Preliminary evaluation of multiple atmospheric re-entries in Lunar return missions

D A Grishko, V V Leonov, M A Ayrapetyan and O S Shvirkina

Bauman Moscow State Technical University, Moscow, Russia
E-mail: dim.gr@mail.ru

Abstract. The paper focuses on the usage of multiple atmospheric re-entries while coming back to the Earth in Lunar-return mission. In order to deal with the flight duration and thermal loads the pericentre altitude should be variable. After each passing through the atmosphere an apocentre becomes significantly lower, so it is possible to achieve required target orbit in several revolutions, starting with the higher initial pericentre altitude.

1. Introduction
To date, the missions of "Apollo" program are the only ones that successfully realized the manned spaceflights [1] to the Moon with landing on its surface in the period of 1969-1972. During these flights the astronauts managed to collect the samples of Lunar soil, to install the laser reflectors (so the accuracy of measuring the distance between the Earth and the Moon significantly augmented), to study how the Moon environment acts on humans and hardware and to carry out some scientific research experiments. Unfortunately, "Apollo" program was closed and Soviet Moon program followed it, so the Moon investigations have been frozen for a long time. During the last decade the interest to the Moon appeared again and was implemented in practice by Japanese mission "Kaguya", American missions LRO and LCROSS [2], space vehicles from Chinese "Chang’е“ program and Indian "Chandrayaan" program [3]. We can observe the perspectives of manned spaceflights to the Moon [4, 5], that is why here it will be reasonable to study an opportunity of Earth atmosphere usage by the descending modules in return phase of the Lunar mission. This idea, to reduce the velocity by multiple atmospheric re-entries, is not exactly a new one. It was first formulated in 60-s years of XX century, but then was not studied properly because of the closure of Moon programs both in the USA and USSR; also the possibilities of computational hardware of that time were rather limited. This study is focused on preliminary evaluation of trajectory that actively uses the atmospheric drag by the example of "Apollo" descending module. The main advantage of such scheme is that the module sustains short-time thermal overloads while fast passing through the pericentre region, then it orbits around the Earth and finally starts to descend in the atmosphere like the vehicles of "Soyuz" family usually do. Speaking about the flight safety, the described scheme is better than the direct atmospheric entry with near-parabolic velocity.

2. Simplified mathematical model of motion
It is required to get the evaluation of trajectory that uses the multiple atmospheric re-entries, that is why the motion of the descending module can be considered in a very simplified form. It is supposed, that at the initial moment of time the module crosses the sphere of influence of the Moon and comes back to the Earth, being located at the Hohmann ellipse [6]. The apocentre altitude is 100 km higher than the average distance between the Earth and the Moon, the altitude of pericentre is variable. The
following trajectory with respect to the Earth is considered to be plane, the atmosphere is taken into account when the module reaches the height 1500 km above the Earth. The simplified mathematical model of motion can be described in the inertial coordinate system, its centre is situated at the centre of the Earth:

\[
\begin{align*}
\dot{V}_x &= -\frac{\mu}{r^3} x - C_{xa} \cdot \frac{\rho v^2}{2} S_m \cdot \frac{V_x}{V}; \\
\dot{V}_y &= -\frac{\mu}{r^3} y - C_{xa} \cdot \frac{\rho v^2}{2} S_m \cdot \frac{V_y}{V}; \\
\dot{x} &= V_x; \\
\dot{y} &= V_y
\end{align*}
\]

Here \( r = \sqrt{x^2 + y^2} \) is magnitude of module's position vector, \( \mu = 398600.33 \text{ km}^3/\text{sec}^2 \) – Earth gravitational constant, \( v = \sqrt{v_x^2 + v_y^2} \) is magnitude of module's velocity, \( C_{xa} \) is drag coefficient (it is supposed that the module's longitudinal axis always coincides with velocity vector), \( \rho \) is atmosphere density, calculated using Russian standards GOST P 25645.166–2004 (heights 120-1500 km) and GOST 4401-81 (heights 0-120 km), \( S_m \) is cross-section square of the module. The system of equations (1) - (4) was solved using 4th order Runge-Kutta numerical integration with the constant time step.

3. Insertion into the orbit with 200 km apocentre altitude

The descending operations from the International Space Station are the most approved for today. That is why in this study we consider the scheme when using the multiple atmospheric re-entries the module first should be transferred to an orbit with the apocentre altitude of 200 km and only after that propulsion system should provide the module with a breaking impulse with the following landing on the Earth.

It is known, that while orbiting the Earth at low heights, the apocentre altitude decreases significantly faster than the altitude of pericentre. That is why, it is possible to create an orbit with the required altitude of apocentre during the several revolutions and the altitude of pericentre will be approximately the same as initial value.

The drag intensity depends on pericentre altitude and this is a non-linear function of height above the Earth. There is such an altitude of pericentre that will make it possible to create an orbit with 200 km apocentre just after the first passing through the atmosphere (figure 1). In case of the "Apollo"-type module this critical pericentre altitude is equal to 66.5 km. Such trajectory corresponds to the minimal flight time, also the module will have to overcome maximal thermal overloads.
While the pericentre altitude increases, the augmentation of flight time (before 200 km apocentre altitude is attained) does not change uniformly. If the initial altitude of pericentre is changed from 66.5 to 71 km, the module will be able to pass atmosphere twice. If this pericentre altitude is increased for 5-7 km more, four re-entries are possible. If we continue to increase the altitude of pericentre till 90 km, the module will do multiple atmospheric re-entries. In that case the thermal loads will be reduced, but the flight duration significantly augments because during the first revolutions the module goes far away from the height of geostationary orbit, this will lead to the multiple passing through the radiation belts and it seems to be bad in terms of health of crew members.

4. Variable apocentre altitude after the first pass through the atmosphere
The altitude of 200 km for apocentre altitude should not be considered as a fixed value. While coming back from the Moon the real inclination to the Earth equator may differ from the planned, so the special maneuver will be required. Such type of maneuver should be realized in equatorial part of the orbit and as far as possible from the Earth.

As we mentioned in previous chapter, the attainment of the target orbit should be done as fast as possible. At the same time, if the target apocentre altitude is equal to 200 km, it will lead to the extremely low (66.5 km) pericentre altitude and to the significant thermal loads. There is a solution for this problem: after the first passing through the atmosphere we can get an orbit with much higher apocentre and at the following revolutions we can speed up the degradation of orbit using the propulsion system of the module. So we will not only decrease the thermal loads, but also will get a new level of accuracy to control the parameters of the obtained open-ended orbit with respect to the landing regions. The figure 2 represents the dependence between the pericentre altitude of initial orbit and the target apocentre altitude of the orbit that will appear after the first passing through the atmosphere.
Figure 2. The dependence between the pericentre altitude of initial orbit and the target apocentre altitude of the orbit that will be obtained after the first passing through the atmosphere.

5. Attainment of the target apocentre altitude during several revolutions around the Earth
In chapter #3 and #4 we shown two ways how to increase the pericentre altitude of initial trajectory when approaching the Earth: increasing the number of re-entries in the atmosphere or increasing the target apocentre altitude. Both variants lead to the augmentation of flight duration, so let us compare them. The figure 3 contains the plot of flight duration as a function of pericentre altitude of initial trajectory. Each curve corresponds to the concrete target apocentre altitude, the points on each curve represent the number of atmospheric re-entries which are required to obtain this apocentre altitude.

Figure 3. The dependence of flight duration on pericentre altitude of initial trajectory for different target apocentre altitudes and different quantity of atmospheric re-entries.
At figure 3 we can observe the red dotted curve of flight duration, that corresponds to the target orbit with the altitude of apocentre equal to 200 km. One can see that if the pericentre altitude of initial trajectory is 72 km we can either achieve 200km altitude of apocentre with two atmospheric re-entries or approximately 20 000 km altitude in case of single re-entry. The attainment of 200 km apocentre altitude after three re-entries takes the same time as to reach the geostationary heights after one pass of the atmosphere.

6. Conclusion
The usage of descending module’s atmospheric braking makes it possible to achieve the near-Earth orbit with variable altitude of apocentre. If the initial pericentre altitude is low, then we obtain near-circular orbit and the flight duration is minimal, but at the same time the module will have to deal with significant thermal loads. If the initial pericentre altitude increases, it will lead to the elliptical orbit that degrades rather fast because its pericentre is situated in the upper atmosphere. The duration of each atmospheric re-entry remains approximately the same but the thermal overloads are lower due to the higher initial pericentre altitude. In order to decrease the flight duration it is possible to combine the primary atmospheric braking with the additional anti-velocity impulse after the current passing through the atmosphere.

7. References
[1] "Apollo Program Summary Report" 1975 NASA Report JSC-09423 [Internet resource]: https://www.hq.nasa.gov/alsj/APS-R-JSC-09423.pdf
[2] Keller J W, Petro N E and Vondrak R R 2016 Icarus 273 pp 2
[3] Shuanggen J, Sundaram A and Hiroshi A 2013 Advances in Space research 2(52) pp 285
[4] Murtazin R F 2014 Acta Astronautica 101 pp 151
[5] Grabois M R 2011 Acta Astronautica 68 pp 1353
[6] Hohman W 1925 Die Erreichbarkeit der Himmelskörper (Verlag Oldenbourg in München)

Acknowledgements
The research was supported by Russian Science Foundation (project No. 17-79-10450)