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Search for Laser Emission Lines in Spectrum of Tau Ceti

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ABSTRACT

The pursuit of identifying signs of extraterrestrial life has driven the exploration of novel techniques and technologies. High-resolution spectroscopy is one such technique, which has been utilized to detect laser signals in the spectra of stars. The primary objective of this research was to design and evaluate an algorithm that can detect laser signals with precision in the spectra of stars. To achieve this, we injected synthetic laser signals of varying amplitudes and with a predetermined separation of 5 Å across the wavelength into the normalized continuum spectrum of Tau Ceti. The performance of the algorithm in detecting these signals was then assessed. Our findings indicate that the algorithm was successful in detecting and retrieving laser signals that surpassed a certain threshold, with a recovery efficiency rate of %98 for signals with amplitudes exceeding 1.09 of the normalized flux. Specifically, out of the 826 synthetic signals injected, 812 were successfully retrieved, surpassing the preset threshold. Furthermore, we applied this algorithm to Tau Ceti's spectrum without any signal injections and discovered 217 candidates that exceeded the predetermined threshold. Moreover, the algorithm's consistency across the spectrum was verified by comparing the average amplitudes of different sections of the spectrum. Our research provides a promising foundation for designing algorithms that can identify laser signals in a range of stellar spectra and may contribute to the discovery of extraterrestrial civilizations.

1. INTRODUCTION

The ESPRESSO telescope is a highly precise, high-resolution spectrograph, with the capability to measure radial velocity of stars to an accuracy of one meter per second (Pepe et al. (2014)). Observations of the spectra of a particular star can be obtained from the ESPRESSO ESO archive search interface by searching for observations of that star. Typically, these spectra are obtained in the form of 2D images, where the intensity of light is represented as a function of wavelength and position on the detector. However, these 2D spectra can be challenging to interpret. Astronomers often extract 1D spectra from the 2D images, which represent the intensity of light at different wavelengths, averaged over the spatial extent of the spectrum. The 1D spectrum provides a more intuitive representation of the star's spectrum, which is easier to analyze and interpret. These spectra are often used to study the properties and characteristics of stars, and also have potential applications in the search for extraterrestrial intelligence (SETI). Optical SETI involves searching for continuous wave laser signals or pulsed signals at optical wavelengths, while radio SETI focuses on analyzing radio signals for patterns that may be indicative of intelligent origin in outer space.

In this paper, we present an algorithm for detecting laser lines in a modelled emission spectrum using Gaussian fittings, which are then searched for in a stellar absorption spectrum. The primary motivation for this search is the possibility that an advanced civilization may use lasers to signal their presence to other civilizations. The method used to search for extraterrestrial intelligence is Spectroscopic Optical SETI, which involves analyzing the absorption spectrum to detect signs of artificial signals, such as narrowband laser signals, that would be indicative of intelligent life sending signals deliberately (Lipman et al. (2019)). The focus of our laser line spectrum search is Tau Ceti, a G-type star. We use this star as an example to develop an efficient method for applying Gaussian fittings to any number of spectral lines in a given spectrum. Our algorithm identifies and fits Gaussian profiles to each spectral line, calculates the point spread function (PSF) width of each, and then creates a unique Gaussian fit for the spectrum from the averaged PSF widths. This Gaussian fit is then injected into the spectrum to measure our algorithm's sensitivity for signal detection. The algorithm's laser recovery is then applied to the entire spectrum to detect any potential candidate above a set threshold. This method involves using high-resolution spectroscopy to detect such signals, which are distinguishable from natural astrophysical phenomena by their narrow frequency bandwidth and temporal coherence. The outcome of this study will provide valuable insights into the potential existence of extraterrestrial civilizations and their possible communication methods.

2. METHODS

We have developed an algorithm to detect laser signals through analysis of the absorption spectrum of Tau Ceti using the ESPRESSO telescope. Each star's unique spectrum is influenced by factors such as its temperature, chemical composition, and age. The spectrum can be classified into three primary types: continuum, absorption, and emission spectra. The continuum spectrum of a star is a continuous distribution of wavelengths of electromagnetic radiation emitted by the star. On the other hand, an absorption spectrum is produced when a continuous spectrum passes through a medium, such as a gas cloud, that absorbs certain wavelengths of light, resulting in dark lines or gaps in the spectrum. In quantum mechanics, an emission spectrum is generated when an atom or molecule in an excited state transitions to a lower energy state and emits a photon with a specific frequency or energy. The emitted photons appear as bright lines in the spectrum, indicating the specific frequencies at which the photons were emitted. To analyze the absorption spectrum of Tau Ceti, we first normalized the raw data and mapped out the echelle blaze function. We then fit this function to obtain a normalized spectrum in constant radial velocity space. Next, we focused on analyzing the sodium D lines within a specific wavelength range. To accurately identify and analyze the sodium D lines in the spectrum, we took into account the specific characteristics of the Fraunhofer lines in that region. These lines are caused by the absorption of specific wavelengths of light by atoms and molecules in the outer layers of the star's atmosphere, and their wavelengths depend on the chemical composition and temperature of the atmosphere. The sodium D lines are prominent examples of Fraunhofer lines in a stellar spectrum and are located in the yellow-orange part of the visible spectrum. They are named for their proximity to the D-line of the solar spectrum.

In order to determine the current offset of Tau Ceti, we compared its normalized spectrum with an empirical spectrum and employed the NSO Solar spectrum to conduct a chi-squared test. We used the final normalized Tau Ceti's spectrum to develop our algorithm. To fit Gaussian curves to the spectral lines in the reduced spectrum, we developed the algorithm to identify local minima and maxima. To optimize the selection of suitable spectral lines for our algorithm, we implemented various filtering conditions. We excluded small or undesired curves that may not be useful in our analysis by setting a threshold based on the minimum value of normalized flux in the spectrum. Additionally, we improved the detection of spectral lines by setting two other factors to identify suitable candidates rather than small deviations in the continuum spectrum. The finalized normalized spectrum was established to vary its normalized flux between 0 and 1. Therefore, we set the algorithm to run for points that have their difference between the two local maximas of a local minima less than 4 (chosen arbitrary). Additionally, we set a condition accounting for amplitude values between 0.001 and 2 (of normalized flux) and the psf width value of greater than 0. We determined that our spectrum's amplitude limit is at 2, and PSF width values less than 0 should not be considered as they would be too small to be detected. These filtering conditions allowed us to narrow down the search for suitable spectral lines and prevent further errors or algorithm crashes. After the algorithm identifies the point spread function (PSF) of each spectral line, we showed its distribution to determine the typical PSF width in Tau Ceti's spectrum, as shown in figure 1. By calculating its average from all the measured PSF values, a unique Gaussian fit is defined to account for the specific characteristics of these spectral lines. This approach allows tailored Gaussian fits to be obtained for different spectra lines.

3. SIGNAL INJECTION

In order to assess the performance of our laser detection algorithm, we conducted a simulation by injecting 826 synthetic laser signals into the normalized continuum spectrum of our target star at 5 Å intervals of wavelength. The wavelength spacing was arbitrarily chosen and can be varied depending on the number of expected laser lines to be detected. The synthetic signals were generated based on the final Gaussian fit obtained from our spectrum and the measured average PSF width value of 0.065 Å. We could adjust various parameters of the injection, such as the distance, amplitude and width, to tailor the algorithm to specific experimental requirements. Although we fixed the width and spacing of the simulated signals, we assigned random amplitude values to each injection within the range of calculated amplitude values obtained by our algorithm from the continuum spectrum. The assigned amplitude values ranged from 0.234 to 1.885 of the normalized flux, as the distribution is shown in figure 2. We determined the number of synthetic signals injected into the spectrum by selecting a predetermined flux threshold above the continuum spectrum at 1.09 of normalized flux. The analysis revealed the presence of 826 signals, which were subsequently used to assess the recovery of these signals during the detection process. We illustrate our injected synthetic laser lines within the wavelength range of 4700 Å to 4800 Å in figure 3.

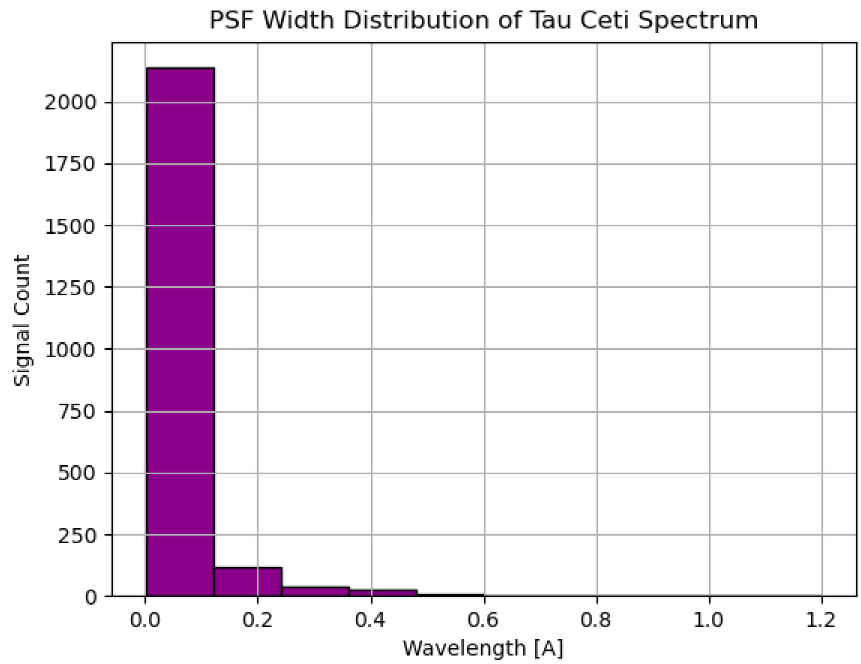

Figure 1. PSF width distribution for the entire Tau Ceti's spectrum: The algorithm utilizes a method of identifying local minima in the spectral lines and subsequently locates the corresponding local maximas to estimate the width of the spectral lines. The psf widths of such candidates were calculated using this approach and were subjected to filtering and threshold conditions. The resulting distribution of psf widths is presented in the plot, and it matches the calculated average value of 0.065 Å across the entire spectrum.

3.1. *Results*

In our experimental setup, we generated modeled emission spectra of synthetic laser lines with a uniform spacing of 5 Å across the entire wavelength range. These synthetic laser lines were injected into the spectrum ranging from 0.29 to 2.89 of normalized flux, closely resembling the underlying spectrum, as illustrated in Figure 3. The number of injected signals varied depending on the chosen wavelength distance threshold. In our case, with a threshold of 5 Å, we obtained 826 injected signals within the wavelength range of 3772.2 Å to 7897.9 Å. These injected signals were then used to test the sensitivity of our algorithm's laser recovery process.

4. SIGNAL RECOVERY

We evaluated the performance of our laser detection algorithm by utilizing synthetic injected signals. We injected 826 simulated laser signals into the continuum spectrum at predetermined wavelengths equally spaced by 5 Å, allowing for the precise determination of signal location and quantity. Our aim was to assess the algorithm's ability to identify and recover signals above a pre-determined threshold and also evaluate its sensitivity. We measured the efficiency of the algorithm in identifying laser signals within the spectrum by measuring the percentage of the detected signals above a threshold. If the algorithm could not detect a significant number of injected signals, it may indicate a need for further refinement or that the laser signals are too weak to be detected. To identify laser signals above a threshold, our algorithm was designed to recognize the (normalized) flux local maximas of the laser lines that appear above this threshold. However, in cases where the local maximas were located very closely together, we had to implement a selection process where the algorithm chooses the signal with the higher amplitude. This decision was based on the assumption that the Gaussian curve with the higher amplitude would be the better fit for the very closely located points. To ensure that the algorithm identifies only unique signals, we imposed a requirement for the minimum distance between signals based on the assigned wavelength threshold. This criterion guarantees that the algorithm detects only those signals that are spaced apart by a distance greater than the assigned wavelength spacing of 5 Å. By including these measures, we achieved precise identification of laser signals above a predetermined threshold in the

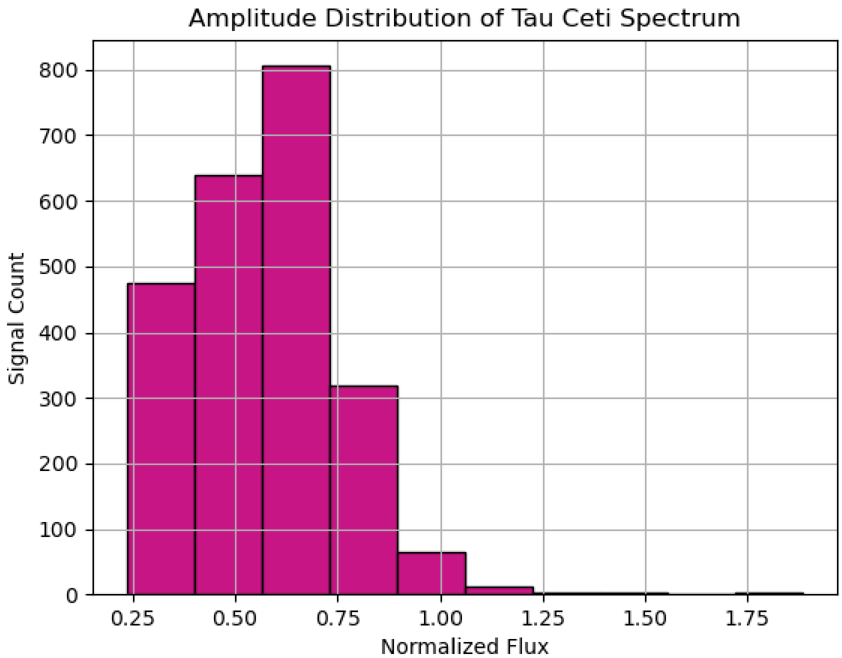

Figure 2. Distribution of amplitudes relative to the flux across entire Tau Ceti's spectrum: The algorithm employs the identification of local minima to calculate the amplitudes of spectral lines. This histogram displays the distribution of amplitude values across the entire spectrum, ranging from a minimum of 0.23 to a maximum of 1.88 of the normalized flux. The algorithm leverages this amplitude distribution to randomly assign amplitudes to the synthetic laser signals that are injected into the spectrum.

star's spectrum. The efficiency percentage was determined by adjusting the flux threshold until it approached %98 (at which point the threshold value closest to %98 was selected). After obtaining the set threshold, we proceeded to apply our algorithm's recovery procedure to the actual spectrum, which involved removing the injected laser lines. This enabled us to configure the algorithm to detect any spectral lines above the set threshold.

4.1. *Results*

To evaluate the effectiveness of our laser detection, we generated simulated laser signals and introduced them into the normalized continuum spectrum of Tau Ceti. Initially, a threshold at 1.5 of normalized flux was employed as a preliminary measure to detect these signals, with a fixed distance of 5 Å between the synthetic signals, consistent with the minimum spacing that our algorithm was designed to detect. By iteratively decreasing this threshold, a sensitivity analysis was performed on the algorithm, and the percentage of detected signals was measured. A recovery efficiency rate of %98 was achieved, whereby 812 out of 826 injected signals were recovered with amplitudes greater than 1.09 of normalized flux, representing the lowest threshold at which the recovery efficiency was maintained as shown in figure 4. The remaining 14 signals that were injected below this threshold were not detected. Subsequently, the algorithm was applied to the spectrum without any signal injection, and 217 signals greater than 1.09 of normalized flux were recovered. Additionally, we evaluated the uniformity of the recovered signals' amplitudes by dividing the spectrum into three sections based on the wavelength ranges: the first section encompassing spectral lines with wavelengths less than 4600 Å, the second section containing spectral lines between 4600 Å and 7100 Å, and the third section comprising spectral lines with wavelengths greater than 7100 Å. Random amplitudes were assigned to the simulated signals in each section, and their respective average amplitudes were computed. The consistency of the algorithm's performance in signal injection and detection across the spectrum was evaluated by comparing the average amplitudes of the three sections, revealing a consistent average of approximately 1.24 of normalized flux across all three sections. We have shown the amplitude distribution across the spectrum for the detected signals in figure 5.

5. DISCUSSION

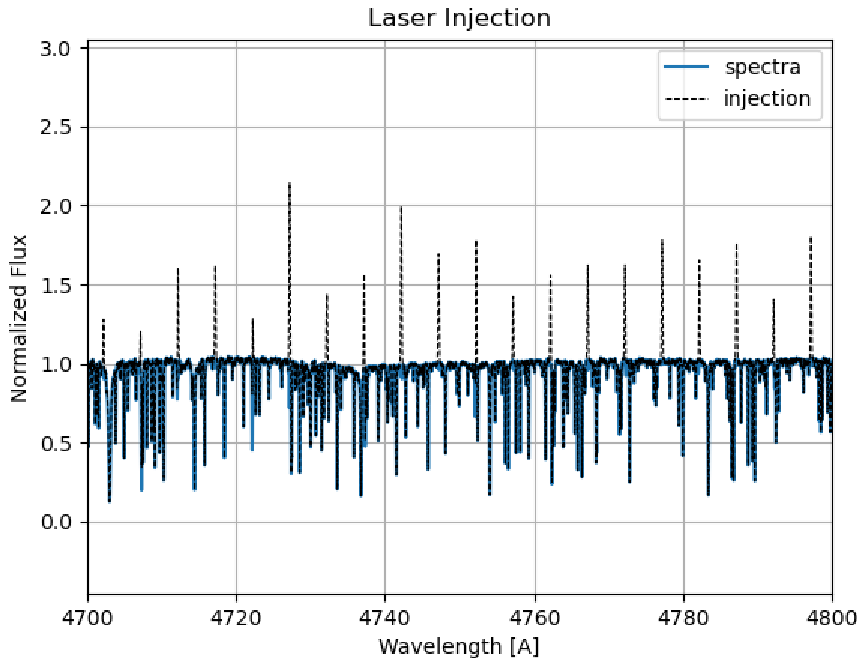

Figure 3. Injected signals across Tau Ceti's spectrum: This plot provides a close-up view of the synthetic laser signals injected into the spectrum, specifically within the wavelength range of 4700 Å to 4800 Å. The injected signals are distributed uniformly across the entire spectrum, with an equal spacing of 5 Å. The algorithm injected a total of 826 signals with a fixed width of 0.065 Å, corresponding to the averaged psf width value of the entire spectrum. The amplitudes of each signal are randomly assigned by the algorithm.

The present study aimed to develop and assess an algorithm that could detect laser signals in stellar spectra. Initially, the algorithm was targeted towards Tau Ceti's spectrum, which was utilized as a representative of a stellar spectrum. Subsequently, it was generalized to operate on any given stellar spectrum. The algorithm's performance was evaluated by injecting signals with various amplitudes derived from the amplitude distribution of the spectrum. The algorithm was designed to identify synthetic laser signals with a predetermined wavelength distance of 5 Å. Its sensitivity in laser detection was quantified by measuring the amplitude threshold at 1.09 of normalized flux, resulting in a detection rate of %98. The detection of laser signals in the presence of noise and other sources of interference was achieved by identifying local maxima of the normalized flux that exceeded the set (amplitude) threshold. This strategy ensured the algorithm's ability to distinguish between laser signals and other sources of noise or interference. The application of the algorithm to the spectrum (without signal injection) yielded 217 spectral lines that exceeded 1.09 of normalized flux. The detection of multiple signals that were in close proximity posed a challenge in the signal recovery process. In order to address this issue, the algorithm was adjusted to select a signal with the higher amplitude to represent the Gaussian-assigned curve accurately. Additionally, a minimum wavelength spacing of 5 Å was implemented to ensure that it only detected signals that were adequately separated from each other. In order to test the injection consistency, the averaged randomly assigned amplitudes were compared across the spectrum. This test revealed a consistent average amplitude value of 1.24 of normalized flux along the signal sections below 4600 Å, between 4600 Å and 7100 Å, and greater than 7100 Å. The algorithm exhibited the potential to detect over half of the injected signals, indicating its ability to identify laser signals in other star systems. However, additional enhancements and modifications are required to enhance the detection rate and minimize false positives. These improvements could be accomplished by smoothing the raw data and optimizing the normalization of the flux, or by refining the procedures for assigning randomly generated parameters in signal injection and signal recovery. An additional means of improvement would be to apply the algorithm to various stars to assess its consistency and identify the areas for further improvement.

6. CONCLUSION

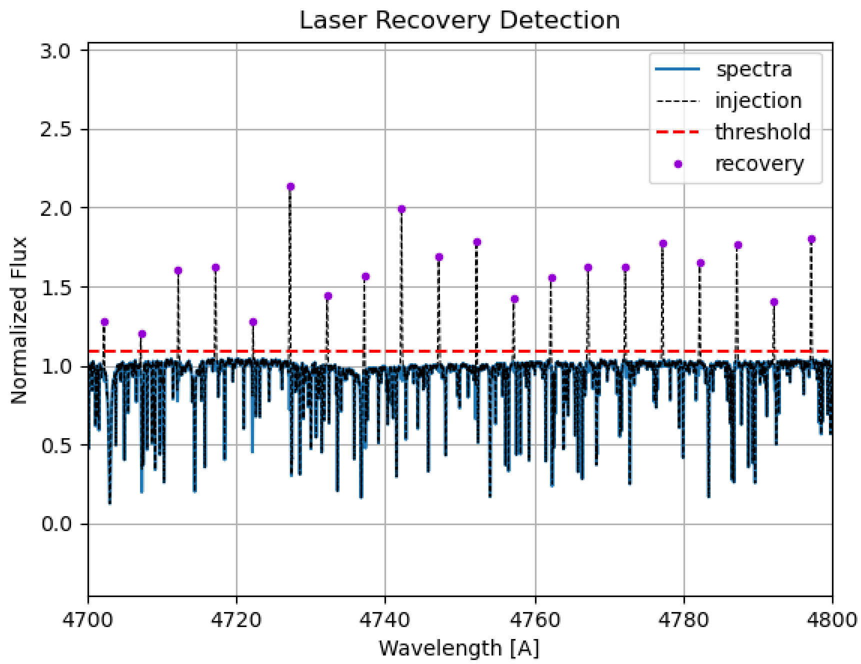

Figure 4. Signal detection test: This plot provides a detailed view of the synthetic signals that were injected by the algorithm, and specifically focuses on the wavelength range between 4700 Å to 4800 Å. The algorithm was set to detect signals with values greater than 1.09 of normalized flux, resulting in the identification of certain signals above the continuum. These detected signals are displayed in the plot as dots located at the peaks (local maximas) of each signal. Based on the threshold condition of 1.09, the algorithm was able to detect 812 out of the 826 injected signals. This corresponds to a detection recovery rate of %98 with 14 undetected signals.

In this study, we aimed to develop and evaluate an algorithm capable of accurately detecting laser signals in stellar spectra. To achieve this goal, we injected synthetic laser signals with varying amplitudes and a fixed distance of 5 Å across wavelength into the normalized continuum spectrum of Tau Ceti. We then assessed the algorithm's ability to detect and recover these signals. Our findings indicate that the algorithm was effective in identifying and recovering laser signals above a predetermined threshold, with a recovery efficiency rate of %98 for signals with amplitudes greater than 1.09 of normalized flux. Its consistency across the spectrum was demonstrated by comparing the average amplitudes of three sections of the spectrum. Our study provides a promising framework for the development of laser signal detectors in a range of stellar spectra and may have implications for the detection of extraterrestrial civilizations. Future studies could explore the algorithm's effectiveness with other types of spectra and in the presence of various sources of noise or interference. It could also be improved to increase its sensitivity and specificity in detecting laser lines in absorption spectra. Moreover, applying this algorithm to other absorption spectra may further investigate the potential existence of extraterrestrial civilizations and their communication methods. Overall, our study provides valuable insights into the possibility of detecting extraterrestrial civilizations through high-resolution spectroscopy and paves the way for further research in the field of optical SETI.

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Software: Astropy, Matplotlib, SciPy, NumPy, Jupyter Notebook, VS Code

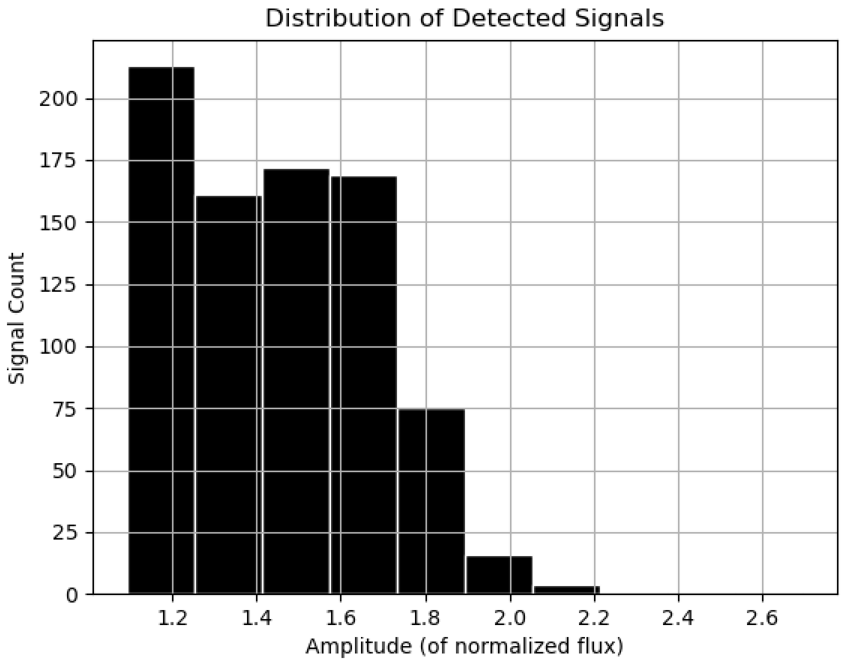

Figure 5. Amplitude distribution of laser recovery: The detection efficiency of the algorithm was determined to be %98 based on the analysis of 826 synthetic signals injected into the normalized continuum spectrum of Tau Ceti, with a threshold set at 1.09 of normalized flux. Of the injected signals, 14 were undetected by the algorithm. The distribution of the detected signals across the modeled emission spectrum is presented as a histogram plot.

Facilities: Berkeley SETI Research Center, European Southern Observetory, ESPRESSO Telescope

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