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NASA Computational Case Study: Where Is My Moon?

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A moon or natural satellite is a celestial body that orbits a planet, dwarf planet, or an asteroid. Several reasons motivate discovering and studying moons of planetary bodies. Here, we learn how astronomers search for moons of planetary bodies or perform satellite search. In particular, we look for moons of Pluto using Hubble Space Telescope's data.

Planets and dwarf planets follow elliptical paths with the Sun at one of its two foci. *Asteroids*, small bodies in the solar system primarily located between Mars and Jupiter, also orbit the Sun.[1] A moon or natural satellite orbits a planet, dwarf planet, or asteroid, called its *primary*.[2] Scientists seek to understand the origin, early history, and evolution of our solar system by studying moons of these bodies.[1–6] From the orbital characteristics of natural satellites and combining Newton's and Kepler's laws, the mass of the primary asteroid can be calculated.[3] This can be done from Earth-based telescopes without the need for in situ spacecraft measurements.[4–6] Scientists also study planetary bodies using robotic spacecraft.[3,7–9] Protecting spacecraft from collision with a natural satellite was the primary motivation for the satellite search conducted as the Dawn spacecraft went into orbit around the main belt asteroid Vesta.[10] Secondary motivation was scientific investigation of the asteroid.[10]

Background

Searching for moons around planets has a long history. For example, it was in 1878 that Asaph Hall discovered two moons of Mars—Phobos and Deimos—with the 26-inch Refractor Telescope at the Naval Observatory in Washington, DC.[11,12] With advances in imaging instruments and technologies as well as robotic exploration of the outer solar system, there has been an increase in satellite search and discoveries around many planets, including Jupiter, Saturn, Uranus, Neptune, and Pluto,[2–6,13] with some of the outer planets having more than 50 natural satellites. No additional satellites of Mars have been found.

Pluto and its moons have a fascinating story. In 1930, Clyde Tombaugh discovered Pluto, and then Pluto's largest moon, Charon, was discovered in 1978.[14] It was much later in 2005 that two smaller moons—Nix and Hydra—were discovered using observations of the Hubble Space Telescope (HST).[15,16] This discovery resulted in changing the classification of Pluto from a planet to a dwarf planet. In order for a body to be considered a planet it has to orbit the Sun, have enough gravity to form a spherical shape and enough mass to clear its neighborhood of debris.[17] In other words, it should be the dominant gravitational body in its orbit. Any object, like Pluto, that meets the first two requirements but not the third one is called a dwarf planet. Pluto's fourth and fifth moons—Kerberos and Styx—were discovered in 2011 and 2012, again using HST data.[3–10,13,18,19]

Satellite Search Problem

Moons or satellites of a celestial body are confined to a region of that body's gravitational influence. Scientists approximate the region where the gravitational force of the *primary* body (such as Earth or Mars) dominates that of the more massive yet more distant body, the Sun, as a spherical region called the *Hill sphere*.[4–6] When a celestial body, which we refer to as the primary, with mass m_p rotates around a more massive body with mass M, the

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radius of the Hill sphere for the primary body is calculated as

$$r_H = a_p \left(\frac{m_p}{3M} \right)^{\frac{1}{3}}, \quad (1)$$

where a_p is the semi-major axis of the primary's orbit going around the Sun (for example, Earth-Sun distance or Mars-Sun distance). Astronomers consider several criteria for validating a potential moon detection as a natural satellite of its primary:

1. It's expected to reside within the primary's Hill sphere.
2. It should be an unknown object and not be listed in any star catalogue.
3. For high-resolution data like those obtained from Hubble, it should have a point spread function (PSF). That is, it shouldn't appear as a spike only in one pixel. Furthermore, it should have the correct PSF, one matching that of its observing camera.
4. It should be observed more than once and in consecutive frames.
5. It should obey Newton's and Kepler's laws of motion.

Usually, the first three criteria can be verified with a single dataset. The fourth criterion requires consecutive observations of the same area. Potential moons that meet the first four criteria are identified. Then, follow-up observations are made at a later time to verify the discovery.

Question 1

Considering a mass for Mars of 0.64×10^{24} kg, a solar mass of 1.99×10^{30} kg, and a Mars semi-major axis of 1.53 astronomical units (AU), what would be the radius of Mars's Hill sphere in kilometers?

Hint: An AU is the average distance of Earth from the Sun and is about 1.49×10^8 kilometers.

Astronomers often describe distances to an object from an observer's point of view in terms of the angular field of view occupied at those distances. For very distant targets this angle is quite small, and its value in radians is approximately equal to its tangent. Figure 1 demonstrates this concept for calculating the Hill sphere of Mars. The radius of the Hill sphere, R_H, can be projected on the *celestial sphere*, an imaginary sphere with Earth at its center and a desirable radius (in our example, equivalent to the Earth-Mars distance, *d*). After this projection, R_H is approximated by the arc length it occupies on this celestial sphere, which in radians is equal to its field of view angle, θ, from an observer's point of view from Earth.

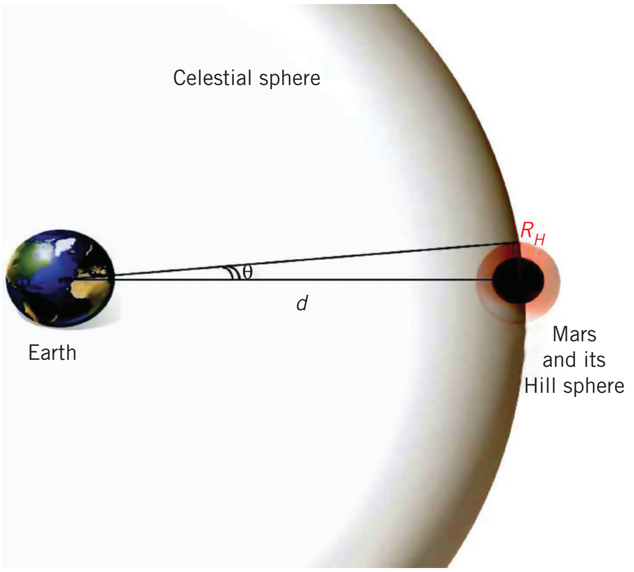

Figure 1. Distance and angular relationship of Mars's Hill sphere.

Question 2

Derive an equation for the relationship between distances and small angles in arcseconds. Using this relationship, how many arcseconds is the radius of Mars's Hill sphere, R_H? How many degrees is the same radius?

Hint 1: In astronomy, distances are often described in terms of angles. When this is done, it's implicit that this distance is at a very far location from an observer's point of view (on Earth in our example) and can be approximated by its projection on a celestial sphere.

Hint 2: For very small angles, like θ in Figure 1, $\theta \approx \tan(\theta)$. What is the relationship between θ and R_H?

Hint 3: One degree is divided into 60 arcminutes (60′), and each arcminute is divided into 60 arcseconds (60″). How many arcseconds are there in a circle?

Question 3

Considering a mass for Pluto of 0.0125×10^{24} kg and a semi-major axis for Pluto's orbit around the Sun of 5906.38×10^6 kilometers, what is the radius of Pluto's Hill sphere in kilometers? How does Pluto's Hill sphere compare to that of Mars? What does that imply?

Hint: Use the Earth-Sun distance of 1 AU and Mars-Sun distance of 1.524 AU to calculate the Earth-Mars distance.

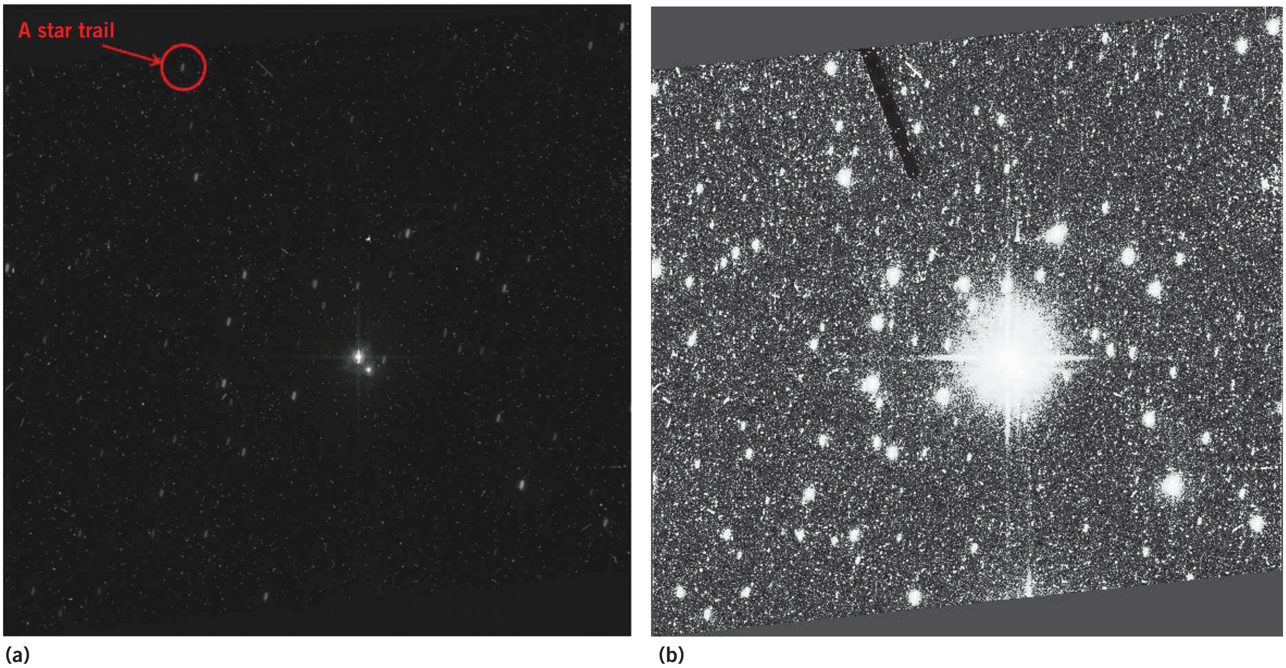

Figure 2. What you should see when you complete Activity 1. (a) Image `j91601m7q_drz.fits` in log scale with a marked star trail, and (b) image `j91601m7q_drz.fits` after histogram matching.

Satellite Search Algorithm

Let's start searching for satellites of Pluto using images of Pluto provided by HST.[8]

Activity 1

In the Web extra at doi:10.1109/MCSE.2014.116, read image file `j91601m7q_drz.fits`. Read its header information and report the observation date and time, exposure time in seconds, and size and data type of the stored image. Display the image.

Hint 1: Flexible Image Transport System (FITS) is the standard astronomical data format.[20] Various tools are available for reading and writing this format at http://fits.gsfc.nasa.gov. In particular, you can view a FITS image and its header using SAOimage software (SAO stands for Smithsonian Astrophysical Observatory).[21] Matlab also supports this format; see the `readfits` and `fitsinfo` commands or related open source .m files available at Mathworks (www.mathworks.com/matlabcentral) for more information.

Hint 2: Display the image in log scale. How differently would it appear when you apply histogram matching first? Figure 2 demonstrates what you should see when you complete Activity 1 (without the red marks and text). This image, and others that you will work with in this case study, are HST observations of Pluto made on 15 February 2006, and were retrieved from the Multimission Archive at STScI (MAST; http://archive.stsci.edu).

Activity 2

Repeat Activity 1 for image files named `j91601m9q_drz.fits`, `j91601mcq_drz.fits`, and `j91601meq_drz.fits`. What time was each observation made? How long was the exposure time of each observation?

A major issue you should take into account when processing astronomical data is problems due to movement and moving objects. There may be one or more sources of movement when looking at images of the same area of the sky. First, moons and planetary bodies move over time. Second, we often deal with a moving spacecraft, resulting in *motion parallax* and a camera on the spacecraft that has some vibrations referred to as *jitter*. As a consequence, a pixel with the same coordinates in each frame of the camera doesn't usually correspond to the same location in the sky. Therefore, we need to perform *image registration* on different frames. Image registration refers to finding the transformation(s) that would align two or more images of the same object or scene that are obtained at different times, from different viewpoints or sensors.[7] We need to apply the necessary translation, scaling, or rotation to images such that their corresponding pixels represent the same physical location and have the same spatial resolution. The image to which all other images should be aligned is called the *reference* image. Other images are considered input images. Then, for each point $P_i = (x_i, y_i)$ in an input image, the objective of any image registration algorithm is to find a transformation matrix $\boldsymbol{T}$, such that after being applied to input points P_i they're aligned with their corresponding points in the reference image, $P_r = (x_r, y_r)$.[7]

$$\begin{pmatrix} x_r \\ y_r \\ 1 \end{pmatrix} = \begin{pmatrix} s\cos(\theta) & s\sin(\theta) & t_x \\ -s\sin(\theta) & s\cos(\theta) & t_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_i \\ y_i \\ 1 \end{pmatrix}. \quad (2)$$

There are many different algorithms for finding a transformation matrix that could register one image to another.[7] As you can see from Equation 2, the key for finding such a transformation is knowing pairs of corresponding input and reference point coordinates, often referred to as *control points* or *feature points*. There are several approaches for finding such control points. In *supervised* or *manual* image registration, the user's knowledge of data or image is used. Users manually select feature points and provide them as input to the registration algorithm. In *unsupervised* or *automatic* image registration algorithms, these points are selected by an algorithm based on different criteria. One of the most common approaches in such algorithms is based on finding the peak location of the autocorrelation of the two images. Often times a hybrid approach is employed: the user selects some feature points and then an automatic algorithm limits the search area around those points for fine tuning the selected corresponding points.

Suppose two points A, B in the sky have the coordinates shown in Table 1.

Activity 3

Consider `j91601m7q_drz.fits` to be the reference image. Find the linear transformation that aligns each input image to the reference image. Apply the registration to each frame.

Hint: We can solve for the transformation matrix, using Equation 2, without solving for s and θ separately.

Note: From this point on, we work with registered frames.

Hubble observations of Pluto were made while the telescope was tracking Pluto. Therefore, successive images of Pluto would have Pluto and any of its moons almost in the same position in images and the stars moving, when viewed in sequential order (such as in a movie).

Table 1. Coordinates of two points in different frames.

File name	Coordinates	
	A	B
`j91601m7q_drz.fits`	(738, 490)	(764, 468)
`j91601m9q_drz.fits`	(744, 492)	(769, 470)
`j91601mcq-drz.fits`	(740, 496)	(766, 472)
`j91601meq-drz.fits`	(734, 494)	(760, 470)

Question 4

If we added images of the consecutive observations made from Pluto, how would you expect the stars to appear? How about moons? How would you expect the stars and moons to appear in the integrated image, if Hubble was pointing to a fixed location in the sky instead of tracking Pluto?

Activity 4

Add the provided image frames and display the result. How does the result match your expectations of the outcome? How does it differ?

Next, we have to identify noisy and bad pixels and remove their effects. One of the main obstacles in dealing with astronomical images is the abundance of *cosmic rays*, high-energy particles coming from sources far away in the galaxy. They usually appear randomly in astronomical images and degrade the quality of the images, with intensity values being orders of magnitude larger than those of the sky. Therefore, astronomers often need multiple images of the same area in the sky captured around the same time for identification and removal of the cosmic rays.

Question 5

Having multiple measurements of the same area in the sky, how do you suggest cleaning the images to remove the cosmic rays? Does this approach remove moons and stars as well? Explain why. What would be the ideal outcome?

Activity 5

Consider a stack of registered image frames. First, apply a one-dimensional median filter along the frames' direction to the stack of images, using Matlab's `medfilt1` function or its equivalent as described here (see http://en.wikipedia.org/wiki/Median_filter). Then, add all of the frames. Display and save the results in a .jpg file. How does this result compare with those you obtained from Activity 4? Can you improve the results?

Hint 1: How many observations of each pixel do you have? This gives you the dimension of the points you are working with.

Hint 2: What is the range of possible median filter lengths that you can use? Experiment with each possible filter length. Which one would yield better results?

Hint 3: Replace each pixel with the return value of the median filter along the frames' direction. How do you choose input values for the median filter function applied to each pixel? How would you handle image boundaries?

A more statistically robust approach for removing cosmic rays, and also in this case star trails, is to apply the *resistant mean* algorithm, also referred to as the *trimmed mean* algorithm. Details of this algorithm are available elsewhere[22] in the commercial Interactive Data Language (IDL; www.ittvis.com/language/en-US/ProductsServices/IDL.aspx) often used by NASA scientists. The algorithm works as follows. For a given input vector *y* with *npts* number of elements and a given cutoff factor *c*, compute `res_mean`:

1. *ymed* = **median**(y).
2. *abs_dev* = **abs**(*y* − *ymed*).
3. *med_abs_dev* = **median**(*abs_dev*)/0.6745.
4. if *med_abs_dev* $\leq$ *1E* − 24 then med *abs_dev* = **mean**(*abs_dev*)/0.8
5. *cutoff* = *c* ∗ *med_abs_dev*;
6. Let *good_indices* be the vector of indices *i* for which *abs_dev(i)* $\leq$ cutoff.
7. Let *num_good* be the number of elements stored in *good_indices*.
8. Let *good_points* be those elements in *y* whose index appears in *good_indices*.
9. *res_mean* = **mean**(*good_points*).

The choice of constants in steps 3 and 4 arise from properties of a normal distribution. As the number of samples drawn from a normal distribution approaches infinity, their median absolute deviation (*med_abs_dev*) becomes 0.6745 times their standard deviation. Similarly, the mean absolute deviation, for a large enough number of samples drawn from a normal distribution, is 0.8 times their standard deviation. So far, we have calculated an initial estimate of the `res_mean` value by truncation of *y* values on a normal distribution. We can refine this value a bit more by compensating for the effects of this truncation and by a polynomial approximation for *sigma_good* if necessary (as shown in step 12). The coefficients for the polynomial approximation of *sigma_good* were derived empirically by the algorithm's author.[22]

10. *sigma_good* $= \sqrt{\sum_{i=1}^{num\_good}(good\_points - res\_mean)^2 / num\_good}$
11. *sc* - **floor**(max(*c*,1.0))
12. if (*sc* $\leq$ 4.5) then sigma_good = sigma_good/ $(-0.1398 + 0.8896sc - 0.2300sc^2 + 0.0196sc^3)$
13. *cutoff* = *c* ∗ *sigma_good*
14. Repeat steps 6-9, return *res_mean*.

Activity 6

Repeat Activity 5, except this time instead of a median filter, calculate the resistant mean of the values. Display and save the results in a .jpg file. How do results from Activity 5 and 6 compare with each other? Which one looks cleaner?

Hint: Apply a cutoff factor of 3 or more (recommended factor: 4).

You have now finished processing the data. Next, we need to review the final products of Activity 5 or 6 (whichever is cleaner) to identify potential moons. Of course, not every remaining point or feature is necessarily a moon. Some bright stars, galaxies, and even cosmic rays might still appear. Let's see if we can identify moons that meet the first four requirements for a moon, as mentioned in the previous section.

Question 6

What is the radius of Pluto's Hill sphere in pixels for images you worked with? That is, how many pixels away from the center of Pluto should you search? Are all the pixels in the image within Pluto's Hill sphere?

Hint 1: What was the Hill sphere of Pluto in kilometers or degrees? Use your response to Question 3.

Hint 2: What is the pixel resolution of the images you worked with in kilometers? How about arcseconds?

Hint 3: Use the header files to identify the HST camera and instrument that made the observations. Then, refer to the HST Data Handbook, to find the pixel resolution in arcseconds.[23] Convert this resolution to kilometers if needed, using the same relationships that helped you answer Question 2.

After restricting the search to those pixels that are within the Hill sphere and identifying moon candidates, we must eliminate any candidate that is a star or any candidate that can't be a moon. A star catalogue of the same area of the sky can help with this task. However, for these datasets, we can identify the stars without catalogue entries.

Activity 7

Eliminate any moon candidate that's a star from your final product.

Hint 1: Revisit registered image frames, and locate the moon candidates in them. Are they trailed, similar to the star trail marked in Figure 2a, in individual frames? If yes, what does it imply?

Hint 2: We're working with long-exposure HST images from when it was tracking Pluto. Recall your response to Question 4 and results from Activity 4.

Activity 8

Do the remaining moon candidates appear in all frames? Do they appear as point sources, or do they have a PSF, with one matching or close to that of the HST's instrument that made the observation?

Hint: Refer to *The HST Data Handbook*, to find the PSF of the instrument that made the observation.[23]

Activity 9

Declare any moons you have discovered for Pluto!

Hint: Do they pass moon criteria 1 through 4?

In this case study, you learned about the satellite search problem. You worked with a subset of 2006 Hubble images of Pluto that was used to verify the discovery of Nix and Hydra.[15,16] In fact, Figure 3, showing Pluto and three of its moons, was made by processing the same images you worked with!

It could have been you discovering moons of Pluto! You can join astronomers around the world searching for moons of planetary bodies using NASA's publicly available data. Some of these data archives are in the Planetary Data System (PDS; http://pds.nasa.gov) and MAST (http://archive.stsci.edu). NASA's New Horizon mission will approach Pluto on 14 July 2015 after a nine-year journey (see www.nasa.gov/mission_pages/newhorizons/main/#.VEAnAr6xHbc). Scientists may find even more moons of Pluto using its data. NASA's Dawn mission will carry out a satellite search for dwarf planet Ceres between February and March 2015. Are you ready to help find Ceres' and more of Pluto's moons?

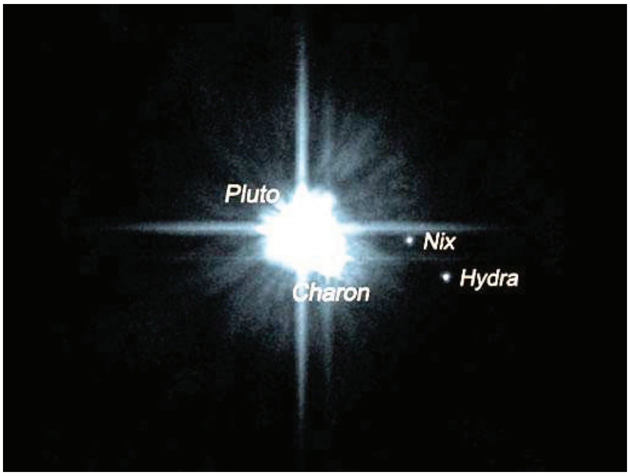

Figure 3. Pluto and its moons from observations made by the Hubble Space Telescope. North direction is towards the right, and East is towards the top of the image. (Image Credit: NASA, ESA, H. Weaver [JHU/APL], A. Stern [SwRI], and the HST Pluto Companion Search Team.)

Challenge 1

Can you use a different filter or approach for removing cosmic rays and the stars such that only Pluto and its three moons remain in the final product? Document your computational steps and display your result in a .jpg file.

Challenge 2

Consider 2005–2006 HST data of Pluto and those that led to discovery of the fourth moon of Pluto—Kerberos—in 2011[18,19] (you can obtain the data from MAST at http://archive.stsci.edu). Why wasn't Kerberos discovered in 2005–2006? Does it appear in 2005–2006 HST images?

Challenge 3

In our case study, Hubble was tracking Pluto, which resulted in Pluto and its moons appearing in almost the same location (slight movements exist due to spacecraft jitter) in consecutive frames while stars moved. It often can be the case that the spacecraft would point to a fixed direction in the sky instead of tracking an object. In that case, stars would appear in the same location and planets and moons would move from frame to frame. How would the satellite search algorithm be different in that case?

In fact, that was the case for the Dawn mission when searching for moons of Vesta in July 2011.[10] You can obtain July 2011 Dawn data of Vesta from the PDS (http://pds.nasa.gov). Which images, from which Dawn instrument, will you choose for satellite search? How does your result look after every step of your algorithm? Do you think you have found some moon candidates? Can you rule out the possibility of them being a star or a galaxy?

Note: Compare the pixel resolution of Dawn data with HST data. What does it imply? Can you expect any moon to have a PSF?

Challenge 4

Search for satellites of Ceres, after Dawn's Ceres Satellite Search data becomes available in the PDS (http://pds.nasa.gov).

Challenge 5

Search for more satellites of Pluto, after New Horizon's Satellite search data becomes available in the PDS. ■

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