Influence of non-gravitational effects on the Centaur upper stage of the Surveyor 2 spacecraft

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Abstract. A small near-Earth asteroid, discovered by the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) on September 17, 2020, turned out to be a part of the Centaur upper stage of the Surveyor 2 spacecraft launched by NASA on September 20, 1966 and subsequently crashed. This object had moved in a heliocentric orbit until it was under the influence of Earth's gravitational field. As a result, a close approach to the Earth took place at a distance of about 50000 km on December 1, 2020. Despite the fact that the Centaur escaped back into a new orbit around the Sun in March 2021, it is of special interest for research, in particular, to consider the impact of non-gravitational effects on its orbital characteristics. Thus, it was calculated that the maximum displacement of the object trajectory due to the influence of solar radiation pressure over 15 years (the next close approach will take place in 2036) can be about 10.3-13.5 km, depending on the albedo. Estimations of the Yarkovsky effect showed that the magnitude of the expected change in the semi-major axis of Centaur’s orbit is from -8.1·10^{-13} to 1.6·10^{-13}, depending on the angle of its rotation.

1. Introduction
On September 17, 2020, a small near-Earth asteroid was detected by the Pan-STARRS at the Haleakala Observatory in Hawaii. The asteroid was given 2020 SO designation by the Minor Planet Center. However, the scientists at the Center for Near-Earth Objects Studies (CNEOS) at NASA’s Jet Propulsion Laboratory have suggested that 2020 SO is an artificial object since its orbit was unusually Earth-like. Astronomers around the world, including those at the Laboratory of Observational Astrometry at Pulkovo observatory, have conducted many observations of this object to improve the orbital elements, as well as to define its physical characteristics. Analysis of the orbit showed that 2020 SO approached the Earth several times over the decades. Moreover, one of the closest approaches, occurred in late September, 1966, matches with the launch date of the Surveyor 2 mission [1]. Spectroscopy observations also showed that the object composition is similar to 301 stainless steel [2], from which the Centaur upper stage was made. Some discrepancy in spectrum data can be attributed to the fact that the object has been in harsh conditions of space for a long time.

The Surveyor 2 lunar lander was launched aboard the Atlas-Centaur rocket booster on September 20, 1966. The spacecraft separated from the Centaur upper stage, which continued its movement past the Moon and disappeared in space. On September 23, 1966, the Surveyor 2 crashed onto the lunar surface as a result of control loss during the midcourse correction maneuver when one of its thrusters failed to ignite [1]. Meanwhile, the Centaur upper stage had moved around the Sun until it was influenced by
Earth's gravitational field. As a result, there was a close approach to the Earth at a distance of about 50000 km on December 1, 2020. The new data, obtained during this encounter, confirmed that 2020 SO is the Centaur upper stage [2]. Despite the fact that it escaped back into a new orbit around the Sun in March 2021, it is of great interest for research today. Particularly, it is worth calculating the influence of solar radiation pressure and the Yarkovsky effect since these non-gravitational effects obviously contribute to its orbital motion.

2. Results
The following initial data on the epoch 2459000.5 (2020-05-31) was taken for the Centaur upper stage:

- \( e = 0.03400029 \) — the eccentricity [3],
- \( a = 1.037130 \) au — the semi-major axis [3],
- \( H_V = 27.654 \) — the absolute magnitude in V band [3],
- \( D = 10 \) m — the diameter [4],
- \( n = 0.93315614^\circ/d \) — the mean motion [3],
- \( P = 0.0026 \) h — the rotation period [4],
- \( M = 179.787366^\circ \) — the mean anomaly [3],
- \( \delta = 0.15 \) — the geometric albedo derived from the formula [5]:
  \[
  \lg D = 3.122 - 0.5 \lg \delta - 0.2 H_V, 
  \]
- \( k = 1.07 \) — the optical coefficient derived from the formula [6]:
  \[
  k = 1 + 4 \delta/9. 
  \] (2)

The following physical characteristics were taken for 301 stainless steel:

- \( \rho = 7880 \) kg/m\(^3\) — the density [7],
- \( \varepsilon = 0.59 \) — the emissivity coefficient [8],
- \( K = 16 \) W/m·K — the thermal conductivity [7],
- \( C = 500 \) J/kg·K — the heat capacity [7].

It should be noted that the real physical characteristics may differ considerably from those given, since the space environment could significantly affect them.

Several values of the orientation of rotation axis (\( \gamma = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ \)) were chosen because the angle is unknown.

Calculations of solar radiation pressure influence were made using the numerical integration of motion equations. This method is described in detail in [9]. The next close approach will take place in 2036, therefore, 15 years were taken as the integration time. It stands to mention that solar radiation pressure is a non-linear process. The displacements along the heliocentric radius-vector \( \Delta r \) and the orbit \( \Delta l \), as well as the total displacement \( \Delta d \) are presented in table 1.

| Displacement (km) | \( \Delta r \) | \( \Delta l \) | \( \Delta d \) |
|-------------------|---------------|---------------|---------------|
|                   | 9.83          | 8.91          | 10.26         |

However, the results of radar observations [4] showed that Centaur’s albedo, on the contrary, is close to 1.0, which indicates a high reflectivity of its surface and corresponds to a steel. In this case, the optical coefficient \( k \), calculated using the equation (2), is equal to 1.44. Thus, the orbital displacements of the Centaur upper stage in the next 15 years were recalculated for \( \delta = 1.0 \). The results are presented in table 2.
The Yarkovsky effect was calculated using the Gauss-Everhart integrator [10]; the model was taken from [11, 12]. The results are given in table 3.

### Table 3. The components of radius-vector \( r (X, Y, Z) \) and velocity vector \( V_X, V_Y, V_Z \) of the Centaur upper stage in heliocentric coordinate system at the initial moment of integration (2020-05-31) and after one revolution around the Sun at different angles of orientation of rotation axis. The last column shows the values of semi-major axis \( a \) and the magnitudes of its change \( \Delta a \) due to the Yarkovsky effect.

| \( \varphi \)  | \( r (X, Y, Z) \) (au) | \( V_X, V_Y, V_Z \) (au/d) | \( a, \Delta a \) (au) |
|---------------|------------------------|---------------------------|------------------------|
| 0º            | -0.2375311290452       | 15.9190950375699·10^-3   | 1.0371299427710        |
|               | -1.0458557838083       | -3.6181558642544·10^-3   |                        |
|               | 0.0012543123136        | -0.0353459306308·10^-3   |                        |
|               | -0.2377238926181       | 15.9184048057000·10^-3   |                        |
|               | -0.10458119524664      | -3.6211936741335·10^-3   | 1.0371299427708        |
|               | 0.0012547403030        | -0.0353422866535·10^-3   | 1.646568864265·10^-13  |
| 45º           | -0.2377238917389       | 15.9184048102032·10^-3   | 1.0371299427713        |
|               | -0.10458119524626      | -3.6211936613280·10^-3   | 1.0371299427713        |
|               | 0.0012547403010        | -0.0353422866535·10^-3   | -2.8730420049134·10^-13|
| 90º           | -0.2377238907196       | 15.9184048154330·10^-3   | 1.0371299427718        |
|               | -0.10458119524577      | -3.6211396464875·10^-3   | 1.0371299427718        |
|               | 0.0012547402985        | -0.0353422866766·10^-3   | -8.0746840349368·10^-13|
| 135º          | -0.2377238912605       | 15.9184048126839·10^-3   | 1.0371299427715        |
|               | -1.0458119524586       | -3.6211936543801·10^-3   | -5.2016420300234·10^-13|
|               | 0.0012547402998        | -0.0353422866649·10^-3   | -1.646568864265·10^-13|
| 180º          | -0.2377238919415       | 15.9184048090208·10^-3   | 1.0371299427712        |
|               | -1.0458119524607       | -3.6211936643076·10^-3   | -1.646568864265·10^-13|
|               | 0.0012547403014        | -0.0353422866501·10^-3   |                        |

### 3. Conclusion

The influence of non-gravitational effects, such as solar radiation pressure and the Yarkovsky effect, on the motion of the Centaur upper stage of the Surveyor 2 spacecraft was considered in this article. It was shown that Centaur’s trajectory can be deviated by solar radiation pressure by the time of the next close approach to the Earth in 2036 by a maximum of 10.3-13.5 km, depending on the albedo, while the computation of the Yarkovsky effect showed that the magnitude of the expected change in the semi-major axis of Centaur’s orbit varies from -8.1·10^-13 to 1.6·10^-13, depending on the angle of its rotation. The Centaur upper stage is a small and light-weight object; therefore, non-gravitational forces affect it much more noticeably than a heavy and solid asteroid. This fact was also considered in establishing the real nature of this object. The results obtained in this article are estimates, and it is necessary to understand that the real physical characteristics of the Centaur can significantly differ from those given, since, firstly, it completed its mission and is empty of fuel now, and, secondly, its presence in harsh space environment could not but affect its features.

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