Statistics and Space Missions

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An unpublished essay, found amongst the belongings of a deceased 18th Century minister, may have a dramatic effect on future planning and practices in space science.

Intro

In the 18th Century, Thomas Bayes studied theology and logic at the University of Edinburgh before becoming a nonconformist minister at Tunbridge Wells, England (Barnard and Bayes, 1958). After his death, his friend Richard Price found an essay on the theory of probability amongst his papers and submitted it to the Royal Society. The work was to have major impact on the world of statistics. Rather than viewing probability as the frequency of an observation in a large, measured data set, Bayes viewed probability as reasonable expectation of a situation. This new way of understanding probability accommodated updating of initial or "prior" beliefs into "posterior" beliefs when new data became available.

Pros and Cons

When the two statistical approaches are compared, traditional (frequentist) statistics has an inflexibility that excludes prior knowledge and beliefs, a dependence on relatively large sample sizes, and a restricted binary approach to hypothesis testing (accept or reject). Bayesian statistics, by contrast, provides the incorporating prior knowledge from previous studies, expert opinions, and subjective judgments, the accommodation of small sample sizes and limited initial data by leveraging prior information, and the ability to update prior probabilities as new evidence emerges. In practice Bayesian approaches also support decision-making where posterior probabilities can help to evaluate costs or benefits of different options and promote transparency and interpretability through explicit specification of prior beliefs or assumptions.

Application to space

Bayesian statistics are increasingly being applied to space science, proving invaluable in areas where uncertainty and limited data are common. Space science often involves exploring the unknown, such as distant planets and moons. These challenges necessitate methodologies capable of handling incomplete or sparse data. Bayesian approaches excel in this regard by incorporating prior knowledge and updating predictions as new information becomes available. This flexibility allows scientists to refine models and protocols as new data emerges. Bayesian statistics are allowing space scientists to make informed decisions in the face of significant unknowns.

Representative sample sizes for asteroids

Bayesian statistics can help in the distribution and analysis of primitive materials in asteroids or their meteorite fragments (Carter and Sephton, 2013). Estimated representative samples sizes are required when analysing parts of meteorites using high resolution techniques and are also needed when curators are deciding on how much precious material can be allocated to scientists for study. Using the Murchison meteorite and Bayesian statistical methods, researchers determined the smallest representative sample mass of meteorites of this class. Findings revealed that micrometer-sized samples are representative with 90% probability if the sample is a cube shape. Larger samples (>0.5 mm) achieve 99.9% representativeness regardless of shape.

Success on Mars missions

Bayes approaches can be employed to identify the parts of space missions that define success (Sephton and Carter, 2015). When Mars missions that aim to detecting biosignatures of life are examined, key factors for success include optimal mission design, site selection, and sample targeting. Bayesian statistics reveal that sample return missions (Figure 1) have higher probabilities of detecting biosignatures than in situ missions. For missions with safe landing as a priority, avoiding samples that do not contain biosignatures important, while for missions sample choices are a priority having a test that is able to correctly recognise the evidence is most important.

Figure 1. Illustration depicting NASA's Perseverance rover operating on Mars (Credit NASA/JPL-Caltech). Perseverance is collecting samples for return to Earth.

Indigenous organic matter

Indigenous organic matter has recently been detected on Mars, but for decades there has been uncertain detections of carbon on life search missions to Mars (Sephton and Carter, 2014). The Viking landers and the Mars Science Laboratory missions had positive responses for organic compounds but, without conclusively recognising source, contamination was suggested as an origin. Bayes provides a solution to this uncertainty by, rather than interpreting each mission in isolation, combining the detections as a sequence of positive responses to an indigenous carbon test. In summary, Bayes tells us that more detections lead to more certainty, a better test will lead to a greater increase in certainty when a positive response is observed, and a sample that is more likely to contain indigenous carbon (because of geologic context).

Sample return

Bayesian statistics has been applied to determine under what scenarios samples returned from Mars could be harmful to Earth's biosphere (Kminek et al., 2022). With the detailed composition of returned samples incompletely known the Bayesian approach allows protocols to be developed and decisions to be made ahead of time. In particular, estimating representative sample sizes and designing analytical workflows benefit from existing terrestrial practices and mitigate the unknowns associated with samples that have yet to arrive in Earth's laboratories. Bayesian approaches therefore can help to preventing the release of harmful organisms from extra-terrestrial materials, a key responsibility for planetary protection.

Clean rooms

In addition to backward contamination, as materials are returned from space, forward contamination of potentially habitable environments in space can also benefit from Bayesian statistics (Olsson-Francis et al., 2023). The UK Space Agency is currently funding a study to examine how Bayesian approaches can help to avoid contaminating space craft during their construction in clean rooms (Figure 2). By examining current practices and statistically assessing them, allows suggested improvements to be offered.

Figure 2. ESA's Jupiter Icy Moons Explorer in a clean room (Credit ESA-SJM Photography).

Conclusions

Bayesian statistics excels in contexts where uncertainty, limited data, or the need for dynamic updates is present. This statistical approach is suited to several challenges faced by space missions.

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Figure sources

Figure 1

https://images.nasa.gov/details/PIA23764

Figure 2

https://www.esa.int/ESA_Multimedia/Images/2021/05/Juice_moving_clean_rooms2