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Sputnik 1: **The Beginning of the Satellite Age**



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A Problem-Based Historical Narrative

1) The Dream of a Satellite and a Rocket That Was Not Yet Ready

May 1954 to January 1956, Moscow and Soviet design centers

Before the name Sputnik was heard around the world, Sergei Pavlovich Korolev, chief designer of the Soviet missile program, and Mikhail Tikhonravov had been pressing the Soviet government to pursue an artificial satellite capable of orbiting Earth. On 30 January 1956, the government approved development of a scientific satellite known as Object D, a large, instrumented spacecraft whose complexity would later become a major source of delay [1].



Figure 1 Sergei Korolev (1907–1966), the chief designer and leading architect of the Soviet space program. Credit: Mos.ru, licensed under CC BY 4.0.

On the other side of the emerging space competition, the United States had announced in July 1955 that it would place a scientific satellite in orbit as part of the International Geophysical Year (IGY). The American program was named Vanguard. One of the leading figures in the IGY effort was the American geophysicist Lloyd Berkner; he will reappear later in this story [2].

2) The Simplest Satellite for an Ambitious Goal

5 January to 15 February 1957, Moscow

By the beginning of 1957, Object D had fallen behind schedule. Korolev feared that the United States might place a satellite in orbit first. He therefore proposed postponing the larger spacecraft and instead building two much simpler satellites: Prosteishiy Sputnik-1 (PS-1) and Prosteishiy Sputnik-2 (PS-2). In Russian, prosteishiy sputnik means “simplest satellite.” The Soviet government approved the proposal on 15 February 1957 [3].

Prosteishiy Sputnik-1, later known simply as Sputnik 1, was an aluminum-alloy sphere about 58 cm in diameter with a mass of 83.6 kg. It contained batteries, two radio transmitters, a thermal-control system, a fan, and pressure and temperature sensors. Four rod antennas projected from the sphere. Korolev was unusually attentive to the quality and polish of its outer surface. During one test, angered by poor workmanship, he reportedly exclaimed, “This ball will be exhibited in museums!” [4].

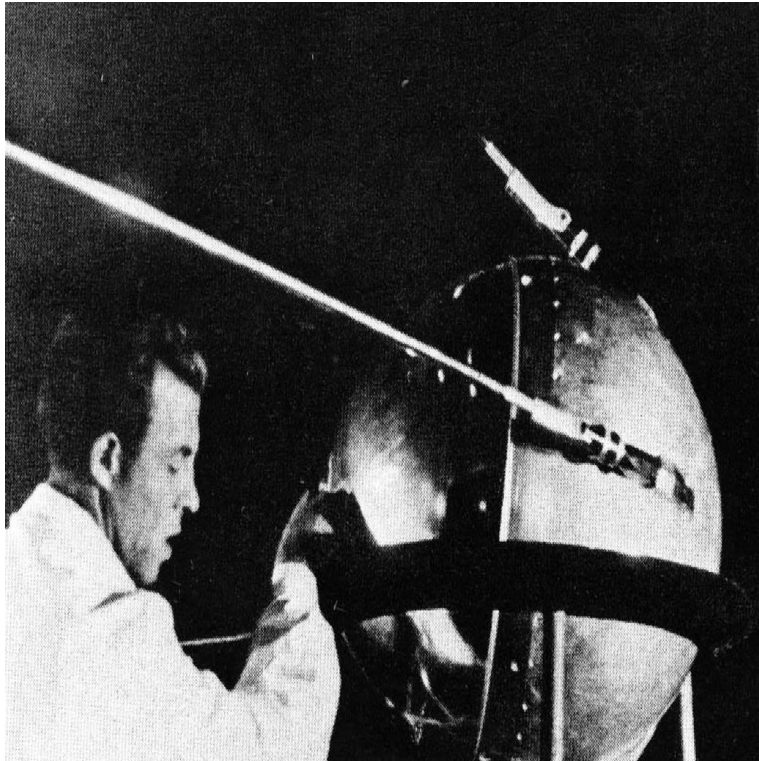


Figure 2) Sputnik 1 during final preparation before launch, 1957. Credit: NASA, Public Domain.

3) A Chain of Failures

15 May to 7 September 1957, rocket test range near Tyuratam, Soviet Kazakhstan

The first three R-7 test attempts in May-July 1957 were unsuccessful, severely disrupting Korolev's schedule. The fourth R-7 test, on 21 August, was successful, and another successful flight followed on 7 September [1], [4]. Korolev was now only weeks away from the possibility of making the Soviet Union the first nation to place an artificial satellite in Earth orbit.

4) The Rockets and Satellites Conference

30 September to 5 October 1957, Washington, D.C., United States

At the IGY Rockets and Satellites Conference, scientific representatives from several countries, including the United States and the Soviet Union, discussed rockets, satellite tracking, orbital calculations, and scientific instrumentation. The Soviet representative, Sergei M. Poloskov, spoke about his country's satellite plans. Those present knew that the Soviet Union intended to launch a satellite, but they did not know exactly when [5]. The Soviet State Commission had initially selected 6 October as the target launch date. Korolev, still worried that the United States might act first and misinterpreting plans for a paper at the Washington conference as a possible sign of an imminent American launch, proposed moving the Soviet attempt forward by two days. The launch was therefore advanced to 4 October [1], [6].

5) A 1.5-Kilometer Walk Beside a 29-Meter Giant

Early morning, 2 October 1957, Tyuratam, Soviet Kazakhstan

The modified R-7 with Sputnik mounted at its tip, more than 29 m long, was rolled from the assembly-and-test building toward the launch pad at the range later known as Baikonur [7]. Korolev and the other chief designers walked in front of the vehicle, covering the approximately 1.5 km route in silence [4].

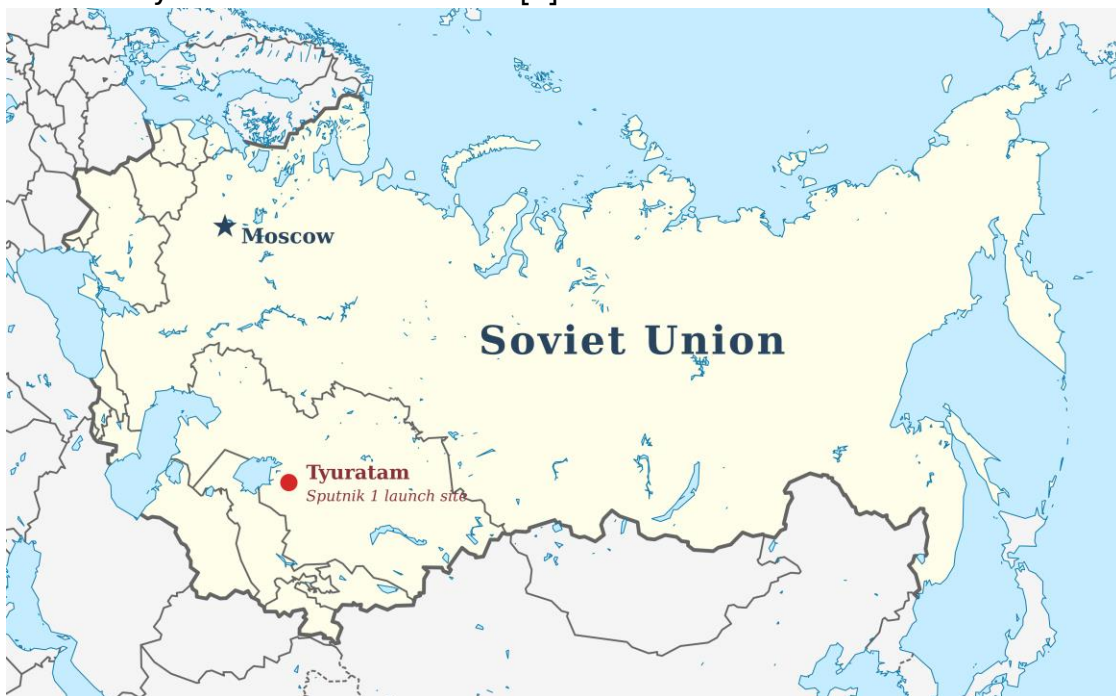


Figure 3) Sputnik 1 launch site near Tyuratam, Soviet Union. Base map: Hellerick, Wikimedia Commons, CC BY-SA 3.0; labels and location markers added.



6) The First Orbit

Friday, 4 October 1957, 22:28:34 Moscow Time, early hours of 5 October local time at Tyuratam (19:28:34 GMT/UT)

The R-7 engines ignited. A little more than five minutes later, PS-1 separated successfully from the core stage and entered an elliptical orbit [8]. For the first time in history, a human-made object had not merely reached space; it had attained the speed required to continue circling Earth. Korolev's long pursuit of being first had become reality.

Problem 1: Parameters of Sputnik 1's Initial Orbit

Use the following preliminary information:

The gravitational parameter $\mu = GM$ is the product of the universal gravitational constant and the mass of the central body. For Earth, its value is approximately $\mu = 3.986 \times 10^{14} \text{ m}^3/\text{s}^2$.

An ellipse has two principal axes. The major axis is its longest diameter, and the semi-major axis, denoted by a , is half of it. For an Earth-centered orbital ellipse, if the distances of perigee and apogee from Earth's center are r_p and r_a , respectively, then:

$$a = \frac{r_p + r_a}{2}$$

For two bodies moving under their mutual gravitational attraction, the orbital period is given by the following form of Kepler's third law:

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

The vis-viva equation relates the speed of an object at a particular point in an elliptical orbit to its distance from the center of Earth:

$$v = \sqrt{\mu \left(\frac{2}{r} - \frac{1}{a} \right)}$$

Here r is the satellite's instantaneous distance from Earth's center. At perigee, r is smaller and the speed is greater; at apogee, r is larger and the speed is smaller. Thus orbital speed is not constant in an elliptical orbit.

Using the information above, model Sputnik 1's initial orbit as an ellipse with a perigee altitude of 228 km and an apogee altitude of 947 km. Take the mean radius of Earth to be 6371 km and answer the following questions.

- Find the distances of perigee and apogee from Earth's centre, and then determine the semi-major axis of the orbit.
- Use Kepler's third law to calculate Sputnik 1's orbital period and compare your result with the historical value of approximately 96.2 min.
- Use the vis-viva equation to calculate Sputnik 1's speed at perigee and apogee. Explain physically why the two speeds differ.



- d) Until separation, Sputnik 1 and the R-7 core stage were nearly at the same position and shared almost the same translational velocity; the core stage also entered orbit. Does this imply that, after separation, the core stage and Sputnik 1 occupied exactly the same orbit? Explain.

Solution 1

a)

$$r_p = R_E + h_p = 6371 + 228 = 6599 \text{ km}$$

$$r_a = R_E + h_a = 6371 + 947 = 7318 \text{ km}$$

$$a = \frac{6599 + 7318}{2} = 6958.5 \text{ km} = 6.9585 \times 10^6 \text{ m}$$

$$T = 2\pi \sqrt{\frac{(6.9585 \times 10^6)^3}{3.986 \times 10^{14}}} \approx 5776.8 \text{ s} \approx 96.28 \text{ min}$$

This result is very close to the historical value of about 96.2 min. The small difference reflects rounding of the altitude data and gravitational parameter, together with the idealized two-body model.

- b) Using the values of r_p and r_a obtained in part a):

$$v_p = \sqrt{3.986 \times 10^{14} \left(\frac{2}{6.599 \times 10^6} - \frac{1}{6.9585 \times 10^6} \right)}$$

$$v_p \approx 7.970 \times 10^3 \text{ m/s} \approx 7.97 \text{ km/s}$$

$$v_a = \sqrt{3.986 \times 10^{14} \left(\frac{2}{7.318 \times 10^6} - \frac{1}{6.9585 \times 10^6} \right)}$$

$$v_a \approx 7.187 \times 10^3 \text{ m/s} \approx 7.19 \text{ km/s}$$

Contemporary descriptions commonly summarized Sputnik's orbital speed as about 8 km/s [9].

In the two-body model, mechanical energy is conserved. As the satellite moves closer to Earth, gravitational potential energy decreases while kinetic energy increases. Its speed is therefore greatest at perigee and smallest at apogee; Sputnik's speed was not constant along its elliptical orbit.

- c) No. Immediately before separation, the core stage and Sputnik 1 had nearly the same state of motion. After separation, however, even a small relative separation velocity, together with differences in ballistic properties and subsequent perturbations, is sufficient to place them in very similar but not exactly identical orbits.

7) Beep... Beep... "I'm Alive."

4 October 1957, Moscow Time (early hours of 5 October at Tyuratam), near the launch pad, shortly after launch

A group of engineers waited in a vehicle about 800 m from the launch pad for confirmation from the spacecraft. Only a few minutes after launch, the radio pulses were received: beep... beep... Sputnik was operating [8].

Sputnik 1 carried two radio transmitters operating at 20.005 MHz and 40.002 MHz. They transmitted keyed radio-frequency pulses, typically a few tenths of a second long. Changes in pulse timing could encode simple information about internal pressure and temperature, while ground receivers converted the radio signal into the familiar audible “beep” [1], [10].

Problem 2: Doppler Shift of Sputnik 1

In a radio link, if the distance between the transmitter and receiver changes, the received frequency differs from the transmitted frequency, a phenomenon known as the Doppler effect. For speeds much smaller than the speed of light, the following nonrelativistic approximation may be used:

$$\Delta f \approx -(v_r/c)f_0$$

Here f_0 is the transmitted frequency, c is the speed of light, and v_r is the rate of change of transmitter-receiver distance¹. If that distance is decreasing, v_r is negative; in that case the received frequency is greater than the transmitted frequency.

$$v_r = dR/dt$$

If the satellite approaches the receiver, R decreases and $v_r < 0$. If it recedes, $v_r > 0$. Let the satellite’s altitude above Earth’s surface be h , Earth’s radius be R_E , and let θ be the central angle between the Earth-center-to-satellite direction and the Earth-center-to-receiver direction. Then the line-of-sight distance is $R = \sqrt{R_E^2 + r^2 - 2rR_E \cos\theta}$. The satellite’s geocentric distance is $r = R_E + h$. In the expression above, the time-dependent quantities on the right-hand side are r and θ . If the elliptical orbit is approximated as circular, r is constant and only θ varies with time.

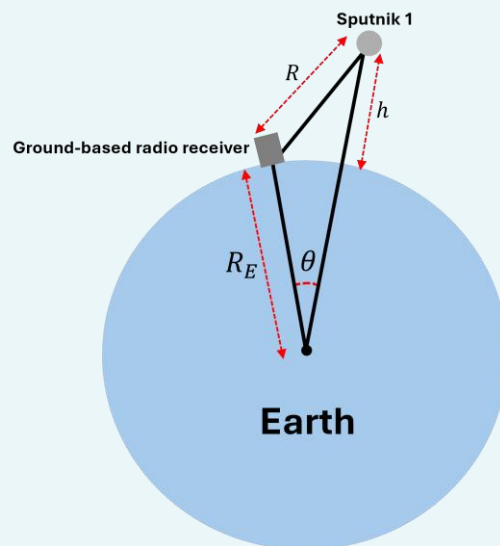


Figure 4) Earth-satellite geometry for the Doppler-shift model in Problem 2. Diagram not to scale.

¹ For satellite motion, the Doppler effect depends not on the satellite's full orbital speed, but only on the component of velocity along the line of sight between the satellite and the receiver. This component is called the radial velocity, or range rate.



- a) Using the definitions above and approximating the orbit as circular, show that:

$$\frac{dR}{dt} = \frac{rR_E \sin \theta}{R} \omega$$

where $\omega = \frac{d\theta}{dt}$ is the satellite's angular rate.

- b) Consider Sputnik 1's transmitter at $f_0 = 20.005$ MHz. At an instant when $\theta = 3^\circ$, estimate the Doppler shift.

Use $h = 250$ km, $R_E = 6371$ km, $\mu = 3.986 \times 10^{14} \frac{\text{m}^3}{\text{s}^2}$, $c = 3.00 \times 10^8$ m/s.

- c) What can a ground receiver infer from the measured Doppler shift about the satellite's motion and relative geometry? State the limitations of such an inference.

Solution 2

- a) With the circular-orbit approximation, r and Earth's radius are constant, while R and θ vary with time. From the geometry: $R^2 = R_E^2 + r^2 - 2rR_E \cos \theta$
Differentiate both sides with respect to time:

$$2R \frac{dR}{dt} = 2rR_E \sin \theta \frac{d\theta}{dt}$$

$$v_r = \frac{dR}{dt} = \frac{rR_E \sin \theta}{R} \frac{d\theta}{dt} = \frac{rR_E \sin \theta}{R} \omega$$

The sign of v_r gives the direction of range change: negative while approaching and positive while receding. The derivative written above corresponds to increasing θ , i.e., the receding branch.

- b) $r = R_E + h = 6371 + 250 = 6621$ km $= 6.621 \times 10^6$ m
 $R = 10^3 \sqrt{6371^2 + 6621^2 - 2 \times 6621 \times 6371 \cos 3^\circ} \approx 4.22 \times 10^5$ m
 $\omega = \sqrt{\mu/r^3} = \sqrt{3.986 \times 10^{14} / (6621 \times 10^3)^3} \approx 1.172 \times 10^{-3}$ rad/s
 $v_r = \frac{rR_E \sin 3^\circ}{R} \omega = \frac{6621 \times 6371 \times 0.052}{422} \times 1.172 \times 10^{-3} \approx 6.13 \times 10^3$ m/s

The differentiation above assumes increasing θ and therefore a receding satellite. If the satellite is approaching at this instant, the sign is reversed and $v_r = -6.13 \times 10^3$ m/s. For the approaching case:

$$\Delta f \approx -\left(\frac{v_r}{c}\right) f_0 \approx -\left(\frac{-6.13 \times 10^3}{3.00 \times 10^8}\right) (20.005 \times 10^6) \approx +4.09 \times 10^2 \text{ Hz}$$

- c) The receiver compares the known transmitted frequency with the received frequency and obtains their difference, the Doppler shift. Using the same relations in reverse, and assuming the simplified circular model with the altitude and other orbital parameters known, the measurement can be used to estimate the angle that describes the satellite's position relative to the receiver. However, a single Doppler measurement does not by itself determine a unique three-dimensional satellite position; real tracking uses a time series of measurements together with additional orbital information.

8) The Same Day, Thousands of Kilometers Away in Washington

4 October 1957, about 18:15 EDT (22:15 GMT), Washington, D.C., United States

Participants in the week-long IGY Rockets and Satellites Conference had gathered at the Soviet Embassy for a reception marking the end of the meeting. Walter Sullivan, science reporter for The New York Times, received word of the launch by telephone. The news reached Lloyd Berkner, the geophysicist introduced earlier, who called for the room's attention and announced [5]:

"I have just been informed by the New York Times that a Russian satellite is in orbit at an elevation of 900 kilometers. I wish to congratulate our Soviet colleagues on their achievement."

Korolev was not in Washington to hear the congratulations. He was at Tyuratam, where the satellite had just begun its first hours in orbit [5].

By the time Radio Moscow made its official announcement, Sputnik had already passed over the United States twice without the general public realizing it [5].

Problem 3: Seeing It Again

Take Sputnik 1's orbital period to be $T_s = 96.2$ min and, in a simplified model, take Earth's rotation period to be $T_E = 24$ h = 1440 min and Earth's radius to be $R_E = 6371$ km.

Assume that the satellite's orbital plane remains fixed relative to inertial space over one day, approximate the orbit as circular, and neglect small real changes in the orbit as well as the difference between a solar day and a sidereal day.

- Approximately how many orbits does Sputnik 1 complete in 24 h?
- Show that after 24 h the satellite is still slightly short of returning to the same point in its orbit as on the previous day. Express this shortfall as an angle in degrees.
- Suppose Sputnik 1 passes directly overhead an observer at a particular clock time. In this simplified model, approximately how far would the observer have to move along Earth's surface so that, 24 h later at the same clock time, the satellite would again be directly overhead?
- Should this displacement be in the same direction as the satellite's motion along its ground track, or in the opposite direction? Explain.

Solution 3

- $$N = 1440/96.2 \approx 14.97$$

Thus Sputnik completes about 15 orbits per day, but not quite 15 full orbits.
- $$15 \times 96.2 = 1443 \text{ min}$$

Therefore 15 complete orbits require 3 min more than one 24 h day:

$$1443 - 1440 = 3 \text{ min}$$

The satellite moves through 360° in one complete orbit. The angular distance corresponding to 3 min is therefore: $\Delta\theta = 360^\circ \times (3/96.2) \approx 11.23^\circ$

Thus, at the same clock time on the following day, the satellite is still about 11.2° short of the orbital position it occupied the previous day.

- c) To convert this angular separation to an approximate surface distance s , use the arc-length relation: $s = R_E \theta$

First convert the angle to radians: $\theta = 11.23^\circ \times (\pi/180) \approx 0.196 \text{ rad}$

$$s \approx 6371 \times 0.196 \approx 1250 \text{ km}$$

The observer would therefore need to move approximately 1250 km along Earth's surface in this idealized model.

- d) After 24 h, the satellite has not yet reached the point at which it passed over the observer on the previous day. The observer would therefore have to move toward the satellite's current sub-satellite point, opposite to the satellite's direction of motion along the idealized ground track.

9) The News Crosses Borders

Early hours of 5 October 1957, Barcelona, Spain

In Barcelona, the Eighth International Astronautical Congress was under way. Some participants, including science-fiction writer Arthur C. Clarke, reportedly learned the news when journalists woke them to obtain their reactions. A subject long associated with science fiction had suddenly become front-page reality [5].

11 October 1957, near Manchester, north-west England

In Britain, the large radio telescope at Jodrell Bank, whose construction had been dogged by financial difficulty, suddenly acquired an unexpected role after Sputnik's launch. On 11 October, Jodrell Bank successfully tracked the much larger carrier rocket that had placed Sputnik in orbit [11]. The episode demonstrated the new telescope's strategic and scientific value and helped secure its early operational future.

10) Orbiting in Silence, and the End of the Flight

26 October 1957, Earth orbit

After about three weeks, Sputnik 1's batteries were exhausted and its transmitters fell silent. The spacecraft stopped sending radio signals but remained in orbit [12].

4 January 1958, Earth orbit

Atmospheric drag in the tenuous upper atmosphere gradually removed orbital energy, causing Sputnik 1's orbit to decay. On 4 January 1958 the satellite re-entered the atmosphere and was destroyed [12]. The Soviet team around Korolev had little time to rest; its next missions were already under way.

Several other major events unfolded while Sputnik 1 was still in orbit. On 3 November 1957 the Soviet Union launched Sputnik 2, carrying Laika, a small female dog of roughly

5-6 kg, who became the first animal to orbit Earth. No recovery system was provided, and Laika died within hours when the spacecraft overheated [13]. Before the flight, physician Vladimir Yazdovsky reportedly took Laika home so that she could spend time with his children [13].

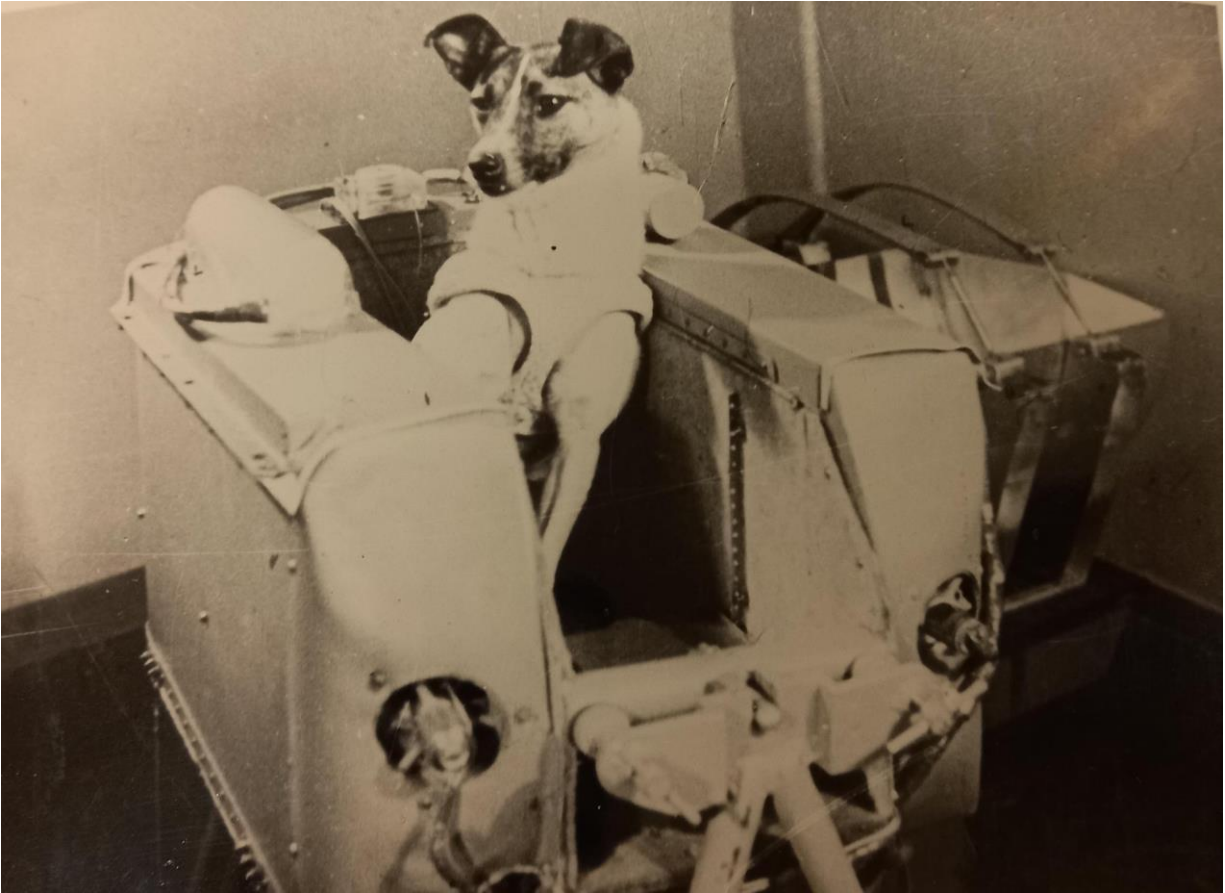


Figure 5) Laika in a mock cockpit. Public domain. Source: Wikimedia Commons.

On 6 December 1957 the United States attempted to launch Vanguard TV-3. The rocket rose only about 4 ft (1.2 m), lost thrust, fell back onto the pad, and exploded. Newspapers produced mocking names such as “Flopnik” and “Kaputnik” [14]. The small Vanguard satellite itself was thrown clear and recovered; contemporary accounts report that its transmitter was still operating after the accident [15]. It seems Korolev's prediction came true for this satellite rather than Sputnik. It ended up in a museum! On 31 January 1958, 27 days after Sputnik 1 re-entered, the Juno I launch vehicle placed Explorer 1 in orbit. It was the first successful U.S. satellite, and data from James Van Allen’s instruments contributed to the discovery of Earth’s radiation belts [16]. Soon afterward, on 17 March 1958, Vanguard 1 also reached orbit. It remains in orbit and is the oldest human-made satellite still circling Earth [17]. In the race to be first, the decisive moment came in October 1957; in the race to remain aloft, the story unfolded differently.

**Problem 4: What Can an Orbital Period Tell Us?**

For one revolution around Earth, take the initial orbital period of Sputnik 1 to be 96.2 min and that of Explorer 1 to be 114.8 min [9], [16].

- Determine the ratio of the semi-major axes of the two orbits.
- From these two periods alone, can the instantaneous speed of Explorer 1 at a particular point in its orbit be compared uniquely with the instantaneous speed of Sputnik 1 at a particular point in its orbit? Explain.
- For a simple comparison of velocity scale, now approximate both orbits as circular and take each orbital radius to equal its semi-major axis. Determine the ratio of their orbital speeds.
- Interpret the results physically. What does Explorer 1's longer period imply about the scale of its orbit?

Solution 4

- a) Because both satellites orbit Earth, the same terrestrial gravitational parameter applies. From Kepler's third law: $T^2 = \frac{4\pi^2}{\mu} a^3$

Therefore, for the two orbits: $T_E^2 / T_S^2 = a_E^3 / a_S^3$

$$a_E / a_S = (T_E / T_S)^{2/3} = (114.8 / 96.2)^{2/3} \approx 1.125$$

Thus Explorer 1's semi-major axis was approximately 1.125 times that of Sputnik 1, about 12.5% larger.

- No. The orbital period determines the semi-major axis, but the instantaneous speed in an elliptical orbit is not constant. A satellite moves faster near perigee and more slowly near apogee. To determine instantaneous speed, one also needs the satellite's position in the orbit, for example, its distance from Earth's center.
- Under the circular-orbit approximation:

$$v = \sqrt{\mu/a}$$

Therefore:

$$v_E / v_S = \sqrt{a_S / a_E} = 1 / \sqrt{1.125} \approx 0.943$$

In this approximation, Explorer 1's orbital speed is about 94.3% of Sputnik 1's, or about 5.7% lower. The same scaling follows directly from the circular-orbit relation $v \propto T^{-1/3}$.

- Since $T^2 \propto a^3$, a longer orbital period corresponds to a larger semi-major axis. Explorer 1's longer period therefore implies a larger orbital scale. The period alone, however, does not determine the orbit's eccentricity, perigee and apogee altitudes, or the satellite's instantaneous speed at a specified point. Note that the conclusions in parts (a) and (d) remain valid for elliptical Keplerian orbits because Kepler's third law involves the semi-major axis. Only part (c) introduces the circular-orbit approximation in order to compare characteristic speeds.

Alignment of the Problems with General Educational Goals and Content

Problem	Core scientific concepts	Mathematical and analytical skills	General educational goals and competencies
1 - Initial orbital parameters	Elliptical orbit, perigee and apogee, semi-major axis, Kepler's third law, vis-viva equation, orbital energy	Converting altitude to geocentric distance; powers and roots; substitution into equations; comparison with historical data	Modeling orbital motion; connecting geometry and dynamics; physical interpretation of changing speed; evaluating approximations
2 - Doppler shift	Radio-wave Doppler effect, radial velocity, line of sight, angular motion, Earth-satellite geometry	Law of cosines; differentiation with respect to time; sign analysis; calculating rates of change of range and frequency	Connecting geometry, motion, and waves; distinguishing total speed from line-of-sight speed; inferring motion from measurements while recognizing ambiguity
3 - Seeing it again	Orbital period, Earth's rotation, relative motion, satellite ground track, circular-orbit approximation	Ratios and proportions; converting time to angle; degree-radian conversion; arc length; estimation	Understanding reference frames and relative motion; building a simplified model of a real system; recognizing limits of approximation
4 - What an orbital period tells us	Kepler's third law, semi-major axis, circular versus elliptical orbits, orbital speed	Ratios; fractional powers; deriving scaling relations; percentage change; quantitative comparison	Determining what can and cannot be inferred from a measured quantity; distinguishing exact Keplerian conclusions from approximation-dependent results

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