Detecting Short-Period Binary Companions to Sub-Subgiant Stars

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Abstract

Sub-Subgiants (SSGs) are unique stellar phenomena that are fainter and cooler than the typical giants and subgiants. The cause of these anomalies is not well understood, though one hypothesis is that SSGs are binaries with companion stars in short-period orbits of 2 - 30 days. Tidal forces between the stars may synchronize the rotation period of the SSG to the orbital period, and the resulting rapid rotation generates strong magnetic fields. These magnetic fields may inhibit energy transport in the star, creating giants that are cooler, larger in radius, and less luminous than their slower rotating counterparts. To test this hypothesis, we utilize data taken using the Robert G. Tull Coudé spectrograph on the 2.7 m Harlan J. Smith telescope at McDonald Observatory. We determine radial velocity (RV) measurements for 56 stars in the SSG Sample. Many SSGs are found to have highly variable RVs, indicating they are short-period binary systems. We simulate several possible binary populations with a variety of underlying orbital period distributions including the full distribution of periods observed in galactic binary populations, a limited galactic binary period range of about 2 to 30 days, and include a tidally synchronized sample population sampled from the Variable Star Index (VSX) as is hypothesized for the SSGs. We find that our observed population closely resembles the RV distribution expected from our simulation of binaries with periods of 2 to 30 days, supporting the hypothesis that a very high fraction of SSGs are standard short-period binaries and contrary to the hypothesis that they may be tidally synchronized.

We can test the hypothesis that Sub-Subgiants are short-period binaries by looking for Radial Velocity variations in a spectroscopic sample of 56 Sub-Subgiant stars.

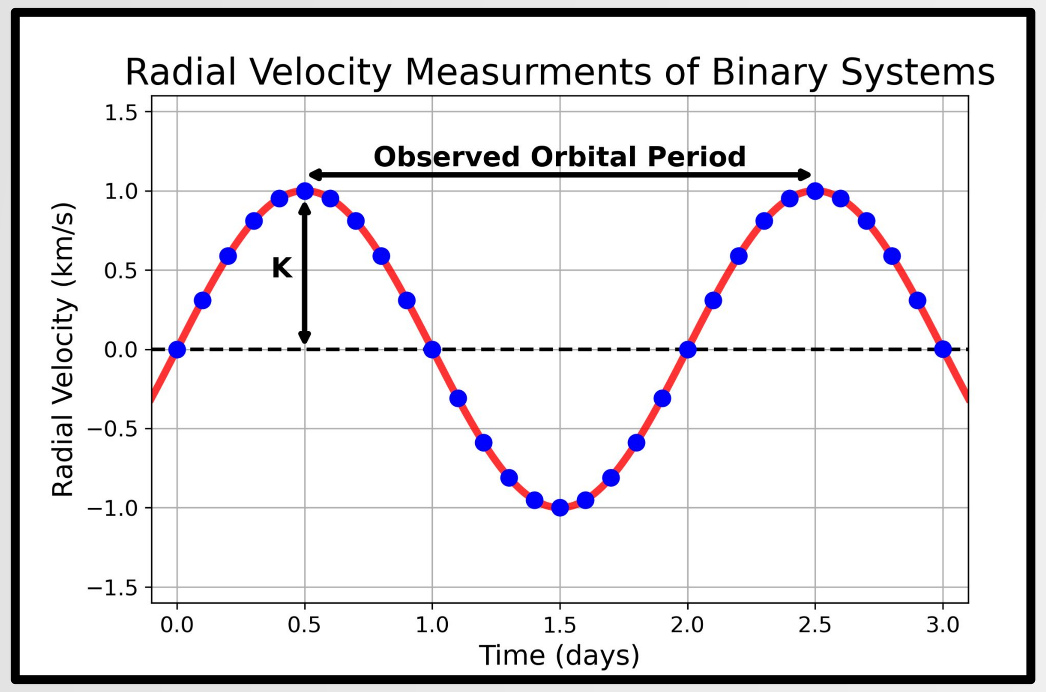

Figure 1. In the ideal circular orbit case a measured binary will have the variable radial velocity measurements shown in this figure.The RVs will follow a simple sine wave whose peak radial velocity, denoted by K, is the semi-amplitude of the measurements. The period of the system's orbit is the periodicity of this wave.

The ideal binary mass function used to simulate each possible period distribution is:

$$\frac{M_2^3 \sin^3 i}{(M_1+M_2)^2} = \frac{P_{\rm orb}\, K^3}{2\pi G}\left(1-e^2\right)^{3/2}$$

The sample: 34 spectra of 56 sub-subgiant stars. Each SSG in our sample has at least 3 spectroscopic measurements.

RV Measurement Technique: Compute broadening functions from spectra (see Figure 2, left). Fit a Gaussian to the broadening function to measure the radial velocity (RV) of each observation (Figure 2, right).

Assessing Binarity: Compute the standard deviation of the RV measurements for each star. A standard deviation greater than 1 km/s indicates the SSG is RV variable, and thus has a binary companion.

Population Statistics of the SSG Sample: Perform a Monte Carlo simulation to simulate possible RV distributions using three orbital period distributions:

1. Log Normal distribution of binary periods from Duquennoy and Mayor (1991) and Raghavan et al 2010.
2. A Log Normal distribution (Duquennoy and Mayor (1991)) limited to periods less than 30 days.
3. Assume tidal synchronization such that the orbital periods of all SSGs are equal to their rotation periods given in Leiner et al. 2022.

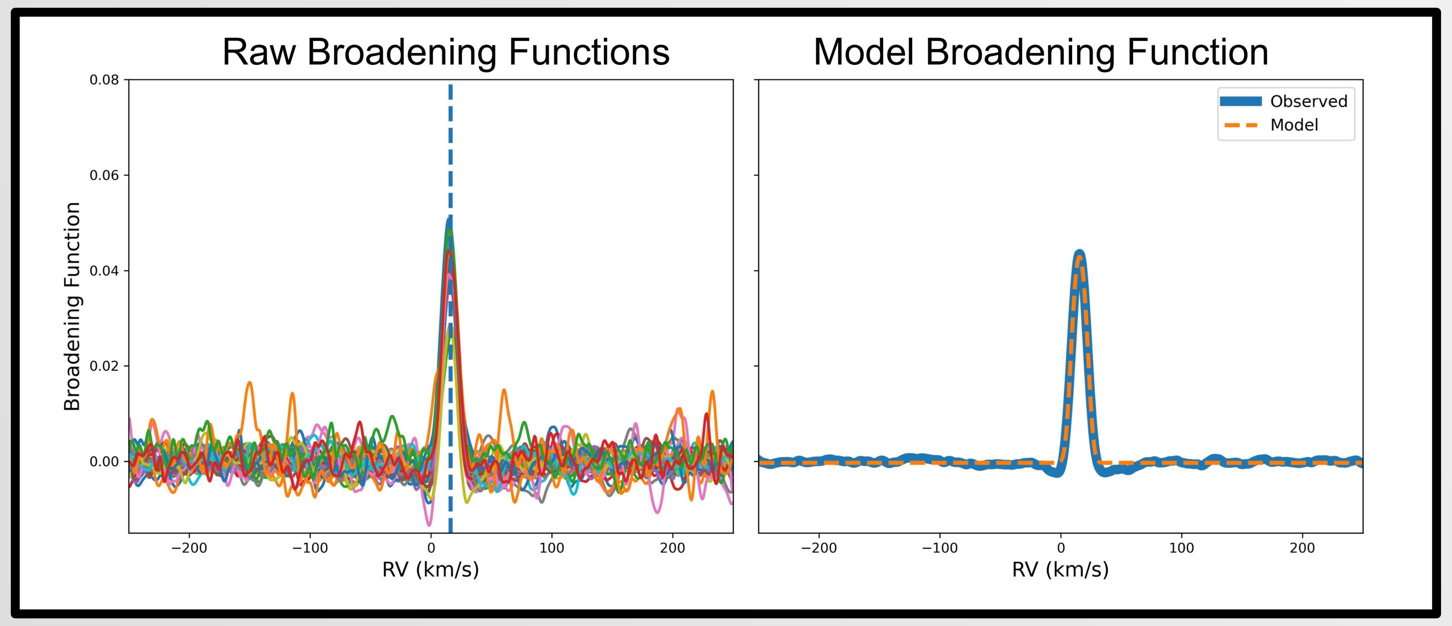

Figure 2. The Python package Saphires was used to develop broadening functions for the entire spectrum observed, for each observation date (left). From this function estimates for the peak of each measurement were made and the reduced function was fit (right). We use the fitted profile to obtain a highly accurate RV measurement.

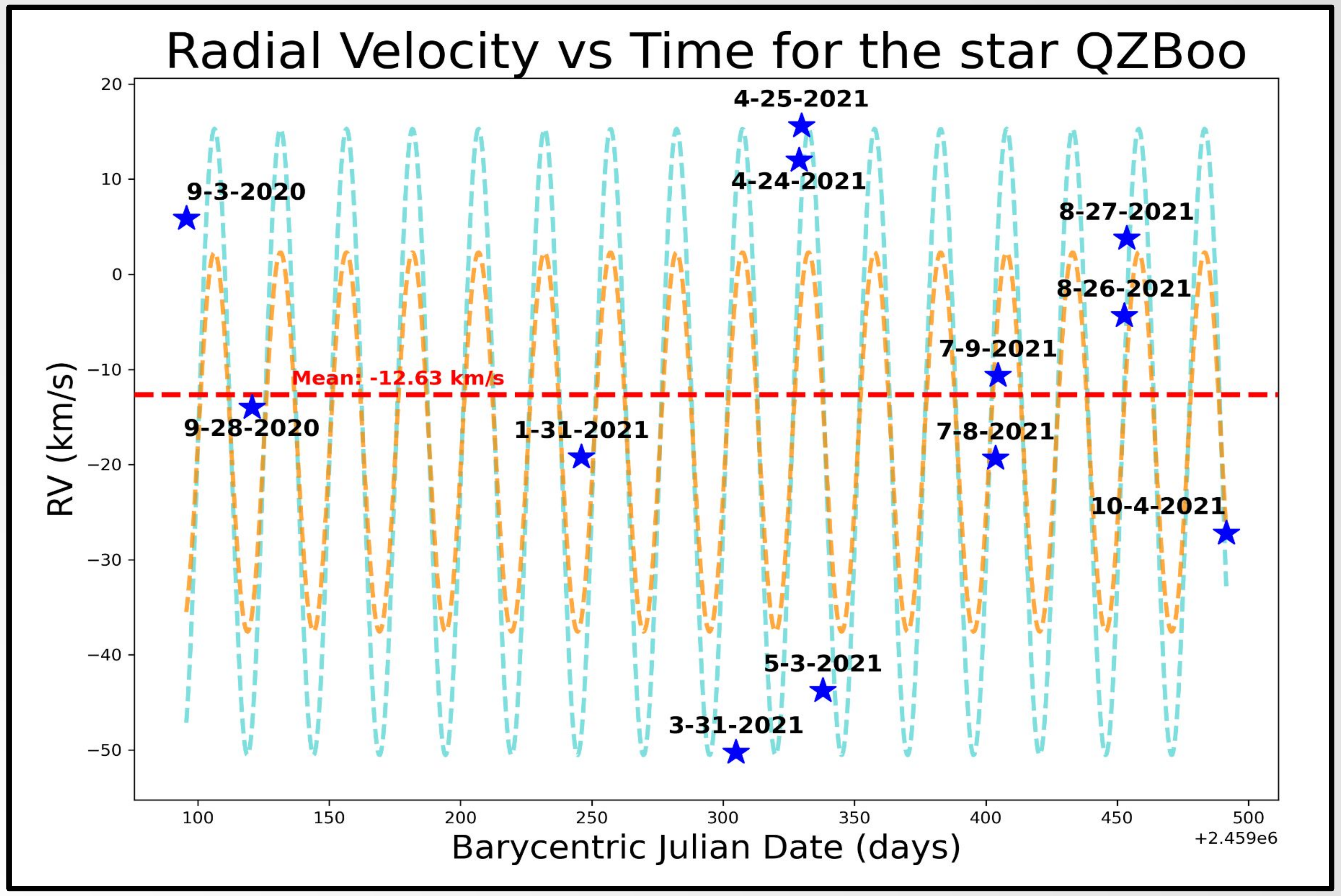

Figure 3. This plot displayed our observed radial velocities (blue) over time for QZBoo, one of the 56 stars analyzed. The high variability of these measurements indicates a quickly rotating binary system. Overlaid are two estimations of period measurements for this star, which assumes a period of approximately 4 days. The light blue line represents a K value using the true Amplitude of the recorded RVs, while the orange line represents an assumed amplitude of the Standard Deviation of these measurements. It is important to distinguish between the two for the final measurements, as the Standard Deviation assumption does not account for the entire range of recorded values, especially for highly variable RVs.

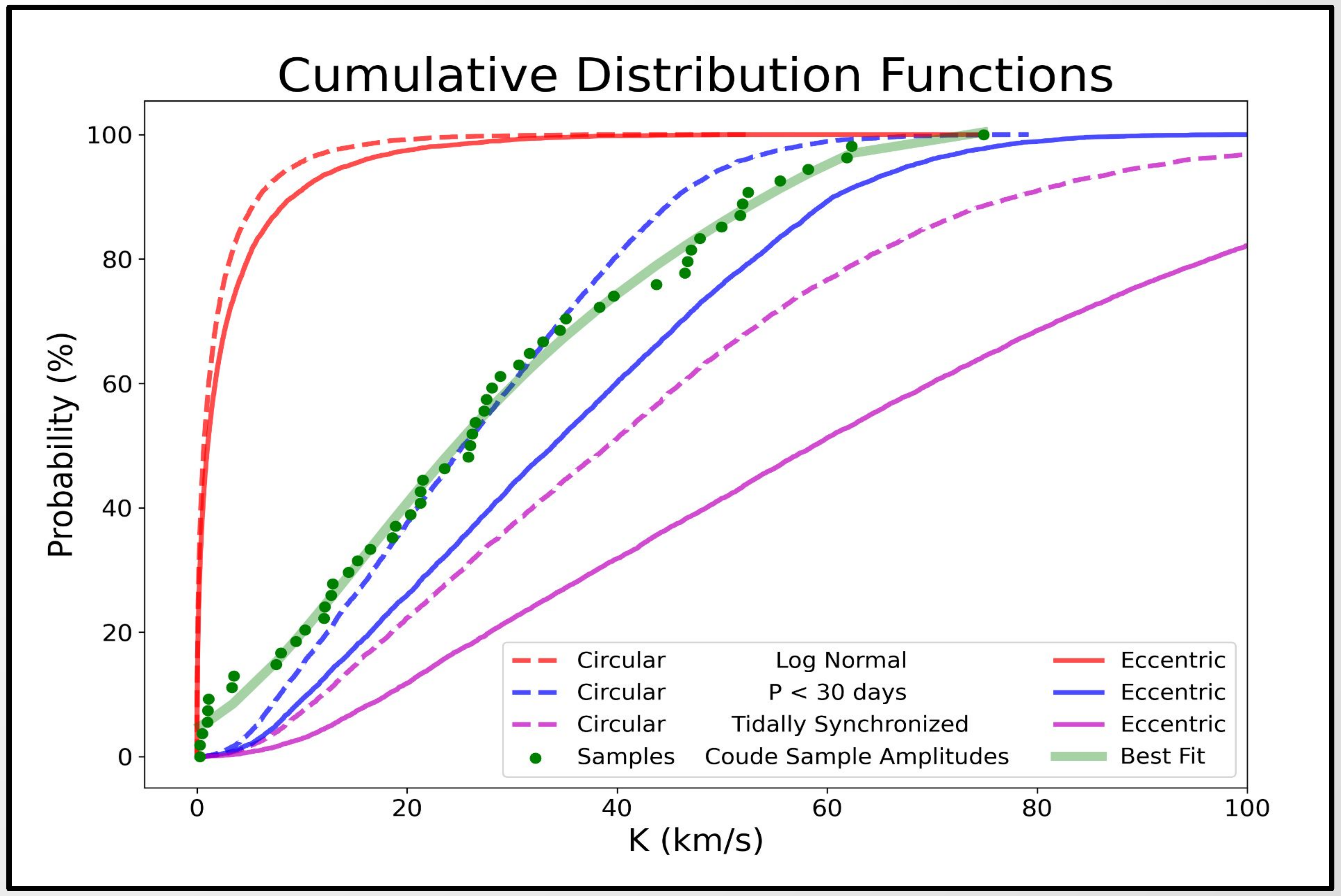

Figure 4. This plot displays the simulated amplitude values compared to the recorded amplitudes from our Coudé sample (green). The full Log Normal distribution (red) shows that we can expect most of the radial velocities (K) to be relatively small, as expected from longer period variables. As the range is limited to less than 30 days (blue), the probability that the radial velocity is slow decreases as the stars must orbit faster. The tidally synchronized sample (purple) is simulated from the visual variability of stars and produces an even faster distribution of stellar periods. Circular orbit assumptions are shown by the dashed lines, while eccentric assumptions are solid.

Conclusions

The orbital period simulations that best match the observed RV variation of the SSGs is the assumption of a log-normal period distribution with a maximum period of 30 days (Figure 4). This supports that hypothesis that SSGs are found almost exclusively in short-period binaries. However, our results are not consistent with the assumption that all SSGs are in tidally synchronized binaries.

Next Steps

- Investigate the best metric of measuring orbital amplitude from RV observations by simulating binary orbits with randomly sampled RV measurements.
- Simulate more possible orbital period distributions

Sources

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Leiner, E., Geller, A. et al. 2022, ApJ, 927, 222

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Interactive Analysis and Visualization of Parametric Design Spaces for Conceptual Aircraft Design

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Abstract

The aerospace industry is increasingly reliant on conceptual design spaces to evaluate and explore early-stage aircraft designs, including both new concepts and improvements on existing models. However, the high dimensionality and complexity of these design spaces present significant challenges in fully exploring potential design alternatives. Traditional methods often fail to fully leverage combinatorial design spaces and lack sufficient visualization tools, making it difficult to understand how design decisions impact performance and limiting the effectiveness of the conceptual design process. This research aims to address these challenges by developing an interactive analysis and visualization tool for aircraft conceptual design. Key objectives include (1) employing combinatorial methods, such as Latin Hypercube sampling, to create a design space that captures interactions between design variables, (2) developing efficient algorithms for design space exploration, (3) incorporating uncertainty quantification and reliability simulations for design effectiveness assessment, and (4) facilitating design decision-making through enhanced visualization tools. The research utilizes the SUAVE aircraft design tool to analyze each design generated within the Latin Hypercube-based design space. Initial progress includes the creation of an interactive application that integrates SUAVE for design evaluation and comparison through robust analysis.

The purpose of this research is to develop an interactive tool that enhances the exploration, analysis, and visualization of complex aircraft conceptual design spaces, enabling more effective design decision-making in early-stage aerospace concepts.

Methods

Objective (1) was completed through the exploration of MDO (Multidisciplinary Design and Optimization) tools, ultimately settling on the method of Latin Hypercube sampling for design space creation. Latin Hypercube is able to evenly and efficiently explore every corner of the design space without bias, and works most effectively for conceptual designs where the desired outputs are often undefined and require a broad, balanced exploration of possibilities.

Objective (2) was completed through the incorporation of the SUAVE aircraft design tool developed at Stanford University, which is a powerful analysis tool for exploring the specific design of aircraft attributes. Through SUAVE, we can perform detailed analyses on the various design configurations.

Objectives (3) and (4) are continuously being explored as the application is developed, with some functionality already being created. Each aircraft design is run through the SUAVE analysis and compared for robustness against each other design, for which comparison plots such as CDFs (Cumulative Distribution Functions) can be created to analyze the overall design performance.

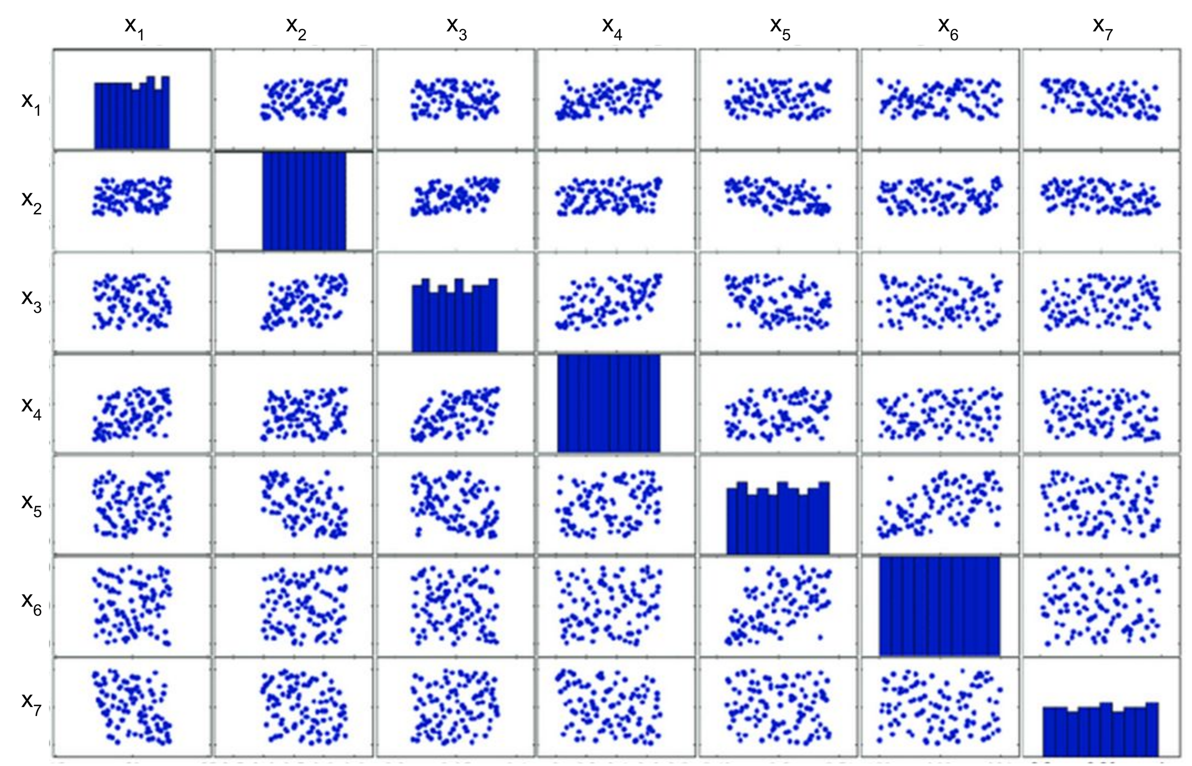


Figure 1. Visualization of the Latin Hypercube method. Each column and row represents a separate variable range to be sampled, defining a full design space without overlap.

Image Credit: Mohanty, Sankhya & Hattel, Jesper. (2014). Numerical Model based Reliability Estimation of Selective Laser Melting Process. Physics Procedia. 56. 379–389. 10.1016/j.phpro.2014.08.135.

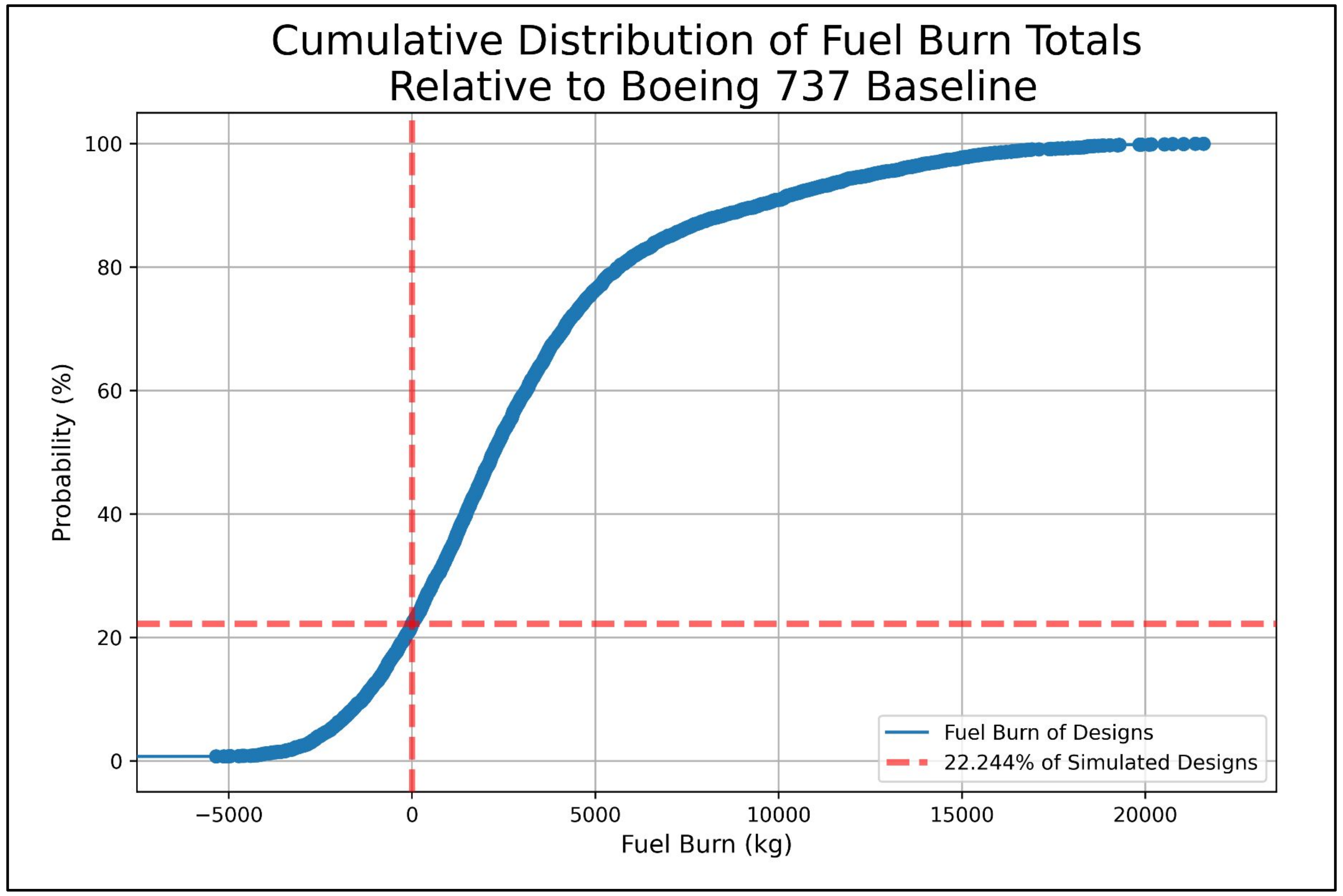


Figure 2. This analysis shows the final results of a Fuel Burn analysis using SUAVE. Just over 22% of the 5,000 designs generated within the design space demonstrate more efficient fuel consumption than the current Boeing 737. This dataset can be used to analyze design conditions that may inform modifications to the current design.

Results

An interactive conceptual design tool has been developed to create a design space which works in conjunction with SUAVE for in-depth analysis. Aircraft concepts are generated in a design space governed by Latin Hypercube sampling to ensure diverse configurations, and run through SUAVE to produce accurate results for a variety of output conditions. Each generated aircraft concept undergoes rigorous analysis, yielding a range of performance metrics.

Future Work

- Add Visualization functionality through AVL (Athena Vortex Lattice) which is a powerful tool for both visualization of the aircraft and aerodynamic analysis.
- Add more analysis variables, as the only current output calculates a design's fuel consumption.
- Add more design variables.
- Improve decision making tools, including the ability to highlight the most impactful variables or rerun a new design space to produce more optimal designs.

SUAVE
An Aerospace Vehicle Environment for Designing Future Aircraft

This research was conducted in conjunction with SUAVE, an open source platform for aircraft conceptual design

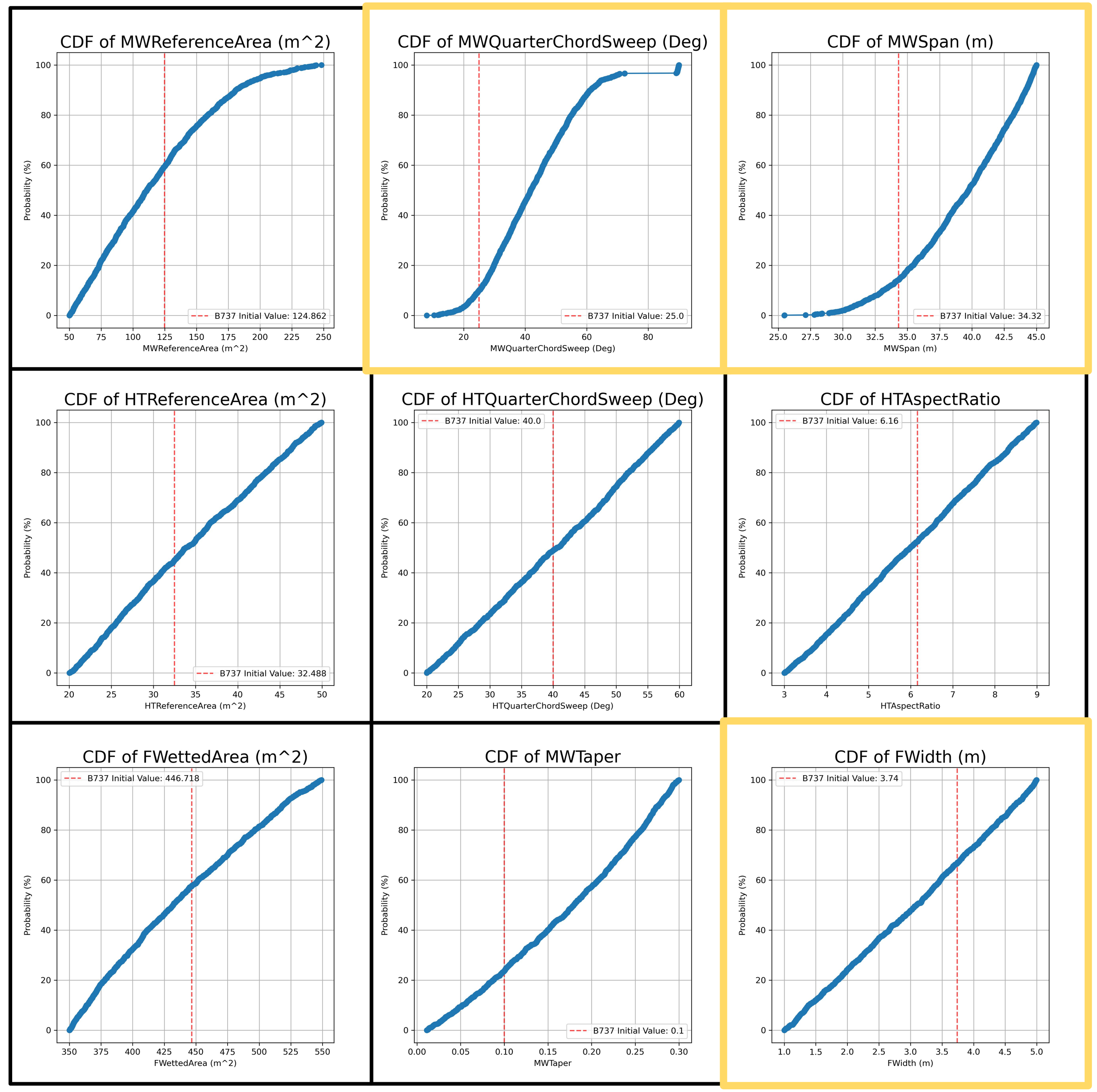
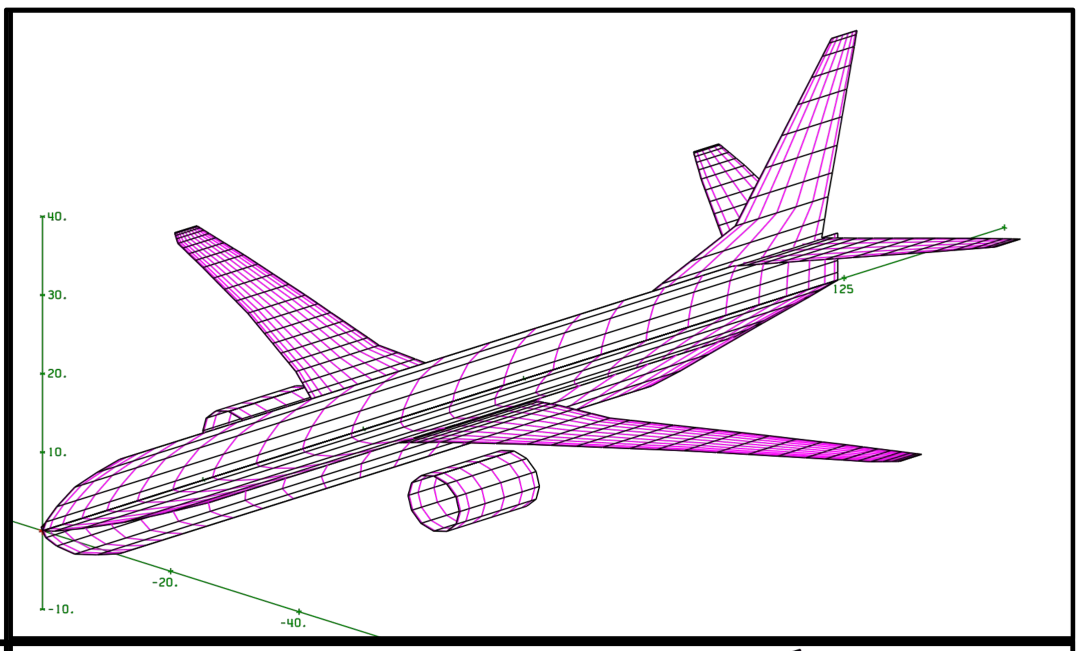


Figure 3. These nine plots display a set of variables from the fuel analysis in Figure 2, with three highlighted as promising for future design improvements. Each point represents a design condition that reduced Boeing 737 fuel consumption. This approach can be applied to optimize many more aircraft components.

The current Main Wing Quarter Chord Sweep and Span are at the lower end of efficient designs, suggesting that increasing their angle or length could improve fuel efficiency.

In contrast, the Fuselage Width is at the higher end, indicating a reduction in width may also enhance fuel efficiency. However, changes to fuselage width may be limited by other factors, like passenger capacity.



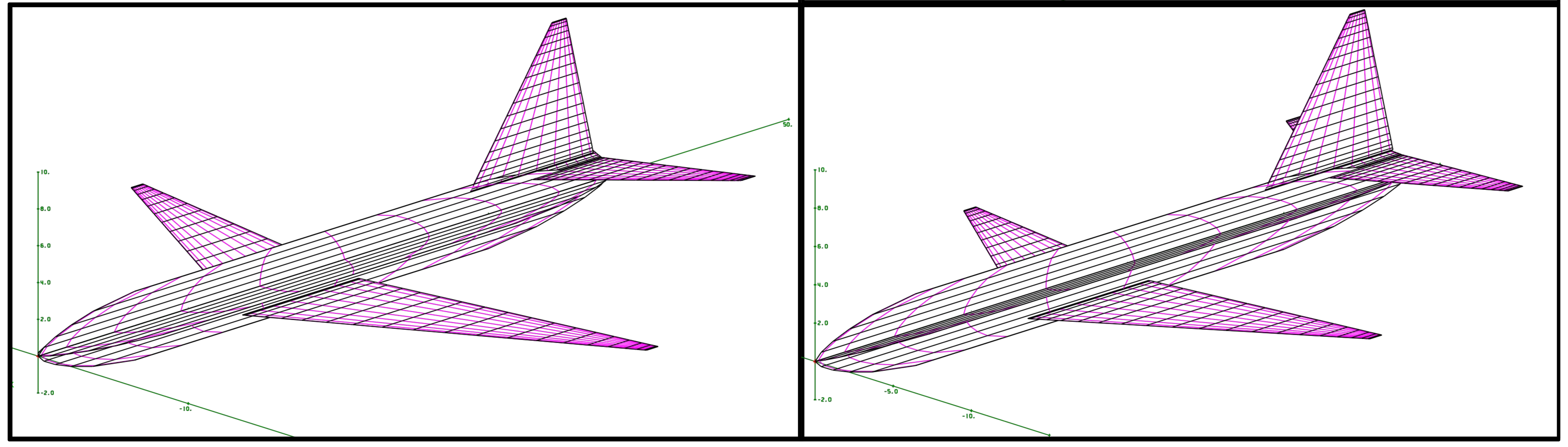


Figure 4. This figure presents three designs generated from the interactive interface: the baseline SUAVE Boeing 737 (left), a fuel-efficient 'good' design (right), and the standard AVL Boeing 737 (top). The AVL plots demonstrate how future visualization tools could be integrated within the application. As additional visualization capabilities are developed, complete plots for each design will facilitate clearer comparisons of performance and key design features.