netary Protection

Trajectory Analysis and Collision Avoidance

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Planetary Protection Compliance

- Objective: to ensure that human exploration does not contaminate any sensitive celestial body with biological organisms from another celestial body.

Sensitive celestial bodies:
Earth, Mars, Europa, Enceladus, …

Planetary Protection Compliance

- Objective: to ensure that human exploration does not contaminate any sensitive celestial body with biological organisms from another celestial body.

Sensitive celestial bodies:
Earth, Mars, Europa, Enceladus, …

- Many strategies exist to accomplish that goal:
  - Ensure that bioburden is not carried on a vehicle.
  - If it is, navigate the vehicle such that it does not impact another sensitive body (surface or atmosphere).
  - If you can't, then ensure that arrival does not contaminate that body.

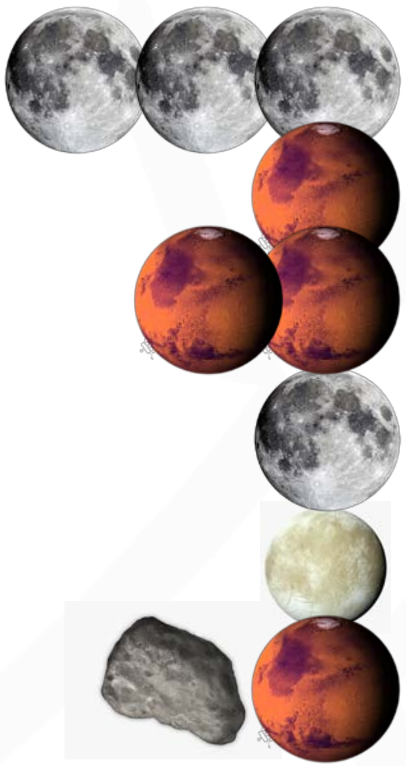
spores is low enough

This discussion

Do spores burn up in atmosphere?
Are spores destroyed by radiation?
Are spores exposed to conditions that may provide conditions for life now or in the future?

Spacecraft Navigation

- My own role in Planetary Protection Compliance is in mission design and navigation.
  - Mission Design and Navigation for GRAIL and Chandrayaan-1 at the Moon.
  - Mission Design Lead for the EMM Mars mission.
  - Mission Design Lead for the NASA/SIMPLEx ESCAPADE Mars mission (two spacecraft heading to Mars in 2024).
  - Navigation Lead for the CAPSTONE lunar mission in a couple of months.
  - Planetary Protection MDNav reviewer for Europa Clipper.
  - Mission Design Lead for an asteroid mission on the horizon.



Spacecraft Navigation

- How do we navigate a spacecraft in such a way as to comply with Planetary Protection?
- We begin by introducing the mission to the appropriate PPO and immediately engaging with them.

- Then, pull out covariance analyses, small-number statistics, Bayesian relationships, and confidence intervals and start working.

Probability of Impact Analysis

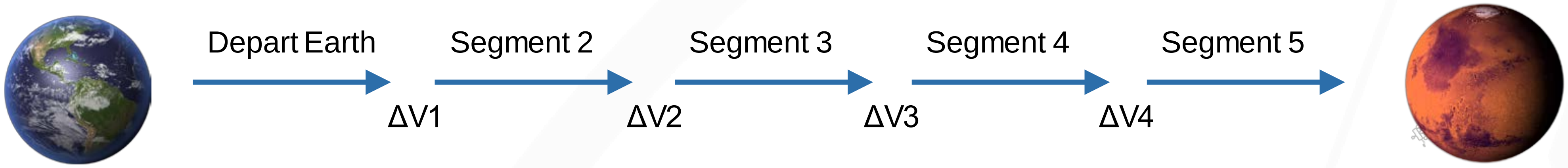
- The probability of impacting a sensitive body is:

The probability of being on an impact trajectory at some time X the probability of remaining on that impact trajectory, accumulated for all time from Year 0 to Year 50.

$$P(Impact) = \int_0^{50\ years} P_1(t) \times P_2(t)dt$$

If this probability is sufficiently low, then we comply with PP.

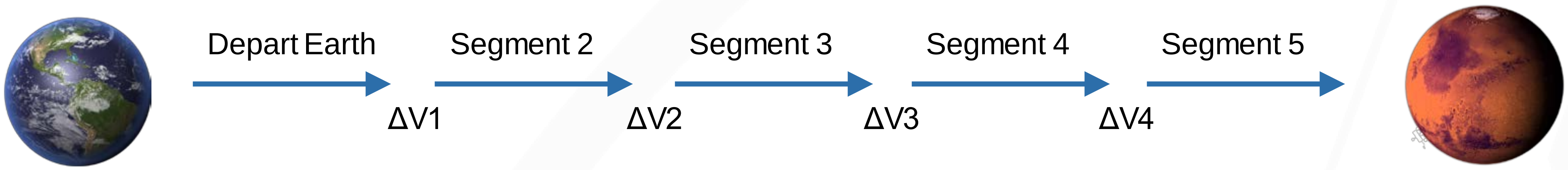
Probability of Impact Analysis



- Typical missions have many events
  - TCMs en route to Mars
  - Mars Orbit Insertion
  - Orbit reduction (aerobraking, maneuvers, etc)
  - Etc.

- This yields a potentially large branching structure, where we must evaluate what the probability is that we're on an impact trajectory at any point X the probability that we remain on that impact trajectory.
- Failures may branch away and never impact the sensitive body. Or they may result in an impact.

Probability of Impact Analysis

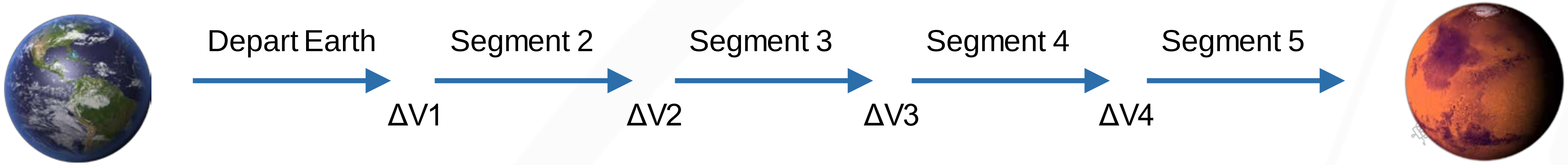


The probability of impacting Mars in this interplanetary cruise would be =
The probability that any segment impacts Mars

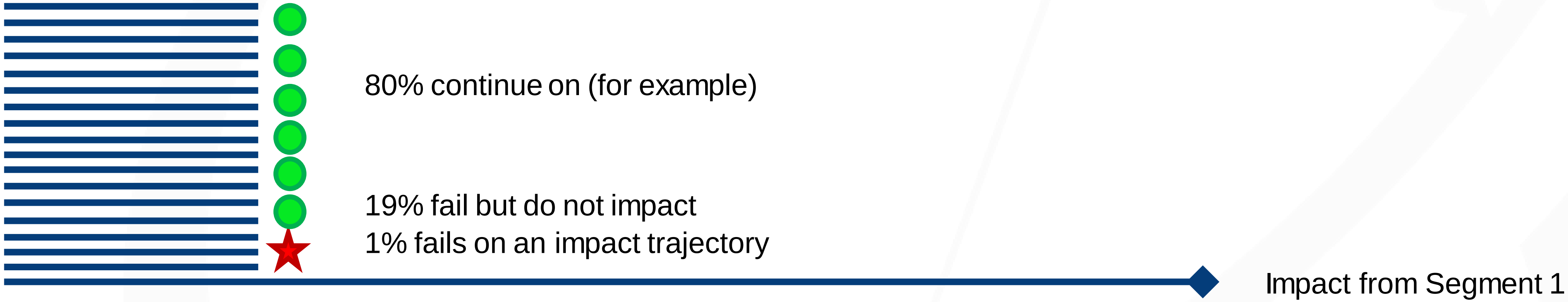
P(Segment N results in impact) =

P(Previous segments do not result in an impact) X
P(Segment N is on an impact trajectory) X
P(spacecraft remains on that trajectory)

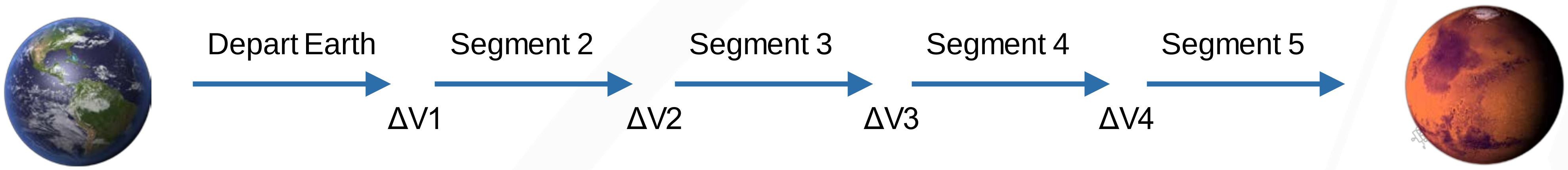
Probability of Impact Analysis



This diagram shows the idea that there are possible outcomes at every stage of the mission.
In each segment, there is some probability of failure. Some of those failure outcomes result in an impact.



Probability of Impact Analysis



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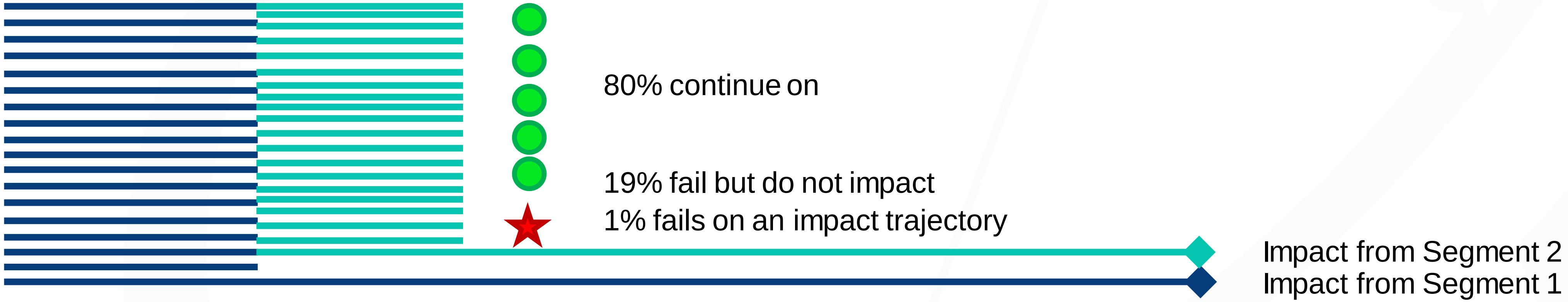
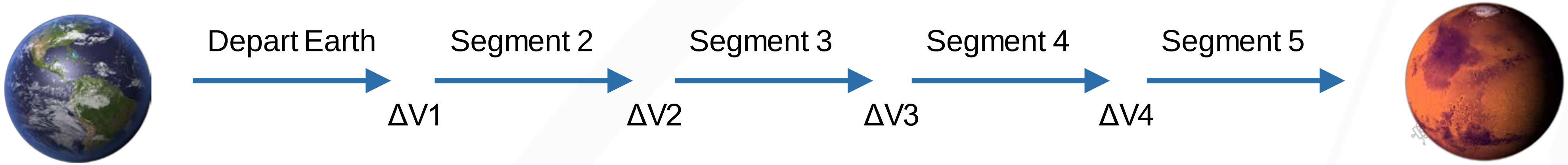


Probability of Impact Analysis



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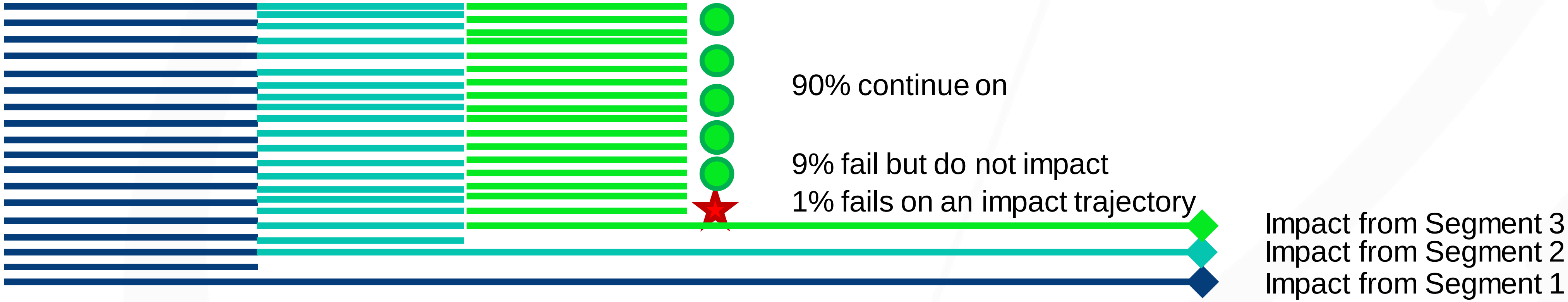
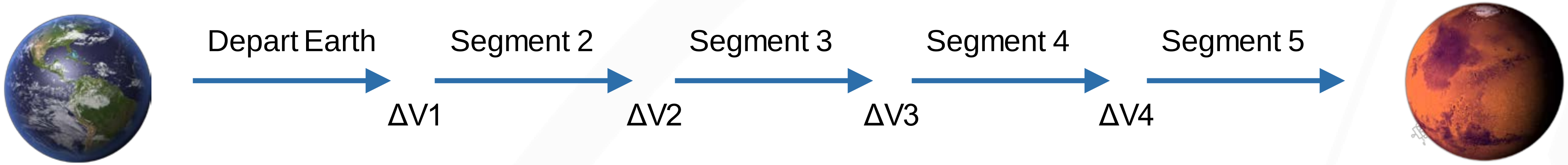


Probability of Impact Analysis

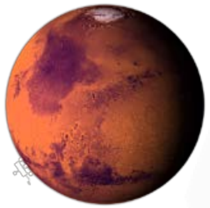


This diagram shows the idea that there are possible outcomes at every stage of the mission.
In each segment, there is some probability of failure. Some of those failure outcomes result in an impact.

Probability of impact =
Percent of impacts

Probability of Impact Analysis

Depart Earth → $\Delta V1$ → Segment 2 → $\Delta V2$ → Segment 3 → $\Delta V3$ → Segment 4 → $\Delta V4$ → Segment 5



Example:

1% chance of impact
3% chance of impact
3% chance of impact
10% chance of impact
1% chance of impact

Probability of Impact = ?

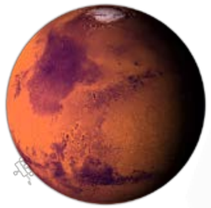
1% + 3% + 3% + 10% + 1% = 18%? No

100% – (99% * 97% * 97% * 90% * 99%) = 17%

Bayesian Statistics

Probability of Impact Analysis

Depart Earth → ΔV1 → Segment 2 → ΔV2 → Segment 3 → ΔV3 → Segment 4 → ΔV4 → Segment 5 →



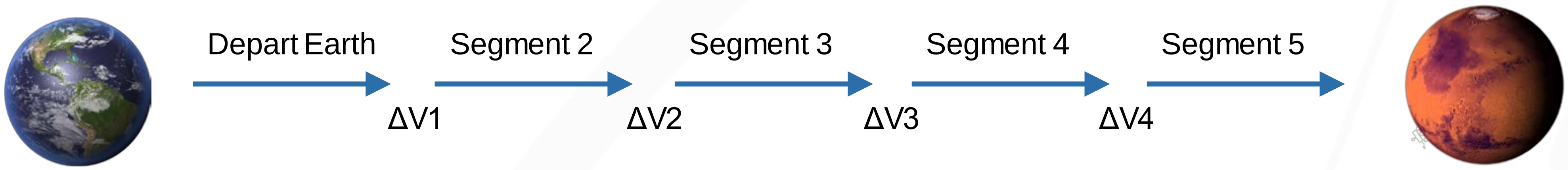
- P(impact) = 1.0 - PRODUCT of all segments
  [1.0 - P(on an impact trajectory) X P(spacecraft fails in this segment)]

Navigation covariance and
Monte Carlo analyses

Spacecraft reliability analysis
Spacecraft fault tree analyses
Meteoroid impact

The spacecraft can no longer
change its course.

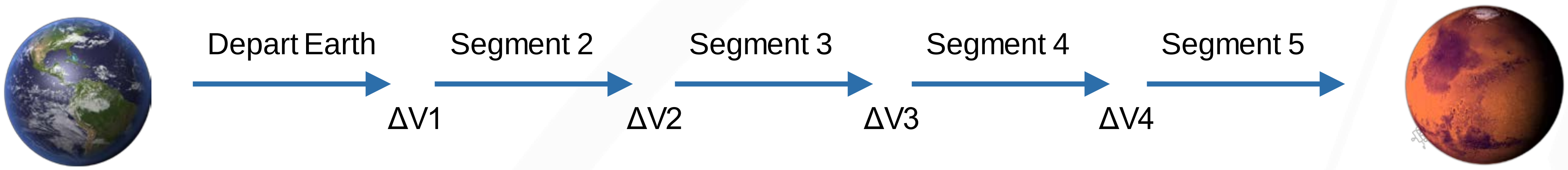
Probability of Impact Analysis



- P(impact) = 1.0 - PRODUCT of all segments
  [1.0 - P(on an impact trajectory) X P(spacecraft fails in this segment)]

If this is ZERO, then we can be on an impact trajectory anytime until the end and fully satisfy PP.

Probability of Impact Analysis

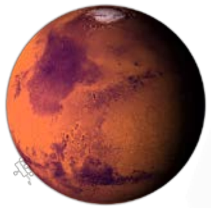


- P(impact) = 1.0 - PRODUCT of all segments
  [1.0 - P(on an impact trajectory) X P(spacecraft fails in this segment)]

But this is not zero.
And this is often difficult to quantify, with surprises and gotchas.

Probability of Impact Analysis

Depart Earth → $\Delta V1$ → Segment 2 → $\Delta V2$ → Segment 3 → $\Delta V3$ → Segment 4 → $\Delta V4$ → Segment 5



- P(impact) = 1.0 - PRODUCT of all segments

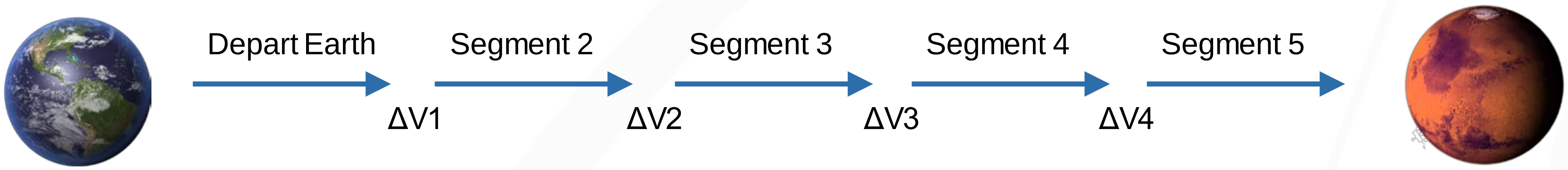
  [1.0 - P(on an impact trajectory) X P(spacecraft fails in this segment)]

One low-cost solution to this is to set this to a value of 100%.

This is very conservative but fully defendable.

This removes this piece from the equation.

Probability of Impact Analysis



- P(impact) = 1.0 – PRODUCT of all segments

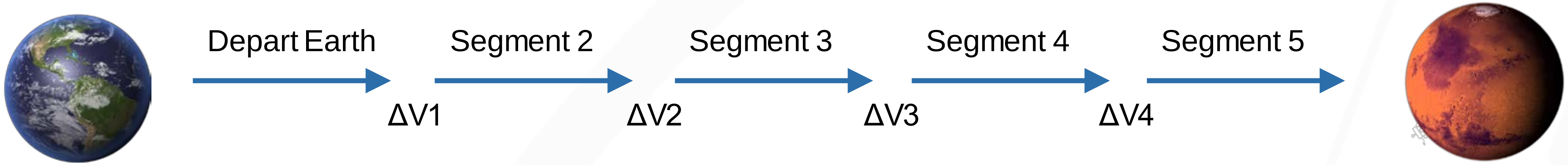
  100%

  [1.0 – P(on an impact trajectory) X P(~~spacecraft fails in this segment~~)]

But what if there are a LOT of small segments?

This is a large product with a lot of terms and the P(on an impact trajectory) term becomes dependent on the NUMBER of segments.

Probability of Impact Analysis



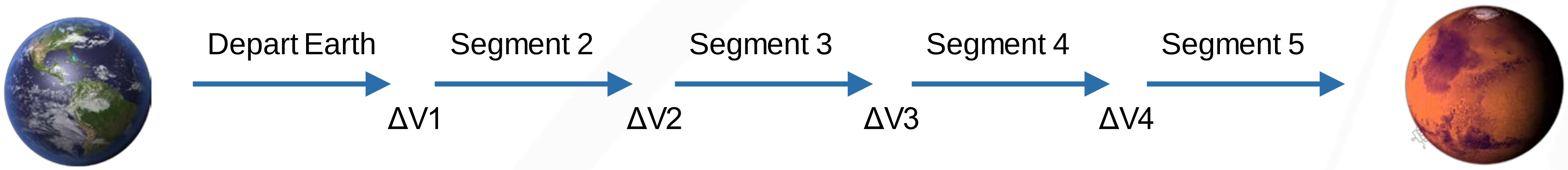
- P(impact) = 1.0 – PRODUCT of all segments

100%

[1.0 – P(on an impact trajectory) X P(spacecraft fails in this segment)]

Solution: the spacecraft can only fail once.
So, assume the spacecraft fails at the WORST moment.
That segment becomes the driving probability.

Probability of Impact Analysis



- P(impact) = 1.0 – MAXIMUM across all segments [1.0 – P(on an impact trajectory)]

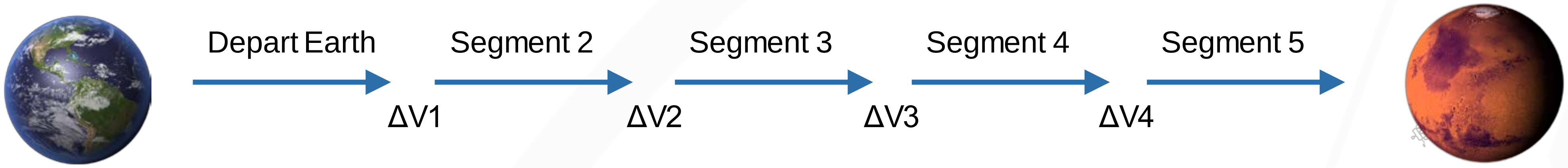
- Or
- P(impact) = MAX(P(on an impact trajectory))
  All segments

Conservative analysis
Assuming spacecraft fails at worst possible time
Likely costs some small amount of fuel
But could save $
And it is very defendable

Probability of Impact Requirement

- Category I: Concurrence on PP Plan.
- Category II: Simply document the mission's reference trajectory and final resting space.
- Category III:
  - P(impact) for a non-clean vehicle: < 0.01% over 50 years
  - P(impact) for a vehicle built and integrated in an ISO Level 8 cleanroom: < 1% over 20 years and < 5% over the subsequent 30 years.

Probability of Impact Analysis: Cat III



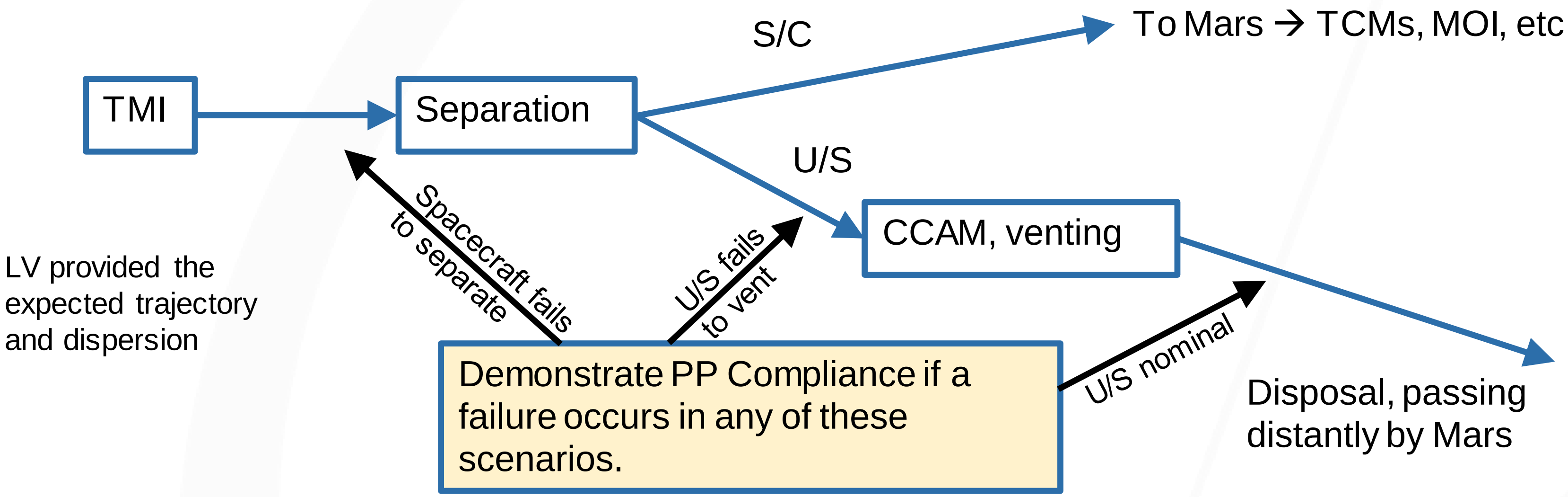
- P(impact) = MAX [P(on an impact trajectory)]

  < 1% for Years 0 - 20

  < 5% for Years 20 - 50

Real Mars example

- This is an example of the event tree that had to be evaluated for a recent Mars mission:



Real Mars example

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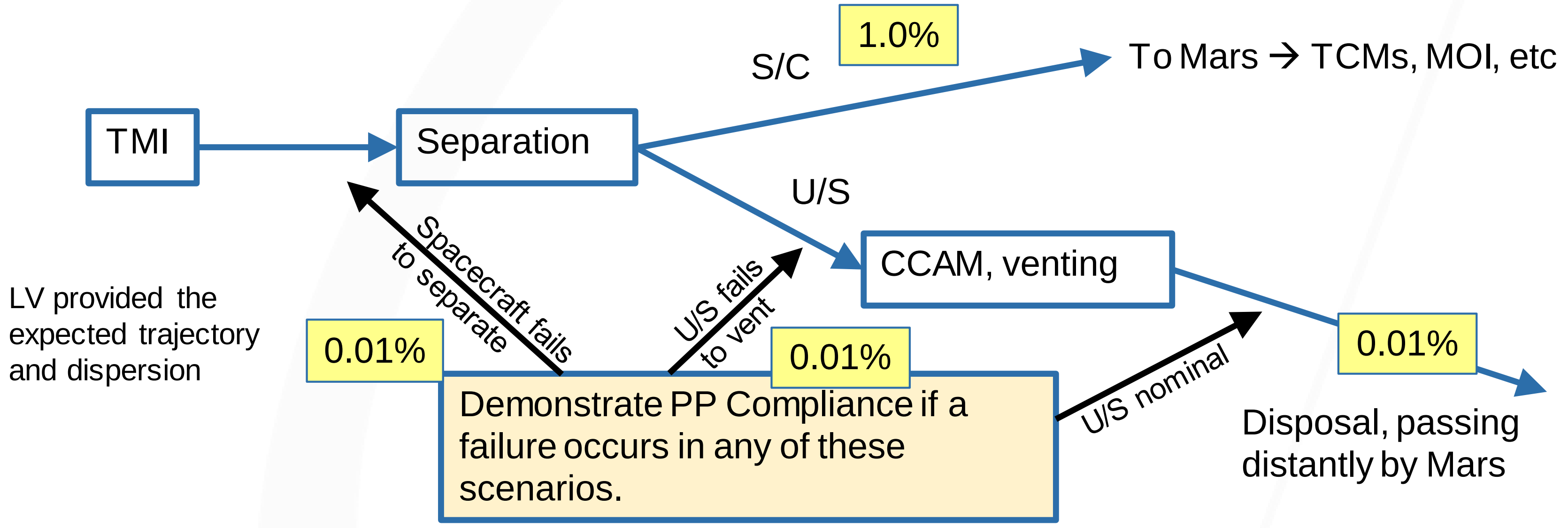
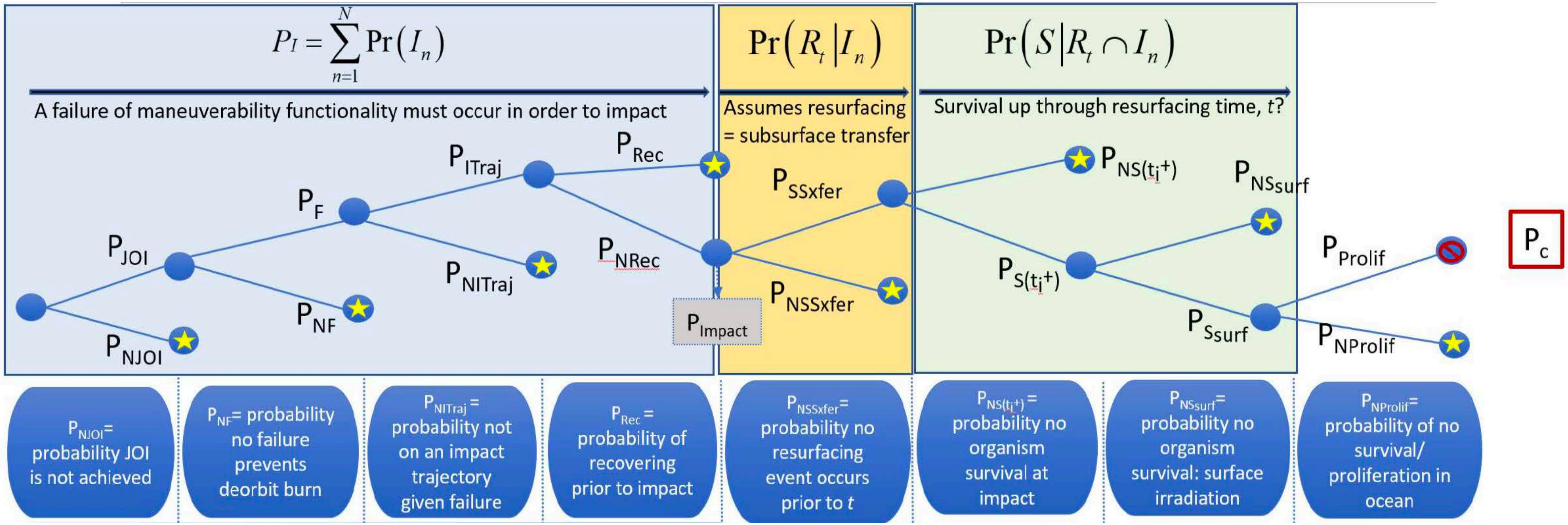


Assumption: any impact has a probability of 1.0 that spores survive and thrive on the surface.

If we assume 100% failure rate, then we have to ensure that each of these paths complies with PP.

Mission such as Europa Clipper

- Evaluating the probability of contaminating Europa:

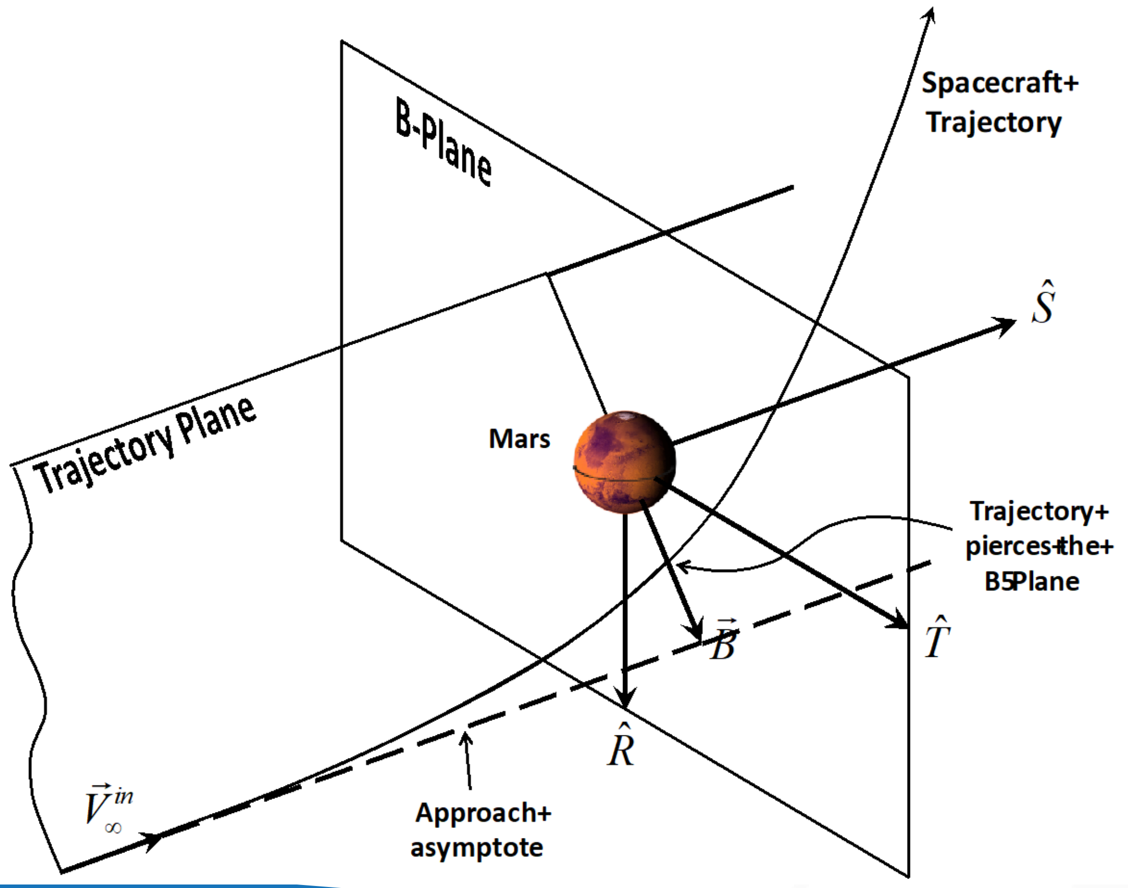


Navigation Impact Analysis for Mars

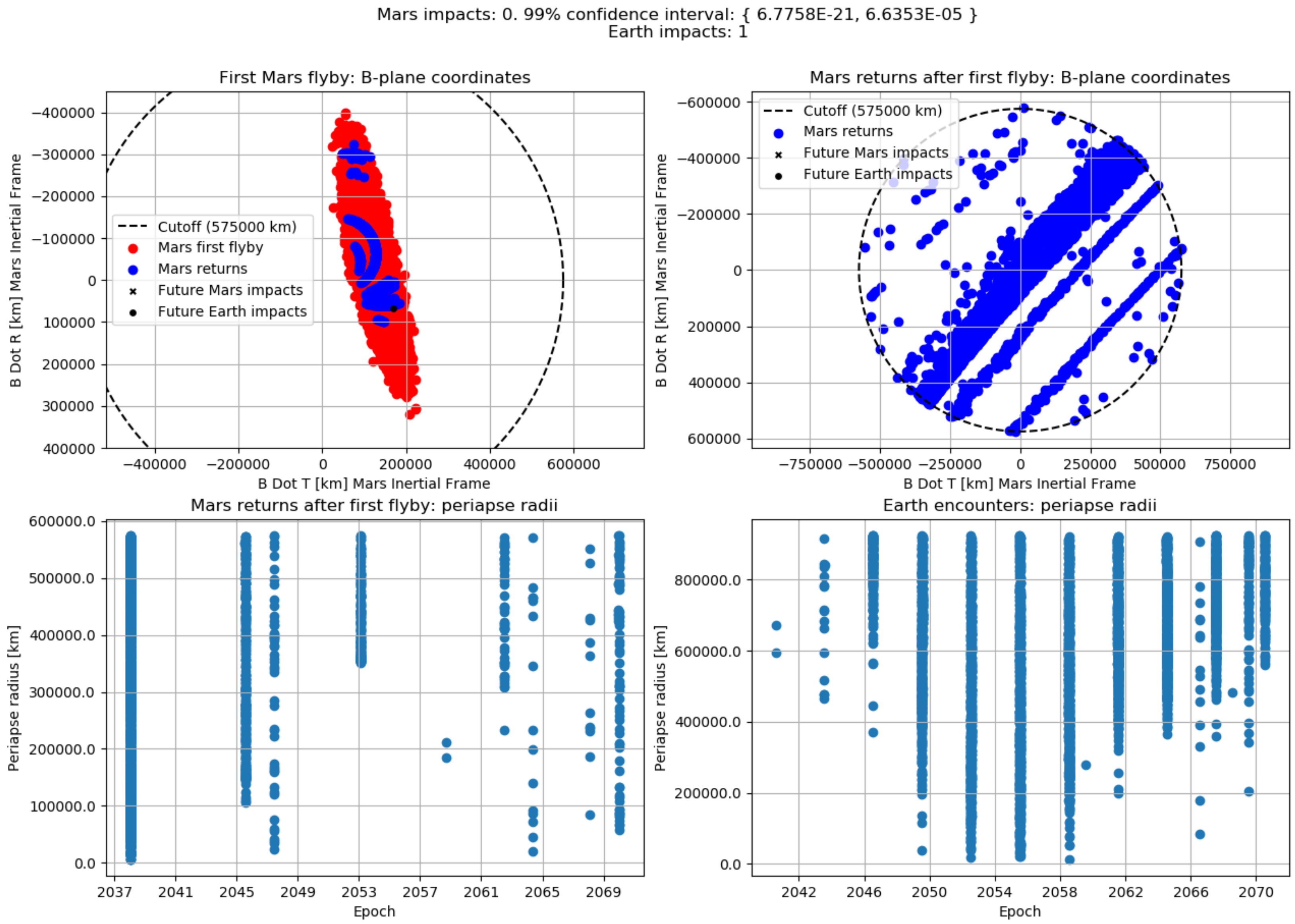
- For each segment of the mission (pre-MOI, post-MOI, etc)
  - Initialize the segment via a covariance, either from the LV provider or the previous segment.
  - Perform a Monte Carlo that draws a set of random variables (Gaussian, uniform, as appropriate to the variable) to model example trajectories, including:
    - Initial conditions.
    - Orbit determination uncertainty at each key point.
    - Maneuver execution error parameters for each maneuver.
    - Errors in the physical system (gravity, solar radiation pressure, atmosphere, etc)
    - Etc.
  - Evaluate the impact analysis
    - Return *True* if an impact occurs, as well as when and how the impact occurred.
    - Return *False* if no impact occurred.
    - Record the close approach with Mars within the 50 years, for reference.

What sort of result do we see?

- For Mars, we use the B-Plane as a tool for analysis

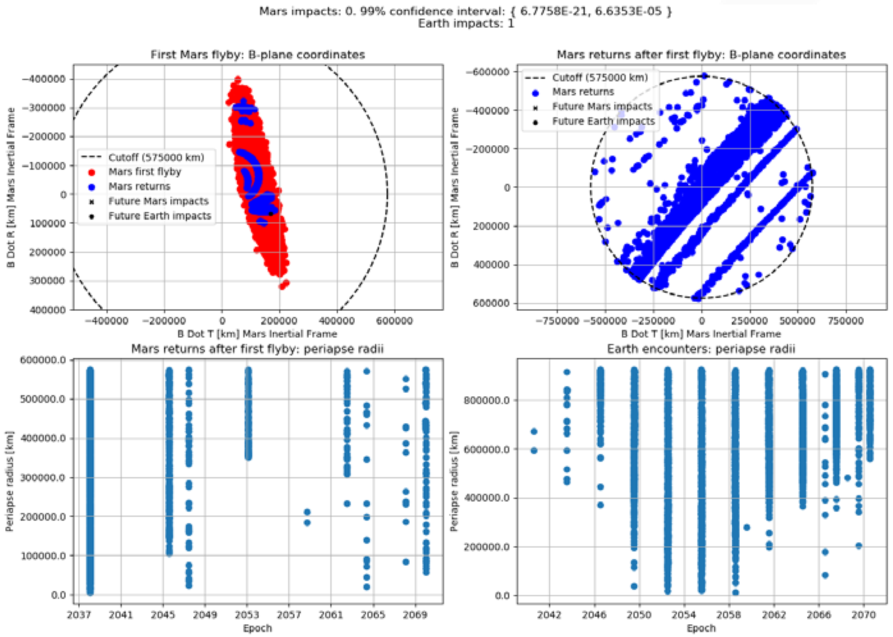


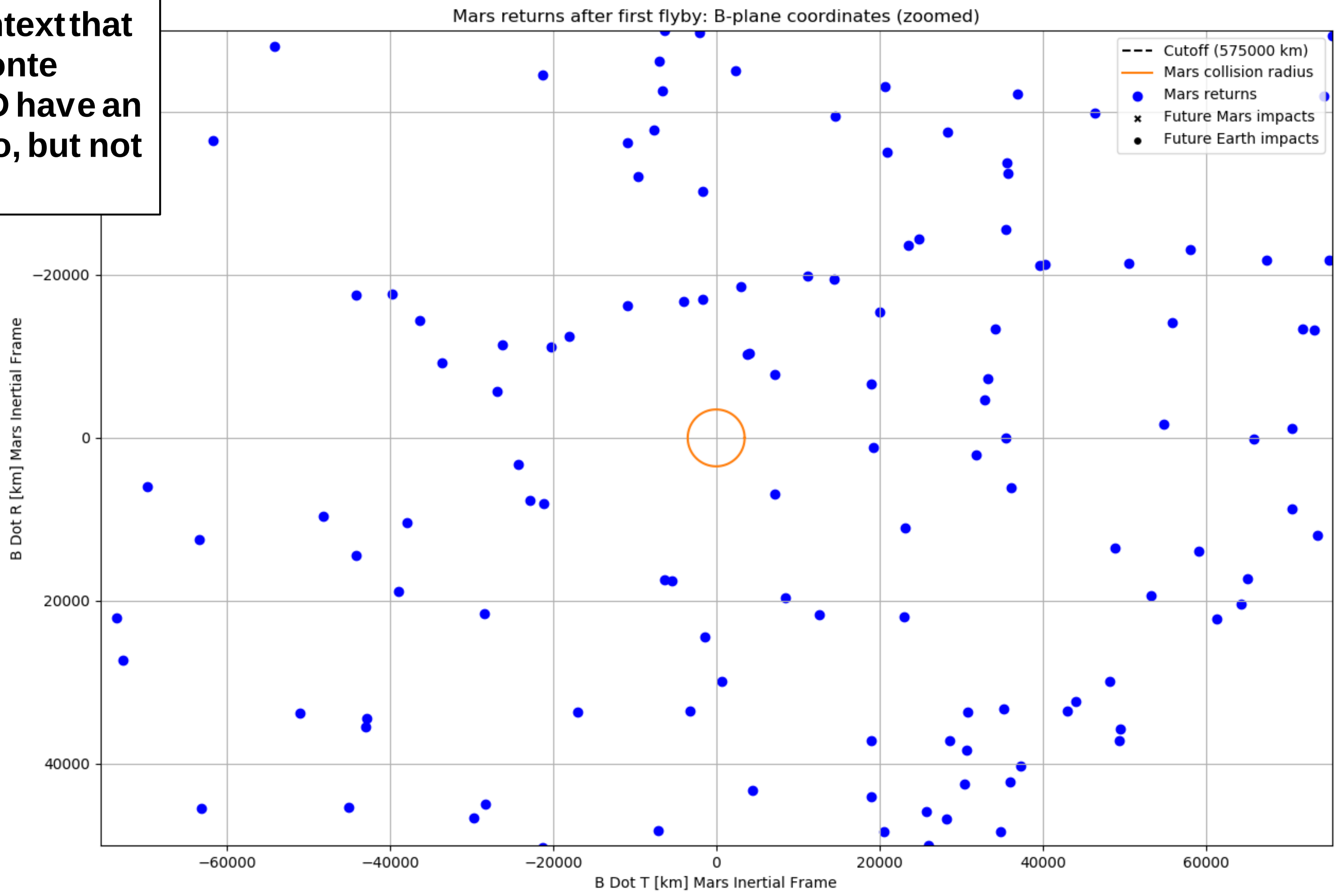
Mars Mission: Launching Day 1



Mars Mission: Launching Day 1

This zoom-in provides context that any given Monte Carlo COULD have an impact or two, but not many!





Probability Assessment

- It takes a large amount of time to run each case, so we don't want to run more cases than necessary.
- The Bernoulli confidence interval (CI) is the normal approximation, where the estimate of the probability of the event $\hat{p}$ is the number of observed events x divided by the number of trials n:

$$\hat{p} = x/n$$

$$CI = \left[\hat{p} - z\sqrt{\frac{\hat{p}(1-\hat{p})}{n}},\quad \hat{p} + z\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}\right]$$

- The parameter z is the number of standard deviations between which some percentage of the normal distribution lies.
  - 99% confidence, $z = 2.576$.
- We could then state that we have a 99% confidence that the *true probability of the event* p lies within the confidence interval.

- This process has two main flaws:
  - If no impacts occur, $\hat{p} = 0$ and $CI = [0,0]$ → not useful
  - If $\hat{p}$ is small, the CI can be negative → not meaningful

Probability Assessment

- Conservative variation is the Wilson interval:

$$CI = \left[\frac{n}{n+z^2}\left(\hat{p} + \frac{z^2}{2n} \pm z\sqrt{\frac{4n\hat{p}(1-\hat{p}) + z^2}{4n^2}}\right)\right]$$

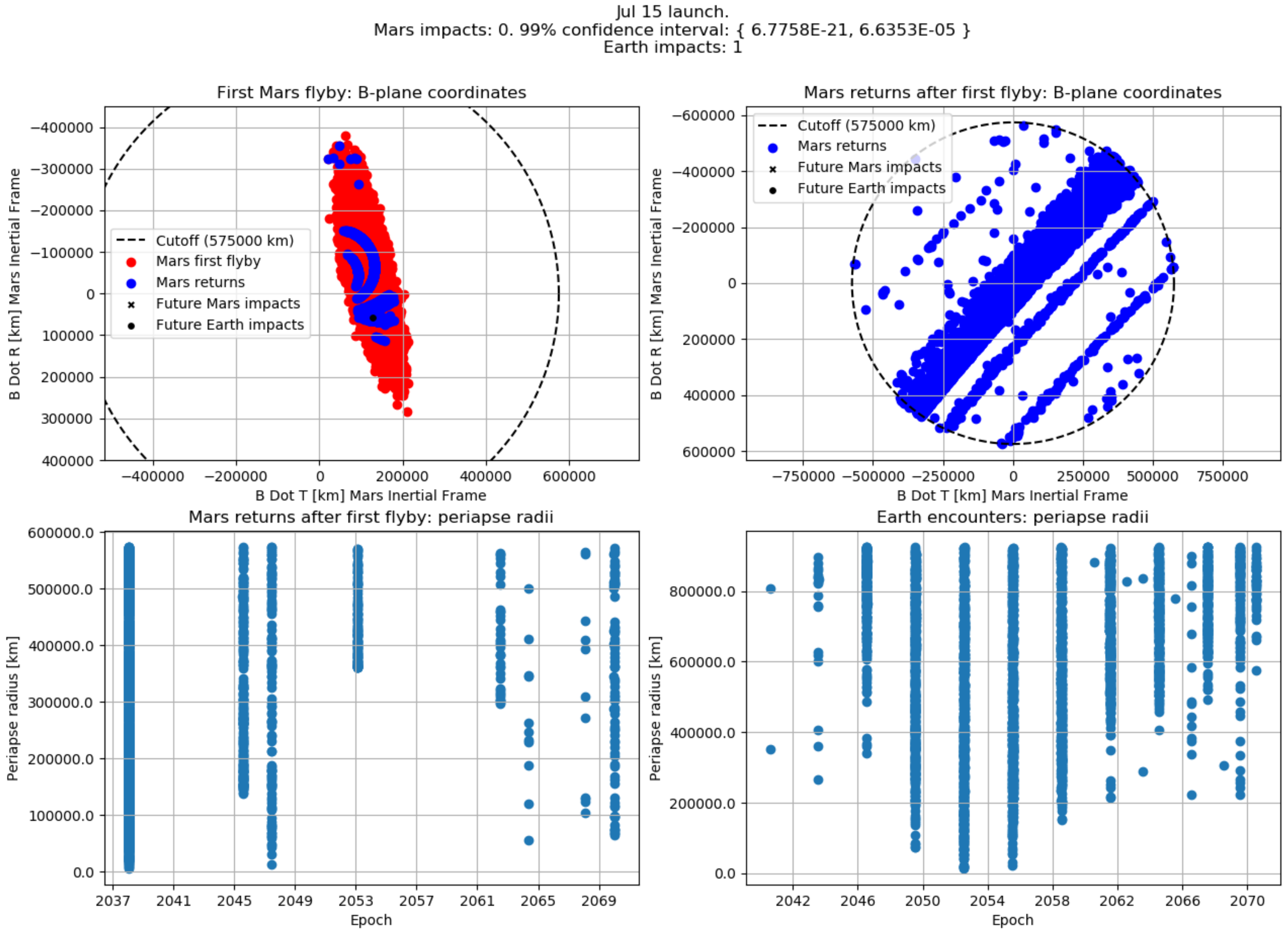
- If $\hat{p} = 0$, then:

$$CI\Big|_{x=0} = \left[0, \frac{z^2}{n+z^2}\right]$$

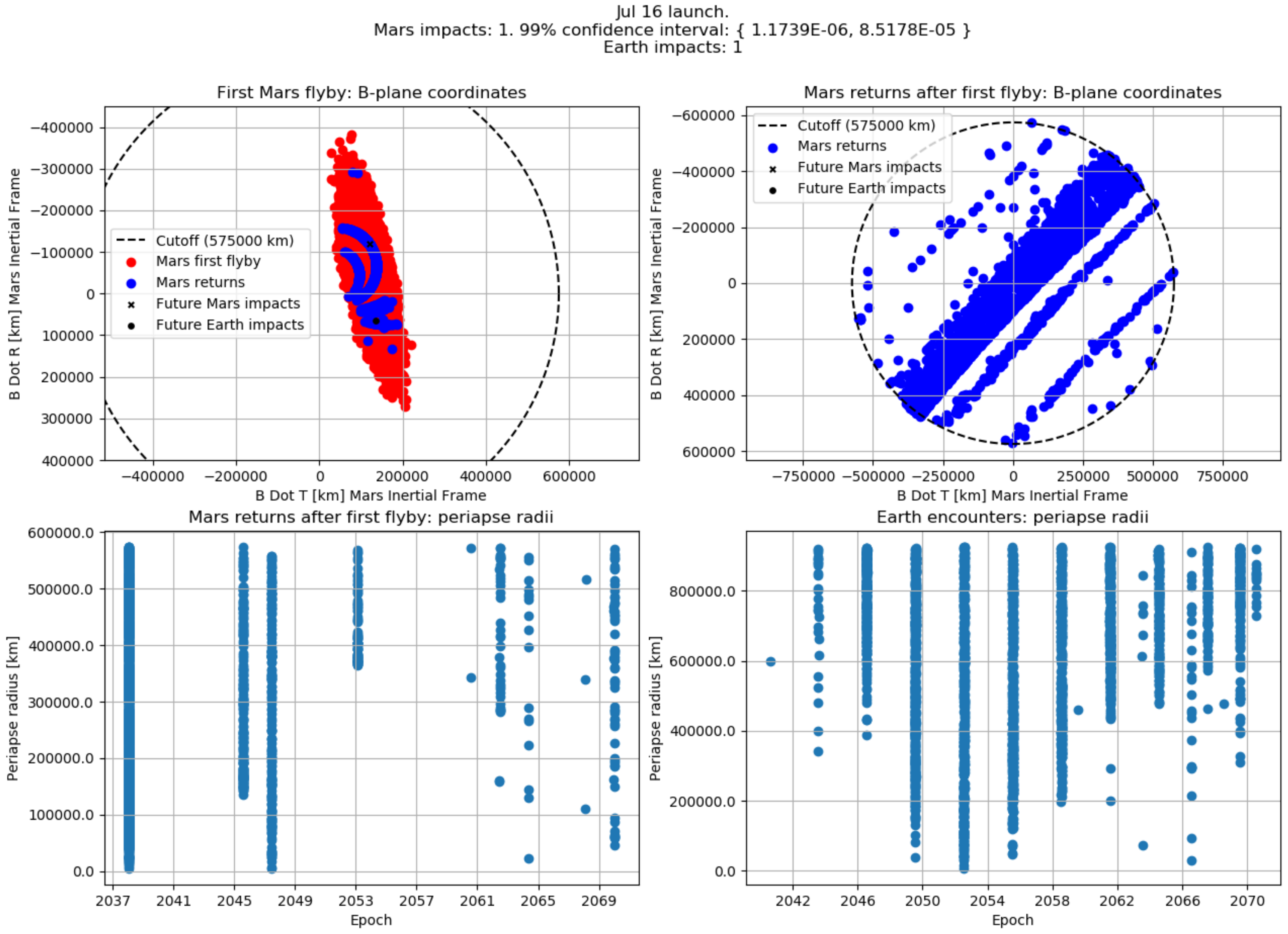
- It is desirable that this CI has a lower bound of zero, since it may be impossible to impact Mars!

- If $x = 0$, then $n = 66{,}352$ to have a 99% CI that $p < 10^{-4}$
- If $x = 1$, then $n = 85{,}178$ to have a 99% CI that $p \propto \left[0.0137 \times 10^{-4}, 1.0 \times 10^{-4}\right]$
- If $x = 2$, then $n = 102{,}447$ to have a 99% CI that $p \propto \left[0.0381 \times 10^{-4}, 1.0 \times 10^{-4}\right]$
- If $x = 3$, then $n = 118{,}774$ to have a 99% CI that $p \propto \left[0.0638 \times 10^{-4}, 1.0 \times 10^{-4}\right]$

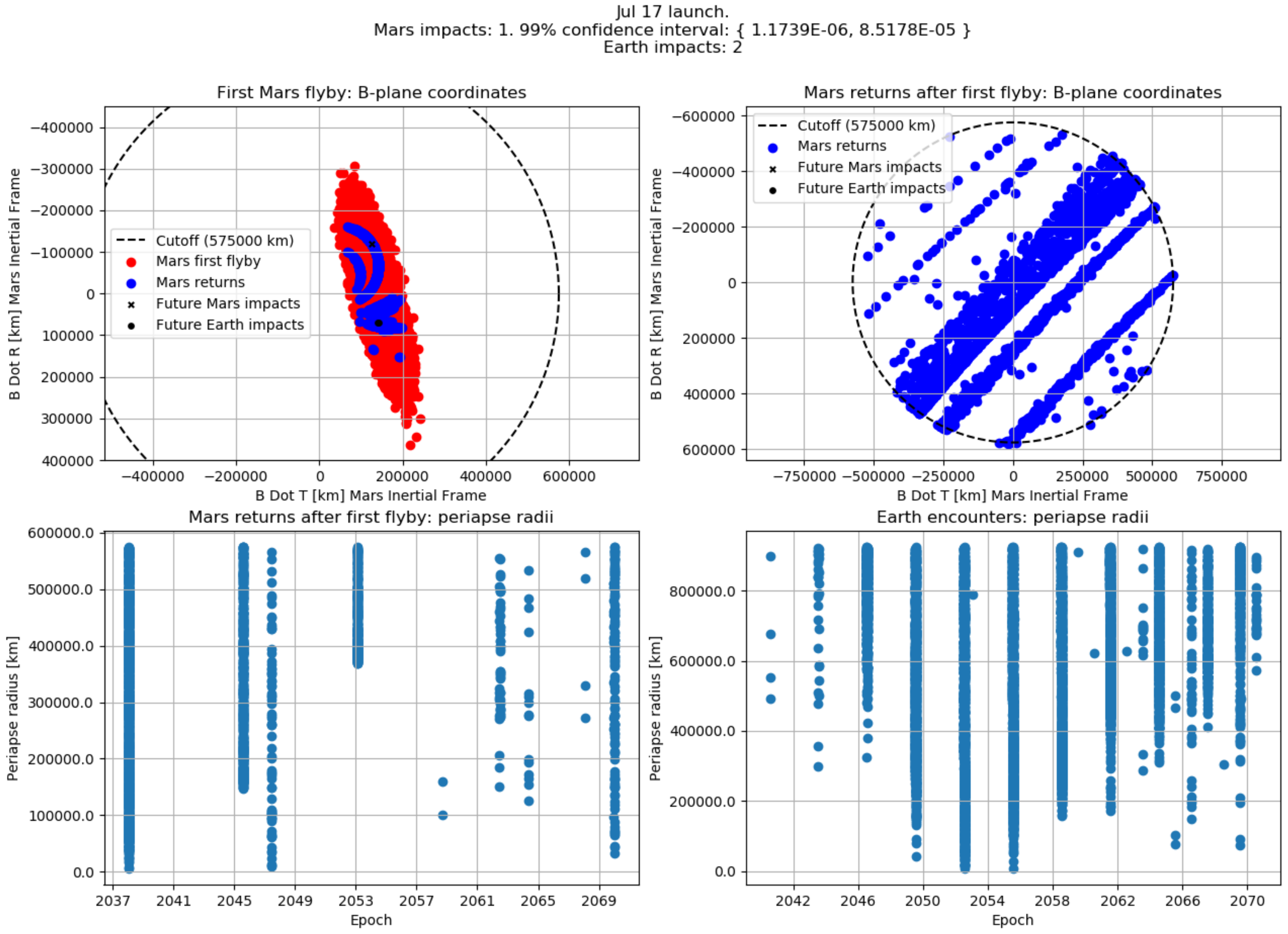
July 15 Results: 0 impacts



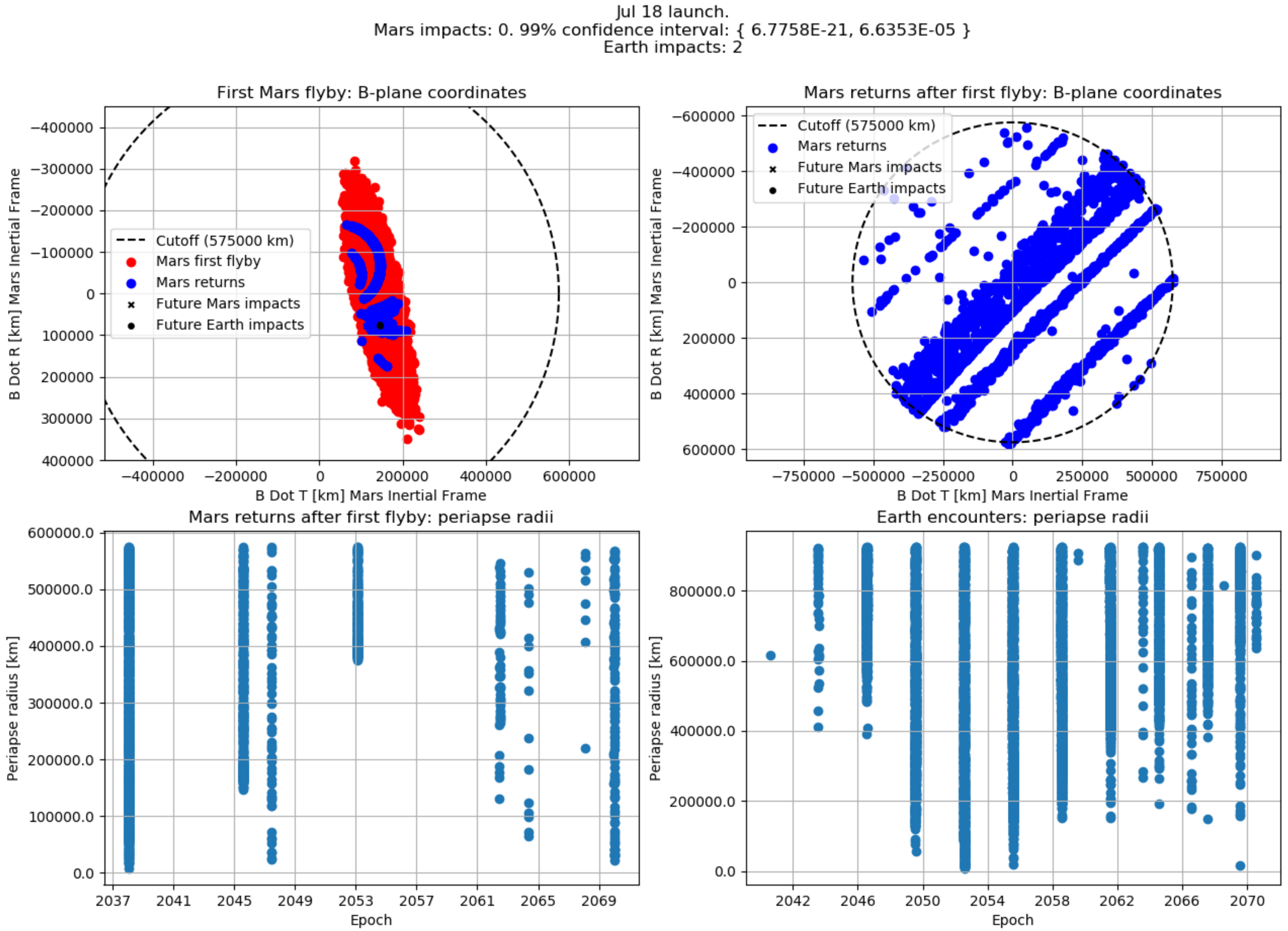
July 16 Results: 1 impact



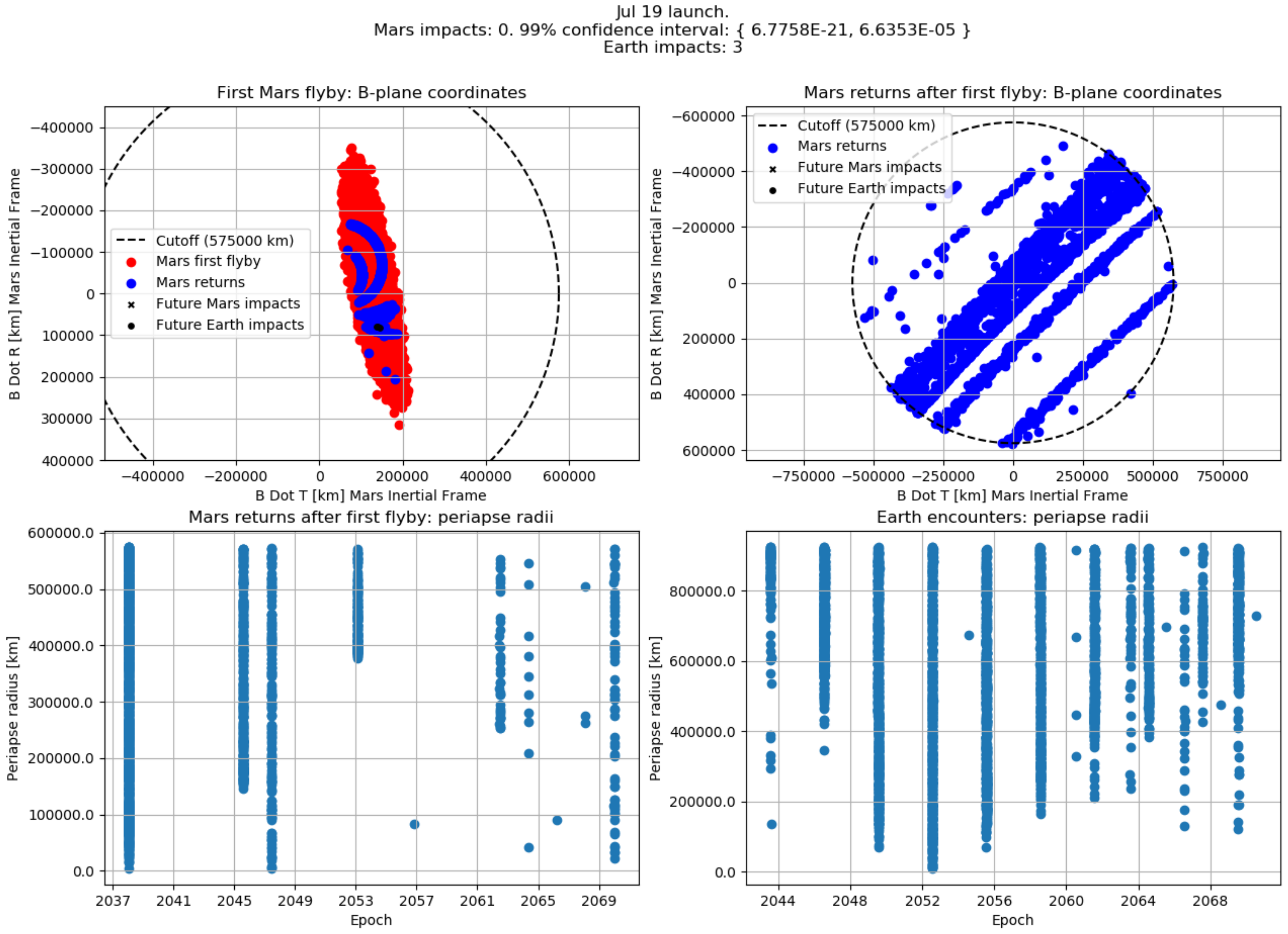
July 17 Results: 1 impact



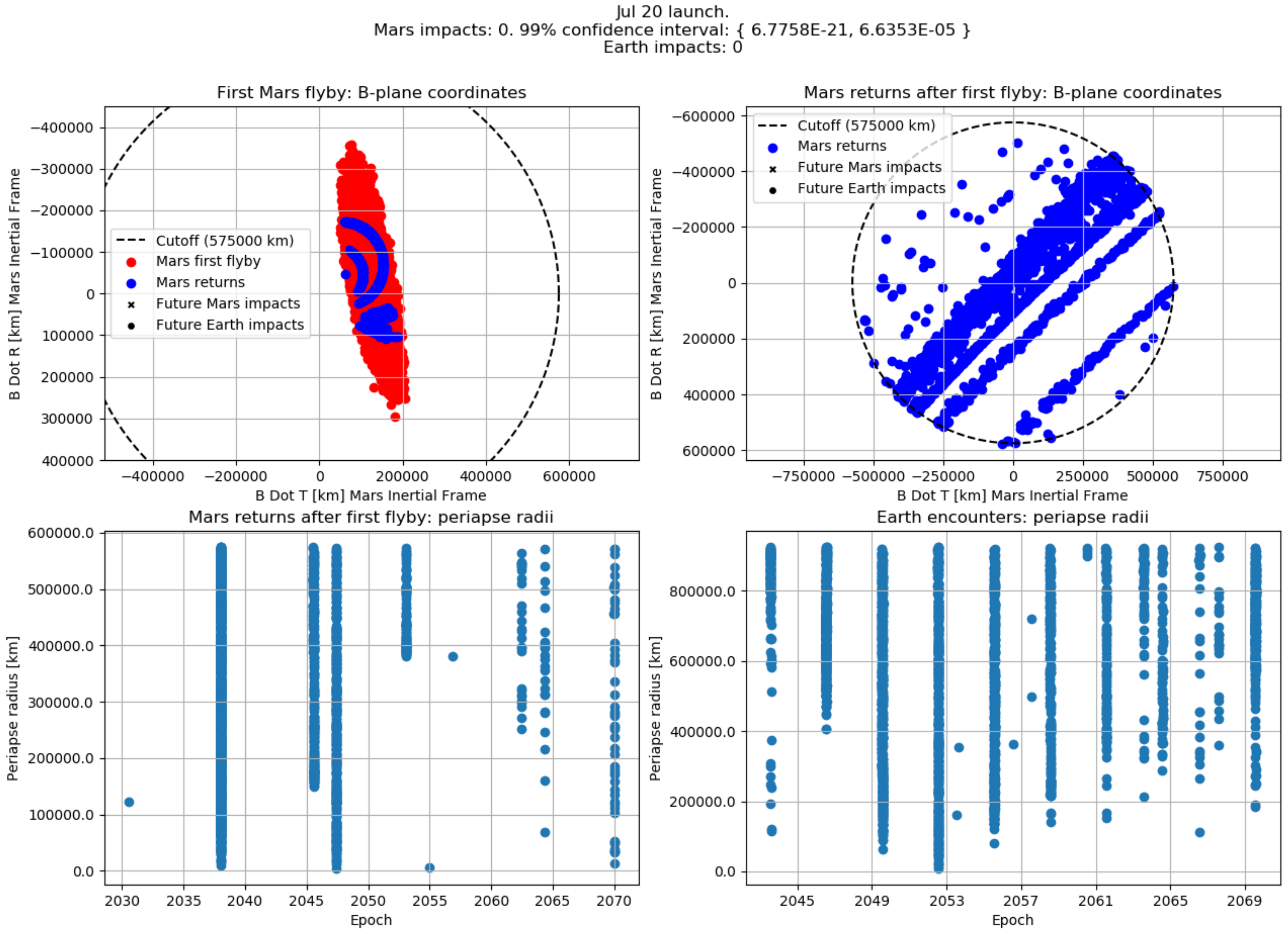
July 18 Results: 0 impacts



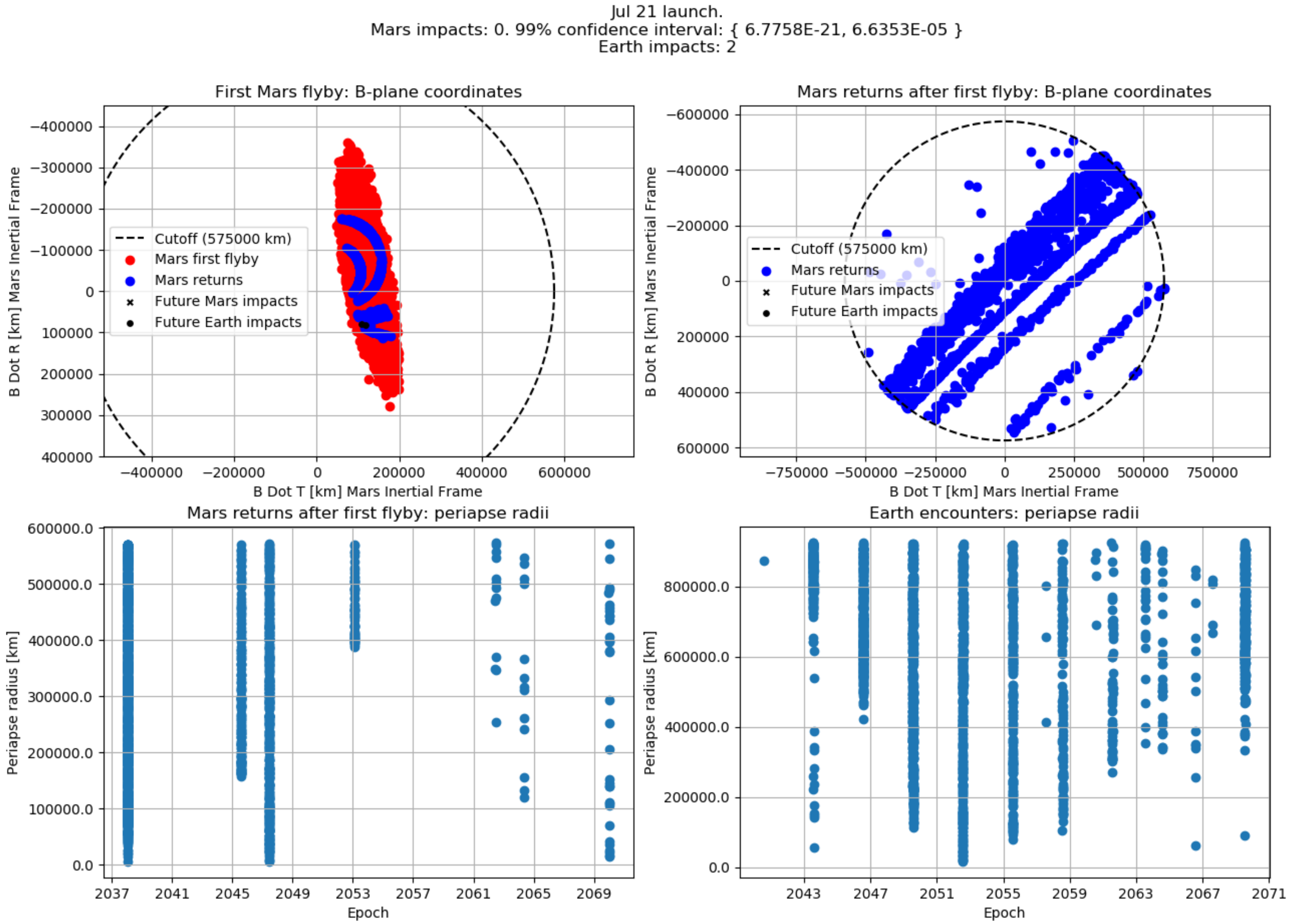
July 19 Results: 0 impacts



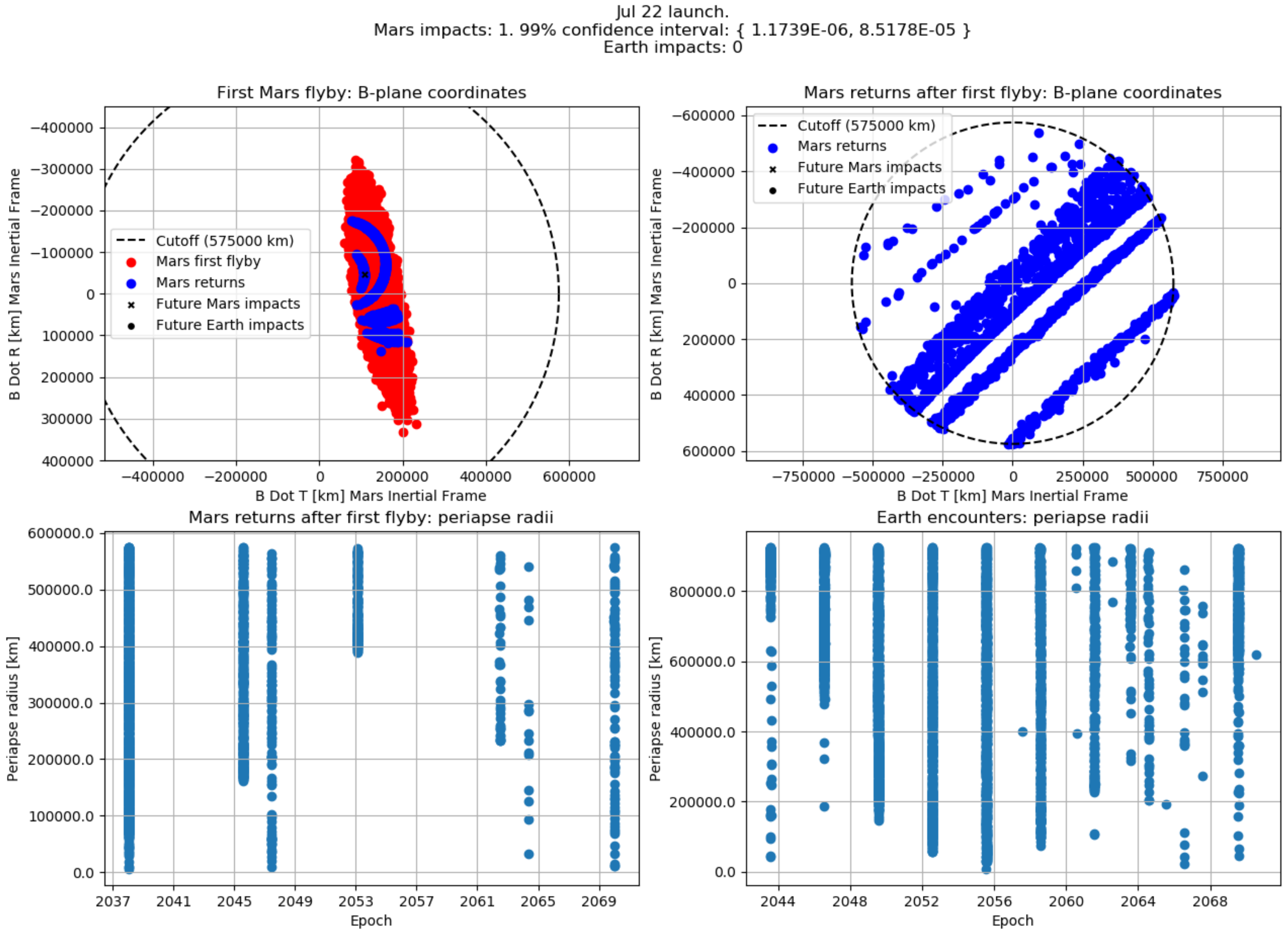
July 20 Results: 0 impacts



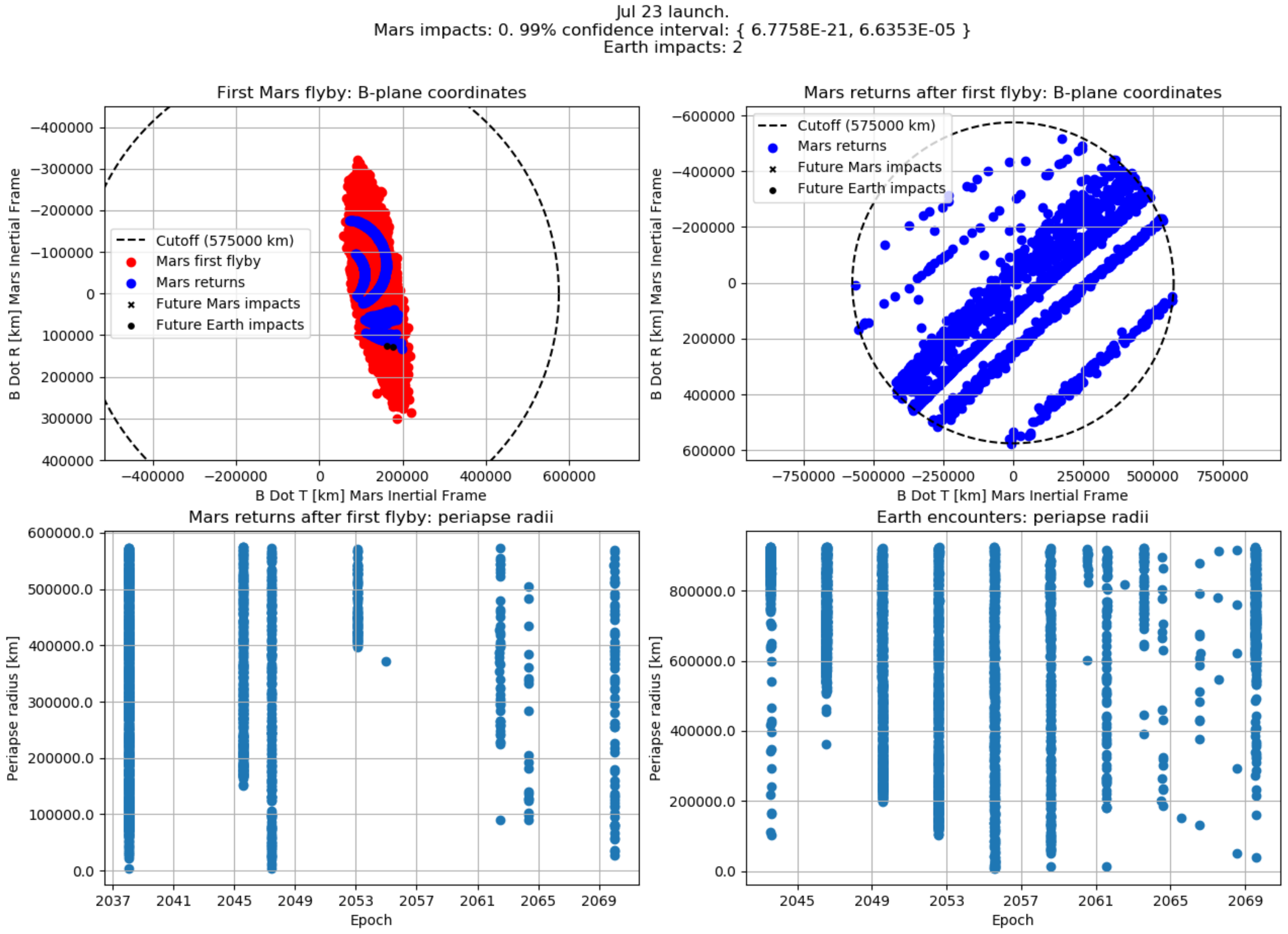
July 21 Results: 0 impacts



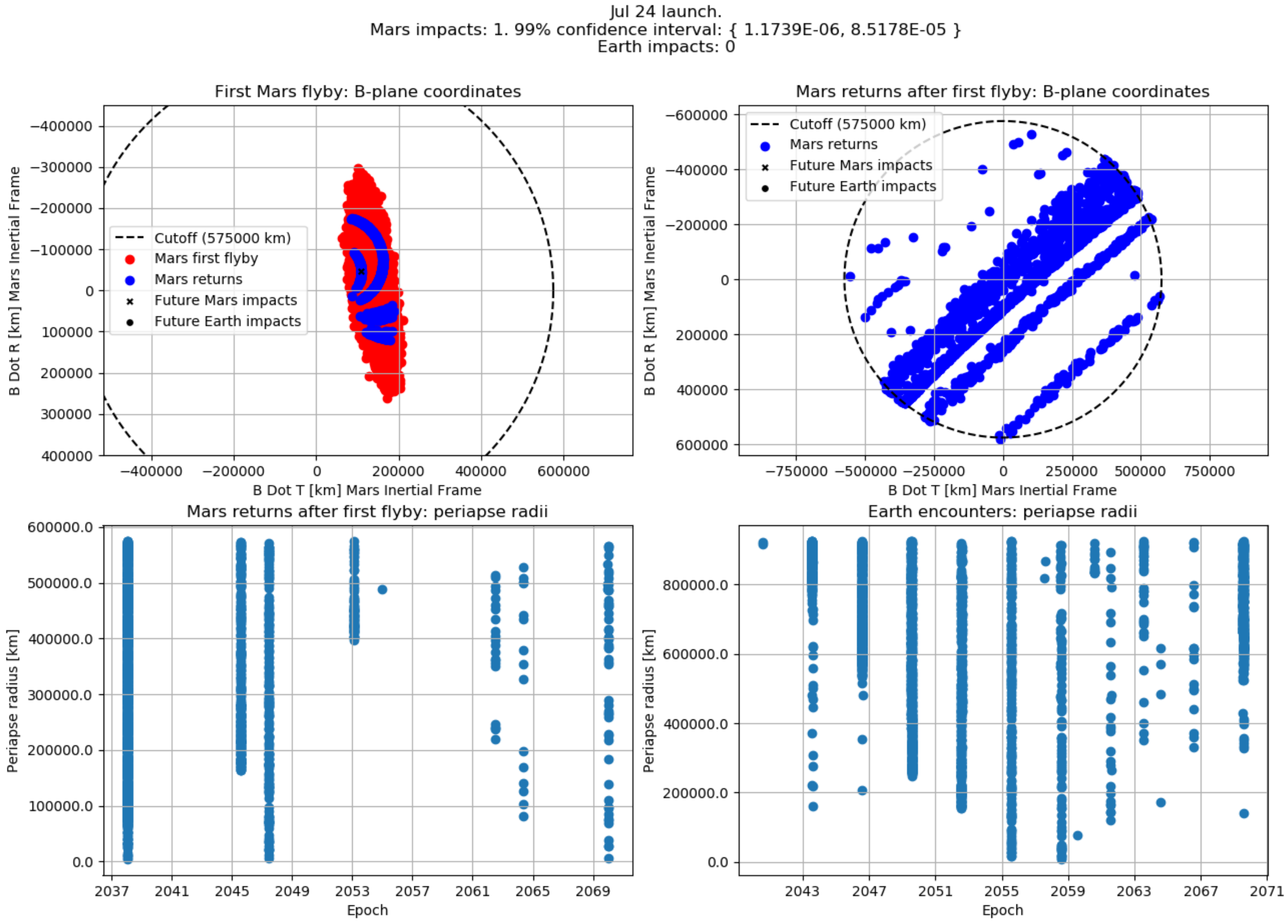
July 22 Results: 1 impact



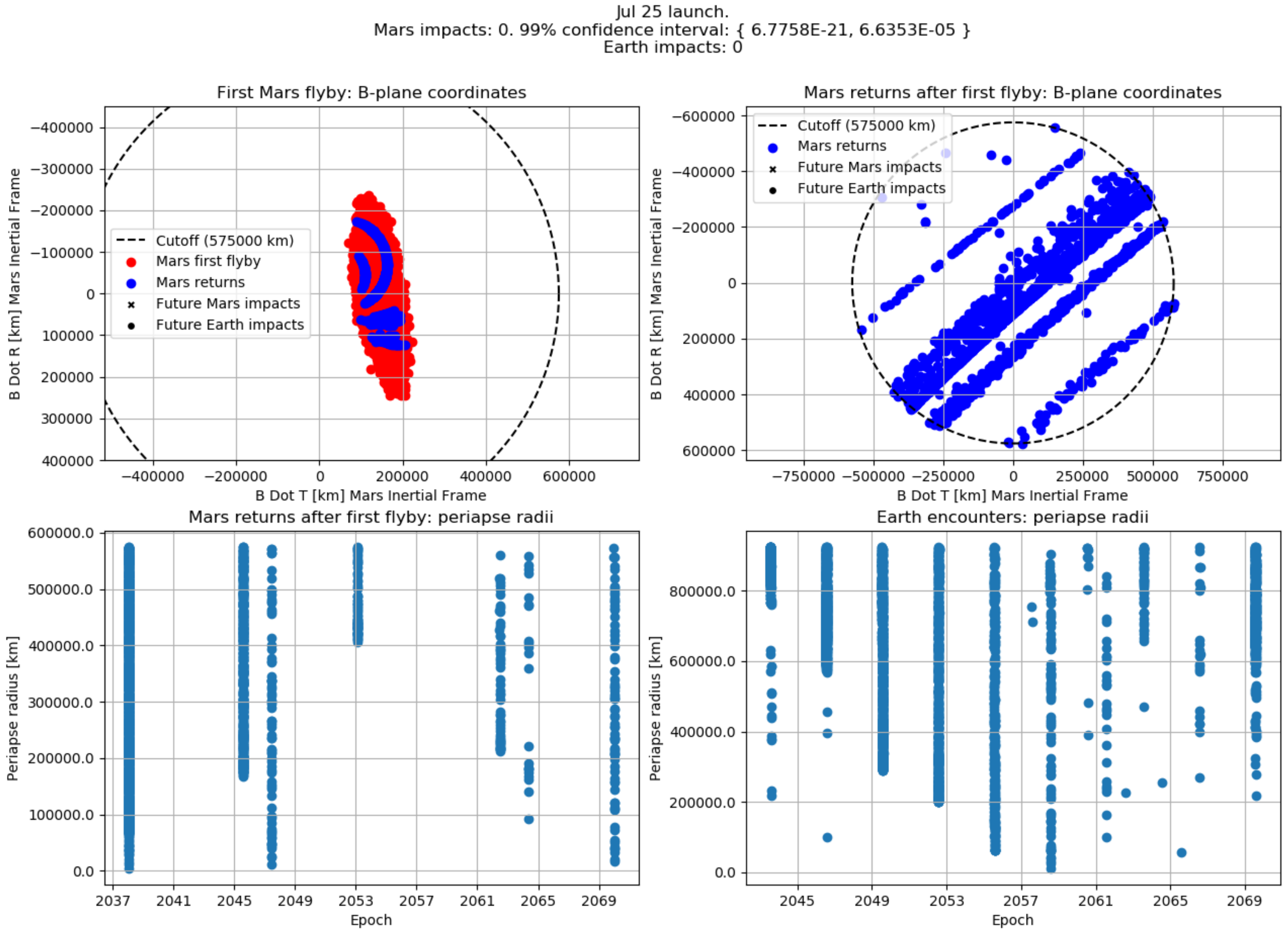
July 23 Results: 0 impacts



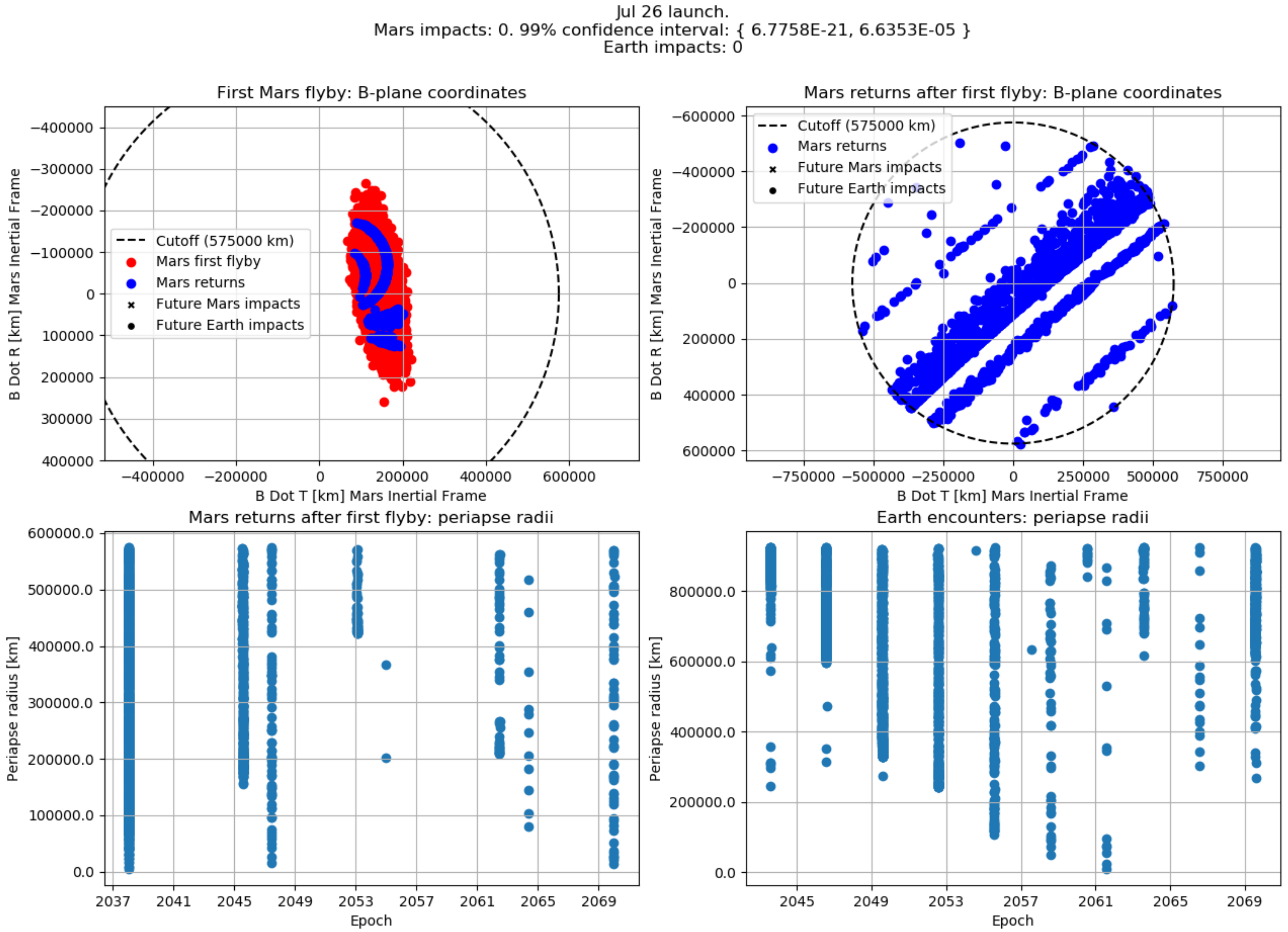
July 24 Results: 1 impact



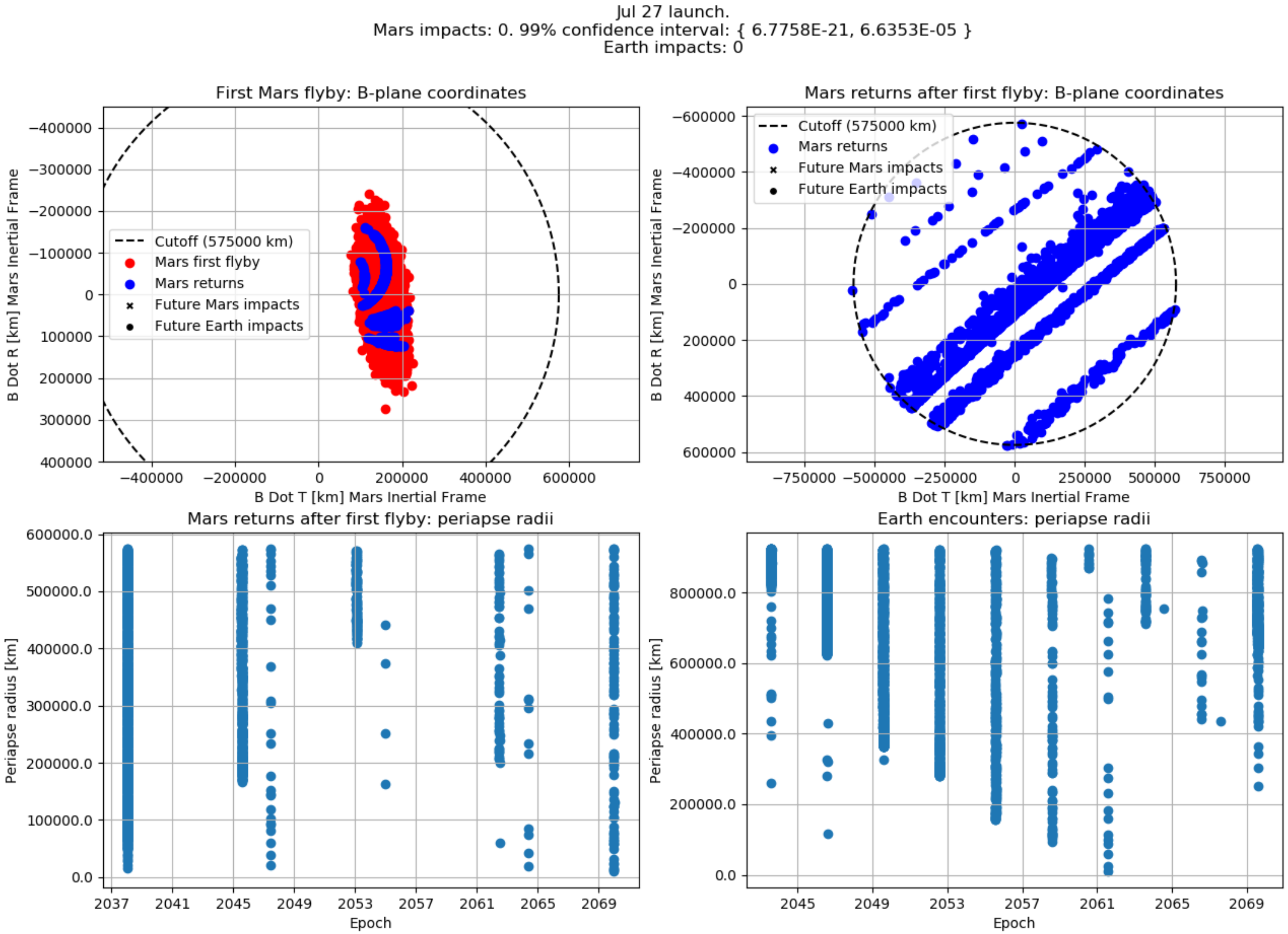
July 25 Results: 0 impacts



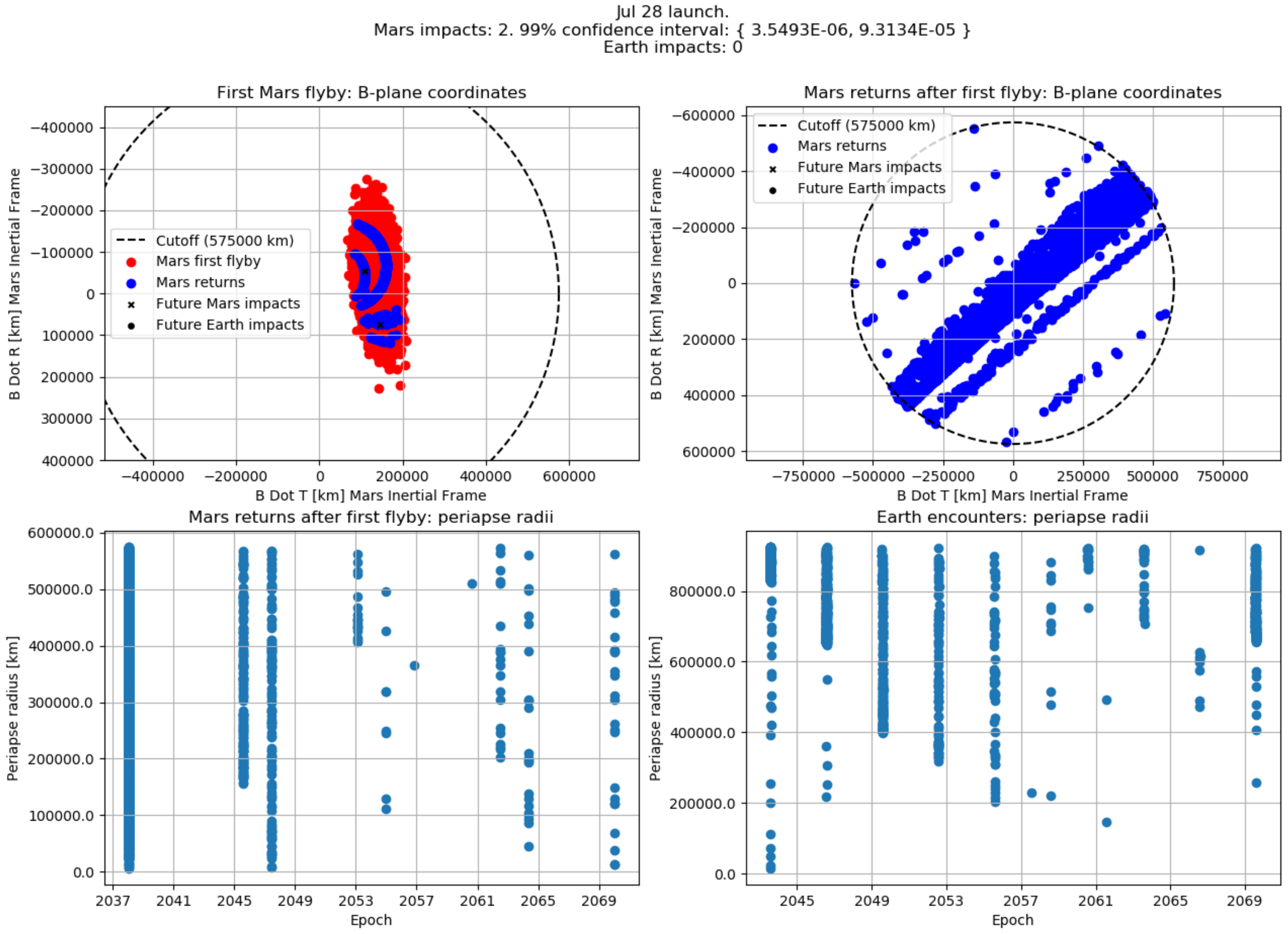
July 26 Results: 0 impacts



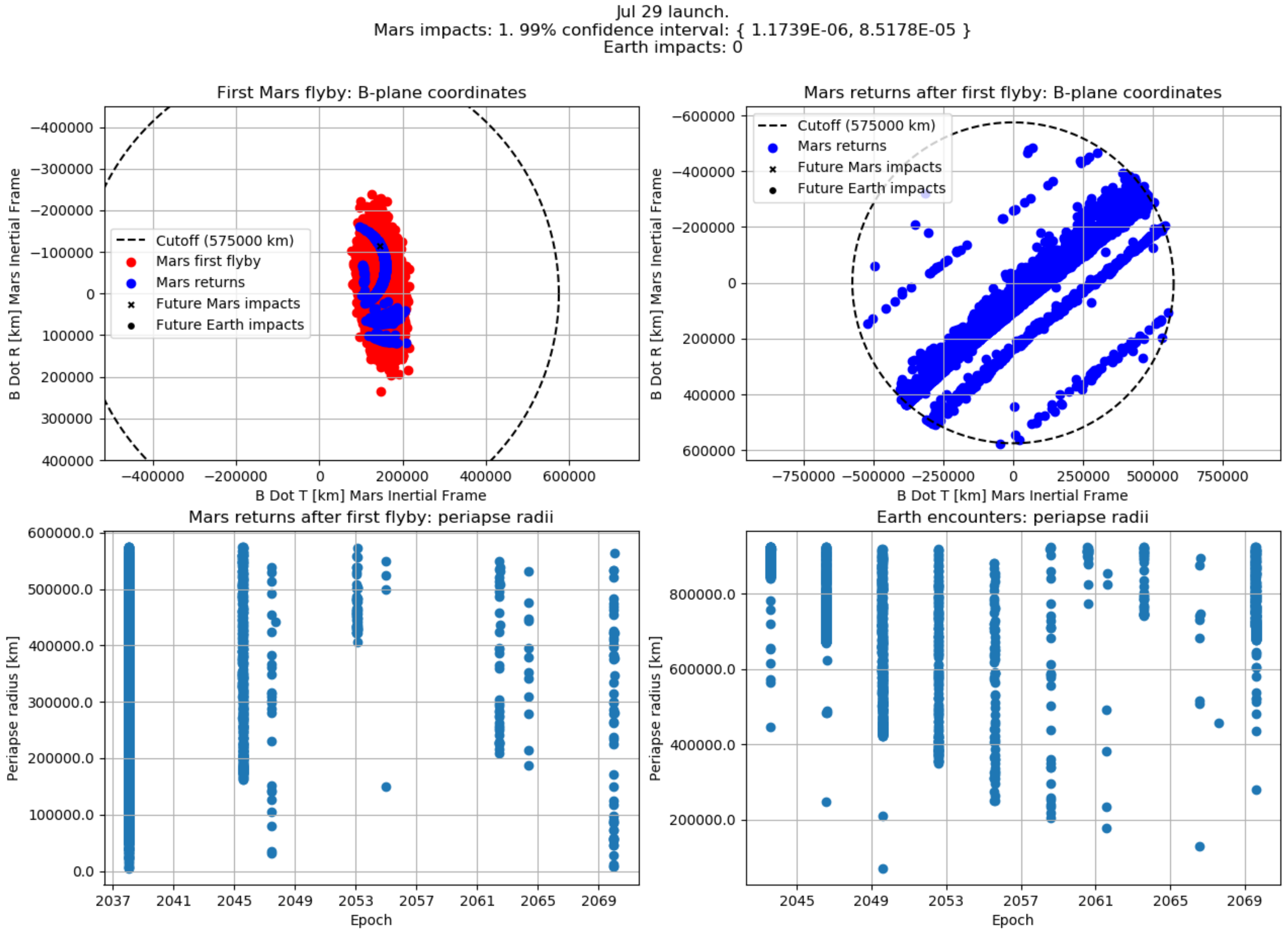
July 27 Results: 0 impacts



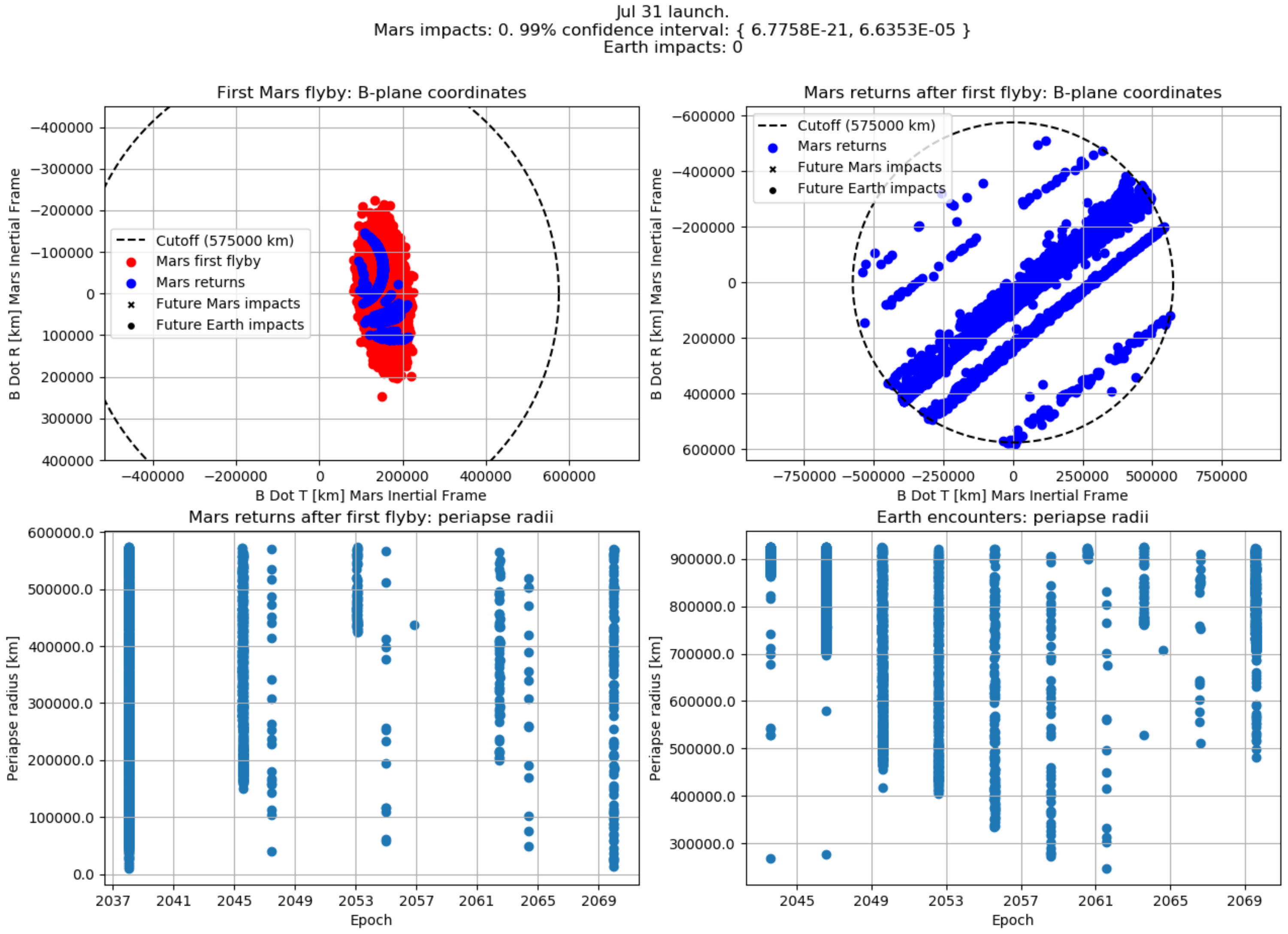
July 28 Results: 2 impacts (10,000 additional runs!)



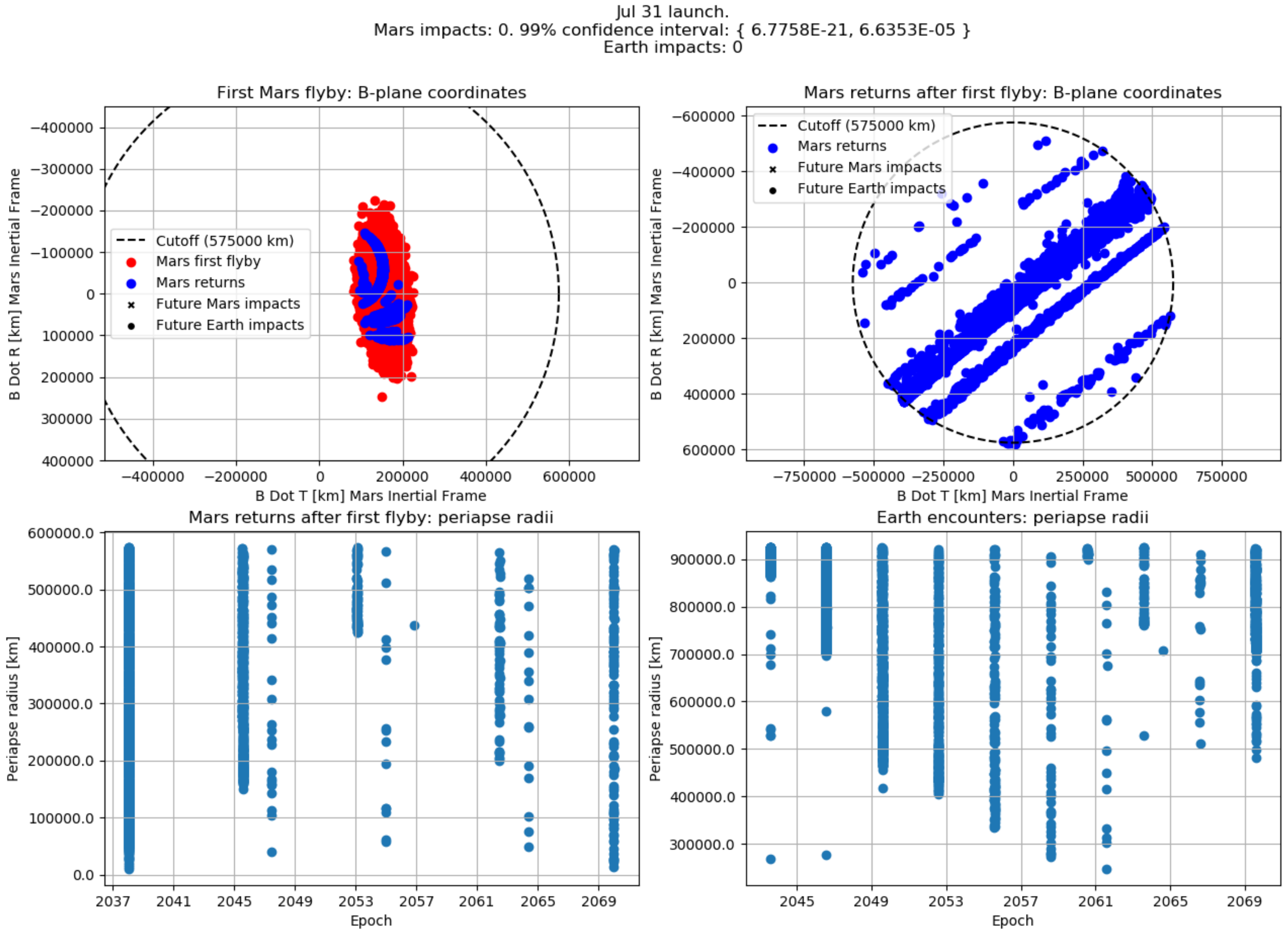
July 29 Results: 1 impact



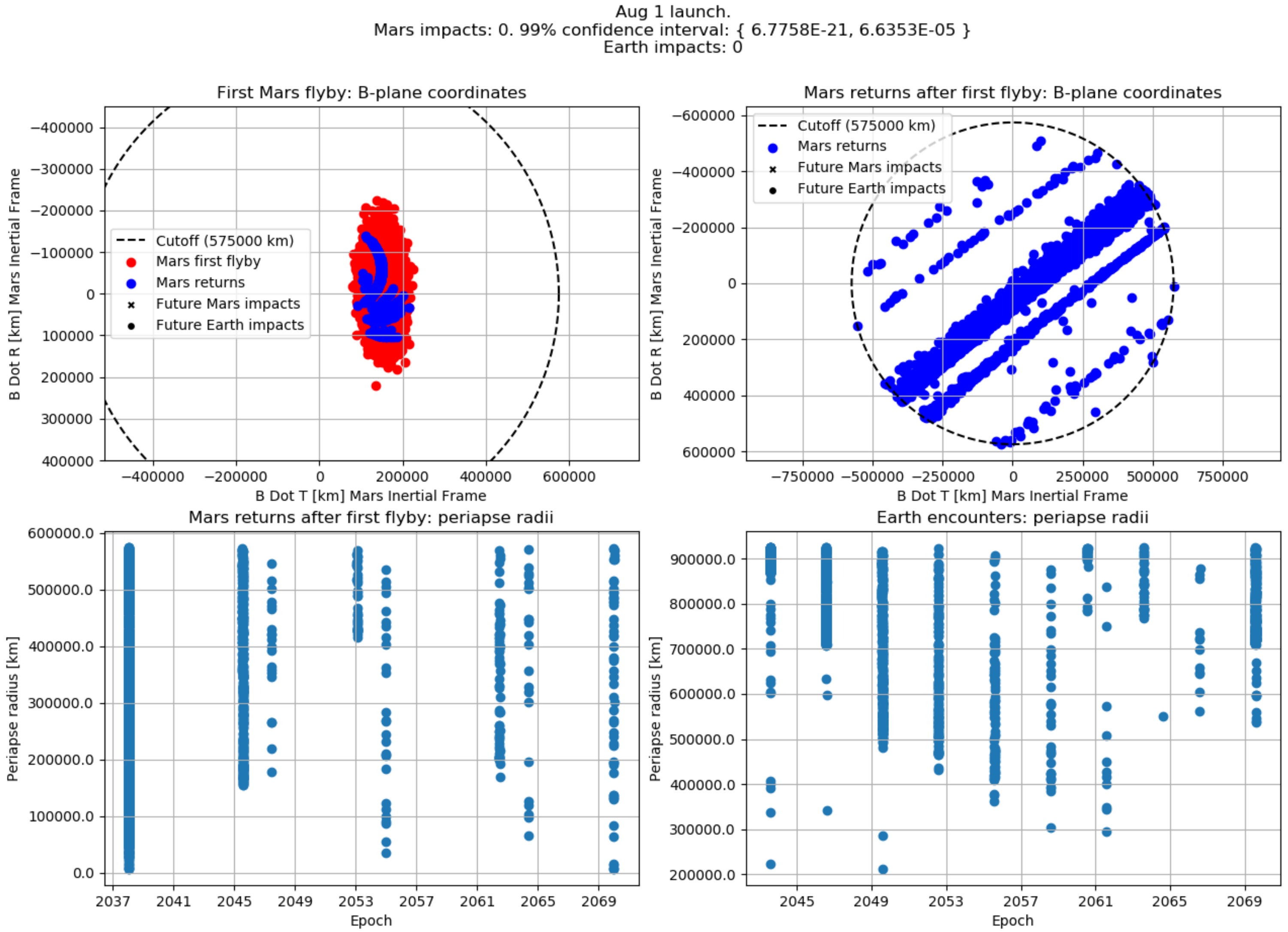
July 30 Results: 0 impacts



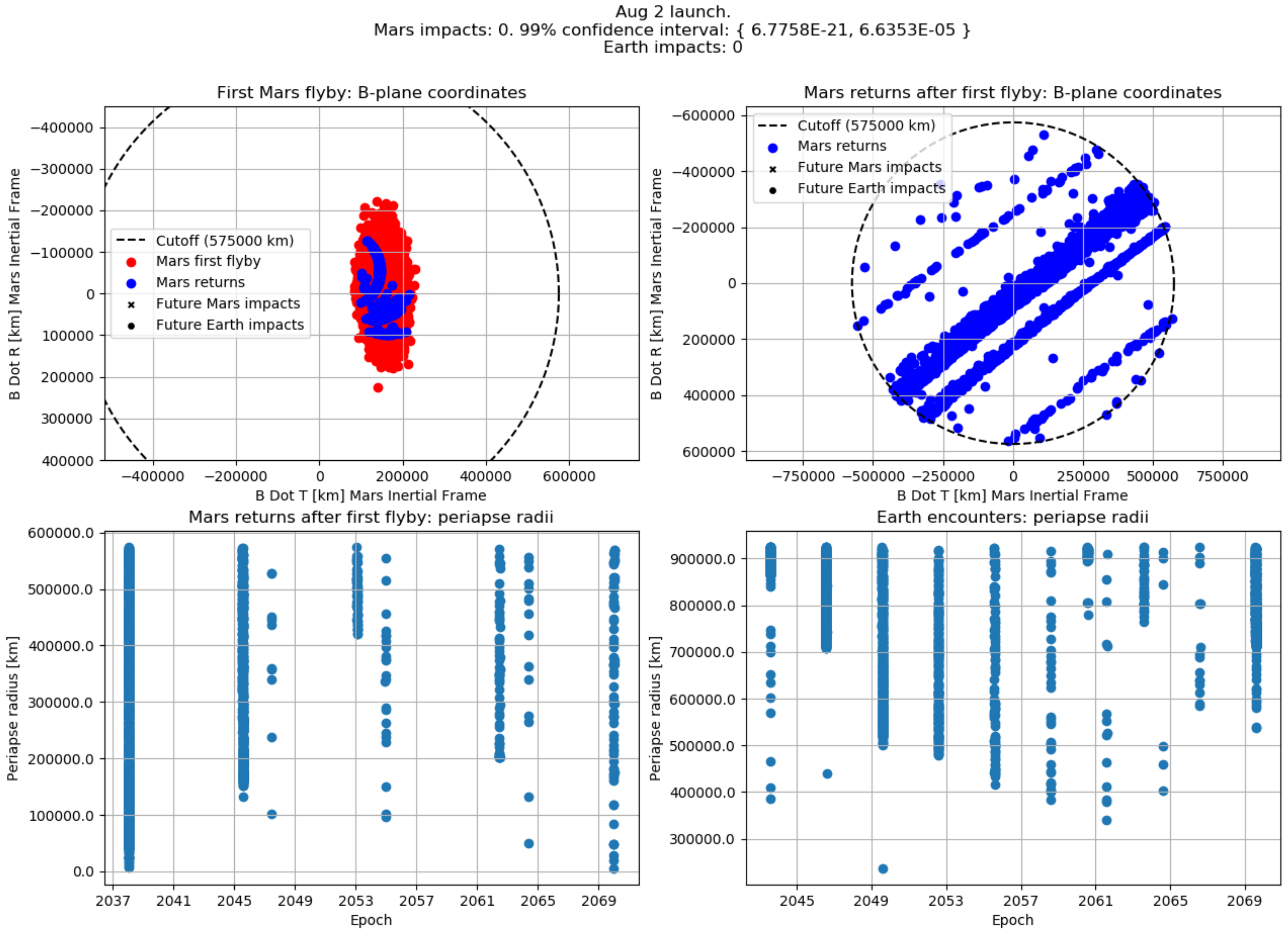
July 31 Results: 0 impacts



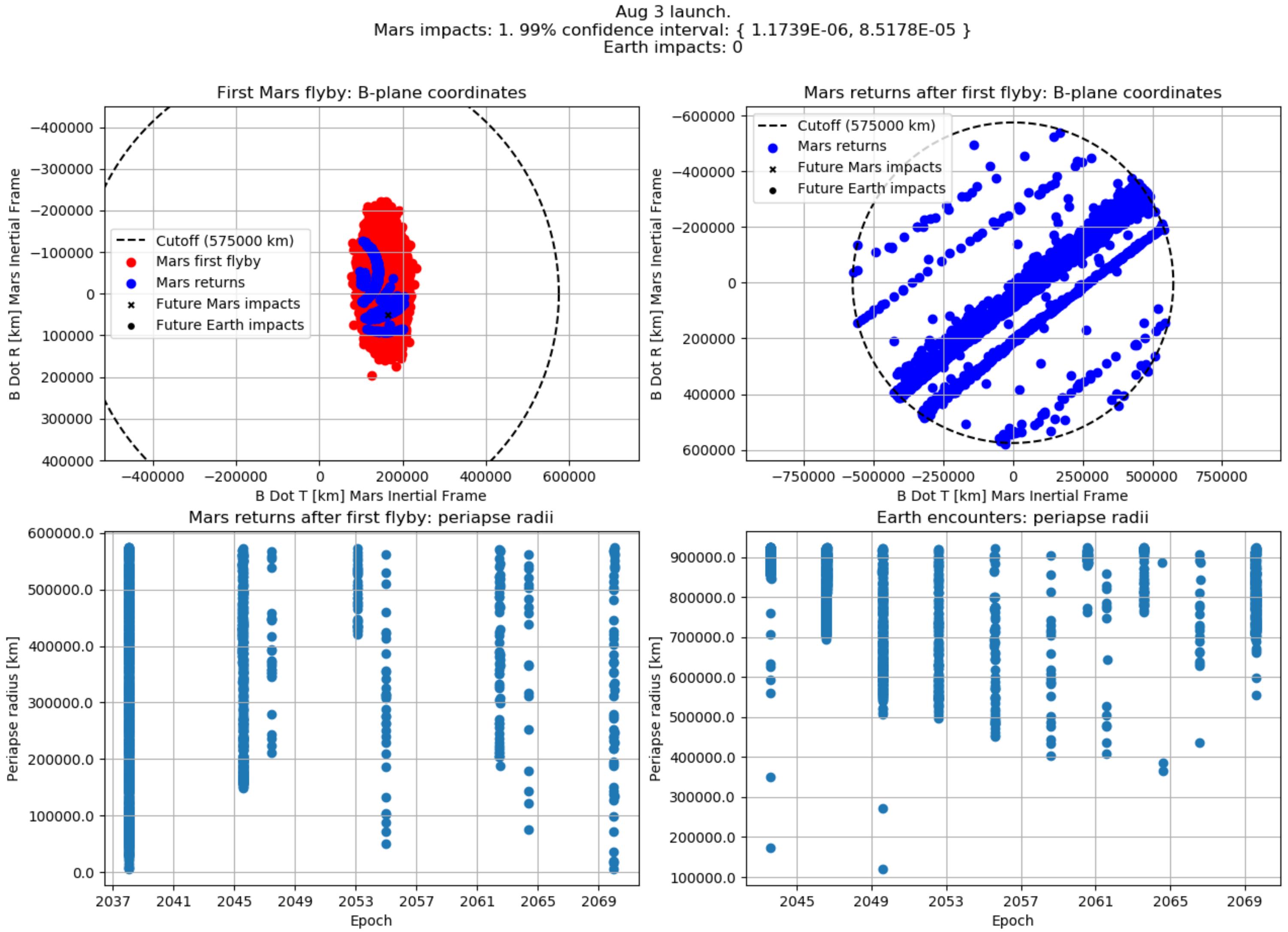
Aug 1 Results: 0 impacts



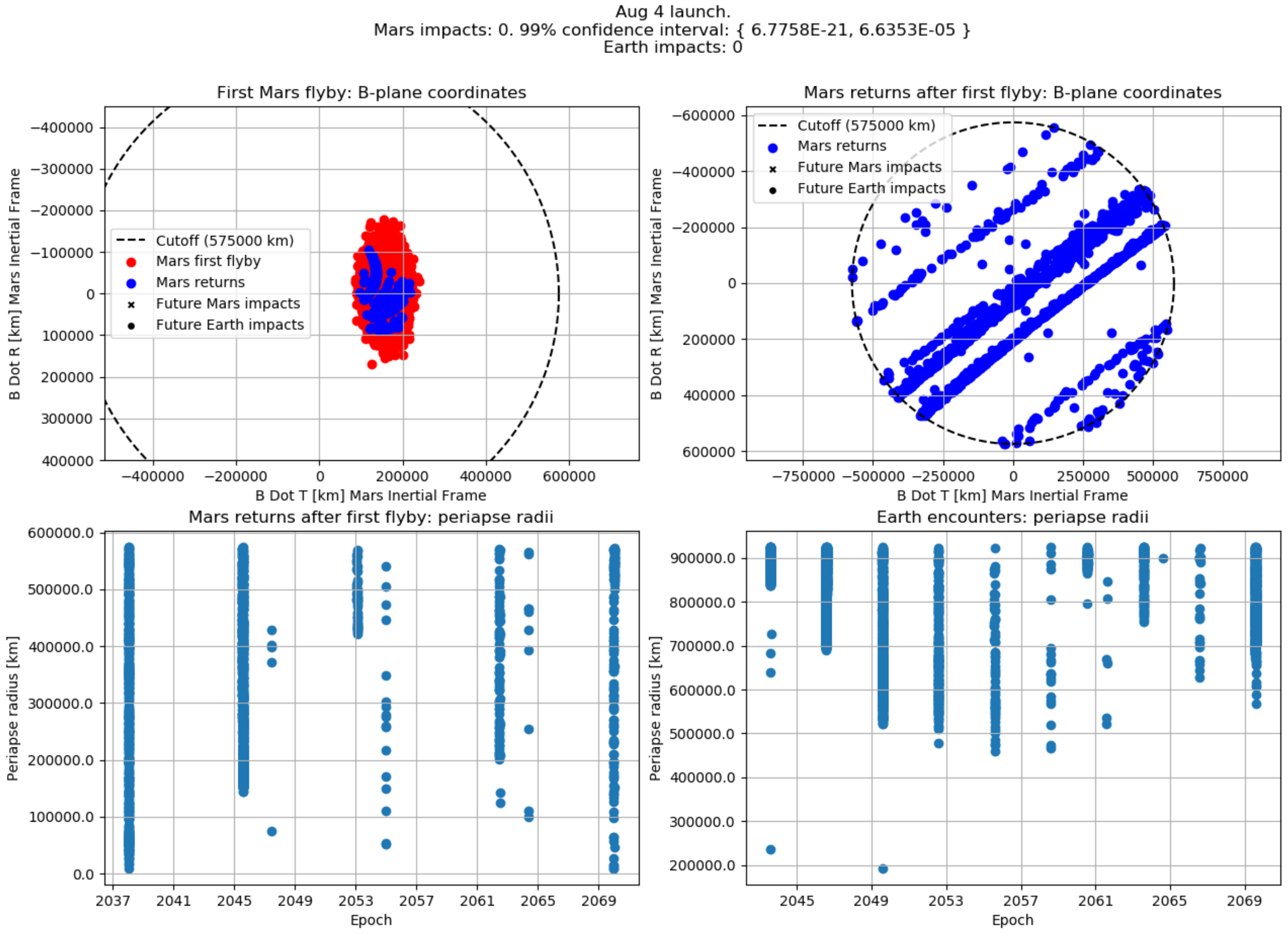
Aug 2 Results: 0 impacts



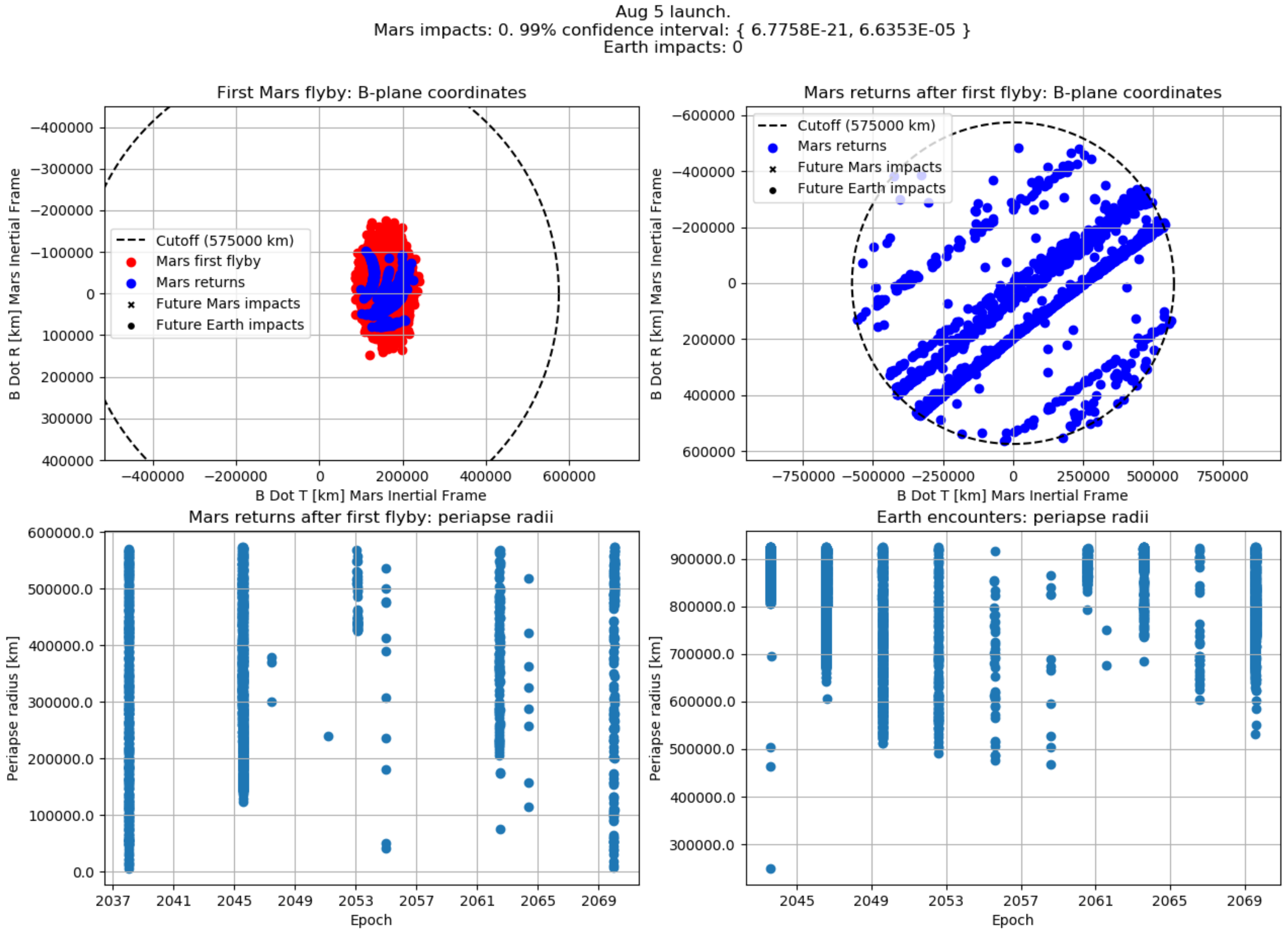
Aug 3 Results: 1 impact



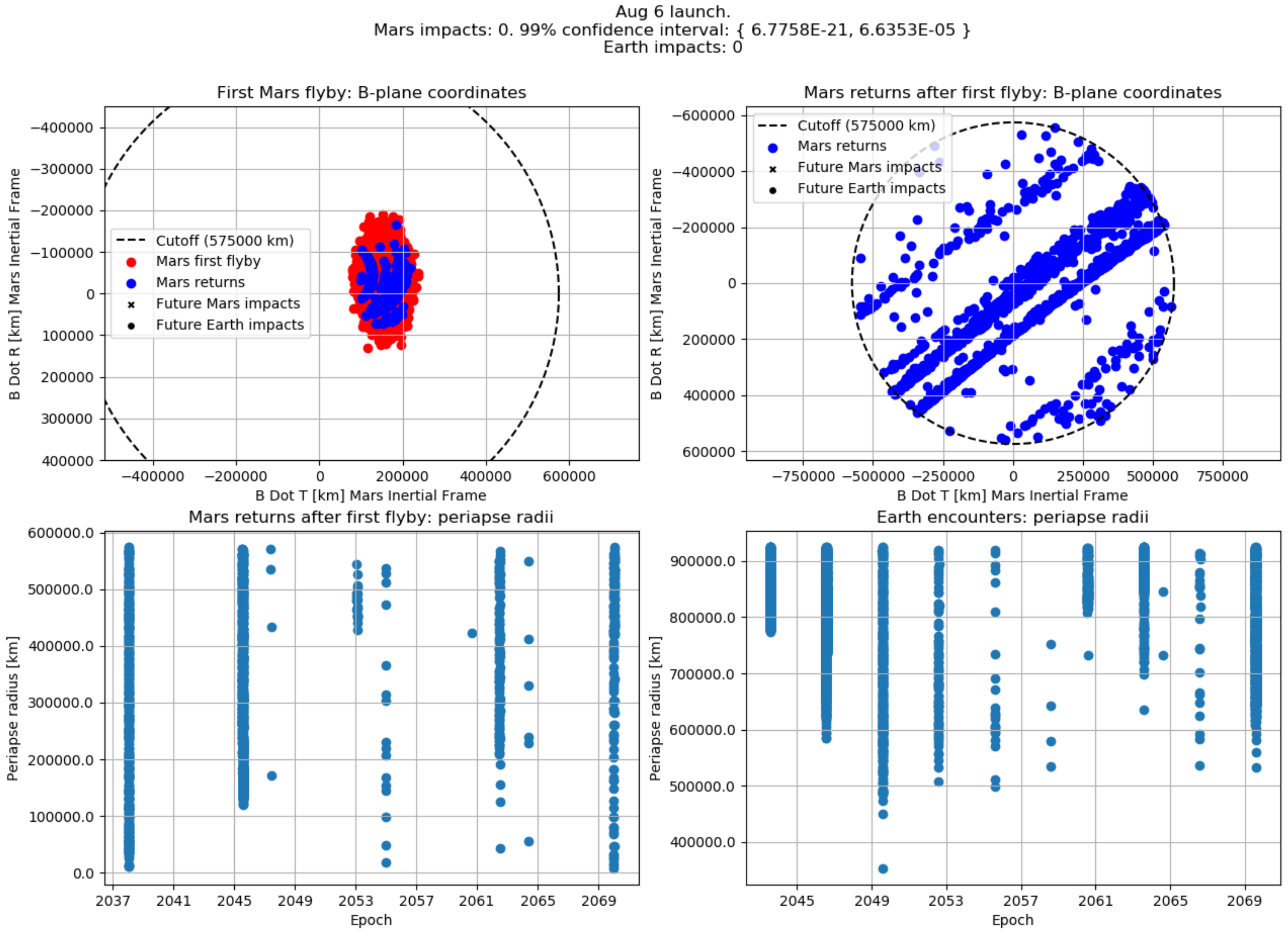
Aug 4 Results: 0 impacts



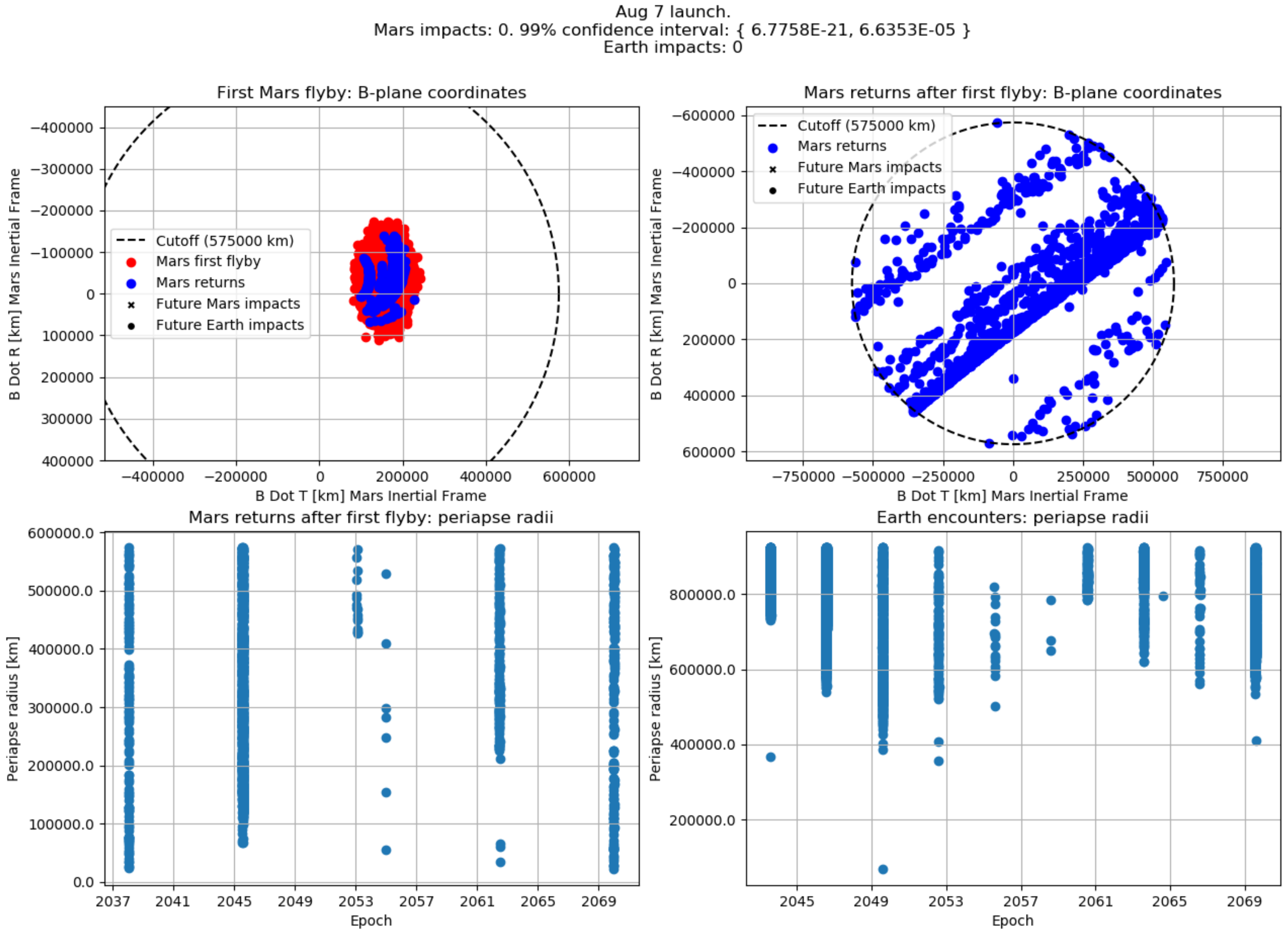
Aug 5 Results: 0 impacts



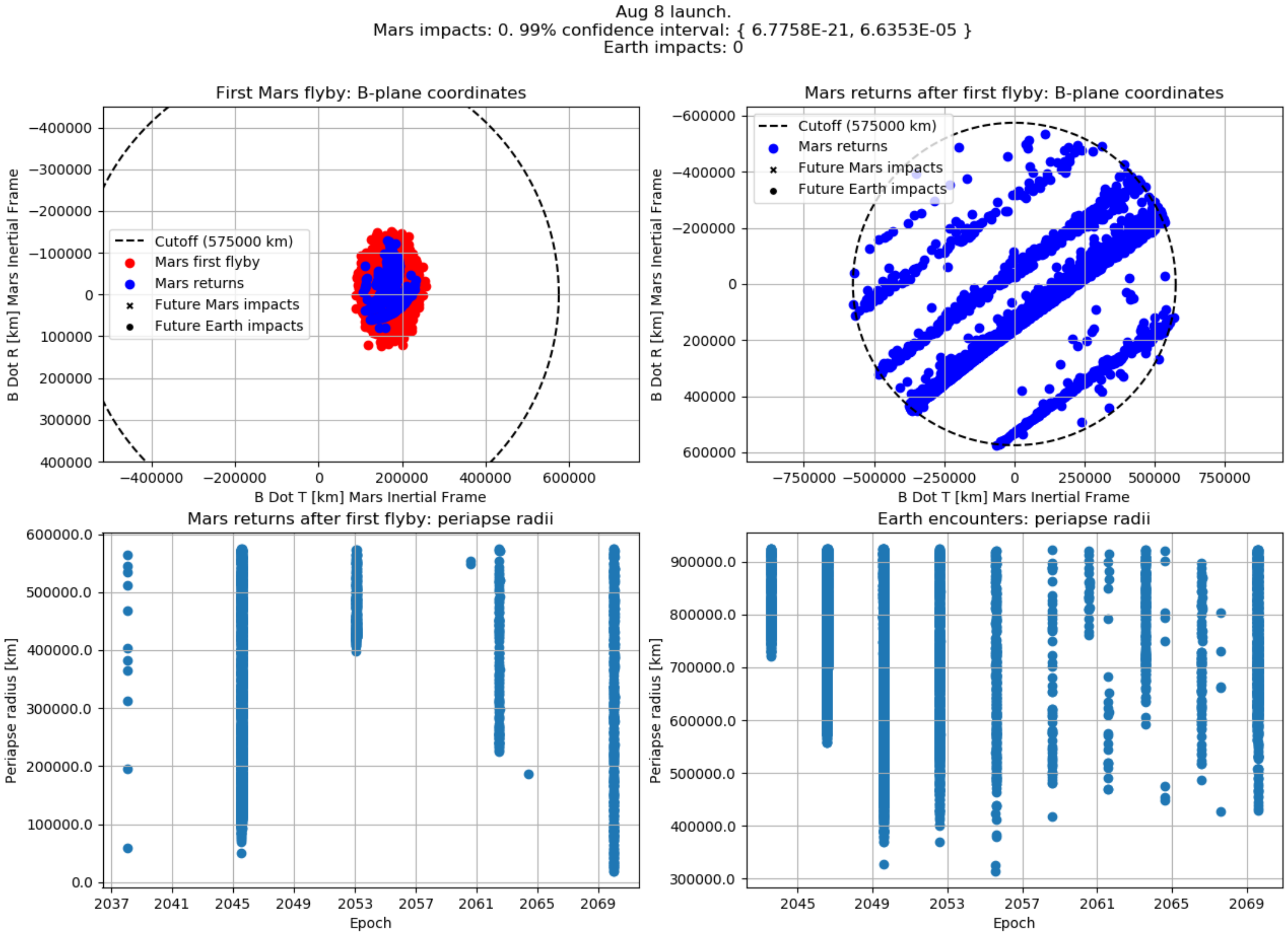
Aug 6 Results: 0 impacts



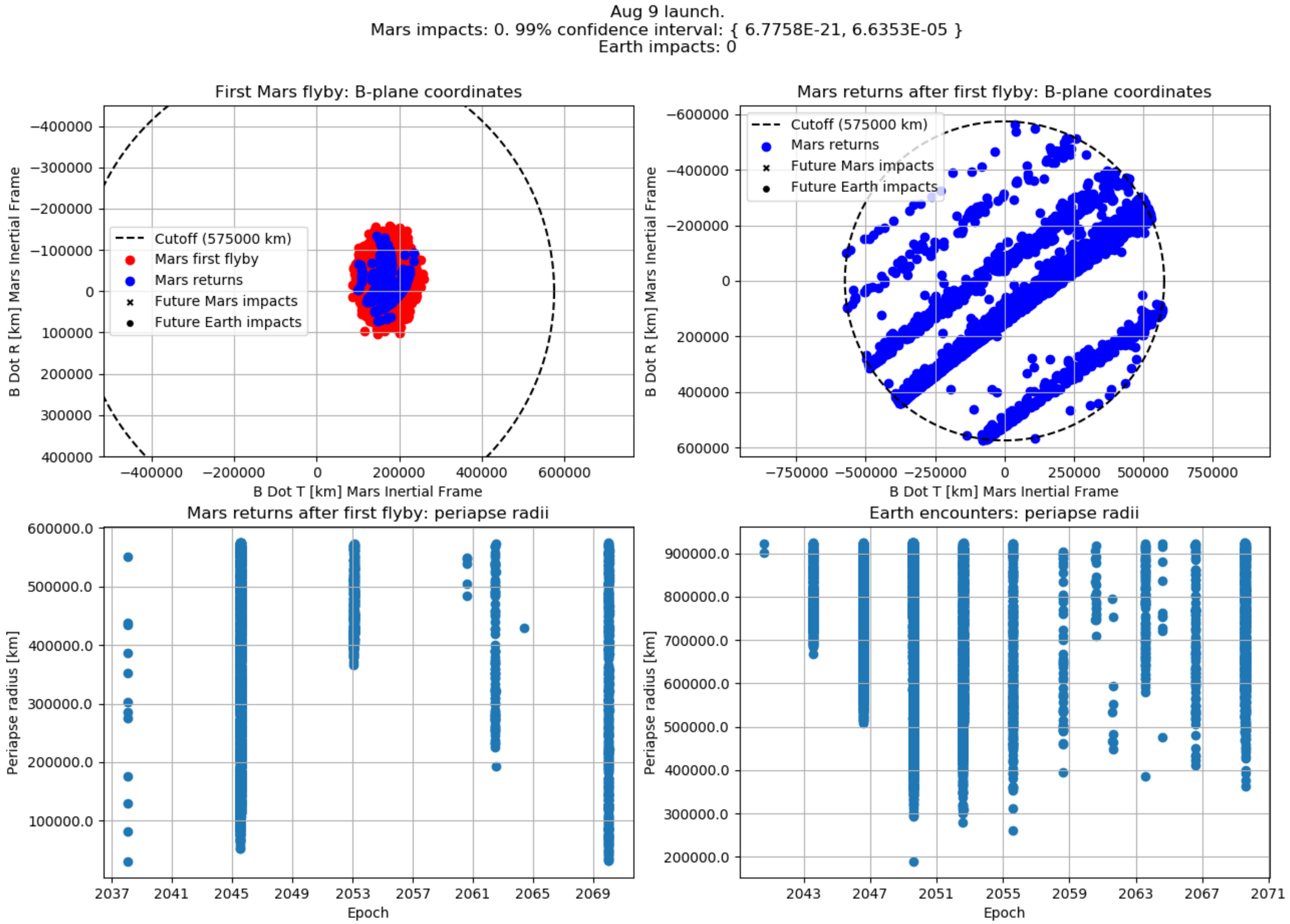
Aug 7 Results: 0 impacts



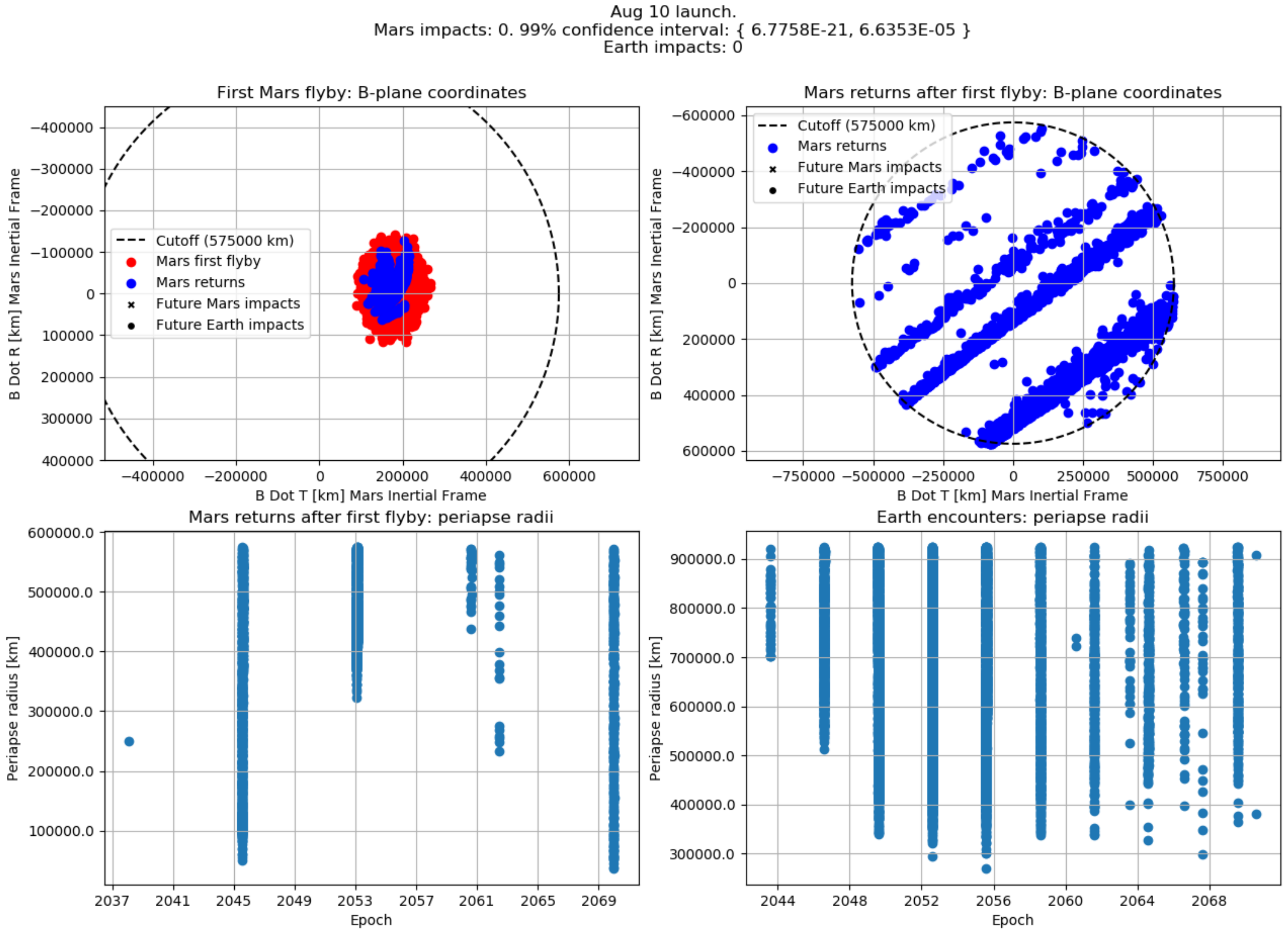
Aug 8 Results: 0 impacts



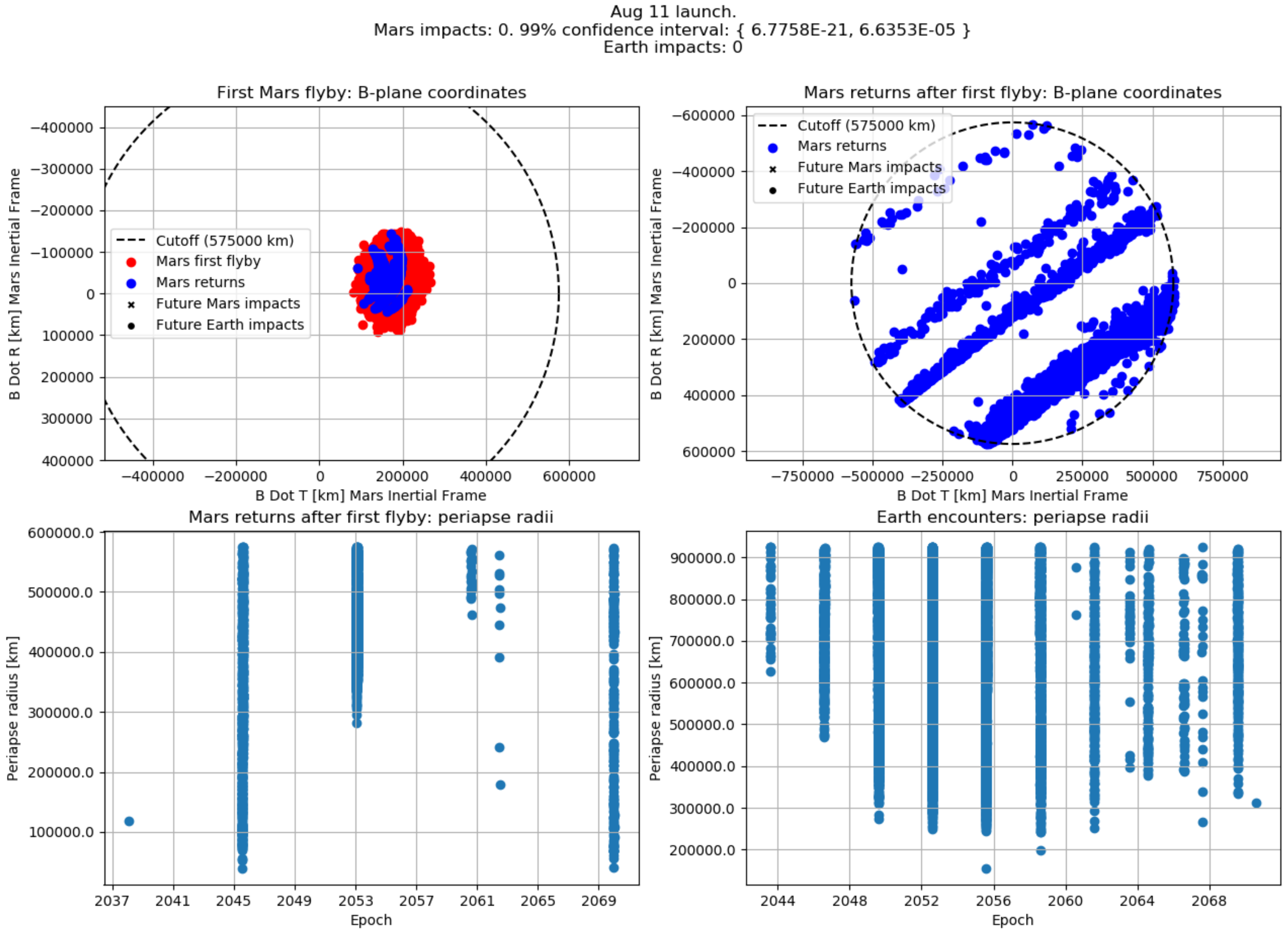
Aug 9 Results: 0 impacts



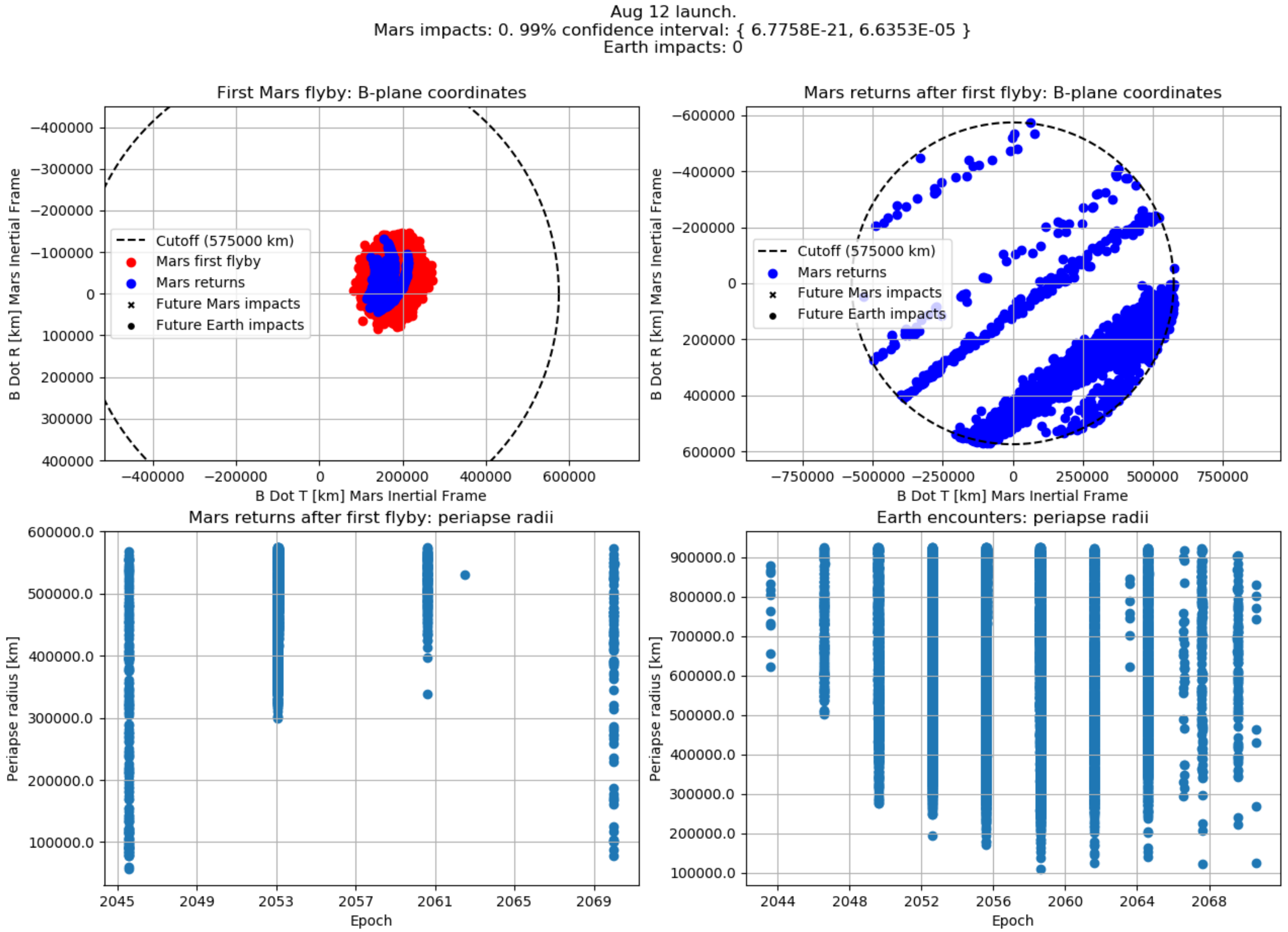
Aug 10 Results: 0 impacts



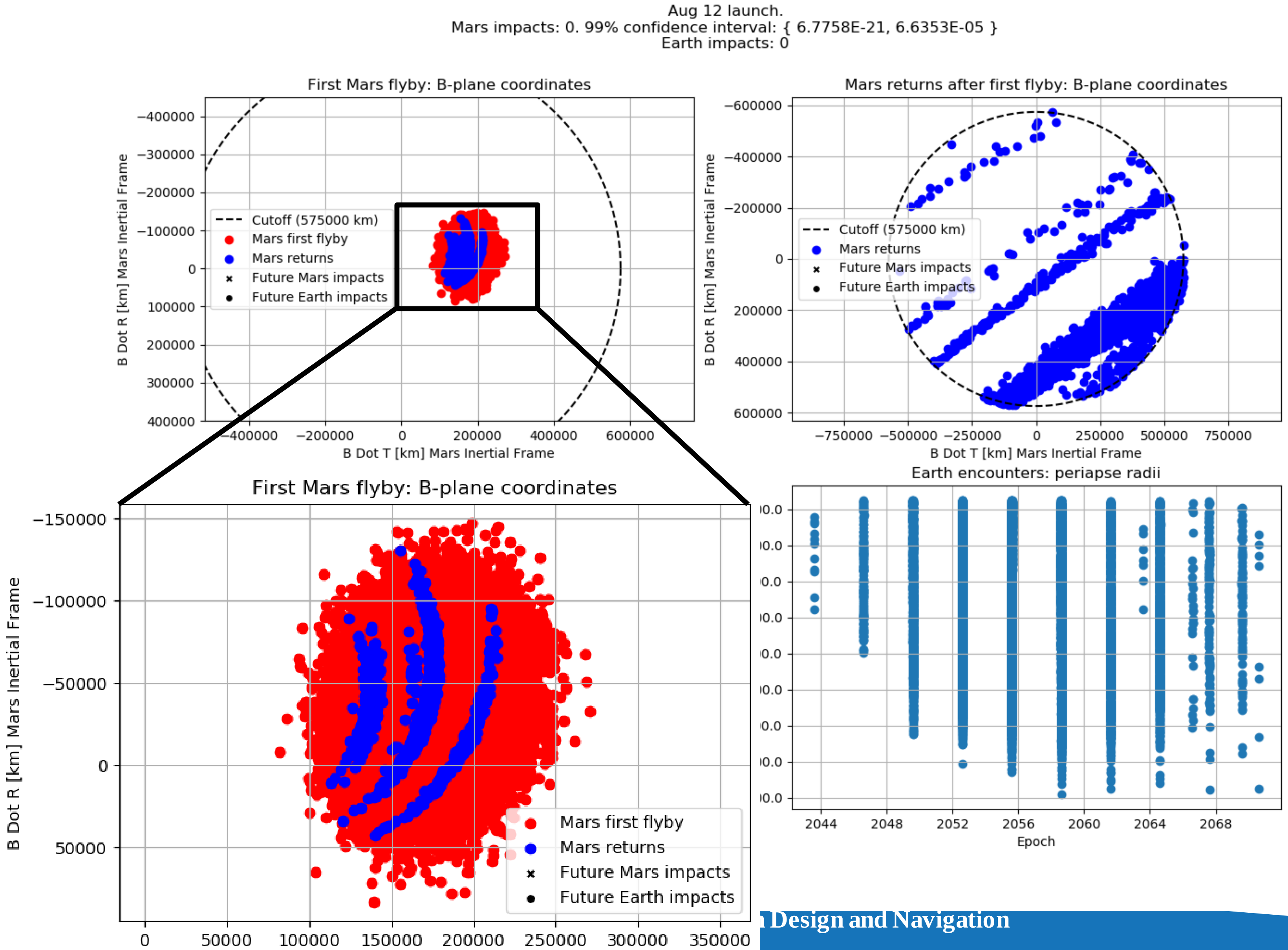
Aug 11 Results: 0 impacts



Aug 12 Results: 0 impacts



Aug 12 Results: 0 impacts



Probability of Impact Assessment

- That entire analysis covered one piece of the mission.
- Additional analyses were needed for:
  - If the spacecraft did not separate from the launch vehicle
  - If the launch vehicle did not perform a collision avoidance maneuver
  - If the launch vehicle had different amounts of fuel onboard
  - If the spacecraft remained active after a failure
  - Orbital analysis assuming we get into orbit!

Probability Assessment

- Bottom line:
  - We need to evaluate if we impact any sensitive body immediately.
  - If we don't, we may return to any sensitive body at a later date - many resonances to consider.
  - If we pass by a body out of its orbital plane, we should pass by that body once again out of its orbital plane in the future, orbital perturbations notwithstanding.

  - From orbit, evaluate long-term perturbations to ensure that periapse does not drop into the atmosphere or onto the surface within ~50 years.

netary Protection

Trajectory Analysis and Collision Avoidance

Presented by:

Dr. Jeffrey Parker

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Chief Technology Officer