

Using INTEGRAL in Changing Radiation Settings Using Machine Learning for Efficient Spacecraft Operation

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Abstract

The European Space Agency's astronomical observatory known as INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) has been responsible for numerous significant scientific discoveries over the past few decades. Since 2002, it has been in an extremely elliptical orbit around Earth, passing through the Van Allen belts, which contain high-energy ionized particles that have the potential to harm the spacecraft's onboard equipment. Thus, predicting the entry and exit times of its radiation belts is an essential component of INTEGRAL's mission planning and operation. Using a variety of machine learning techniques, we evaluate the potential of a novel, compact data representation. Gradient-boosted trees with quantile loss are found to be the most effective approach in the experimental validation. With uncertainty adjusted to the 95th percentile, our method allows INTEGRAL to carry out two additional hours of scientific measurements per orbit. INTEGRAL is shielded from harm and sees an increase in its scientific return as a result of this strategy. It is simple to apply it to other spacecraft with similar orbits and easily extend it.

Keywords: Spacecraft operation • INTEGRAL • Gradient boosting • Neural networks • Machine learning • Gradient boosting

Introduction

Since 2002, the European Space Agency's (ESA) astronomical observatory INTEGRAL has orbited the Earth. IBIS, an imager with spectroscopic capabilities and sensitivity between 20 keV and 1 MeV, and SPI, a spectrometer with imaging capabilities and sensitivity between 20 keV and 10 MeV, are the mission's two main hard X-ray and γ -ray instruments. The spectro-imager JEM-X, which is sensitive between 4 and 35 keV, and the optical camera OMC are the mission's two monitors. The majority of INTEGRAL's time (approximately 55 hours per orbit) is spent observing high-energy sources like black holes, neutron stars, active galactic nuclei, nuclear emission line regions, and other exotic astronomical bodies in its highly elliptical 64-hour orbit. It also detects γ -ray bursts in real time, dozens per year. In 2017, INTEGRAL was able to independently confirm the gravitational wave event that the LIGO/VIGO gravitational wave detectors had reported to the scientific community. INTEGRAL, alongside Fermi, the high energy afterglow signature of the collision of the two neutron stars was observed. The incomparable multi-messenger capability of INTEGRAL results in a high over-subscription rate for observational time (3.55) and continues to generate a large quantity of highly valuable scientific data [1,2].

According to Li and Hudson, INTEGRAL is able to spend the majority of its time outside of the Van Allen radiation belts on Earth due to the highly eccentric nature of its orbit, which has an apogee height of approximately km and a perigee height of approximately 6000 km. Situated in the magnetosphere's innermost region. However, Walker and Palmer found that the passage through these belts in the remaining time poses a significant threat to INTEGRAL's and its scientific payload's endurance. Specifically, these belts are packed with high-energy ionized particles that have the potential to harm the electronics and high-voltage instruments on board the spacecraft. The consequences can be severe and immediate, resulting in an irreparable decline in performance. Single-event upsets can also result from a stray high-energy particle striking a

surface and depositing energy, causing the on-board electronics to power on or off unexpectedly [3].

Literature Review

The INTEGRAL mission's long-term success is dependent on the precise estimation of its radiation belt entry and exit times, which enables precise planning of the on-board equipment's orderly deactivation and activation. Every 8s, the INTEGRAL central data management unit's on-board autonomy function sends environmental data to each instrument. This data includes ground-specified events like predicted radiation belt entry/exit times and eclipses, as well as radiation readouts from the INTEGRAL radiation experiment monitor (IREM), which measures radiation in terms of soft electron, proton, and dose. The onboard instruments respond to the predicted entry/exit times, which are typically calculated several months in advance, and guarantee an orderly instrument shutdown prior to the spacecraft's entry into the belts and prompt instrument restart after the spacecraft leaves the belts [4].

The instruments are forced to perform emergency shutdowns and restarts solely based on the IREM readouts if they are unable to perform orderly shutdowns and timely restarts, a situation that may result from incorrectly predicted entry/exit times. A lengthy recovery procedure and a delay in instrument operation follow. These circumstances significantly limit the amount of time INTEGRAL has available to carry out its mission: Therefore, the spacecraft's capacity to successfully carry out scientific observations is directly impacted by an accurate prediction of these occurrences. The goal of this work is to accurately and efficiently predict INTEGRAL's entry and exit times across Van Allen Belts from beginning to end. We evaluate the suitability of two distinct data representations of the spacecraft's telemetry—positional and per-orbit—for a variety of machine learning techniques. Quantile regression also gives us safety margins for the predictions that we get [5].

The experimental evaluation reveals that employing our pipeline results in more than 200 additional hours of scientific work per 100 revolutions. The current model, which is based on fitting a sinusoidal curve and using an amplitude-dependent safety margin modulated around two standard deviations of the fit residuals, performs significantly worse than the proposed method. Additionally, it enhances an earlier, more advanced attempt to predict INTEGRAL's position at a given time. Within ESA's INTEGRAL Mission Planning & Spacecraft Operations, the findings and methods proposed in this work are currently in the "preparation and testing for deployment" stage of development [6].

For all tree-ensemble methods, we fix the number of trees to optimize the proportion of features considered when splitting the data. In the case of KNN, we

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are interested in the optimal number of nearest neighbors, k . We also optimize for other parameters, such as the learning rate, the maximum depth of each tree, and the smallest possible leaf size, for the gradient boosting methods (GB, XGB). We use the scikit-learn Python library's implementations for the KNN, RF, and GB methods for more information on the parameters and parameter ranges considered). The xgboost Python library is what we use for XGB. Since only the GB (scikit-learn) implementation supports quantile regression, we try both XGB and GB. This lets us learn models that can deal with noisy data by predicting the conditional median rather than the mean [7].

The Pytorch framework is used to implement the neural network models. RNNs, in particular, are designed to work well with time-series data, but the other methods need more engineering to take the temporal aspect into account. In order to accomplish this, we add additional historical data to each example, giving it access to the features and targets of the previous examples. The values n and m are referred to as feature histories and auto regression histories, respectively [8].

Discussion

We optimize a number of network architecture-related and optimization-related parameters when training FCNN networks. After each layer, with the exception of the final one, we employ dropout, batch normalization, and ReLU activation. To learn the network's weights, we employ the Adam optimizer and mean squared error. We reserve 20 percent of the training set for early stopping while we set the maximum number of learning epochs. Additional information about the FCNN optimization procedure can be found in Appendix A [9].

The primary result of examining the impact of various preprocessing parameters on random forests is that per-revolution representation is significantly superior to positional representation. We can see that more accurate models are produced when entry/exit altitudes or phases are used as the target, both of which use a representation per revolution. Raw IREM count predictions by models are highly unstable. Additionally, modeling is significantly more effective due to the more compact per-revolution representation. We use only the per-revolution representation to predict the entry/exit altitudes (i.e., fix the target parameter) after learning a RF model with positional representation for up to 2 hours and a model with per-revolution representation for only 15 seconds. We are able to search a wider range of modeling parameter values as a result of this [10].

Conclusion

Our method for predicting INTEGRAL's entry and exit times from the Van Allen belts is described in this paper. In order to directly predict entry and exit times, we propose a novel data representation called per-revolution, mapping the issue to a multi-target regression task. The data will be represented in a smaller format thanks to this, which will also improve predictive accuracy. The empirical comparison of several machine learning methods revealed that the gradient-boosted trees with quantile loss performed the best on these tasks. Our model, adjusted for uncertainty at the 95th percentile, provides a gain of three full INTEGRAL revolutions over the course of 100 revolutions, or on average, 2 additional hours per revolution for scientific measurements when compared to the model that is currently used to predict INTEGRAL's entry and exit times. The scientific return of the spacecraft is further enhanced by these enhancements,

which make it easier to plan missions more efficiently and make better use of the onboard scientific equipment. In light of these enhancements, in addition to being applicable to INTEGRAL's mission planning and operation processes, the presented methods can also be extended to other spacecraft with comparable orbits (like XMM-Newton), increasing their value.

Acknowledgement

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Conflict of Interest

None.

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