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New Horizons Pluto–Kuiper Belt mission: design and simulation of the Pluto–Charon encounter☆

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Abstract

The primary goal of the New Horizons Pluto–Kuiper Belt mission is to explore Pluto by 2020, before Pluto's atmosphere collapses as predicted by scientists, and then explore the Kuiper Belt objects in an extended mission. The baseline mission plans to launch in January 2006, using a Jupiter gravity assist trajectory to reach Pluto. The New Horizons spacecraft will arrive at Pluto as early as 2015, depending on the launch vehicle. For such a mission, whose exploration takes place during a brief flyby period after a long cruise, a thorough planning of the encounter is especially critical to the realization of optimal science observations. A detailed Pluto encounter trajectory design that achieves both solar occultation and Earth occultation by both Pluto and Charon is described in this paper, along with discussions of the design rationale and considerations. Science observations and measurements planned for the Pluto–Charon encounter are simulated and analyzed, and a comprehensive Pluto–Charon encounter process filled with detailed science observation simulations is demonstrated in a 3-D animation.

1. Introduction

NASA's Pluto–Kuiper Belt (PKB) mission will be the first scientific reconnaissance exploration of Pluto and the Kuiper Belt objects. The spacecraft, New Horizons, will be sent to Pluto by the year 2020, before Pluto's atmosphere completely freezes to the ground as predicted by planetary scientists. New Horizons will conduct a series of science investigations on Pluto and its large moon, Charon, during a close flyby of the Pluto–Charon system. In an extended mission after the Pluto encounter, the spacecraft will visit one or more of the Kuiper Belt objects (KBOs) and observe them closely for the first time. First discovered [1] in 1992, the Kuiper Belt objects, which populate the region beyond the orbit of Neptune, are believed to be the key to the understanding of the early development of the solar system. In the recent solar system exploration survey conducted by the National Research Council [2], the Kuiper Belt and Pluto were rated the top priority mission for solar system exploration in the next decade.

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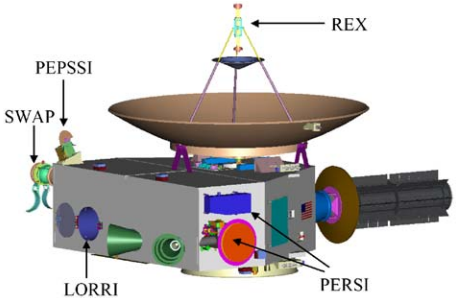

- Wet mass: 445 kg
- Power at Pluto: 220 W
- Communications: X-band, 2.1m high gain antenna
- Data downlink rate at Pluto: 768 bits per second
- Onboard data storage: 2×48 gigabits
- Attitude control: 3-axis and spin-stabilized modes
- Propulsion: Hydrazine monopropellant

Fig. 1. New Horizons spacecraft.

The PKB mission is being carried out by the Johns Hopkins University Applied Physics Laboratory, which is currently developing the mission and designing the spacecraft. Fig. 1 shows the New Horizons spacecraft and its main features. The PKB mission team, headed by Principle Investigator Dr. Alan Stern of the Southwest Research Institute, also includes Stanford University, the NASA Goddard Space Flight Center, and Ball Aerospace (for supporting the science payload development), the NASA Jet Propulsion Laboratory (for Deep Space Network tracking and spacecraft navigation), and Boeing (for providing the 3rd stage to the launch vehicle). The launch vehicle is expected to be selected by NASA at the end of December 2002.

The science payload [3,4] carried by New Horizons includes a core image package PERSI, a radio science instrument REX, a particle instrument PAM, and a high-resolution imager LORRI. PERSI, consisting of a visible imager MVIC, an infrared imager LEISA, and a UV spectrograph ALICE, will provide a global surface mapping and compositional spectroscopy of Pluto and Charon. REX is an up-link, passive radiometry designed for investigating Pluto's atmosphere, and it will probe the atmospheric structure and measure the surface temperatures of Pluto and Charon. Detecting charged particles using its two sensors PEPSSI and SWAP, PAM will analyze energetic particles and solar wind around Pluto and Charon. Complementary to PERSI's visible imager MVIC, LORRI's narrow angle and long focal length will allow it to take higher resolution images during the Pluto encounter (LORRI is also good for taking OpNav images at a great distance from Pluto).

2. Mission profile

Several mission scenarios [5] have been analyzed and considered since the Concept Study in 2001. The baseline mission design uses the Jupiter Gravity Assist (JGA) trajectory to reach Pluto as early as possible. The flight time to Pluto is a function of the launch energy, C_3, and the allowable maximum launch C_3 depends on the capability of the launch vehicle and spacecraft lift mass. With the spacecraft dry mass being reduced, the current baseline mission design calls for the arrival at Pluto as early as July 2015 after launch in 2006. However, the Pluto arrival time is subject to change until the launch vehicle is selected and its performance finalized. A general mission profile of the New Horizons PKB baseline mission is summarized in Table 1. Backup opportunities for launch in 2007 and 2008 also exist using the Pluto-direct trajectory, and New Horizons will then arrive at Pluto in 2019 or 2020.

The baseline mission plans for New Horizons to launch in January aboard either a Delta IV 4050H or an Atlas V 551 with a Boeing Star 48B upper stage from the Cape Canaveral Air Force Station, Florida. Fig. 2 shows an example of the integrated mission trajectory of New Horizons from launch to Pluto and beyond, displayed in a 3-dimensional view. Along a JGA trajectory, New Horizons will fly by Jupiter in February 2007, on its way to Pluto in order to gain energy and increase its flight speed towards Pluto. After a long cruise from Jupiter to Pluto of more than 8 years across the solar system, passing over the orbits of Saturn, Uranus, and Neptune, the spacecraft will arrive at Pluto in July 2015. It will continue to explore

Table 1
Baseline mission profile

Launch date	January 2006
Launch window	20 days
Maximum C_3	$166\,km^2/s^2$
Declination of launch asymptote	$-6°$–$-10°$
Launch vehicle	Delta IV 4050 H or Atlas V 551 with Boeing Star 48B upper stage
Trajectory to reach Pluto	Jupiter gravity assist
Jupiter flyby	February–March, 2007
Jupiter flyby distance	>32 Jupiter radii
Jupiter flyby velocity	20–21 km/s
Pluto arrival time	2015 or 2016 depending on launch vehicle
Pluto flyby speed	12.2–13.8 km/s
Pluto flyby distance (from center)	11,000 km
Solar distance at Pluto encounter	32.9 AU (2015 arrival)
Earth distance at Pluto encounter	31.9 AU (2015 arrival)
Kuiper Belt Object encounter	Expected as early as 2018
Nominal ΔV budget	300 m/s

the Kuiper Belt and encounter one or more KBOs before reaching the solar distance of 50 AU.

A comprehensive science investigation accompanied by a variety of measurements is to be executed during the Pluto–Charon flyby to accomplish the science objectives set for the PKB mission. Because of the complexity involved with measurement conditions and requirements for a particular geometry regarding the position of the spacecraft relative to Pluto, Charon, Earth, and Sun at the flyby, the Pluto encounter trajectory has to be carefully designed in order to meet all the science requirements.

3. Pluto encounter design requirement and goal

The goal for the Pluto–Charon encounter design is to optimize the encounter geometry and flyby trajectory under the arrival constraints to maximize the science accomplishments. The design of the spacecraft encounter trajectory and the selected Pluto encounter time should meet the requirements of the science observations and measurements in accordance with the capability of the spacecraft and its science payload.

3.1. Observation priority

In the encounter design, the observation selection follows the same priority order as defined for the science objectives. The highest priority is given to the observations for accomplishing the Group 1 science objectives defined by the NASA Science Definition Teams: the atmosphere of Pluto and global geology, morphology, and surface composition of Pluto and Charon. In the same measurement category, Pluto is considered the primary observation body. Since Charon also holds essential information for

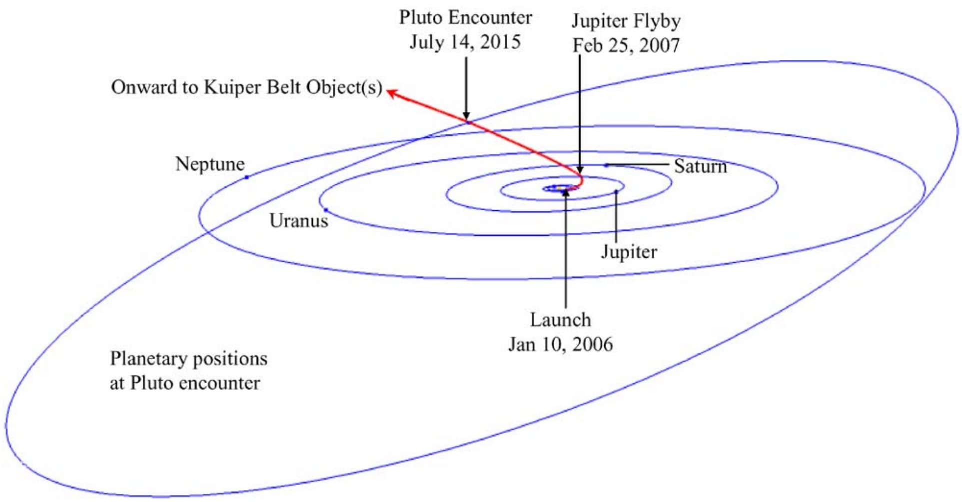

Fig. 2. New Horizons mission trajectory.

understanding the Pluto–Charon binary system, the mission is aimed at taking as many measurements at Charon as possible without undermining the fulfillment of Pluto objectives.

3.2. Requirements for remote sensing

The PERSI and LORRI instruments, through the visible imaging, IR spectral mapping, and UV measurements, carry out an investigation of the global geology, morphology, and surface composition for the PKB mission. The critical measurement conditions for the remote sensing are the solar phase angle and the flyby distance. The Pluto arrival condition determines the solar phase angle at encounter, while the appropriate flyby distance depends on the field of view (FOV) of the sensors. The flyby distance should be less than 25,000 km from the surface for visible imaging, resulting in a resolution better than 1 km per pixel, and less than 161,300 km from the surface for the IR mapping for achieving a resolution better than 10 km per pixel. An overall goal for remote sensing is to cover as much of the Pluto and Charon surfaces as possible.

3.3. Requirements for atmosphere investigation

The investigation of the atmosphere is implemented by measuring the UV and radio signals that travel through the atmosphere. The execution of these measurements will require that the spacecraft must pass through the solar and Earth occultation zones so that the UV signals emitted from the Sun and the radio signals transmitted from the Earth will propagate through the region surrounding Pluto and Charon before reaching the spacecraft. For Pluto, both solar occultation and Earth occultation are required by the science team; and for Charon, only the solar occultation is required, while the Earth occultation should be achieved if possible.

The REX instrument designed for the atmosphere measurements carried by New Horizons is an up-link-based passive radiometry. During the anticipated Earth occultation period, high-powered radio signals will be transmitted to the spacecraft from the Deep Space Network (DSN) stations; simultaneous transmission from two DSN stations to the spacecraft during the Earth occultation is highly desirable for improving the signal-to-noise ratio and providing redundancy.

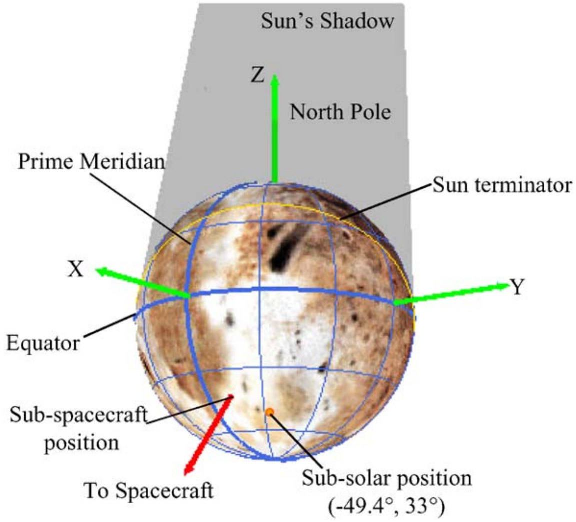

Fig. 3. View of Pluto at approach.

4. Pluto–Charon encounter design

Current encounter design selects a Pluto arrival date in July 2015, assuming that the launch vehicle is capable of delivering the New Horizons spacecraft at the required launch C_3. The spacecraft will arrive at Pluto from a heliocentric transfer trajectory inclined 2.4° above the ecliptic plane, as shown in Fig. 2. This heliocentric transfer orbit determines the conditions upon arrival at Pluto, including the direction of the incoming trajectory asymptote with respect to Pluto.

4.1. Pluto at approach

Fig. 3 displays a representative view of Pluto at approach. The spacecraft sub-position shown in the figure is at 10 days before its closest approach to Pluto. New Horizons approaches Pluto from the southern hemisphere at a solar phase angle of 15°, an excellent illumination condition for a full spectrum survey of Pluto and Charon on the approaching hemispheres. The sub-solar position is at latitude of 49° south, showing that the southern hemisphere is sunlit and the north cap is in the permanent Sun shade. Pluto rotates one revolution about every 6.4 Earth days.

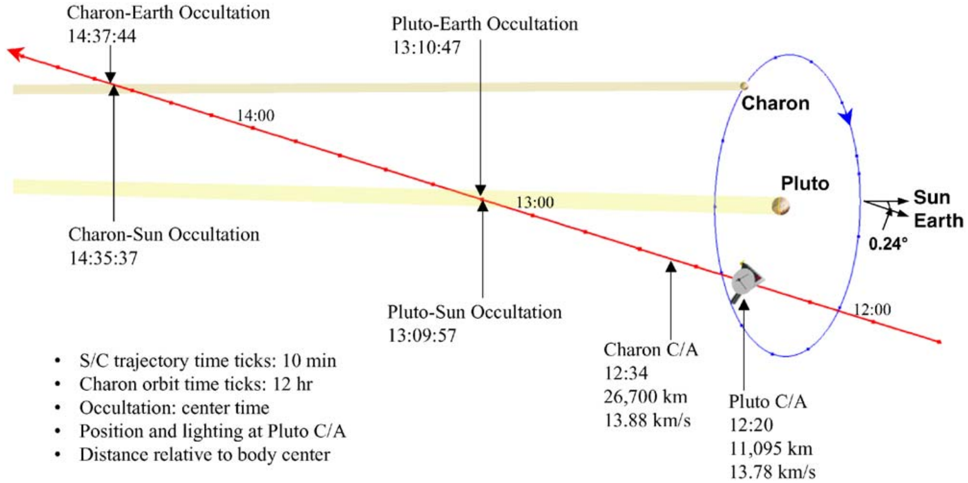

Fig. 4. Pluto–Charon encounter geometry on July 14, 2015.

4.2. Pluto–Charon encounter sequence

The New Horizons Pluto–Charon flyby sequence selects to encounter Pluto first and Charon second. This arrangement provides opportunities to acquire images of Pluto's surface area that is in the permanent Sun shade in the north cape. Sunlight reflected off of Charon's surface would illuminate the dark side of Pluto when it is positioned in front of Charon, analogous to the moonlight seen at night on Earth. Charon's large disk, about half the size of Pluto, is believed to be able to shed adequate light for imaging the dark surface of Pluto.

The Pluto–Charon encounter geometry is depicted in Fig. 4, showing the spacecraft flyby trajectory and the key events happening in the time sequence during the Pluto–Charon encounter. The encounter starts with the closest approach to Pluto taking place at 12:20 UTC time, followed with the closest approach to Charon 14 min later. Within the next 2 h, New Horizons continues to travel through the solar and Earth occultation zones of Pluto and Charon. Pluto occultation occurs first at about 46 min after Charon closest approach and the Charon occultation is 1 h and 25 min later. In both cases, the solar occultation starts before the Earth occultation but with a short time separation. Detailed encounter parameters are listed in Table 2.

Table 2
Pluto–Charon encounter parameters

Date of encounter	July 14, 2015
Solar distance	32.9 AU
Earth distance	31.9 AU
Pluto closest approach (C/A) time	12:20
Pluto C/A distance	11,095 km
Pluto C/A relative velocity	13.78 km/s
Charon C/A time	12:34
Charon C/A distance	26,700 km
Charon C/A relative velocity	13.88 km/s
Time of Sun occultation by Pluto	13:04:32–13:15:21
Time of Earth occultation by Pluto	13:05:18–13:16:16
Time of Sun occultation by Charon	14:32:50–14:38:23
Time of Earth occultation by Charon	14:34:55–14:40:33

Note: Time is in UTC. C/A distances are relative to object center.

As shown in Fig. 4, New Horizons flies by Pluto inside Charon's orbit. It crosses Charon's orbital plane at about 42°. Charon is orbiting Pluto in the retrograde direction, and the angle between Charon's orbit normal and the spacecraft's outgoing asymptote is about 132°. Charon's orbit around Pluto is nearly circular with a mean distance of 19,600 km and an orbit period of 6.387 Earth days. The considerable size of Charon (∼590 km radius) relative to Pluto (∼1200 km radius) causes the center of mass of the system to not fall within Pluto, a unique situation in the solar system.

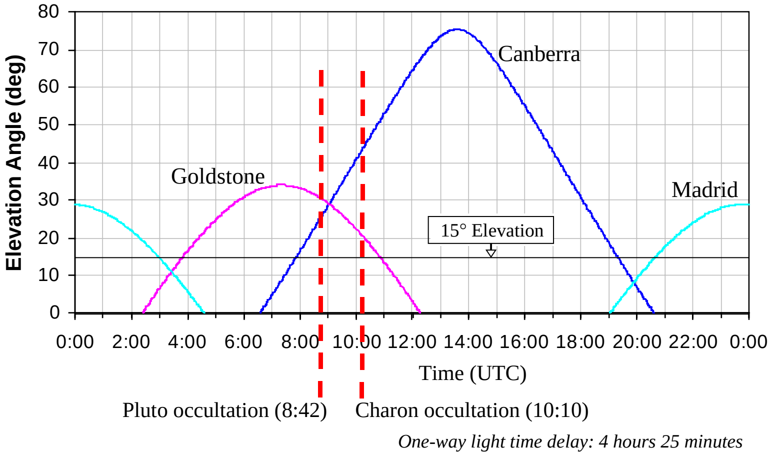

Fig. 5. DSN access profile.

4.3. Pluto and Charon occultation

The Pluto–Charon encounter design shown in Fig. 4 achieves both solar occultation and Earth occultation at both Pluto and Charon. During the Earth occultation when the REX measurements are to be conducted, two DSN stations are simultaneously accessible to the spacecraft. And the Pluto arrival date in July provides the best environments for uplink communications with the spacecraft.

Solar occultation and Earth occultation by Pluto and Charon are the essential elements required for the encounter science. They provide the means necessary for the atmosphere investigation. In order to achieve a high-resolution vertical profile of the atmosphere, diametric occultation is highly desirable. That is, the trajectory path of the spacecraft goes through the center of Pluto disk. Constrained by the Pluto arrival conditions, opportunities for achieving the diametric occultation of both Sun and Earth exist only when the Sun–Pluto–Earth angle is small; this is also the condition for obtaining both solar and Earth occultations at Charon. This opportunity occurs twice per year, one centered in January at the conjunction geometry and one centered in July at the opposition geometry. For the conjunction geometry, the Sun is positioned between Earth and Pluto, and this is the worst configuration for communications with the spacecraft from Earth. The July arrival at Pluto is selected for allowing diametric Earth and solar occultation at Pluto, both solar and Earth occultations at Charon, and the excellent communications links to the spacecraft during the Pluto–Charon encounter.

The REX measurements desire two simultaneous DSN uplinks to the spacecraft with elevation angles greater than 15° during the Earth occultation. Fig. 5 shows the DSN access profile at the Pluto–Charon encounter, where the elevation angles of the spacecraft viewed from the three DSN stations are plotted as a function of ground transmission time. Ground transmission time should be 4 h and 25 min earlier than the actual occultation time to account for the one-way light time delay. At the ground transmission time indicated in Fig. 5, two DSN stations, Canberra and Goldstone, have elevation angles greater than 15° and are therefore able to transmit to the spacecraft during the Earth occultation at both Pluto and Charon.

4.4. Outgoing trajectory

New Horizons will continue its journey to make encounters with the KBOs. One of the considerations in the Pluto encounter design is whether the outgoing trajectory of the spacecraft can be altered at the Pluto encounter by adjusting the B-plane aiming point so that it will fly towards the first KBO target. Calculations show that Pluto can hardly bend the spacecraft flyby trajectory because of its low mass and the relatively high spacecraft flyby speed. This is demonstrated in the encounter trajectory in Fig. 4, where the flyby trajectory is almost a straight line, implying that the Pluto flyby cannot help alter the spacecraft's trajectory towards KBOs and that trajectory change maneuvers are needed for targeting the KBOs.

5. Observation modeling and simulation

A 3-D animation simulating the Pluto–Charon encounter process was created for a July 2014 arrival scenario during the Concept Study. Although the planning for the Pluto arrival date has changed since then, the science observations planned for the Pluto–Charon encounter remains essentially the same. In the animation, detailed science observations covering 27 observations of different instruments over a 26 h period during the Pluto–Charon encounter are modeled and simulated.

The observations are simulated with realistic physical models of Pluto, Charon, spacecraft, and instruments. Motions of the spacecraft, as well as Pluto and Charon, are generated according to their true positions. The spacecraft's position is specified by the designed encounter trajectory, and the positions of Pluto and Charon are described by the planet and satellite ephemeris files. The science observations at the Pluto–Charon encounter are created based on the science observation sequence timeline prepared by the science team [6,7]. Instrument measurements are simulated according to the sensor's FOV and defined operation modes. Several coordinate systems, both spacecraft body-fixed and inertial reference frames, are established to fulfill the instrument pointing at a specific target and to implement the action into the spacecraft operations. The Spacecraft's maneuvers, including slewing and scanning during observations, are defined by the spacecraft attitude quaternion file that is modeled with both measurement requirements and spacecraft operation constraints. A few clips of the simulated observations from the animation are presented here.

5.1. UV surface sampling of Pluto

Fig. 6 illustrates the event of Pluto surface sampling by the UV imager, ALICE, several hours before the closest approach to Pluto. ALICE's FOV is $6.0^\circ \times 0.1^\circ$.

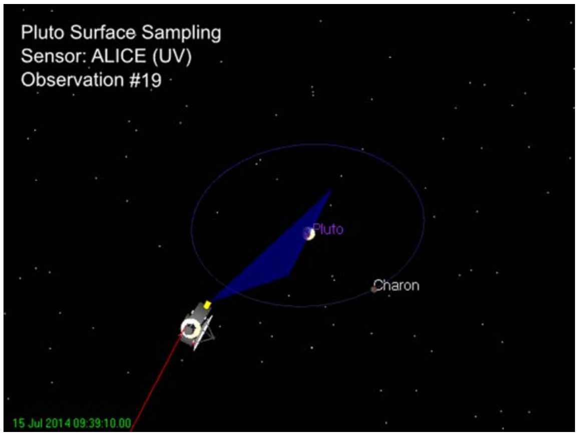

Fig. 6. UV surface sampling of Pluto.

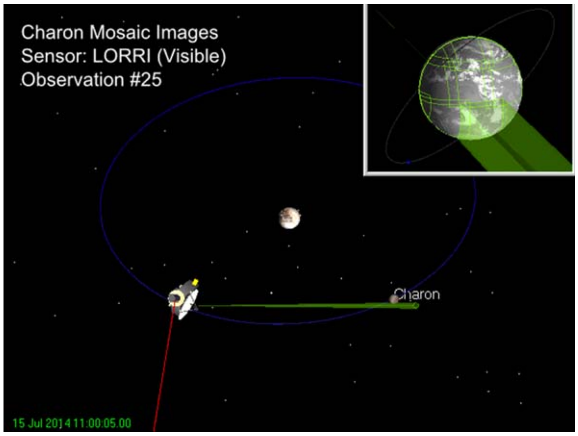

Fig. 7. Charon mosaic imaging.

5.2. Charon mosaic images

Fig. 7 demonstrates the process of taking mosaic images of Charon by LORRI. Margins are planned for each image frame that forms a 3×3 array to cover the entire surface of Charon, as seen in the close-up window.

5.3. High-resolution mapping of Pluto

Shown in Fig. 8 is the event of high-resolution mapping of Pluto, minutes before the closest approach to it, using both the visible imager MVIC and the narrow angle imager LORRI simultaneously. The FOV

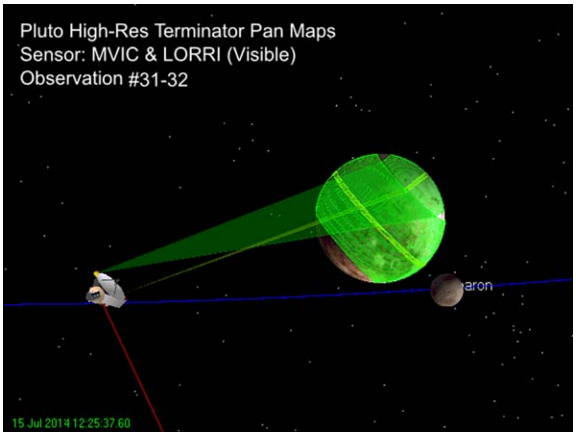

Fig. 8. Pluto high-resolution mapping.

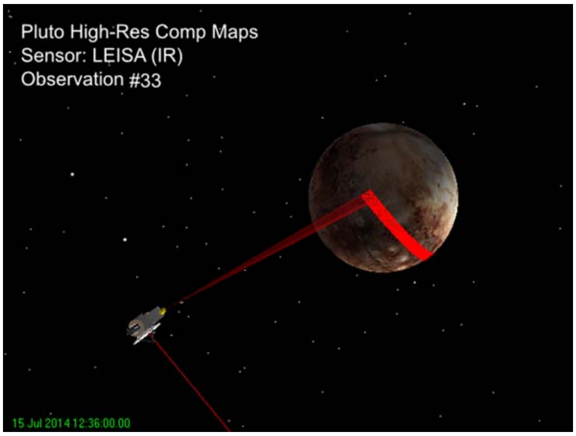

Fig. 9. Pluto high-resolution IR mapping.

of MVIC is 5.7° × 0.15°, and the FOV of LORRI is 0.29° × 0.29°. (MVIC and LORRI are mounted at different locations on New Horizons.) This mapping includes two scan operations, one horizontal and one vertical. The narrow strips in the center are the footprints of LORRI.

5.4. High-resolution IR mapping of Pluto

Fig. 9 displays the high-resolution composition mapping of Pluto's surface using the IR imager LEISA immediately following the visible mapping. The FOV of LEISA is 0.9° × 0.9°, and the imager is scanning

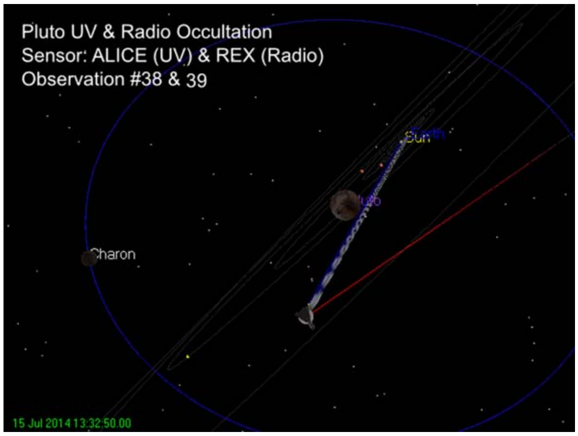

Fig. 10. Solar and Earth occultations by Pluto.

the surface from right to left as the spacecraft passes over Pluto.

5.5. Radio and solar occultation at Pluto

Simulation of UV and radio measurements near the solar occultation and Earth occultation by Pluto is demonstrated in Fig. 10. The white broken line represents the radio signal and the blue line represents the UV signal. The occultation occurs approximately an hour after Pluto closest approach, and the view is from the spacecraft looking back to the Earth and Sun. The solar system and the ecliptic plane appear in the background.

6. Conclusion

A Pluto–Charon encounter design for the New Horizons Pluto–Kuiper Belt mission is analyzed and optimized under the arrival constraints to maximize the science accomplishments at the flyby. The resulting baseline encounter trajectory attains an excellent solar phase angle at the approach and achieves both solar occultation and Earth occultation at both Pluto and Charon, providing a favorable encounter geometry for all the planned science observations and instrument measurements. During the Earth occultation, two DSN stations, Canberra and Goldstone, are able to transmit simultaneously to the spacecraft, greatly enhancing the REX measurements. Similar encounter geometry can also be obtained for later arrivals, but the solar phase angle at approach will increase, and the dark area on Pluto surface will enlarge, so as to cause less of Pluto's surface areas to be imaged.

The simulation of the planned observations greatly enhances the understanding of the Pluto–Charon encounter and proves to be substantially helpful in science planning, instrument design validation, and the verification of the spacecraft pointing requirements.

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