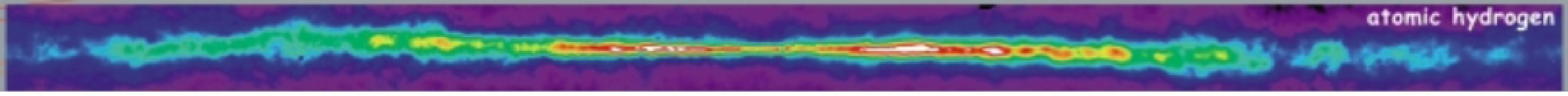

HLDP: A Computational Astrophysics Tool for Hydrogen Line Data Analysis

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Abstract

This study documents the development and application of the Hydrogen Line Data Processor (HLDP), an advanced computational astrophysics tool designed to enhance the analysis of neutral hydrogen measurements obtained with a radio telescope. The primary motivation was the need for sophisticated software capable of automatically detecting radiation peaks in the raw spectrum, processing the data to yield more precise results by eliminating noise and amplifying significant signals. HLDP significantly improved the precision and efficiency of data analysis, aligning the results closely with those from leading institutions such as the Argelander-Institut für Astronomie. The insights gained from this work contribute to a deeper understanding of galactic structures and underscore the importance of advanced software in radio astronomy research.

Keywords: radio astronomy, hydrogen line, neutral hydrogen, computational astrophysics

1. Introduction

Analyzing raw hydrogen line data from radio telescopes presents significant challenges. The raw spectrum often contains substantial noise and extraneous data, making it difficult to draw accurate conclusions from the initial graph. This can lead to errors and misinterpretations.

Previous versions of the **Hydrogen Line Data Processor (HLDP)** focused on background noise reduction and generating basic graphical heat maps. While useful, these versions lacked the sophistication needed for precise analysis.

To address these limitations, I developed an enhanced version of HLDP. This new iteration uses *linear* and *polynomial* filters to derive the final spectrum before converting the observed Doppler shifts into relative velocities and then into velocities relative to the **Local Standard of Rest ($V_{\mathbf{LSR}}$)**, which helps determine the motion of interstellar gas relative to the average motion of stars in the vicinity of the Sun. This approach provides more accurate and detailed analysis by automatically detecting radiation peaks, eliminating noise, and amplifying significant signals.

The primary objective of this report is to document the development and capabilities of this new version of HLDP, demonstrating its effectiveness in improving data analysis and aligning its results with those from leading institutions such as the Argelander-Institut für Astronomie.

2. Software Design

2.1. Overview

In the software design, I aimed to maintain key features of the previous version of HLDP while adding new, more useful functionalities to improve performance.

2.2. Maintained Features

The previous version of HLDP was designed to simply recognize radiation peaks in the spectrum, separate them from the rest of the measurements, and, along with other data, create a heatmap over time of the passage of the galactic arm in the sky where the radio telescope was pointed.

Despite the good results achieved with this version, many of the features and algorithms will not be reused in the new version due to different software objectives. The features retained, because they are useful and compatible with the new goals, include the display of raw data graphs and the graph of fully processed data, as well as the initial linear filter, which is capable of identifying a baseline of the measurements and thereby already identifying radiation peaks.

The creation of the heatmap will not be maintained in this version, but it may be integrated into another piece of software in the future. For more information on the previous version of HLDP, please consult the online repository.

2.3. New Features

In the new version of HLDP, new and more complex filtering algorithms have been implemented, allowing for the complete and much more precise separation of neutral hydrogen radiation peaks from the rest of the spectrum and its noise.

Among the most important new features is the implementation of two **Savitzky-Golay filters**. The first filter is used to create a baseline with greater precision and impact compared to the initial linear filter. The second filter is used to extract and smooth the radiation peaks from the spectrum processed up to that point.

A **Savitzky-Golay** filter is a digital filter used to smooth data and enhance the signal-to-noise ratio without greatly distorting the signal. It applies a polynomial smoothing process to a set of data points, where the degree of the polynomial and the window size are key parameters that determine the filter's performance.

Another crucial feature for radio astronomy data analysis is the conversion from measured frequency to relative **velocity due to the Doppler shift**, and finally to $V_{\mathbf{LSR}}$, which is then plotted in the final graph.

The software also now extracts and displays information about the direction of the measurement being analyzed, including the exact time of the measurement and the **Galactic Coordinates**. This enhancement offers valuable context for the data, aiding in more precise analysis and interpretation.

2.4. Programming and Compatibility

The coding for HLDP is primarily done in **Python**, utilizing its powerful libraries such as:

- **Astropy**: For handling astronomical calculations, including coordinate transformations and time conversions.
- **SciPy**: Specifically for the Savitzky-Golay filter to smooth data and enhance the signal-to-noise ratio.
- **NumPy**: For numerical processing.
- **Matplotlib**: For data visualization.

The software is designed to run on a **Linux** environment, ensuring compatibility with both my main machine and a secondary Raspberry Pi, used for autonomous data gathering over a long period of time.

3. Testing

During the testing phase, HLDP was provided with raw measurement files from previous experiments. In this brief phase, various filter coefficients were adjusted and calibrated to achieve optimal results.

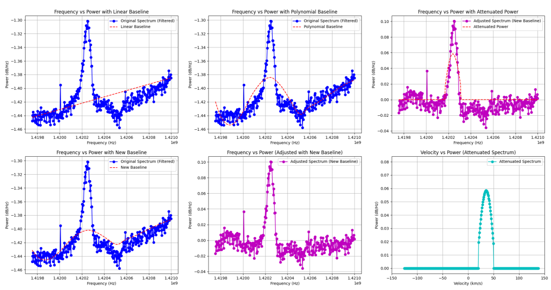


Figure 1: HLDP test image 1, normal peak processing

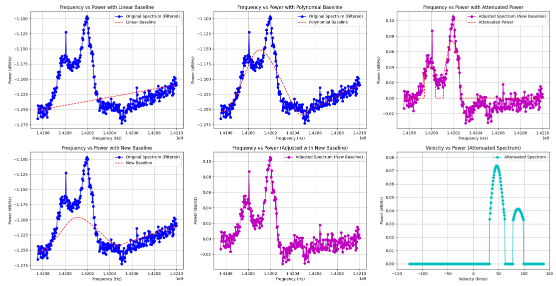


Figure 2: HLDP test image 2, double peaks processing

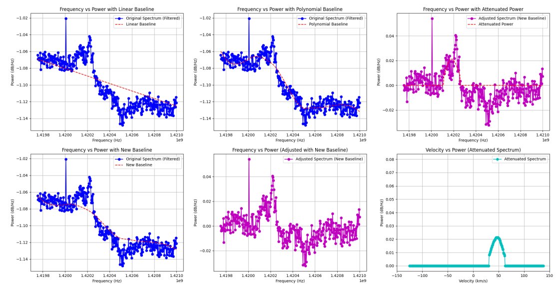


Figure 3: HLDP test image 3, very low peak processing

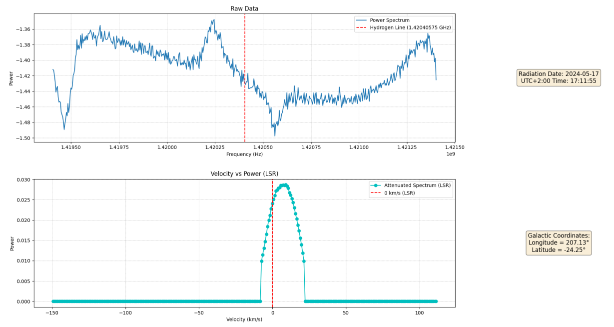
4. Implementation and Validation

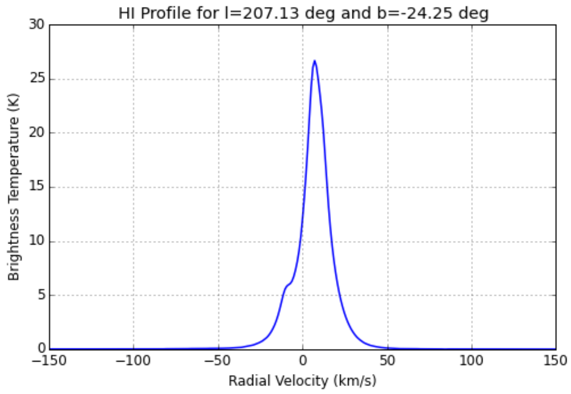
Once the functionality of this new version of HLDP was validated, a new set of raw data was collected to evaluate its performance with real data. The radio telescope was pointed at a specific area of the sky for 9 consecutive hours, observing the passage of the galactic arm.

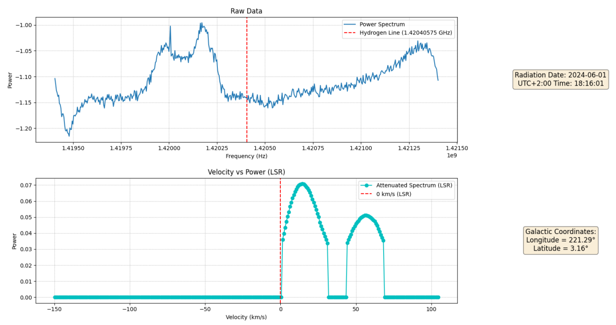
After collecting these data, they were processed with HLDP and then compared with the data from the **HI Survey Server** of the Argelander-Institut für Astronomie. The HI Survey Server is a well-regarded database used by professional astronomers to study neutral hydrogen in the galaxy. It provides high-quality data that are essential for validating new observational tools and methods.

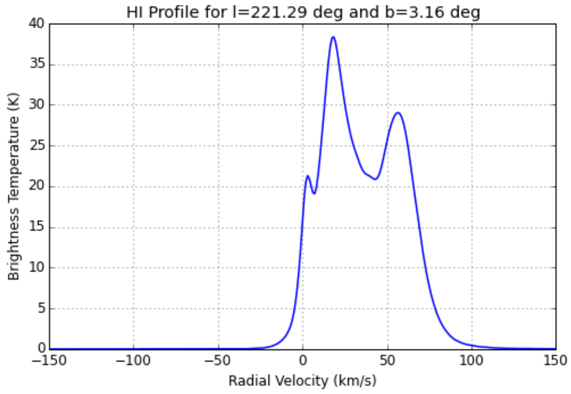
The results obtained with HLDP were fully consistent with those available on the **HI Survey Server**, even exceeding expectations.

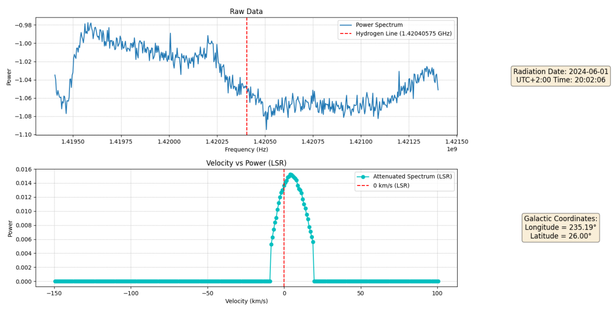
HLDP (left) - HI SERVER (right): data for the same galactic coordinates

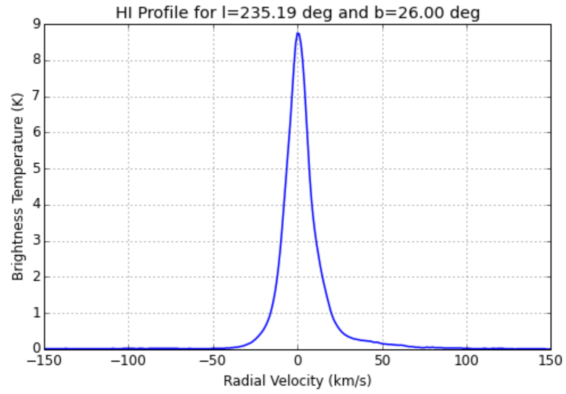












5. Summary and conclusions

The improved HLDP demonstrated remarkable consistency with data from the HI Survey Server of the Argelander-Institut für Astronomie, validating its accuracy and reliability. This makes HLDP a valuable tool for radio astronomy, enhancing both the precision and efficiency of hydrogen line data analysis.

Future work will focus on further refining the filtering algorithms and potentially reintroducing the heatmap feature as a separate module or complementary tool. Expanding HLDP's capabilities to handle larger datasets and more complex observational scenarios will also be a priority. Continuous validation against professional datasets will ensure the software's ongoing robustness and reliability.

6. Resources

- *HI Server Page*: website
- *Online Repository*: github page
- *Argelander-Institut für Astronomie*: website
- *Hydrogen Line Wikipedia*: wiki page