# Rejoinder to Thesis Examination Report for Rogan Shimmin

## Examiner 1: Jeffrey S. Parker

### Specific comments

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| --- | --- | --- |
| Page | Location | Comment |
| xiii | 3rd paragraph | It's a bold statement to declare that this is the most complex mission attempted; there have been other very complex missions as well (ARTEMIS, Dawn, Cassini, etc).  Revised to “**one of** the most complex low-thrust trajectory optimisations”. |
| xv | 5 lines down | I'm amazed that the thrust is so low that it takes 3.3 years to burn 19 kg of pulsed plasma fuel.  Yup, it’s pretty amazing, but it corresponds exactly to a mass bit of 18μg fired at 1Hz. |
| xv |  | Probably not needed to go down to the hundredths of hours and kg. I'd suggest converting the29176.82 hours to days (that's such a large number of hours that it's meaningless to me!).  Duration in days now provided in parentheses immediately after initial use. |
| xv |  | This thesis certainly involves a lot of research, but it is built to be more like a design project than a thesis. I think if you opened it up and considered how this work could be applied to a variety of other spacecraft that would help immensely. (This goes along with previous statements above).  Addressed under later comment. |
| 11 | 3rd paragraph | First, this work is well-written! 2nd, you should examine the Artemis mission design. Artemis involved two spacecraft with very small engines that could be considered to be low-thrust engines, albeit orders of magnitude better than those studied in this thesis. The two Artemis spacecraft used lunar resonances to save fuel before flying past the Moon onto a low-energy lunar transfer.  Artemis mission design now referenced. Additional comparison added during discussion of lunar assists (Ch 6.5). |
| 13 | Table | Which gravity fields are you using for Earth and Moon? I noticed that this is specified later, but it could be mentioned here.  JGM3 and LP165 now included in table. |
| 18 |  | It's stated that the perturbations include Earth, Mars, and asteroids. I would have expected Jupiter to be a far more significant perturbing body, among others.  Revised to read “gravitational assists” rather than perturbations. |
| Ch 3 |  | The literature search is very thorough! It's very well done. I don't have any comments  Thank you. |
| Ch 4 |  | Each individual section is written well enough, but it's kind of a strange collection of things to put into a chapter. Perhaps you could re-arrange it and put the space environment first (or last) and keep all trajectory sections together. Chapter 5 goes further into orbital dynamics, so it's unclear to me why you introduce orbital dynamics in Chapter 4 rather than just waiting to Ch 5.  Ch 4 merged into Ch 5. |
| 49 | 1st sentence | Try to avoid absolute statements that may not be correct under different mission requirements, i.e., "The greatest hazard...". For instance, a super-cooled spacecraft's greatest hazard may be a loss of attitude control, leading to exposure of sensitive parts to the Sun.  Revised to read, “The greatest hazard **to** ***Lunar Mission BW-1***…”. |
| 53 | 2nd paragraph | I'm not familiar with the phrase "gravity drag" except in bizarre general relativistic frame dragging. I'm used to the term being "gravity losses" that are associated with long finite burns rather than impulsive burns.  In the bottom paragraph it sounds like you're referring to an effect of fighting the gravity of the Earth. This is a bit of a confusing discussion because all of these maneuvers perform Delta-V, but just not energy-changing Delta-V.  Revised all references to “gravity drag” to “gravity losses”. Revised second sentence to refer to changing orbital energy. |
| 54 | Upper paragraph | You refer to these numbers later in the thesis, i.e., the 1.1 km/s and 1.6 km/s in different phases of the mission, etc. Can you discuss for a paragraph or two where these Delta-V values come from?  Quick explanation added. |
| 58 | 1st paragraph | "...Ephemeris Time is the number of seconds since…”. ah, but how do you define a second? It's worth looking it up.  Added definitions for “day” and “second”. |
| 63 | Fig 5.4 caption | True anomaly is not mentioned in the caption. As if it needed to be a longer caption ;)  True anomaly was mentioned in the caption for Fig. 5.3, but I have now re-ordered that caption and referenced it in Fig. 5.4. |
| 65 | Bottom paragraph | The scientific notation is very odd for the values of mu. I understand why the Moon's mu value is XXXe9, but why is the Earth's XXXe8? I'd suggest making their exponents the same.  The scientific notation style was copied from IERS, but obviously is arbitrary. I have revised it to match the Moon’s more formal style. |
| 71 | 3rd paragraph | This is a very minor nit (but that's all you've left me); the paragraph "Unfortunately..." shouldn't be indented.  Corrected. |
| 71 | Final sentence of 5.5.2 | R\_peri is the periapsis radius, not the height.  Corrected. |
| 72 |  | "Chobotov (2002,p.223)'s" looks odd with the possessive "'s" after the reference.  Corrected. |
| 72 |  | There are really two forces at hand: solar wind and solar radiation pressure. Solar wind is the effect of particles emitted by the Sun interacting with the spacecraft; solar radiation pressure is the effect of light emitted by the Sun interacting with the spacecraft. I think you should separate these two effects. 5.5.3 is called "Solar Wind", but equation 5.14 appears to be characterizing solar radiation pressure. Are you using a flat plate model or a spherical model?  Introductory discussion of solar wind removed. Chapter renamed “Solar radiation pressure”. Plot legends also updated to reflect change. Text already stated that a spherical model is in use. |
| 76 |  | Can the solar panels be collecting energy while the thrusters are thrusting if the geometry aligns itself properly? It's not clear at this time.  Added clarification that it has not been decided at this time, so for the purposes of this project I have assumed that it is possible. Listed assumptions of solar panel charging model (p 99). Also see later comments on battery management. |
| 88 |  | "at the time of writing this thesis..." - has anything new occurred? A lot of time has passed since the writing of this thesis and my report (sincere apologies!).  Sadly things do not move very quickly on this project; the developmental focus for the thrusters remains the same. |
| 91 | 1st paragraph of 7.2 | If you separate the effects of solar wind and solar radiation pressure, then be sure to update this statement.  Revised. |
| 95 |  | This is a great discussion of the power system and it clears up a lot of questions I'd had.  I’m glad. |
| 95 |  | The batteries are also part of the power system. How many cycles can they take, etc? It would be interesting to consider ways of trickle-charging the battery system (l mention this more later).  The batteries have not been chosen yet, just a rough estimate of how much charge they need to hold, and the resulting weight. Also see later comments on battery cycles. |
| 98 | 3rd paragraph | I'm surprised that the team can design communication passes without impacting the trajectory design at all. I'd expected that there would be some small interference. I've also been curious about safe mode strategies, but presumably that's coming later.  Expanded explanation of communications passes not interfering with trajectory design. |
| 99 |  | It's well within the weeds of the design, but you may consider trickle-charging the final minutes/hours of the battery's charging. That is, get to 95% (+/-) of the battery's charge and then roll away from max-charge and "trickle charge" the remainder of the battery's charge.  Sounds like a wise idea, but as mentioned above, the batteries have not been chosen yet, so issues like trickle charging have not been considered. I have added a paragraph explaining this. I have also highlighted that the spacecraft does not need to chase charge based on the current configuration. |
| 104 | Fig 7.11 | Is it possible to change the text color for the two ylabels? While you can see the coloration on the axis, it's harder to see than I'd like. This is a good graphic though!  Revised as recommended. This was considered at the time of writing, but I could not find the appropriate LaTeX trick before my deadline. |
| 105 | 2nd paragraph | I think it's terrific that you are considering further ways to improve the optimization of the trajectory. But it's also absolutely fine that you didn't get to it in this thesis.  Noted. I wish I could have implemented more of them. |
| 107 |  | Low-energy lunar captures are close to my heart, so I have a lot of feedback to provide in this world. First, I'll warn you that Belbruno believes he did all of the work saving Hiten. Miller believes he did all of the work saving Hiten. For whatever reason they aren't particularly friendly with each other anymore (most people at JPL argue that Belbruno didn't deserve as much credit as he claimed and Miller is too modest to claim it). In any case, I try to refer to Belbruno and Miller at all times regarding the Hiten mission. But "weak stability boundary" is all Belbruno. It's a theory that is pretty weakly defined too! No one is able to use any WSB theory to really do any work. In fact, the researchers in Barcelona (Gomez, et al.) demonstrated that the weak stability boundary is not a practical defined space in Sun-Earth-Moon system! Pretty entertaining.  Thanks for the lesson on internal JPL politics ☺  Another set of researchers has provided more mathematically sound theories to demonstrate lowenergy lunar transfers using "dynamical systems theory" and "invariant manifolds". These include Conley (1968), Koon et al. (2000, 2001), and Parker (2007+), among others. I'll list these references below. The ARTEMIS mission (and corresponding papers) demonstrate a fantastic application of these theories. GRAIL does as well! The 2007 thesis demonstrated how to get captured by the Moon without thrusting at all, though you arrive at the Earth-Moon L2 point. It's possible to do these transfers from the Earth-Moon L1 point as well.  C. Conley, "Low Energy Transit Orbits in the Restricted Three Body Problem," SIAM Journal Appl. Math.,Vol. 16, No. 4, 1968, pp. 732-746.  W. S. Koon, M. W. Lo, J. E. Marsden, and S. D. Ross, "Shoot the Moon," Proceedings of the AAS/AIAA Spaceflight Mechanics Meeting held 2326 January 2000, Clearwater, FIorida, Paper AAS 00166 (C. A. Kluever, B. Neta, C. D. Hall, and J. M. Hanson, eds.), Vol. 105, part 2 of Advances in Astronautical Sciences, San Diego, CA, AAS/AIAA, Univelt Inc., 2000, pp. 1017-1030.  W. S, Koon, M. W. Lo, J. E. Marsden, and S. D. Ross, "Low Energy Transfers to the Moon," Celestial Mechanics and Dynamical Astronomy, Vol. 81, September 2001, pp. 63-73.  J. S. Parker and M. W. Lo, "Shoot the Moon 3D," Proceedings of the AAS/AIAA Astrodynamics Specialist Conference held 711 August 2005, South Lake Tahoe, California, Paper AAS 05383 (B. G. Williams, L. A. D'Amario, K. C. Howell, and F. R. Hoots, eds.), Vol. 723 of Advances in Astronautical Sciences, San Diego, CA, AAS/AIAA, Univelt Inc., 2006.  J. S. Parker, Low-Energy Ballistic Lunar Transfers. PhD thesis, University of Colorado, Boulder, Colorado, 2007.  J . S. Parker and G. H. Born, "Modeling a Low-Energy Ballistic Lunar Transfer Using Dynamical Systems Theory," Journal of Spacecraft and Rockets, Vol. 45, Nov-Dec 2008, pp. 1269-1281.  J. S. Parker, "Monthly Variations of Low-Energy Ballistic Transfers to Lunar Halo Orbits," AIAA/AAS Astrodynamics Specialist Conference, No. AIAA 20107963, Toronto, Ontario, Canada, AIAA/AAS, August 2-5, 2010.  Etcetera; I can provide more references if you need (but I sincerely doubt you need much more that a few of these!).  Thank you for the additional references. I did read Koon (2001) during my literature review, but decided there were more relevant papers to cite. Nonetheless, in my discussion of invariant manifolds and ballistic transfers I have added references to Koon (2001) and Parker (2008). |
| 111 | 1st paragraph | Great explanation!  Thanks. |
| 120 |  | This may just be an artifact of the reduced complexity mission, and I'll keep reading, but I'd suggest modifying the algorithm to optimize the full problem. During the ascent phase it may indeed be good to cease thrusting during periapse since it doesn't directly help solve the problem to further raise apoapse. But the 2nd phase of the mission involves raising apoapse AND higher apoapses provide more time to raise periapse. Thus I'd suggest burning through periapsis at all passages possible. Of course power issues may crop up as well.  Overlap with CONFIDENTIAL. Added “ideal” section to Ch 8 (method) and brief comment in Ch 2 (scope of research). |
| 125 | Last paragraph | I was confused the first time I read this when you said that the spacecraft's apoapse occurs near the Moon's periapse. It sounded like that had something to do with the optimizer. The 2nd time I read it I realized it was a function of the initial conditions. I'd suggest rewording this to state: "For this scenario, the geometry permitted the spacecraft's apoapse to pass near the Moon's periapse..." or something along those lines.  Revised to “For this scenario, the geometry permitted the spacecraft’s argument of periapsis relative to the Earth to be opposite the Moon’s argument of periapsis relative to the Earth, so the spacecraft is furthest from the Earth in the same region of space that the Moon is closest to the Earth.” |
| 126 | 2nd to last | "lt is interesting that...and therefore unstable lunar orbit." - I would revise this sentence. I'd argue that it's a fluke that the two-body energy wrt the Moon is close to zero; it's a coincidence of the relative velocity of the two bodies. I'd suggest not showing the two-body specific energy wrt the Moon until you're pretty close to being captured.  Paragraph and corresponding figure removed from thesis. |
| 126 | Bottom | I'd be interested to see the thrust vector plotted in some sort of body-fixed frame: something like Velocity-Normal-Cross, so you could see how much thrusting is in the velocity direction and how much is normal/cross to it.  As mentioned in the thesis, the higher order optimisation runs were not able to complete in the time available. Consequently the thrust profile did not diverge significantly from the initial guess, and the thrust vector in the VNC frame is dominated by the rotation from LVLH to VNC. I’d be very interested to see it for the completed run too. |
| 137 | Fig 9.21 | It would be interesting to zoom in on the energy relative to Earth to see if we can see any distant lunar flyby effects.  Figure added. |
| 138 |  | Again, same point about the VNC coordinate system (or some similar system). T\_theta is pretty close to T\_velocity, but not quite.  As above. |
| 139 | Fig 9.25a | The solar gravity and solar wind perturbations fluctuate every ~110 days. Why is that? I'd expect something along the lines of ~182 days; not sure why it's every 110 days.  I have no idea; it is an artefact of the computational model.  Ref. Physics (rod crewther?) try fourier analysis |
| 140 | Fig 9.25b | Very cool chart!  Thanks. |
| 141 | 2nd sentence | You have VERY few syntax, spelling or grammatical errors and I APPLAUD that. Though I just spotted one where the word "an" should be "a" ☺  As you may have noticed I use different spelling for some words, but I know we're in different parts of the world.  Corrected. |
| 141 | Fig 9.26 and others | The axis labels are both "Distance from the centre of the Earth/Moon" It would sometimes be nice to see an"x" , "y" , or "z" where appropriate so that I don't have to read the caption quite so closely to know if I'm looking at this in the plane or from out of the plane (Fig. 9.28 especially).  All affected plots revised. |
| 145 | Fig 9.33 | Perhaps the semi-major axis plot could be zoomed in to see the interesting feature(s).  Revised as recommended.  Fit line to check if assists actually assist? |
| 146 | Fig 9.34 | In this chart it would be interesting to see what the acceleration caused by the Earth is – not J2, but the actual point-mass 2-body acceleration.  Revised as recommended. |
| 146 | Fig 9.34 | I should have mentioned it earlier, but it would be interesting to see the order of magnitude of the J3 term in Earth's gravity field. It's something like 3 orders of magnitude smaller, but in some portions of the trajectory it may be greater than the effects of Jupiter or Mars.  The “oblateness” values in these plots were calculated from the JGM3/LP165 geopotential models, not the WGS84 geoid, and consequently the calculation provides a single acceleration rather than breaking it down into J2, J3 and J4 components. Unfortunately without returning to Stuttgart and renewing the software license I cannot postprocess these components.  Consequently “oblateness” labels have been changed to “harmonics” for all figures, and corresponding body text. |
| 148 | Fig 9.36 | It'd be nice to see the orbit of the Moon on this figure.  Revised as recommended. |
| 150 | Fig 9.39 | It'd be nice to break this into two slim plots to eliminate some whitespace, but not a big deal.  Revised as recommended. |
| 151 | Fig 9.40 | The x-axis is starting to get crowded. Perhaps you could subtract 1680 days, place that in the xlabel, and then you'd have 2-digit durations on the axis.  Revised all figures in this phase as recommended. |
| 153 | Fig 9.43a | Is this really lunar oblateness? What is the effect of the Earth's oblateness? What's the magnitude of the lunar gravity itself?  As above, the “oblateness” labels revised to “harmonics”. Furthermore I cannot postprocess the Earth oblateness effects within the lunar frames, and they were not included in the calculation. As seen from Fig 9.34, they are negligible. The plot has been revised to display lunar gravity. |
| 156 | Fig 9.45 | Don't worry about apologizing for the graphics renderer.  I don’t want people to misinterpret the picture. |
| 157 | Fig 9.47 | This figure doesn't convey much except to show that the distance between the spacecraft and Moon is very Iow. I think it would be better to just show the distance between the spacecraft and the Moon so that you can zoom in on it and show something interesting.  Revised as recommended. |
| 158 | Fig 9.48 | l'd delete the energy relative to Earth in this plot because it's not the important aspect of the design.  Revised as recommended.  Also the x-axis labels are getting crowded again.  Revised all figures in this phase as recommended. |
| 160 | Fig 9.51a | Once again I'm curious about the lunar acceleration as well. Perhaps even the Earth's oblateness - it may be higher than the other planets' effects, but I don't know.  Added a comment at the figure reference, highlighting that Earth oblateness carried over from previous phase is the same order of magnitude as Jupiter, Venus, and Mars, but was neglected due to increase in computational time due to large lookup tables. |
| 161 | 2nd paragraph | I love how effective the low-thrust engine is at converting mass to Delta-V. Awesome.  Yeah. It’s pretty cool. |
| 163 | Bottom paragraph | This showed up once or twice before, but I'm a bit uncomfortable referencing "mascons". I feel that that's an informal phrase describing the considerable asymmetry in the lunar gravity field. If you want to keep the terms, that's okay, but I wanted to express my opinion of it.  Revised all references to “mascons” to be “asymmetries in the lunar gravity field”. |
| 163 | Bottom paragraph | Bottom "contines" should be "continues"  Corrected.  The trend of the lunar gravity field causing the orbit to become more eccentric is well documented in the GRAIL papers. The GRAIL mission was carefully designed to accommodate this effect. It's very interesting!  Indeed, this is the reason for the inclined science orbit mentioned in Section 10.5. |
| 164 | Fig 9.55 | Is this really interesting? I suppose it shows that the whole surface of the Moon is covered. But I sure can't see any detail in there.  Figure removed. |
| 165 | Fig 9.57 | The x-axis labels are very crowded!  Revised all figures in this phase as recommended. |
| 168 |  | These figures are really neat. You have a lot of very excellent figures and it's been a pleasure reading this.  Thank you. |
| 173 | Top paragraph | Hmmm, if the optimization problem really is concave, then there's a clear global minimum that most algorithms can find without a brute force. But I think this problem is not concave, but has numerous local minima sprinkled about. To this end, I'd actually like to hear more discussion to see if this is the case or if it really IS truly concave. At which point I think we can have some more interesting discussion about it.  This interpretation depends on terminology; I am accustomed to “convex” optimisation meaning a clear global maximum (or minimum), and “concave” optimisation referring to highly constrained problems.  Revised to “non-convex”. |
| 174 | Table 10.1 | This table is great. But it does illuminate a question. Why is the phase boundary between the Capture phase and the Descent phase set where it is? I'd expect the Delta-V to be roughly swapped for these phases. That is, I'd expect more Delta-V to be performed in the Descent phase than in the Capture phase.  Indeed, I raised this very point in Section 10.2 and recommended to the project management that the phase boundary be moved. Unfortunately I ran out of time to examine the effect of moving the phase boundary, but I’d be very interested to see it. |

### General comments

* This discussion has not discussed contingency circumstances. What strategies are available if the spacecraft misses thrusting for some periods of time? It's likely that the vast majority of the trajectory is very insensitive to a thrusting gaps, but I am concerned with the period of time associated with the lunar capture.

Contingencies / safe modes, particularly lunar capture

* A small amount of text has been included addressing this issue, but I think more is needed to discuss variations in the trajectory across a potential launch period. What differences exist as the launch day changes?

Contingencies for launch date

* What if the GTO orbit has a different geometry? Can this mission start from a lower orbit? I'm sure it can, but the duration of time that it remained within the van Allen belts would increase. Some discussion is warranted.   
  It would be a great result if you found that any launch date used the same thrusting profile for at least a week or so. Then you could use that week to re-optimize the details of the launch, including launch errors.

Contingencies for partial launch failure

* Are there constraints in how quickly the spacecraft can rotate? How quickly DOES the spacecraft rotate during each phase?

The spacecraft is specified to 1° per second, as noted in Section 2.5.

Plot rate of change of attitude in VNC frame?

Create Section 7.1.2, Resolution of attitude control system within modelling?

* It would be interesting to show a short segment, where you can see when the spacecraft is charging its solar panels and when it is actively thrusting. I'm sure there are periods where these are separate and other periods where you can charge **while** thrusting.

Overlap with CONFIDENTIAL issue #1

The final statement of this review will re-address the most important aspect of this review. This thesis includes a significant amount of work on a single design. I highly encourage the author to re-focus numerous statements and discussions throughout the thesis to generalize the work. Do reflect on the lessons learned about this design and discuss how these lessons may be transferred to other design projects, of more or less complexity.

Lessons learned about this design, and how they may be transferred to other design projects, have been addressed in Sections 10.3 and 10.4.

## Examiner 2: CONFIDENTIAL

1. Assessment of Available Power for Electric Propulsion Thrusters

The PhD candidate should verify correctness of the attitude implementation and the calculation of sun aspect angle during EP firing. Further, the candidate should provide detailed analysis of the power generation cycle during Arcjet firing. For individual revolutions he should establish the profiles of power generation, power consumption and battery charging level. It would also be appropriate to provide information about the extent of eclipses for the trajectory described in the thesis and to keep in mind that the vast majority of GTO orbits have a sunpointing apogee.

Verify sun angle

Verify power generation esp. during arcjet – examine individual revolutions

Verify extent of eclipses

GTO orbits are inertial. Maybe the “vast majority” have a sunpointing apogee when they are launched, but over the course of a year this would change (except for the special – and unusual – case of a sun-synchronous GTO).

The Ascent phase had a sunpointing perigee at launch, resulting in no eclipses. I have added a comment to this regard.

1. Identification of Suitable Phase Connect Conditions

Despite the fact that the PhD candidate did not implement an end-to-end optimization, there are ways to improve the solution and take better advantage of the existing "perturbations" , which was one of the key objectives of the PhD research. Hence, the PhD candidate should at least dedicate an additional section in the thesis to an assessment of how additional boundary constraints for the individual phases could be used to generate a CONTINUOUS and more optimized trajectory.

As explained at length in Section 8.2.4 (pages 112-115), any implementation of additional phase connect conditions is arbitrary and requires iterative attempts to push the trajectory towards a more integrated, continuous path, based on the intuition and prior experience of the operator. The project was to develop a technique to optimise the whole trajectory – this was achieved, subject to better computing power or an optimiser compatible with parallel processing.

1. Clear Distinction Between Indirect and Direct Optimization Methods

The PhD candidate should revise chapter 3.3, correctly distinguish between indirect and direct methods, and reference research on genuinely indirect methods for optimization or planetary low-thrust transfers.

The definition of “indirect methods” varies depending on which source you consult. I chose the definition based on implementation (eg von Stryck & Bulirsch 1992, Enright & Conway 1992, Kluever & Pierson 1995, Lee et al 2005, Kemble 2006), which seems more intuitive to me. I assume you are referring to the definition based on differential equations (eg Betts 1993, 1994, 1998, 2000, 2003).

According to your preferred definition, the works I cited by Pontryagin (1962), Haeussermann (1965) and Ohlmeyer and Phillips (2006) would still classify as indirect methods.

The candidate also needs to correct the very first sentence of chapter 3.3, because an optimum value is not a minimum or maximum. Optimization is about finding optimum parameter values that will maximise or minimise a given objective function subject to a set of constraints.

Reworded.

## Additional revisions

Added Tristan Williams to acknowledgements.

Revised Fig. 9.25a to plot Earth oblateness behind the other series.

A number of small typographical errors corrected.

Unwrapped keplerian plots for propagate phase.

Fig 9.43a removed the stray ‘7’.

Added submission date.

Added labels to Fig. 1.1 (p. 2) for Ka-band and S-band.

Added explanation of negative time axis during ascent phase.