.06236978	.0032300	178.6658	294.3839	166.0860	0.0
40423.3771338	1.06242221	.0031600	178.6897	300.5971	166.6814	0.0
40423.4558624	1.06247009	.0031220	178.7099	307.1191	167.1189	0.0
40423.5397081	1.06250165	.0031280	178.7491	314.3773	167.7763	0.0
40423.6235247	1.06256075	.0031330	178.7525	321.5304	168.4644	0.0
40423.7073586	1.06260161	.0031810	178.7654	328.5203	168.9111	0.0
40423.8748308	1.06262335	.0033830	178.7984	341.9411	170.0995	0.0
40423.9567812	1.06229490	.0035870	178.8136	341.8256	171.5603	0.0
40423.9871667			178.817			

- To convert the MJD times in the paper to UTC MJD used by GMAT, subtract 29999.5
- Extrapolating from this table, the inclination at the time of stage jettison would have been about 178.817
- This translates to a heading angle of -89.63 at that moment

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19700028128.pdf

Heading Angle Must Be Close to -90

- Apollo 11 and Apollo 10 had similar orbits
- This map excerpt from Apollo 10 shows the ground track near the landing site
- The heading angle should be close to -90 degrees…parallel to the lunar equator

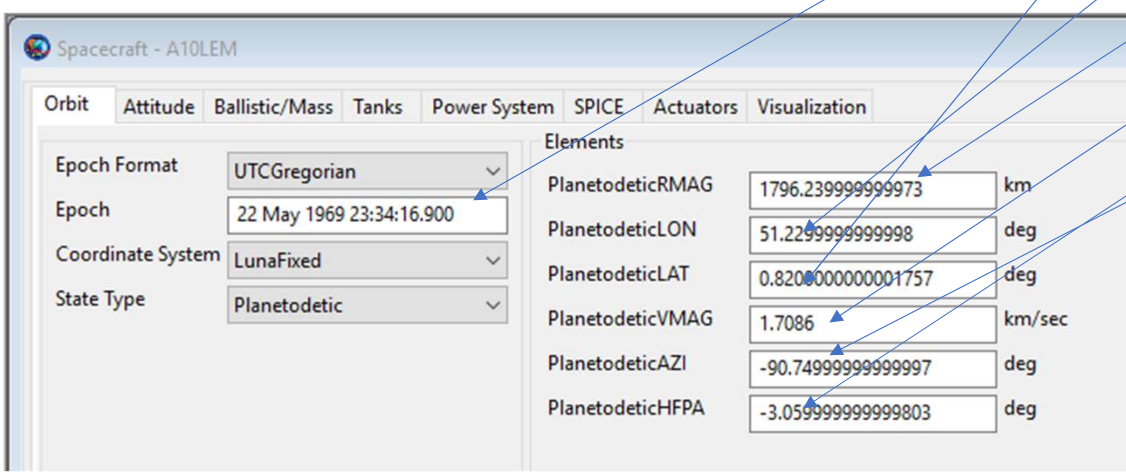


Entering Mission Report Values into GMAT

- Using LunaFixed Coordinates, one can plug in values from Mission Report into the Planetodetic Spacecraft State (after conversions)

TABLE 6-II.– TRAJECTORY PARAMETERS

Event	Ref. body	Time, hr:min:sec	Latitude, deg	Longitude, deg	Altitude, miles	Space-fixed velocity, ft/sec	Space-fixed flight-path angle, deg	Space-fixed heading angle, deg E of N
Cutoff	Moon	100:59:05.9	0.34S	13.67W	19.0	5 672.9	1.88	-91.05
Staging	Moon	102:45:16.9	0.82N	51.23E	31.4	5 605.6	-3.06	-90.75
Ascent orbit insertion								



RMAG -> Altitude + Moon Radius
LON -> Longitude
LAT -> Latitude
VMAG -> Velocity
AZI -> Heading angle
HFPA -> Flight Path Angle

See next page for notes and caveats!

Entering Mission Report Values into GMAT

RMAG: Altitude is relative to the landing site

- Convert nautical mile altitude to km
- Mean Lunar Radius is 1738 km
- Landing Site was -1.929 km below mean radius

Planetodetic VMAG is not the same as Inertial VMAG

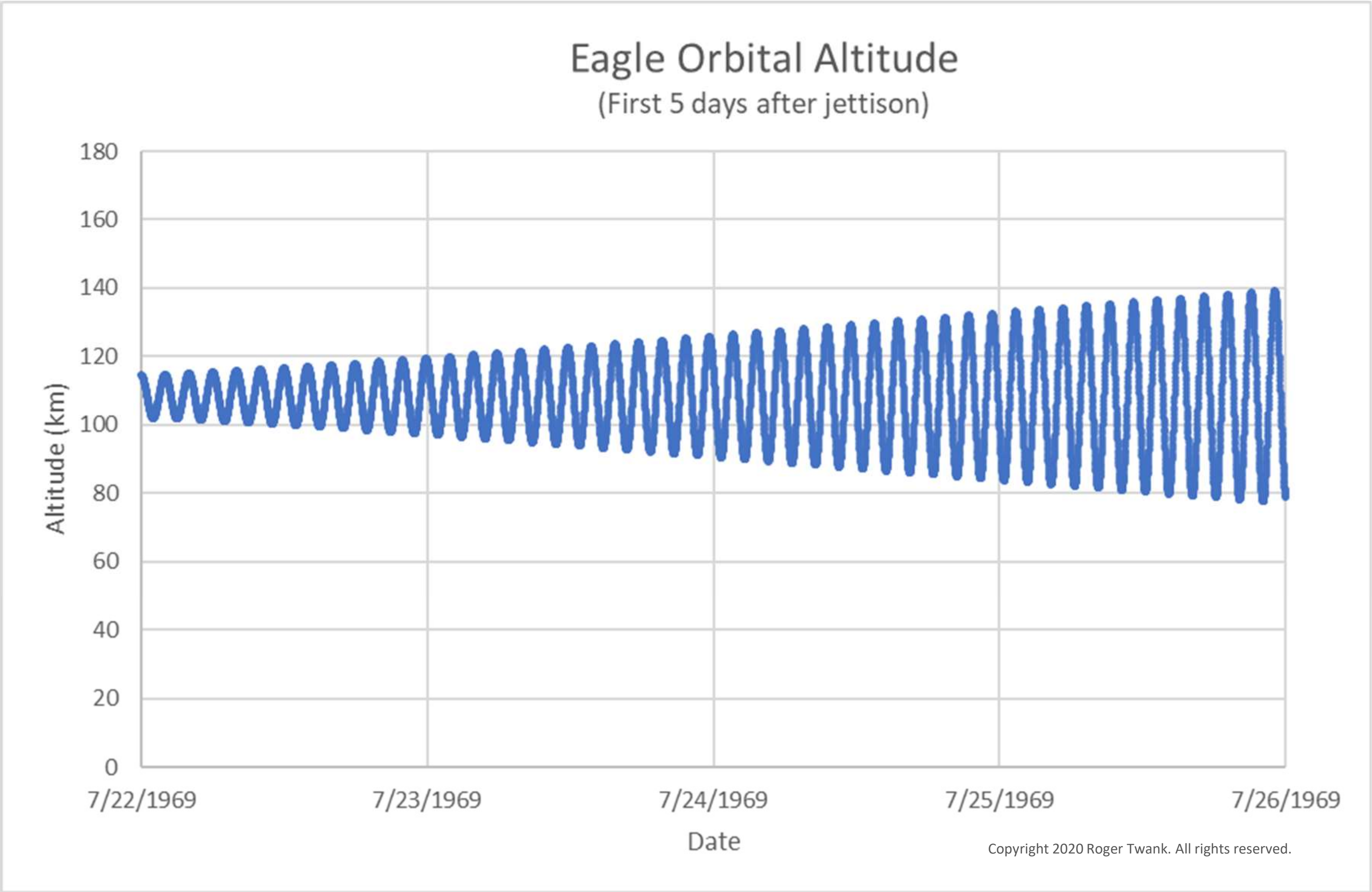
- Table 7-II velocity does not directly translate to LunaFixed coordinates
- Convert ft/sec to km/sec. This is the inertial VMAG.
- In the GMAT "Spacecraft" GUI change to SphericalAZFPA coordinates, then change to MoonInertial coordinate frame, and enter VMAG…in km/secs
- Change back to LunaFixed and Planetodetic, and GMAT converts VMAG to the value for that frame*
- Its about 4.9 m/sec faster due to Moon's rotational speed

HFPA and AZI also differ slightly between fixed and inertial coordinates

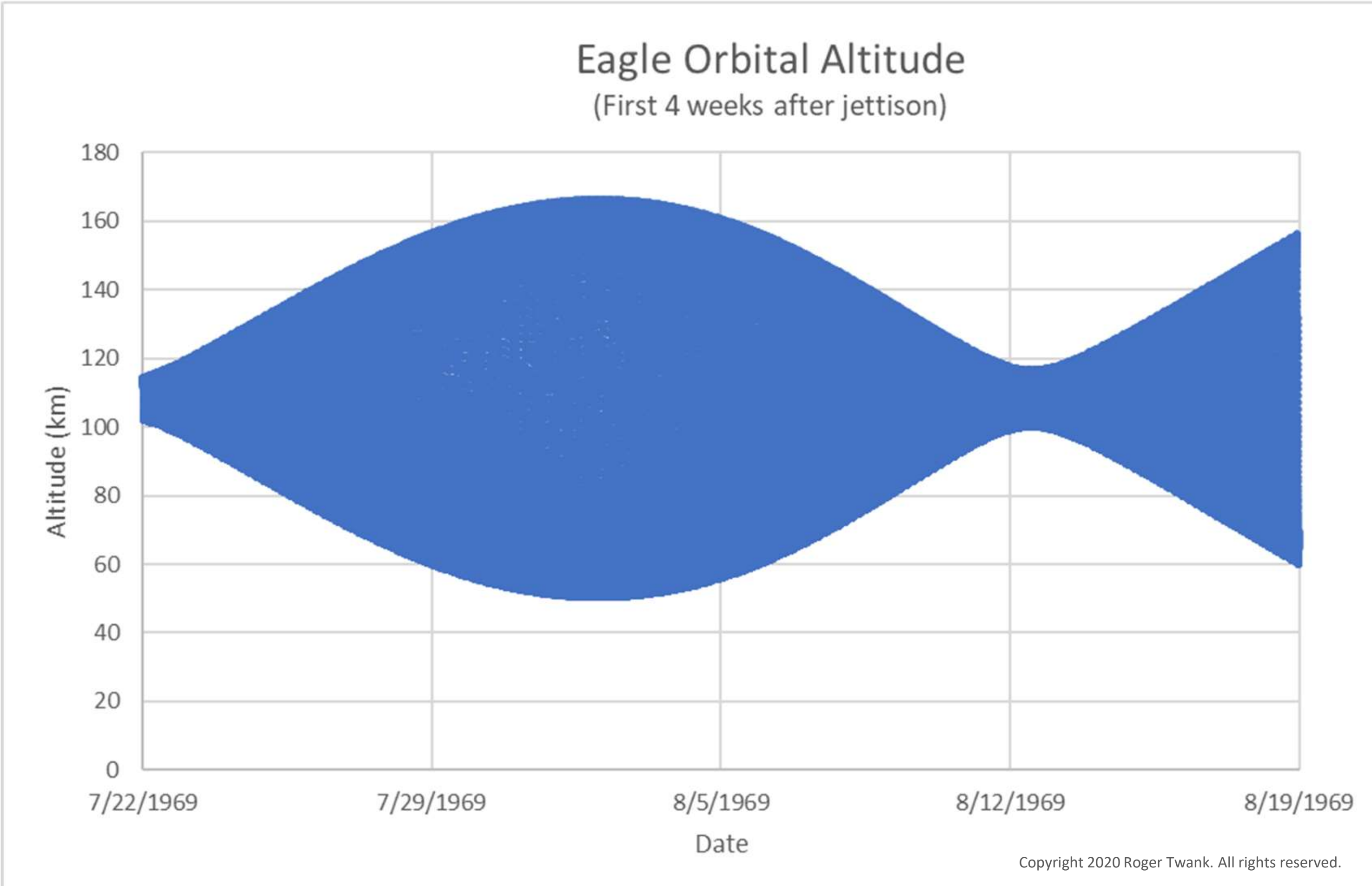
- Insignificant difference at low inclination…I ignore it

* There are better ways to do this in a script, but this works to get you started

Results

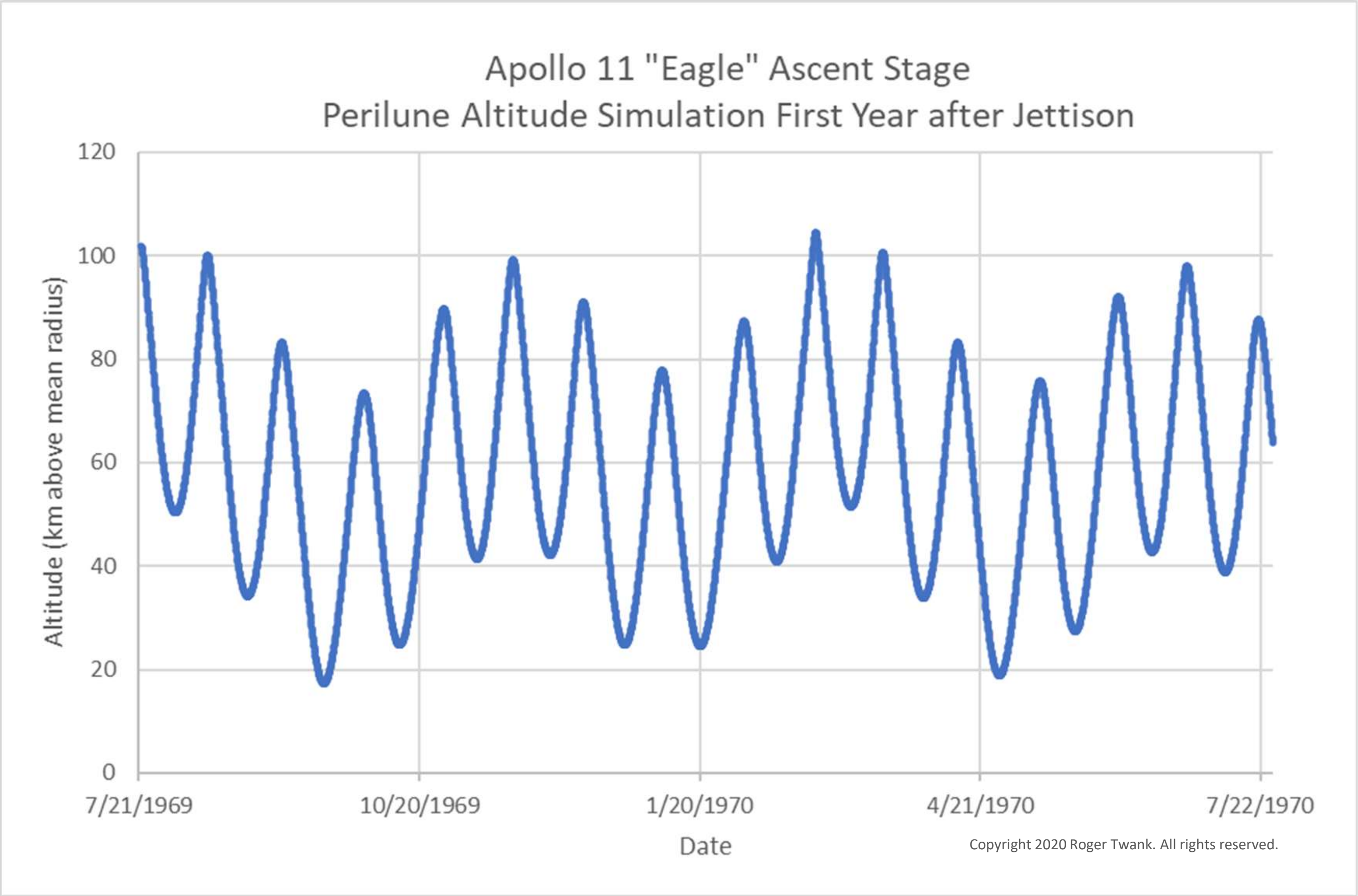


Eccentricity gradually increasing for the first week

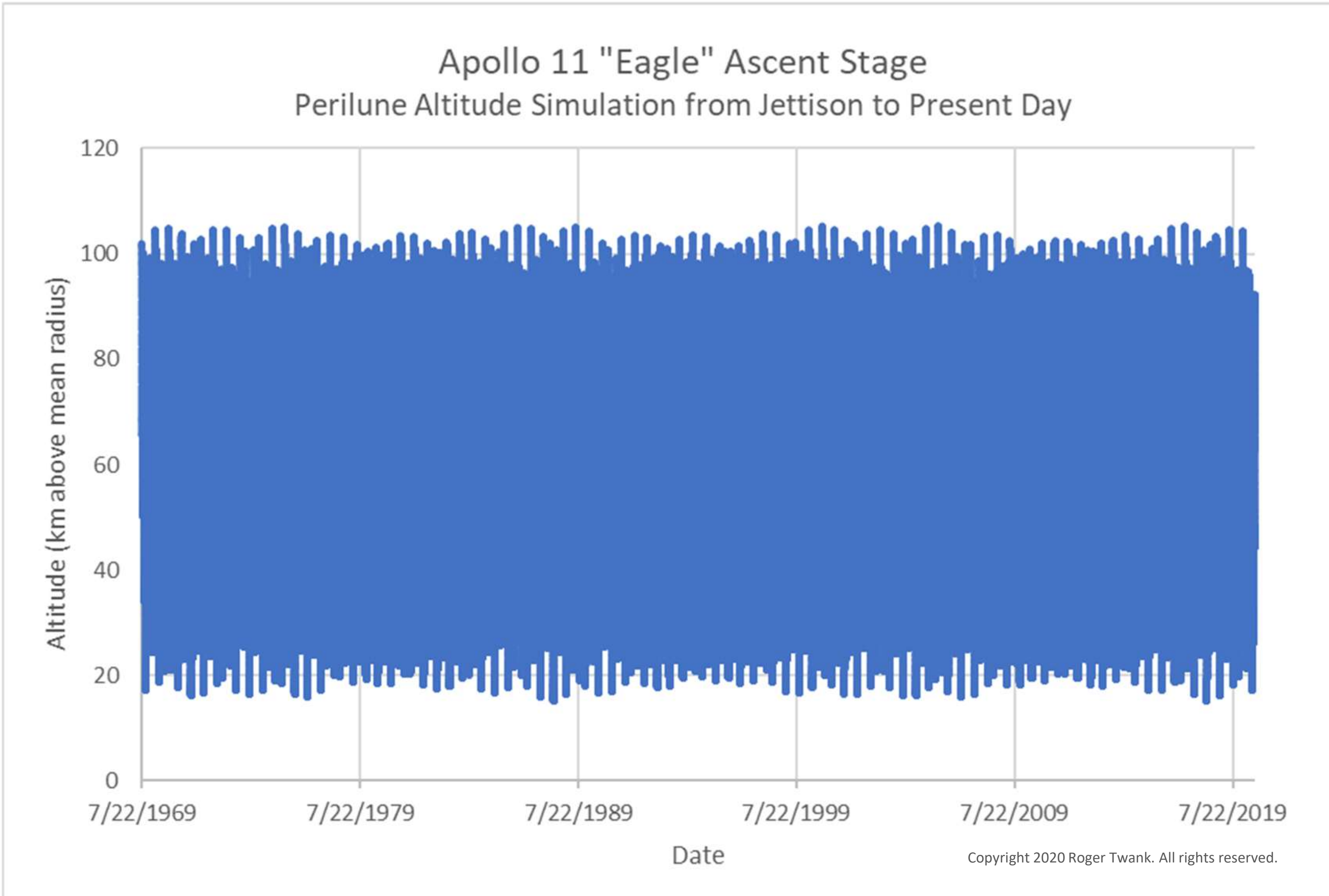


Eccentricity shows a cyclical pattern of increase and decrease

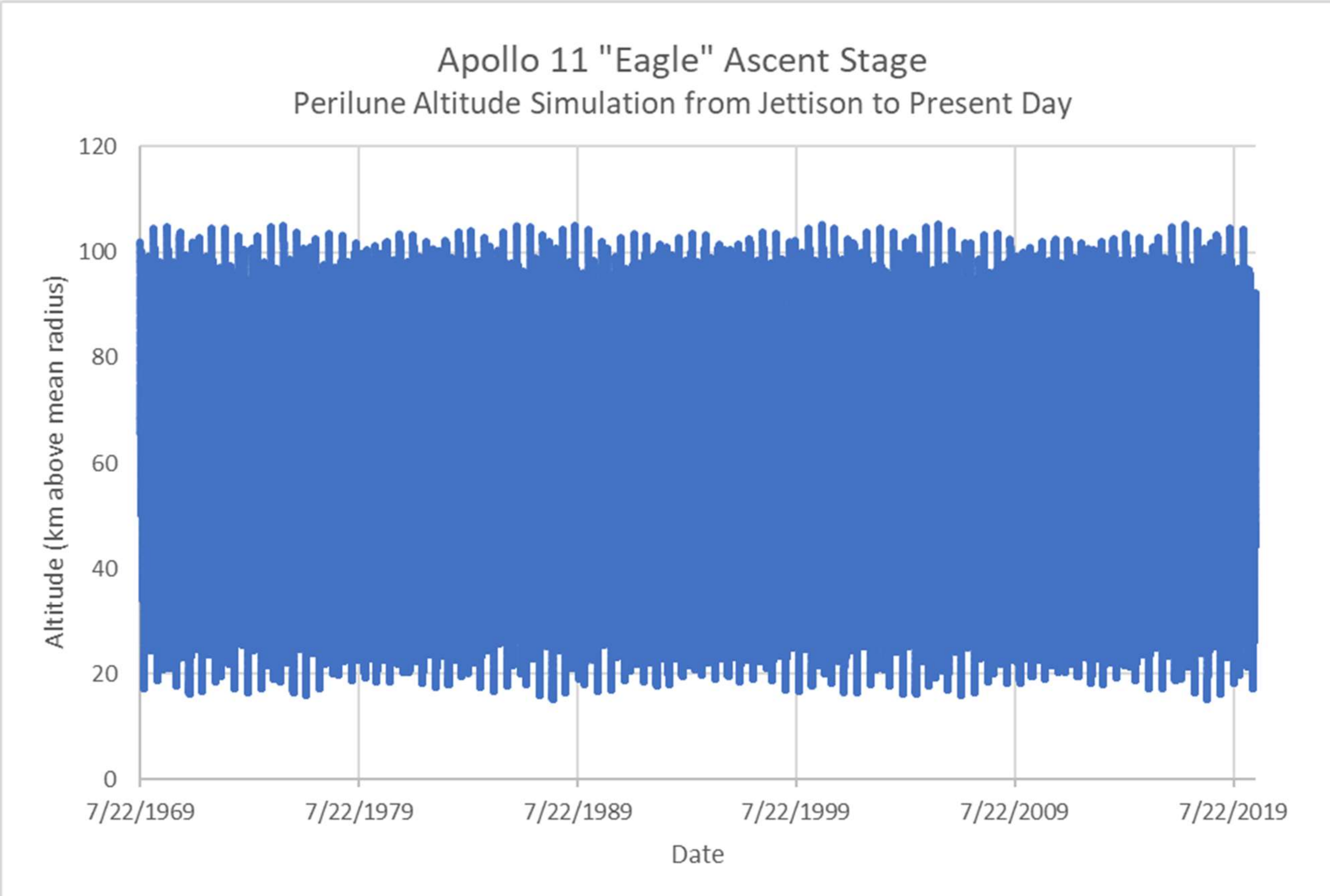
This plot only shows the minimum altitude of each orbit…the “Perilune”



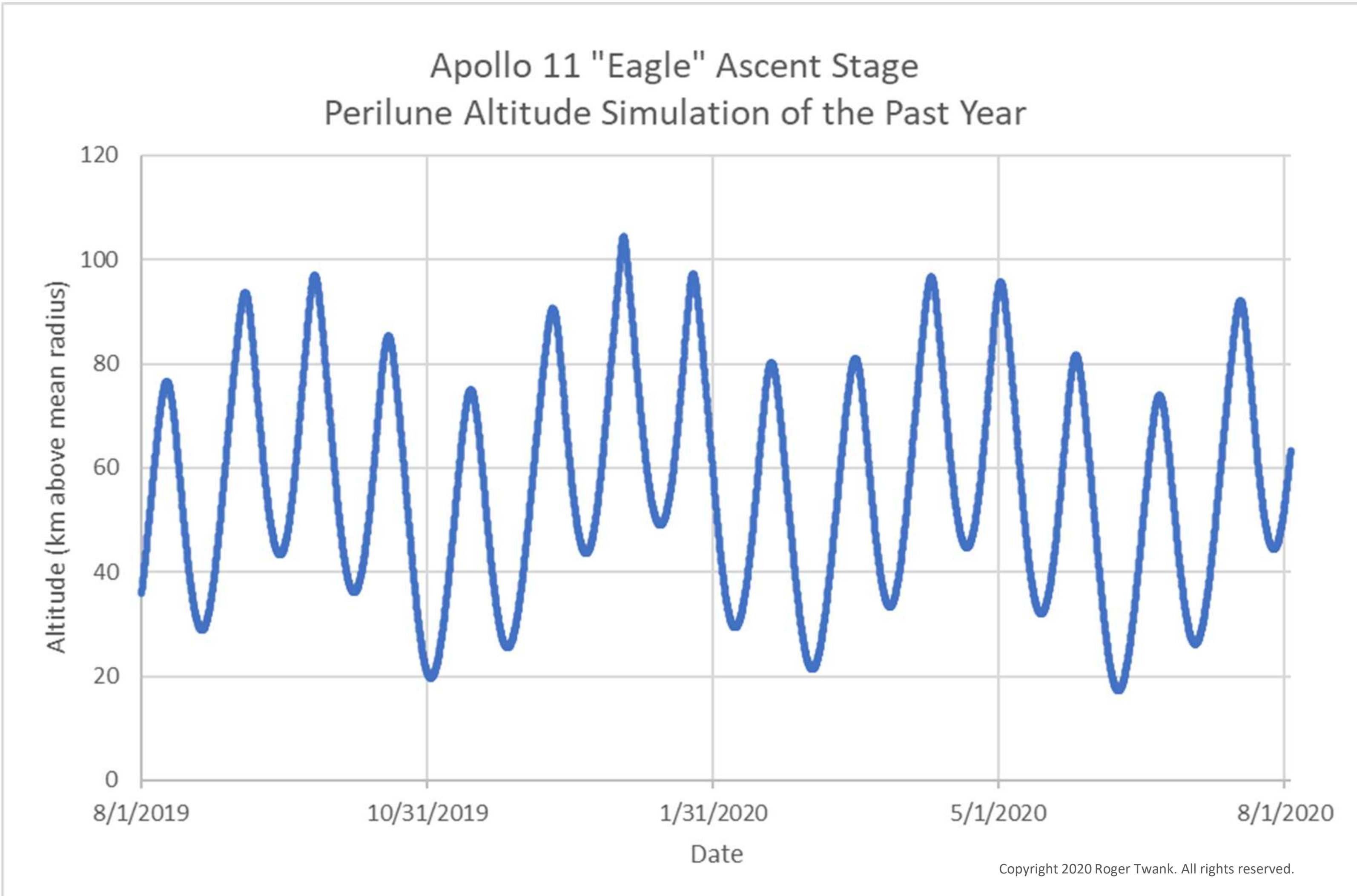
Eccentricity shows a cyclical pattern of increase and decrease



Cyclical pattern of eccentricity persists across decades



Apollo 11 "Eagle" Ascent Stage
Perilune Altitude Simulation from Jettison to Present Day
120
100
80
60
40
20
0
Altitude (km above mean radius)
7/22/1969
7/22/1979
7/22/1989
7/22/1999
7/22/2009
7/22/2019
Date



Cyclical pattern of eccentricity for the past year is similar to the first year

Cycles

- The cycles of eccentricity in the orbit are similar to what I found for the Apollo 10 descent stage (Snoopy)
- There is more about the cause of it on my blog…
  - https://snoopy.rogertwank.net/2020/02/a-deeper-understanding.html

102:45:58 Armstrong (onboard): Engine arm is off. Houston, Tr
Base here. The Eagle has landed.

102:46:06 Duke: Roger, Twank...Tranquility. We copy you on th
You got a bunch of guys about to turn blue. We're breathing aga
lot