Stochastic satellite failure prediction and fleet capacity forecasting

Introduction

The estimation of the operational lifetime of a satellite is a challenging task, difficult to generalize. Typically, it has been done by predicting the different failure modes (e.g. hardware degradation or radiation) and modeling them through physical models. This requires extensive testing campaigns that imply high costs. In addition, traditional predictions tend to be over-conservative in their lifetime predictions, which is undesirable when replenishing launches have to be planned long in advance.

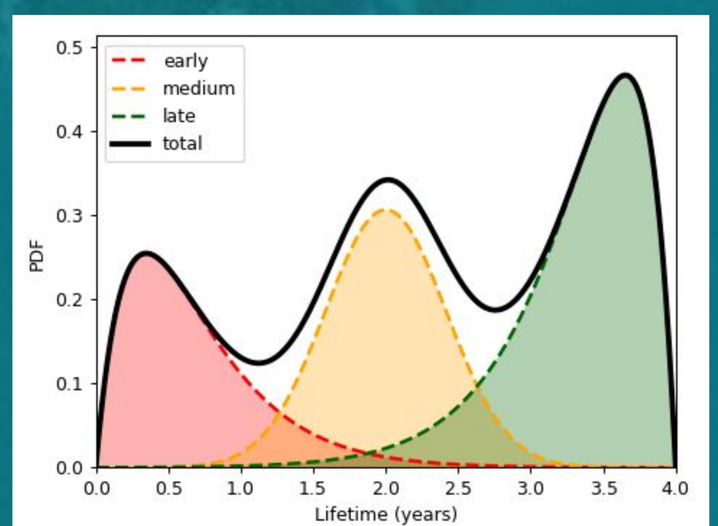
These two factors make the traditional approach to lifetime prediction unsuitable for mega-constellations of small satellites with many off-the-shelf components, like PlanetScope. On the other hand, these constellations offer a lot of data from the launch, operation and retirement of satellites whose bus is very similar to the ones to be launched. This opens the possibility of a completely different kind of model, where the probability of retirement at each point in the lifetime of a satellite is estimated based on historical data from alike spacecrafts. Although this purely statistical approach may lack precision when estimating the lifetime of an isolated satellite, when taking the constellation as a whole, it can efficiently model the rate of failure of the fleet.

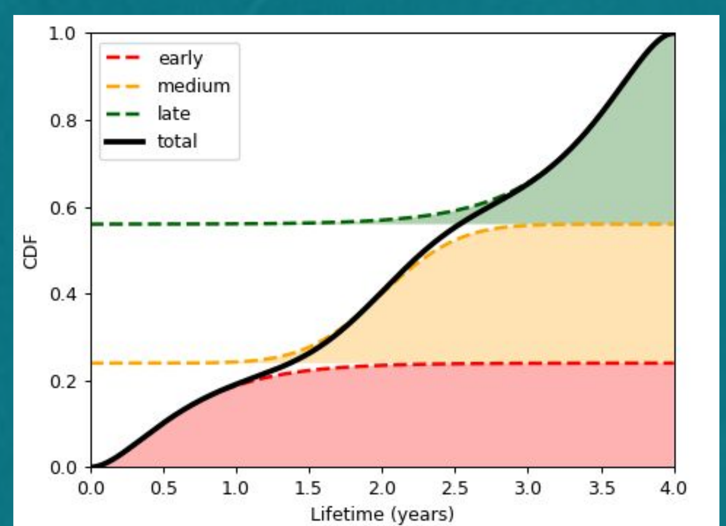
Satellite lifetime model

After looking at the historical data from Dove satellites no longer in operation, three different concentrations of retirement modes were identified, which could be modeled by different statistical distributions:

Date	Most common retirement reasons	Distribution
Early	Failed commissioning, unexpected hardware errors, immaturity of the bus...	Gamma
Medium	Hardware degradation, radiation effects, insufficient redundancy...	Normal
Late	Obsolescence, hardware degradation...	Gamma (reversed)

By weighting these three distributions, and overlapping them, it is possible to estimate the likelihood of retirement of each satellite as a function of time, through the Probability Density Function (PDF). When integrating this function, the Cumulative Density Function (CDF) represents the probability of having retired a satellite at each point in time. When looking at a full batch of satellites launched at the same time, this CDF effectively models the rate of retirement of the group, with better accuracy the higher the number of satellites.





Parametrization

The location and shape of the three distributions that conform the model depend on a number of parameters that add flexibility to the model. Their selection was done so that they preserved certain physical meaning, while minimizing as far as possible the number of parameters and their cross-dependency. The new parameters are:

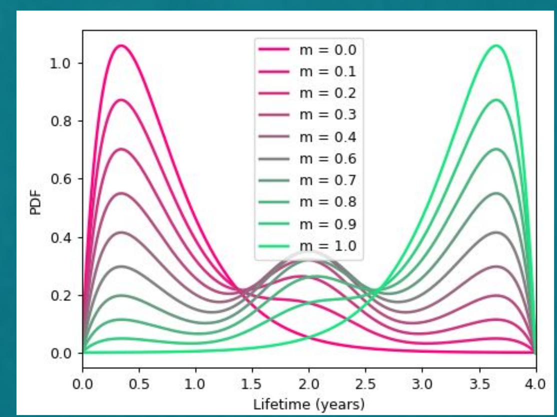
- t_max: maximum lifetime
- phi: overlap factor
- gamma: debugging factor
- m: maturity factor

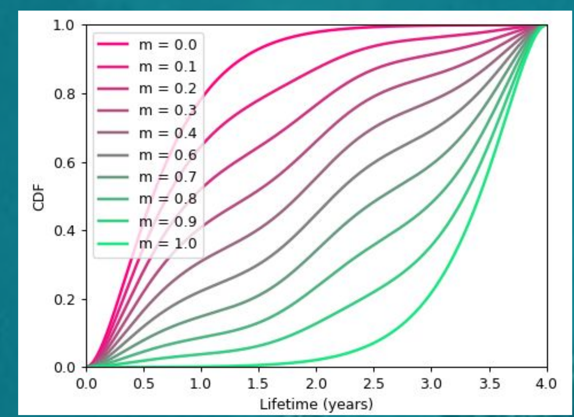
Parameter sensitivity

The selection of the parameters is made for each specific version of the satellites that are launched, using the input from the satellite design and the historical data from operations. The shape of the PDF and CDF is modified through the parameters as the following plots highlight.

Maturity

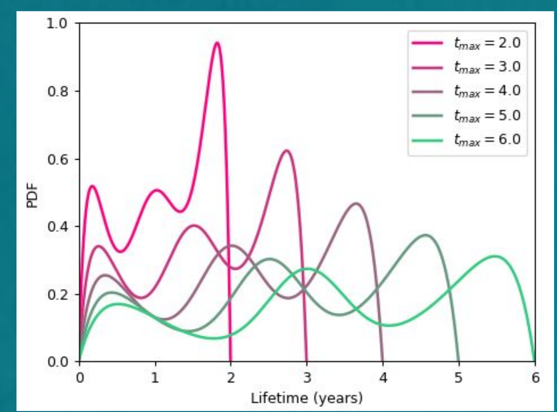
The maturity of the technology onboard the satellites determines the weight between the three distributions. As a result, the probability of retirement is shifted towards late failures as the maturity increases.

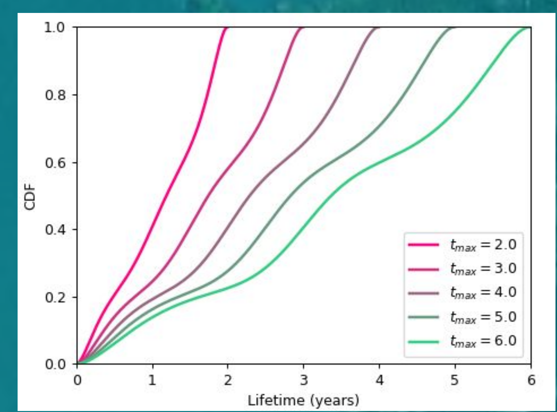




Maximum lifetime

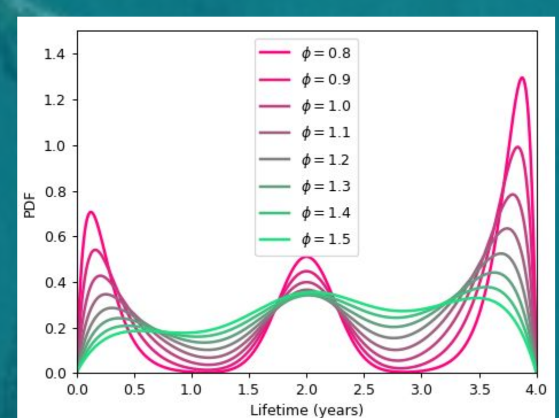
The maximum lifetime determines the retirement age of the satellite in the ideal case. Because of this, is normally selected as the time where the technology on the satellite will be deemed "obsolete", so it can be set before launch. The probability functions are therefore extended or tightened as this factor changes.

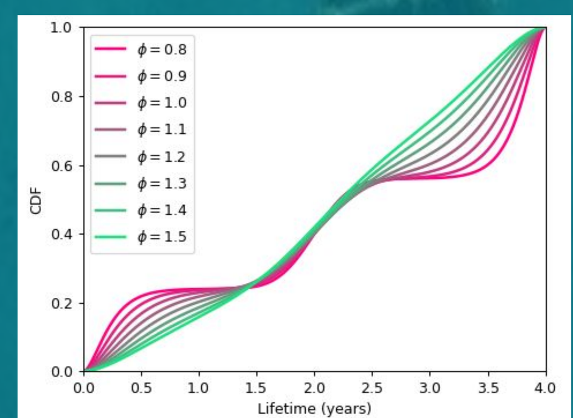




Overlap

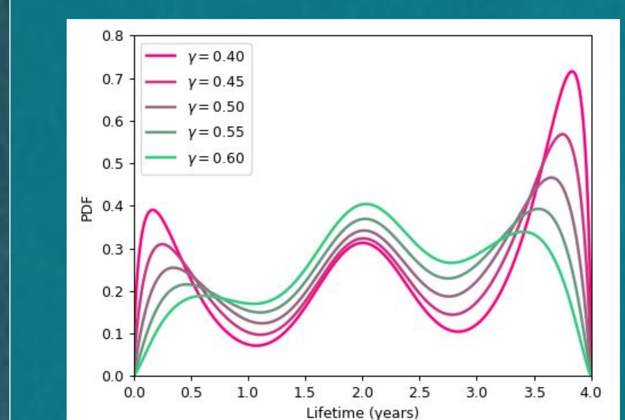
The overlap factor sets how isolated are the three distributions from each other. The larger it is, the closer together and flatter they are.

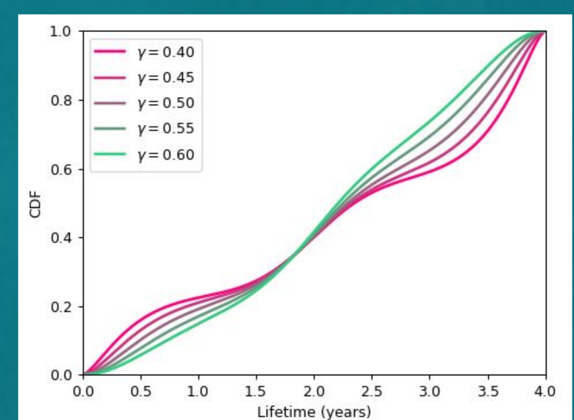




Debugging

The debugging factor sets how fast the retirement occurs in case of early failures, and how late it happens in case of obsolescence.





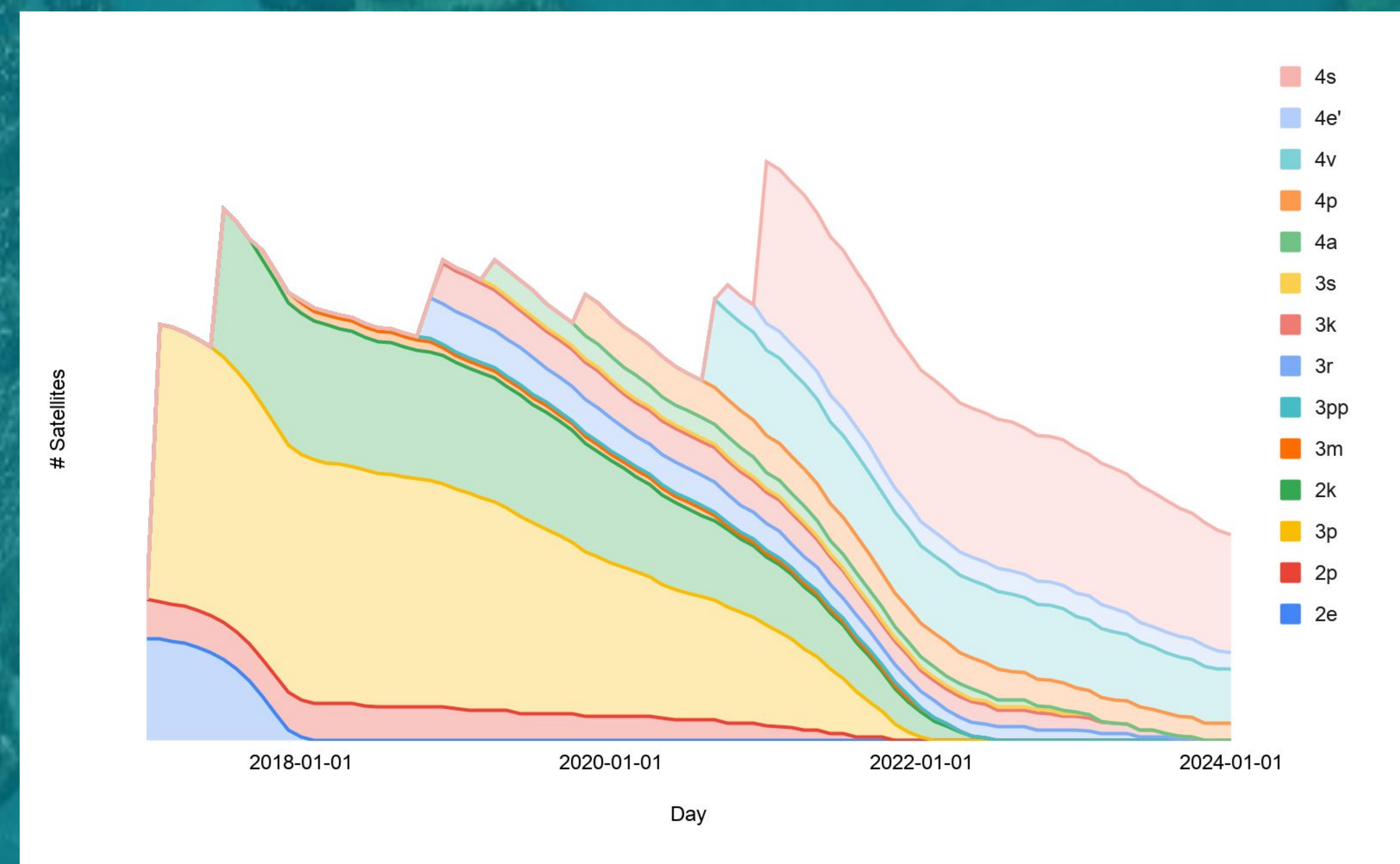
Implementation and results

Each group of satellites launched at the same time (flock) has an associated lifetime model. The parameters are selected as follows:

- Overlap: Fixed as a common value for all flocks.
- Debugging: Fixed as a common value for all flocks.
- Maximum lifetime: Set before the launch by similarity with previously retired flocks. Can also be adjusted at any time.
- Maturity: The maturity is estimated through the fitting of the actual degradation of the flock. For new flocks to be launched, it is set through benchmarking with older flocks.

Thanks to the fitting of the model to historical data through the maturity, the model is able to automatically predict the number of satellites of each flock at each point in time (past and future). It also adjusts its prediction everyday, as new data becomes available.

By stacking together the individual predictions of number of satellites per flock, it is possible to predict the total number of satellites in operation at each point in time. Using this information, decisions are made about whether to pursue or not new launch opportunities in the future. Below, an example of a prediction that could be made by the automated forecasting system, using the actual launch dates of past Planet launches.



Conclusions

The arrival of mega-constellations of low-cost small satellites has changed the paradigm when it comes to satellite lifetime prediction. The traditional approach based on physical modelling and extensive testing proved to be inefficient for these fleets. Instead, what is presented here and used in production by Planet is a purely statistical model, trained automatically everyday with historical data from satellites already launched and retired. This new model allows a better forecasting of the number of satellites at each point in time in the future, quantifying the necessity for replenishing launches.

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