Lunar Dynamics and A Search for Objects Near the Earth-Moon Lagrangian Points

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I. Introduction

The goal at the outset of this project was to begin a CCD (charge-coupled device) imaging search of the L4 and L5 Lagrangian points in the Earth-Moon system in an attempt to discover natural satellites in those regions. Using the 0.5m SC telescope at the Saint Mary's College Norma Geissberger Observatory, the observing plan spanned 60° along the lunar orbital plane x 5° around Earth-Moon L5, 45° x 5° around L4. The limiting magnitude for the detection of libration objects in this search was assumed to be 17-19th magnitude; however it is understood that in order to detect such faint objects, perfect seeing conditions would be necessary. An automated search of selected priority was to be attempted using the Faint Object Classification and Analysis System (FOCAS) software package from the National Optical Astronomy Observatories.

II. Background - What are Lagrangian points?

A precise but technical definition of the Lagrangian points is that they are the stationary solutions of the circular restricted three-body problem in gravitational physics. When looking at the Earth-Moon system, for example, if we assume that the two massive bodies (the Earth and Moon, see Figure 1) are in circular orbits around their common center of mass, there are five positions in space (referred to as L1-L5) where a third body of comparatively negligible mass (i.e. a satellite), could be placed which would then maintain its position relative to the two massive bodies [ESA]. As seen in a rotating reference frame with the same period as the two co-orbiting bodies, the gravitational fields of two massive bodies and the centrifugal force are in balance at the Lagrangian points, allowing the third body to be stationary with respect to the first two bodies; for this reason they are analogous to geostationary orbits [ESA].

Fig.1 – Example of the three-body problem with Earth and Moon as two massive bodies. The above is a contour plot of the effective potential of a two-body system due to gravity and centrifugal force as viewed from rotating frame of reference in which Earth and Moon are stationary. Objects revolving with same orbital period as Earth will begin to move according to the contour lines showing equipotential surfaces. Arrows indicate gradients of potential around Lagrange points: toward (red) or away from (blue) them; forces balanced at points [Wikipedia].

II. Background - Lagrangian points: A History

The Lagrangian points known as L1, L2 and L3 are referred to as the "collinear Lagrange points" and were first 'discovered' by Euler around 1750 [Koon]. Shortly following in 1772, mathematician Joseph-Louis Lagrange made effort to simplify the famous three-body problem on which he was working. He came up with a hypothesis that resulted in the re-formulation of classical Newtonian mechanics and resulted in Lagrangian mechanics. The hypothesis: *The trajectory of an object is determined by finding a path that minimizes the action over time; this path is found by subtracting the potential energy from the kinetic energy*. With this new starting point, Lagrange was able to hypothesize how a third body of negligible mass would orbit around two larger bodies which were already in a near-circular orbit. In the context of a reference frame rotating with the larger bodies, he 'located' five specific fixed points where the third body experiences zero net force. Now known as "Lagrangian points," they remained only in theory for over a hundred years at which point the discovery of the Trojan asteroids in the at the Lagrange points of the Sun–Jupiter system brought his work into the realm of observation [Wikipedia].

II. Background - L4 and L5

The two Lagrangian points to be observed during this project are L4 and L5 which lie at the third corners of the two equilateral triangles in the plane of orbit whose common base is the line between the centers of the Earth and the Moon (Fig.1, Fig.2); L5 lies behind and L4 lies ahead of the smaller mass, the Moon, with regard to its orbit around the larger mass, the Sun [Wikipedia].

The Earth-Moon L4 and L5 have received less scientific attention than the collinear Lagrangian points. Though frequently referenced in space-based science-fiction literature and television, the only serious proposal made regarding L4 or L5 is one from 1974 in which the L5 Society put forth the idea of space colonization and manufacturing taking place in the two triangular points. Because of the lack of wide-spread interest, not much effort has been put into observing these locations in an attempt to detect material there. In 1956 Polish astronomer Kazimierz Kordylewski first began observing what are now referred to as Kordylewski clouds around L4 and L5. Though the actual existence of the two bright clouds thought to contain interplanetary dust is still under dispute, those who have seen them claim that under ideal conditions the clouds can be seen and they appear somewhat redder than Gegenschein with an angular diameter of about 6 degrees and move around the libration points in ellipses of about 6 by 2 degrees [Wiki-Kordylewski].

Figure 2. Gravitational accelerations at L4

Because L4 and L5 lie at an equal distance from each mass, the ratio of the gravitational forces of the two bodies' is equal to the ratio of the masses of the two bodies' (M1/M2). This means that the resultant force acts through the barycenter of the system (the center of mass and of rotation of the system) and is exactly what is required to keep a body in the L4 or L5 in orbital equilibrium with the system. In a given system, in order for L4 and L5 to be considered stable, the M1/M2 ratio needs to be greater than [{25+3*sqrt(69)}/2] [Cornish]; the Earth-Moon system meets this requirement by a small margin. When a body at these points is perturbed, it will begin to move away, but the Coriolis effect bends the object's path back towards the center, as a ball in a bowl returns to its stable point [Freitas, 1980]. Such perturbations are ever-present, as the Earth-Moon system is not an isolated case. The solar gravitational influence causes any object in the L4 and L5 locations to 'orbit' the Lagrange point in an 89-day cycle [ESA] resulting in a more practical idea of a region of stability, or a "Lagrangian area" [Wikipedia].

This makes the astronomer's job a bit trickier. In order to detect objects in L4 and L5 one must search a region rather than simply pointing a telescope at a specific point in space. The best modern search of all the Lagrangian points was conducted by Robert

Freitas and Francisco Valdes in 1982 in which they found no objects, natural or artificial. It is worth continuing this search as opportunities for increased technology and more precise instruments arise; Lagrangian satellite searches may be useful in detecting captured asteroidal bodies or impact ejecta from the lunar surface; this unique and accessible material for astrogeological study could help to confirm theoretical predictions in the four-body problem in celestial mechanics. It is also of practical interest to learn whether the stable libration orbits (particularly L4 and L5) are clear of large obstacles as the stability of these positions is appealing and they may come increasingly into use for global telecommunication satellite systems and solar deep-space telemetry networks, space manufacturing facilities utilizing lunar or asteroidal raw materials (as proposed by the L5 society), large optical and radio telescope arrays, and as part of a comprehensive SETI (Search for Extraterrestrial Intelligence) search for possible alien artifacts in the Solar System [Freitas, 1980].

III. Equipment/Tools

In order to begin this search, I first had to become familiar with the equipment available in the Norma Geissberger Observatory at Saint Mary's College of California. The main elements of the Observatory include a 0.5m Schmidt-Cassegrain telescope made by Meade, positioned on a Software Bisque, Inc. German equatorial mount. The camera used was a Santa Barbara Instrument Group (SBIG) ST-10XME self-guiding, charge-coupled device (CCD) camera with a focal ratio of F/5. An inserted lens was initially used which altered the focal ratio to F/10. Installed on the focus mechanism is a remote focus driver called *RoboFocus* made by Technical Innovations Inc., which is designed to “provide digital control and feedback of the focus position using a stepping motor controlled by a microprocessor” [Technical].

The main software program to be used for this project was *Astronomer’s Control Panel (ACP) Observatory Control Software* that is designed to provide the automation hub for the running of an observatory; this program runs and coordinates multiple software programs (such as *MaxImDL/CCD, TheSky6*, and *AutomaDome*) and allows actions to be programmed ahead of time [Denny]. *TheSky6* Astronomy Software and *AutomaDome* work together to sync the dome slit to the telescope’s view, as well as providing a graphical interface that assists the astronomer in making a viewing plan. Also connected to *ACP* is *MaxIm DL/CCD Version 5* which was designed by Diffraction Limited to image with a scientific-grade CCD camera and includes image processing plus full instrumentation control (including cameras, filter wheels, focusers, autoguiders, and telescopes) [Denny].

IV. Procedure – Ideal

The first step in the observing process is to determine the ideal days and times to observe. This can be done using an ephemeris chart (see Appendix A and B). NASA’s Jet Propulsion Laboratory (JPL) have made a program available to the public that allows the user to input variables such as “Target Body”, “Observer Location”, and desired “Time Span” for an observation, and will return to the user a table of values over time of the position of the “Target Body” (as well as a wealth of other information) [JPL].

If everything runs according to plan, when the time for observing arrives the basic procedure for getting started follows as such: open the dome; (possibly run a quick t-point); cool the CCD camera to its desired temperature (in this case -20°C); connect all the software; import the observation plan into ACP; and press go. The system, even if entirely automated, should be monitored in order to assure the quick recovery of data and return to normal if anything goes wrong. The ideal implemented plan involves tracking L4 or L5 and periodically taking a mosaic-grid of images. MaxIm is able to combine successive pictures into one larger image. Over time, the comparison of these larger pictures would allow the astronomer to detect slight movement of faint objects (such as the ones we're searching for) in relation to the background stars.

IV. Procedure – Problems

From the start I knew the amount of viewing time available would be limited based on the fact that the observations were taking place during the summer months in the San Francisco Bay region known for its summer fog. With this in mind, every attempt was made to be as efficient at possible in order to accomplish the goal. However weather was not the only issue. Despite the precautions taken and precision used in the design and assembly of the telescope and mount, there are inherent errors. There is a method that can be used to minimize such errors known as telescope-pointing (t-pointing). The basic premise of t-pointing is that a software program like *TheSky6* slews the telescope to a particular object (generally bright stars are used) and then the user centers the object in the eyepiece and informs the software of the correction. Generally, at least a dozen stars are chosen in a random pattern around the zenith, and from the centering corrections made the software can account for most systematic error in the hardware. The region around the zenith is usually used because the corrections made there will be most applicable to the entire sky, with error increasing as one moves away from the zenith. However, for this project, the precision of the pointing for the entire sky was not the goal; since the two points to be observed (L4 and L5) lie in the lunar orbital and therefore reach their maximum altitude at approximately 60°, a t-point correction would be more useful centered at the highest point in the path of the lunar orbital. My plan was to follow just such a procedure as soon as I had all the software and hardware functioning.

Alas, it was not meant to be. The camera itself and its computer connection kept me from making much progress for weeks. Initially, the camera had trouble communicating with the computer software, however after much wire-tracing and manual-reading the problem was partially solved. A few nights were spent correcting some focus and alignment issues, but eventually images of stars were procured. (The series of images procured during this problem-solving stage can be found in Appendix C.)

The main coordinating program *ACP* acknowledged its connection to both the camera and the telescope, however would not allow me, as the user, to run an observing plan referring to a mysterious 'Active X' issue that is, as of the printing of this report, still unresolved. This left me with many functional programs, but no way to automate and coordinate them; basically it ensured a decrease in my efficiency during observations.

Also, the decreased precision that comes from manually moving the telescope instead of having it automated in an effort to take a mosaic-grid of images decreased in the likelihood of my finding anything.

V. Results

The night of September 8, 2009 was the last night available to me for observations that was not plagued with moonlight and fog. According to the ephemeris charts for that evening (Appendix A and B) L5 was unavailable for observation, and L4 was not ideal, as the darkest hours did not include it at its maximum apparent elevation (it only went as high as 47°). Images were taken of the region near L4 between the hours of 3 and 5 a.m. on the morning of September 9. L4 was rising through this time, so the accuracy of the telescope's pointing increased with the elevation of L4, however the sky also began to lighten a bit before 5 a.m. The following images (Figs. 3-5) are an example of those that were taken manually and imported into MaxIm in an attempt to have the software piece them together into a larger image (not all have been included as it seemed unnecessary). The reason they remain in pieces is that MaxIm returned an error saying that it was unable to complete the task; apparently my manual adjustments were not fine-tuned enough to allow the program to recognize a pattern in the pieces.

Figure 3

Figure 4

Figure 5

VI. Conclusion

Despite the fact that no conclusive evidence was found, I have succeeded in learning the process necessary to complete this sort of research and plan to continue working until I am able to actualize my 'ideal' procedure and return data that, whether or not it confirms the existence of objects in Lagrangian points L4 and L5, at least reflects the work that went into the search. I now know what sort of issues to expect during the observation process and have a check-list of problems that need to be solved before I can consider this project complete.

Appendix A

An ephemeris chart from JPL for L4 the nights of September 7, and September 8, 2009.

Ephemeris - Pasadena, USA / Horizons
Target body name: L4 (394) {source: Sun-EarthMoon L4}
Center body name: Earth (399) {source: DE405}
Start time : A.D. 2009-Sep-08 00:00:00.0000 UT
Stop time : A.D. 2009-Sep-10 00:00:00.0000 UT
Step-size : 60 minutes
Center geodetic : 237.898611,37.8394075,0.2759957 {E-lon(deg),Lat(deg),Alt(km)}
Center cylindric: 237.898611,5043.60568,3891.5482 {E-lon(deg),Dxy(km),Dz(km)}
Interfering body: MOON (Req= 1737.400) km {source: DE405}
Deflecting body : Sun, EARTH {source: DE405}
Deflecting GMs : 1.3271E+11, 3.9860E+05 km^3/s^2
Atmos refraction: NO (AIRLESS)

Date	Time (UT)	Time (PCT)	R.A (° ' ")	DEC. (° ' ")	Apparent Azimuth	Apparent Elevation
Sept07	03:00	19:00	07 07 08.68	+22 32 20.9	342.5477	-27.6230
	04:00	20:00	07 07 19.25	+22 32 04.1	358.1706	-29.6190
	05:00	21:00	07 07 29.82	+22 31 47.4	13.9502	-28.3682
	06:00	22:00	07 07 40.39	+22 31 30.8	28.6334	-24.0584
	07:00	23:00	07 07 50.93	+22 31 14.3	41.5312	-17.2429

Sept08	08:00	0:00	07 08 01.46	+22 30 57.9	52.6199	-8.5678
	09:00	1:00	07 08 11.95	+22 30 41.6	62.2558	1.4107
	10:00	2:00	07 08 22.41	+22 30 25.2	70.9266	12.2715
	11:00	3:00	07 08 32.84	+22 30 08.9	79.1691	23.7028
	12:00	4:00	07 08 43.23	+22 29 52.4	87.6323	35.4542
	13:00	5:00	07 08 53.60	+22 29 35.8	97.3229	47.2724
	03:00	19:00	07 11 19.19	+22 25 27.2	342.4556	-27.7212
	04:00	20:00	07 11 29.75	+22 25 09.3	358.1053	-29.7336
	05:00	21:00	07 11 40.31	+22 24 51.5	13.9180	-28.4931
	06:00	22:00	07 11 50.86	+22 24 33.9	28.6324	-24.1868
	07:00	23:00	07 12 01.40	+22 24 16.4	41.5546	-17.3696
Sept09	08:00	0:00	07 12 11.91	+22 23 59.0	52.6609	-8.6901
	09:00	1:00	07 12 22.39	+22 23 41.7	62.3100	1.2935
	10:00	2:00	07 12 32.84	+22 23 24.3	70.9919	12.1590
	11:00	3:00	07 12 43.26	+22 23 06.9	79.2458	23.5939
	12:00	4:00	07 12 53.64	+22 22 49.5	87.7224	35.3471
	13:00	5:00	07 13 03.99	+22 22 31.9	97.4295	47.1644

Appendix B

An ephemeris chart from JPL for L5 the nights of September 7, and September 8, 2009.

Ephemeris - Pasadena, USA / Horizons
Target body name: L5 (395) {source: Sun-EarthMoon L5}
Center body name: Earth (399) {source: DE405}
Start time : A.D. 2009-Sep-08 00:00:00.0000 UT
Stop time : A.D. 2009-Sep-10 00:00:00.0000 UT
Step-size : 60 minutes
Center geodetic : 237.898611,37.8394075,0.2759957 {E-lon(deg),Lat(deg),Alt(km)}
Center cylindric: 237.898611,5043.60568,3891.5482 {E-lon(deg),Dxy(km),Dz(km)}
Interfering body: MOON (Req= 1737.400) km {source: DE405}
Deflecting body : Sun, EARTH {source: DE405}
Deflecting GMs : 1.3271E+11, 3.9860E+05 km^3/s^2
Atmos refraction: NO (AIRLESS)

Date	Time (UT)	Time (PCT)	R.A (° ’ ”)	DEC. (° ’ ”)	Apparent Azimuth	Apparent Elevation
Sep 07	02:00	18:00	14 51 51.99	-16 27 47.7	215.1597	27.8638
	03:00	19:00	14 52 01.58	-16 28 29.7	228.3176	19.9554
	04:00	20:00	14 52 11.19	-16 29 11.6	239.4424	10.3743
	05:00	21:00	14 52 20.83	-16 29 53.4	249.1231	-0.3025
	06:00	22:00	14 52 30.50	-16 30 35.2	257.9967	-11.6629
	07:00	23:00	14 52 40.21	-16 31 16.9	266.7230	-23.3991

Sep 08	08:00	0:00	14 52 49.95	-16 31 58.7	276.1120	-35.2357
	09:00	1:00	14 52 59.72	-16 32 40.5	287.4442	-46.8306
	10:00	2:00	14 53 09.52	-16 33 22.4	303.2175	-57.5584
	11:00	3:00	14 53 19.33	-16 34 04.3	328.3169	-65.9174
	12:00	4:00	14 53 29.15	-16 34 46.4	5.4859	-68.7021
	13:00	5:00	14 53 38.97	-16 35 28.5	39.9569	-64.0157
	02:00	18:00	14 55 44.75	-16 44 36.8	215.0246	27.6105
	03:00	19:00	14 55 54.37	-16 45 18.1	228.1472	19.7260
	04:00	20:00	14 56 04.01	-16 45 59.4	239.2515	10.1671
	05:00	21:00	14 56 13.69	-16 46 40.6	248.9173	-0.4917
	06:00	22:00	14 56 23.39	-16 47 21.7	257.7756	-11.8394
	07:00	23:00	14 56 33.14	-16 48 02.7	266.4816	-23.5690
Sep 09	08:00	0:00	14 56 42.91	-16 48 43.8	275.8417	-35.4065
	09:00	1:00	14 56 52.71	-16 49 25.0	287.1358	-47.0131
	10:00	2:00	14 57 02.54	-16 50 06.2	302.8764	-57.7689
	11:00	3:00	14 57 12.39	-16 50 47.5	328.0492	-66.1737
	12:00	4:00	14 57 22.24	-16 51 28.9	5.5841	-68.9780
	13:00	5:00	14 57 32.09	-16 52 10.4	40.3210	-64.2438

Appendix C

This appendix contains a sampling of images obtained during the problem-solving phase of data collection during the month of August 2009.

Figure C1 – One of many images taken August 4, 2009.

On August 4th, I had finally confirmed that the camera was properly connected to the computer and that the two were communicating. The images from this night were the first to indicate that I might be on the right track. However, this 150-second exposure (Fig. C1) is a great example of all the images that were taken that night. The white 'donut'-type shapes are thought to be images/reflections of the mirror within the telescope itself. Above the two donuts, one can see two points that are slightly darker than the surrounding; it is thought that these may be the stars themselves and that there are focus and alignment problems.

Figure C2 - One of many images taken August 8, 2009.

On August 8th a similar result was achieved. As the 30-second exposure in Figure 4 shows, there was little improvement as there is still a white 'donut' visible as well as a suspicious darker point. At this point I was still unable to explain or solve the issue of the dark right-hand side of the image or the reason for the round gray shape in the images.

Through numerous observing sessions between August 9th and 13th, the donut right remained, however the images did not have the stark contrast of light and dark sides.

Figure C3 – Image from August 14, 2009.

On August 14th, I removed the extra lens-piece of the CCD camera used to diminish the focal length, returning the focus length to F10, resulting in images such as the one seen in Figure C3). It may be that each partial ring is from a different star in the field of view, however this was only a 10-second exposure and the longer exposures showed no variation in the number of rings. The effect around the edges can be explained by the fact that the camera had not fully reached its desired temperature of -20°C.

Figure C4 – Hypothesized to be out-of-focus stars from August 16, 2009

On August 16th, after pointing the telescope near Deneb and finding the same sort of image as the previous observing night, I decided to change the position of the camera within the Sidewinder optical manifold and found myself with Figure C4. Because the ratio of dark to light in these discs is not the same as the previous, we can safely assume that whatever alignment issue was present has been resolved and these are simply out of focus stars. Comparison with a catalog image of this point in the sky showed a pattern of stars that seemed to match the one present.

Figure C5 - An image from August 21, 2009: focused stars near Delta Herculis.

By the end of the week I succeeded in correcting the focus problem through trial and error and was able to image stars without rings. The 1-second exposure of a region near Delta Herculis (see Fig. C5 above) is an example of my first successful night.

Works Cited

Castella, Enric and Angel Jorba. '*On the dynamics near the Lagrangian points of the real Earth-Moon system*.' Monografias de la Real Academia de Ciencias de Zaragoza, Vol. 22, pp. 1-10. 2003.

Cornish, Neil J. and Jeremy Goodman. "*The Lagrange Points*" PDF. Accessed via [Wikipedia] most recently on September 11, 2009.

Denny, Robert B. "How ACP Works". Copyright 2007. <http://acp.dc3.com/howworks. html>. Accessed most recently on September 11, 2009.

European Space Agency. "What are Lagrange points?". Updated February 12, 2009. <http://www.esa.int/esaSC/SEMM17XJD1E_index_0.html>. Accessed most recently September 10, 2009.

Freitas, Robert A. Jr. and Francisco Valdes. "A Search for Natural or Artificial Objects Located at the Earth–Moon Libration Points". Icarus 42, pgs 442-447. Revised April 4, 1980. < HYPERLINK "http://www.rfreitas.com/Astro/SearchIcarus1980.htm" http://www.rfreitas.com/Astro/SearchIcarus1980.htm>. Accessed most recently on September 10, 2009.

Freitas, Robert A. Jr. and Francisco Valdes. "A search for objects near the Earth-Moon Lagrangian points". In *Elsevier Science* (USA), 1983.

JPL. "HORIZONS Web-Interface". <http://ssd.jpl.nasa.gov/horizons.cgi>. Accessed most recently on September 9, 2009.

Koon, Wang Sang; Martin W. Lo, Jerrold E. Marsden, & Shane D. Ross. *Dynamical Systems, The Three-Body Problem, And Space Mission Design*. p9. 2006. < HYPERLINK "http://www.cds.caltech.edu/~marsden/books/Mission_Design.html" www.cds.caltech.edu/~marsden/books/Mission_Design.html>. Accessed most recently September 10, 2009.

Software Bisque, Inc. "TheSky6 Professional Edition". Copyright 2009. <www.bisque.com/sc/pages/thesky6family.aspx>. Accessed most recently on September 9, 2009.

St. Mary's College. "Geissberger Observatory Home Page". <http://physics.stmarys-ca.edu/classes/Observatory/ObsIndex.html>. Accessed most recently on September 12, 2009.

Technical Innovations, Inc. *RoboFocus*™ Instruction Manual. January 6, 2003.

Wikipedia: The Free Encyclopedia. "Lagrangian Points". Last modified on September 11, 2009. <http://en.wikipedia.org/wiki/Lagrangian_point#cite_ref-cornish_5-0>. Accessed most recently on September 12, 2009.

Wikipedia: The Free Encyclopedia. “Kordylewski cloud”. Last modified July 20, 2009. <http://en.wikipedia.org/wiki/Kordylewski_cloud>. Accessed most recently on September 7, 2009.

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