Toward a direct measurement of the cosmic acceleration: the first attempt with FAST

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ABSTRACT
Damped Lyman-α Absorber(DLA) of H i 21cm system is an ideal probe to directly measure cosmic acceleration in real-time cosmology via Sandage-Loeb(SL) test. During short observations toward two DLAs in the commissioning progress of FAST, we manage to exhibit an H i 21cm absorption feature from PKS1413+135 spectrum with our highest resolution up to 100 Hz, preliminarily validating the frequency consistency under different resolutions and bandwidths. We make a Gaussian fitting to extract the spectral features, introduce two indicators to describe the fitted velocity uncertainty, and ultimately give a mean redshift and its constraint of $z = \frac{\mu}{\sigma} = 0.24670047 \pm 0.00000019$ in accord with most literature. But our redshift error is still three magnitudes larger than theoretical cosmic acceleration over a decade. Though our first attempt has some flaws in time recording and diode settings, it still proves the correctness of our data process. For a higher-resolution radio observation, we propose four main challenges: (1) an accurate barycentric radial velocity correction; (2) a precise timing standard in data recording; (3) a statistical sample set of DLAs with prominent absorptions; (4) a widely accepted standard of velocity uncertainty in the DLA approach. Only with close corporation among the community, our understanding for cosmic acceleration could advance firmly.

Key words: cosmology: dark energy – cosmology: observations – quasars: absorption lines

1 INTRODUCTION
Since the outstanding supernovae research(Riess et al. 1998; Perlmutter et al. 1999), plenty of theories have been conceived to explain the accelerating expansion of the current universe, which is believed to originate in dark energy. Confused by diverse possible forms of Equation of State(EoS) for dark energy, the profound mystery of expansion remains ambiguous. Nowadays our cosmological probes, SNIa(Scolnic et al. 2018), CMB(Planck Collaboration 2020), BAO(Hong et al. 2016), and Gravitational Wave(Chen et al. 2020), which keep tracking the components of the universe, have made indirect observations for the qualitative cosmic acceleration in model-dependent ways.

The essence for quantitative cosmic acceleration suggests measuring the velocity change of the celestials that faithfully trace Hubble flow at different epochs and naturally have well-recognized stillness in comoving space. Sandage (1962) proposed the first approach measuring the redshift drift of a radio galaxy. Then the technique was reformed to measure the redshift difference of a Lyman-α forest(Loeb 1998) and named Sandage-Loeb(SL) effect eventually. In the FLRW metric, the SL effect is a globally dynamical probe independent of cosmic geometry and a model-independent indicator of cosmic acceleration.

SL effect has been applied to many aspects of cosmology. The possible parameter space of dark energy models is so vast that the predictions of some models are easily tuned to observational results(Weltman et al. 2020). In this case, an adequately high-precision SL-observation is powerful to distinguish from simple Rh cosmology(Melia 2016) to complex interacting dark energy models(Calabrese et al. 2014; Zhang & Liu 2014). Besides, it could constrain modified gravity theories(Li et al. 2013; Bhattacharjee & Sahoo 2020), provide the theoretical value of acceleration and jerk(Martins et al. 2016), restrict curvature parameter and inflationary model(Jimenez et al. 2018), and partly break the degeneracies of cosmological parameters(Yuan & Zhang 2015). It was also used to study the backreaction conjecture from the inhomogeneity(Koksbang 2020, 2021), research the violation of strong energy condition(Heinesen 2021b), and explore the effect of redshift drift in strong gravitational lensings(Piattella & Giani 2017). In the radio DLA path to cosmic acceleration, there have been positive developments over the years.

In the theory, based on FLRW space-time, Martins et al. (2016) studied the second derivatives of redshift. Considering the pure symmetry of motion without dynamics, Lobo et al. (2020) made a Taylor expansion of the time derivative of redshift to n-th order. Heinesen
expressed the redshift drift in the form of physical multipole moments and discussed its effect in large scale conditions. In the simulation, Corasaniti et al. (2007) studied the feasibility of redshift drifte measurements and firstly named it as SL test. The CODEX spectrograph team of ELT (Liske et al. 2008) carefully studied the sensitivity (accuracy) of measured radial velocity versus redshift and SNR via Lyman-\(\alpha\) forests of high-redshift quasars (\(z : 2 \sim 5\)). Kloeckner et al. (2015) researched the cosmic acceleration observability of SKA and related systematics. Yu et al. (2014) forecasted that a CHIME-like survey could detect the acceleration of \(\Lambda\)CDM cosmology within five sigma confidence, and also researched the DLA survey capacity of Chinese new generation of telescopes: Tianlai and FAST (Yu et al. 2017). Bolejko et al. (2019) listed theoretical dynamical contaminations of redshift drift, suggested a method observing the drift of the subtraction of two redshifts within a negligible angular distance to reduce systematical errors, and combined redshift drift with the flux drift of the same origin to improve the availability of observation data. Through EAGLE cosmological hydrodynamic simulations, Cooke (2019) concluded that Lyman-\(\alpha\) forest is a better probe of the acceleration, while cold HI cloud within the galaxy is easily affected by active components and hard to generate a detectable absorption.

In the observation, Darling (2012) observed more than ten DLAs over a decade and obtained the best constraint of redshift drift so far. Although the constraint was three orders of magnitude larger than the theoretical prediction, it confirmed the long-term frequency stability of these DLAs and GBT telescope, indicating that expanding the samples and prolonging the time baseline can reach higher precision. Jiao et al. (2020) distinguished three related concepts in cosmic acceleration, modified the expectation of the FAST DLA survey, proposed a combined observation mode for DLA, and made a comparative observation as a technical pathfinder of cosmic acceleration.

Aiming to extract the precise location of H I 21cm absorption line and to examine the detectability of the line drift within our conditions in the future, we introduce two indicators in Gaussian fitting to express the fitted velocity uncertainty, and discuss some critical challenges in observing cosmic acceleration (SL effect) through H I 21cm absorption systems. In section 2, we briefly talk about the theories about the acceleration, DLA, systematics and indicators we use. We explain our observational settings on FAST and data process in section 3.1, 3.2 respectively, give results in section 3.3 and make discussions in section 3.4. We place our conclusions in section 4.

2 METHODOLOGY

2.1 Cosmic Acceleration Signal

The related formulae derivation of cosmic acceleration were well-described. Here we revise some of their results briefly. For simplicity, let us assume that a radio source with a fixed comoving distance emitted twice at \(t_e\) and \(t_e + \Delta t_e\). In a homogeneous and isotropic universe, the emissions were observed at \(t_0\) and \(t_0 + \Delta t_0\) respectively, with the definition of scale factor \(a(t_0)/a(t_0)\), which indicates that redshift is the function of emitting time and observed time. If \(\Delta t/t \ll 1\), according to Weinberg (1972) \(\int t_0^t dt/a(t) = \int t_e^t dt/a(t) = \int t_e^{t_0 + \Delta t_0} dt/a(t_e)\), we have the relation between two time differentials \(a(t_0)\Delta t_0 = a(t_e)\Delta t_e\).

In a \(\Lambda\)CDM cosmology with a cosmological constant, the expansion rate of the universe is defined as:

\[
E(z) = \sqrt{\Omega_0 (1 + z)^3 + \Omega_m (1 + z)^3 + \Omega_\Lambda (1 + z)^2 + \Omega_{\Lambda 0}},
\]

where \(\Omega_0, \Omega_m, \Omega_\Lambda, \Omega_{\Lambda 0}\) represent the today density parameters of radiation, matter, curvature and dark energy (the constant) separately.

Making a Taylor expansion (Loeb 1998) of the scale factor \(a(t + \Delta t) \approx a(t) + \dot{a}(t)\Delta t\) in the redshift drift \(\Delta \approx a(t_0 + \Delta t_0)/a(t_0 + \Delta t_0) - a(t_0)/a(t_0)\), or taking the total derivative of redshift with respect to observation time (Liske et al. 2008; Martins et al. 2016), we can derive the formula of redshift drift \(\Delta z\):

\[
\frac{\Delta z}{\Delta t_0} = -H_0 E(z) + (1 + z)\left(1 + z_0\right)H_0 E(z_0). \tag{2}
\]

In the case of contemporary observation, \(t_0 = t_0, z_0 = 0\), \(E(z_0) = 1\), \(t_0 = t\), \(a(t_0) = a_0 = 1\), let \(t_e = t\), the final form of redshift drift is:

\[
\frac{\Delta z}{\Delta t_0} = \frac{(1 + z)H_0 - H(z)}{1 + z} = \frac{1 + z - E(z)}{1 + z}H_0. \tag{3}
\]

Conventionally we transform the redshift drift to a spectroscopical velocity drift (Alves et al. 2019):

\[
\Delta v_{LA} = \frac{c \Delta z}{1 + z} = \frac{c}{1 + z}\left[1 - \frac{E(z)}{1 + z}\right]H_0 \Delta t_0. \tag{4}
\]

Applying the inferred late-\(\Lambda\)CDM-universe parameters (Planck Collaboration 2020), \(\Omega_0 = 0.315, H_0 = 67.4 \text{ km s}^{-1} \text{Mpc}^{-1}\), ignoring the slight \(\Omega_0\) and \(\Omega_{\Lambda 0}\), we can obtain \(\Omega_{\Lambda 0} = 0.685\) and draw a graph of the mentioned three kinds of drifts versus redshift in Figure 1.

Our two observed DLAs both have redshift of 0.2 approximately, the predicted redshift drift \(0.60 \times 10^{-10}\) decade\(^{-1}\) and velocity drift 1.5 cm s\(^{-1}\) decade\(^{-1}\), which is a key challenge to resolve such tiny quantities from spectrum at present.

2.2 Damped Lyman-\(\alpha\) Absorber

Damped Lyman-\(\alpha\) Absorber (DLA) is a kind of highly dense H I gas clouds and has evident Lyman-\(\alpha\) absorption characters in quasar spectra. Due to the self-shielding from the ionizing effect of the diffused background radiation, most hydrogen in DLA is neutral and empirically have a minimal H I column density threshold \(N_{H I} \approx 2 \times 10^{20} \text{cm}^{-2}\) (Bird et al. 2014). In the targeted radio band, H I 21cm lines result from H I hyperfine structure absorption. DLA has a high column density and a low temperature <80 K, thus has a relatively low spin temperature and narrow inherent line width, improving velocity uncertainty in our SL test.
Based on the general discussion in Loeb (1998), first, the peculiar
linear acceleration of the sun orbiting the galaxy center can amount
to cosmic acceleration but be easily removed for its known magni-
tude and orientation. Second, the effect that peculiar velocity(\(\delta v\))
of DLA in the comoving coordinate exerts on redshift drift is small
enough(\(\delta v/c < 1\)). However, for our two DLAs are around the red-
shift of 0.2, the condition that \(\delta v/c < 0.60 \times 10^{-10} \text{ decade}^{-1}\) requires
\(\delta v < 0.18 \text{ m s}^{-1} \text{ decade}^{-1}\).

DLAs can be classified into two types, intervening and associ-
ated. The former type usually lies close to a galaxy in the sightline
to the radio source, while the latter dwells nearby the source. The
associated profiles are broader than intervening ones and have more
low optical depth components with high dispersion(Curran et al.
2016), showing more severe effects from the active areas(such as
star-formation or AGN) in the host galaxy. Cooke (2019) conducted
EAGLE cosmological hydrodynamical simulations to confirm the
similar case(simulated star-forming neutral gas in galaxies). Therefore
it is better to observe intervening DLAs.

2.3 Observational Systematics

Relevant systematics can easily affect precise observations. Accord-
ing to Bolejko et al. (2019), the earth’s orbital motion(dipole and
quadrupole components) and self-rotation are at least one magnitude
larger than cosmic acceleration; while tidal motion, plate tectonics
of the continents, the sun’s circling the galaxy center are comparable
to the acceleration; and galaxy’s motion is three magnitudes smaller.

Apart from these complex Doppler effects contributing to system-
atic bias, one also needs an accurate timing standard to establish
the long-term frequency stability of the equipment over one decade.
Time should be controlled better than cosmic acceleration with a
few nanoseconds, ensuring the accuracy of channel labeling and the
distribution of channel spacing(Cooke 2019).

In addition, it is vital to reveal the corresponding physical prop-
erties(distribution, motion, and inner states) of the DLA probe and
to multiply the DLA dataset for reducing bias and averaging errors.
Undoubtedly, tackling all the factors entails unprecedented efforts
and comprehensive collaborations.

With the previous suggestions, it is explicit for us to select suitable
DLAs: (1) be in the observational range of FAST, with declination
in (-14°12', 65°48'), frequency in (1.05, 1.42) GHz, redshift in
(0, 0.3524), representing the lastest accelerating expansion period;
(2) be less affected by peculiar motion and far away from the local
group, with redshift>0.05, while the intervening DLAs and well-
observed ones are preferred; (3) have prominent absorption peaks,
absorption depth deeper than 0.1 Jy in 1.4 GHz, or optical depth
larger than 0.04. We list satisfied DLAs in Table 1, where the few
amounts would hamper our observation and analysis.

2.4 Evaluators of The Spectra

2.4.1 Spectral Resolution and Signal-to-Noise Ratio

Measuring cosmic acceleration from raw spectra, or just constraining
it, requires very high spectral resolution. Two epochs observations
toward a same DLA will give \(v_{ob1} = v_{em}/(1 + z)\), \(v_{ob2} = v_{em}/(1 + z + \Delta z)\),
where \(v_{em} = 1420.405751768\text{ MHz}\) is the frequency of H
\(\text{I}\) 21cm radiation in the rest frame, \(z\) is the first measured redshift,
\(\Delta z\) is the redshift drift. Suppose a ten-year accumulation \(\Delta z_{10}\), the
frequency drift is:

\[
\Delta v_{10}(z) = v_{ob2} - v_{ob1} = v_{em} \frac{\Delta z_{10}}{(1 + z)^2}. \tag{5}
\]

For the line width in the rest frame \(\Delta v_{\text{rest}}\) is much less than the speed
of light, we can turn the frequency drift to the radial velocity drift
via Meyer et al. (2017):

\[
\Delta V_{10}(z) = (1 + z)\Delta v_{\text{rest}} = \frac{c(1 + z)^2}{v_{em}} \Delta v_{10}(z). \tag{6}
\]

We list the \(\Delta z_{10}, \Delta V_{10}, \Delta v_{10}\) versus \(z\) individually within FAST red-
shift range in Table 2. If one wants to find cosmic acceleration from
original spectra, a resolution smaller than the corresponding drift
must be satisfied.

Signal-to-Noise Ratio(SNR) is defined as the signal maximum di-
vided by the signal error, in practice the latter is the root-mean-square
value based on the fixed spectral baseline. With System Equivalent
Flux Density(SEFD) \(\text{SEFD} = 2k_BT_{\text{sys}}A_{\text{eff}}\), the Boltzmann constant
\(k_B = 1.386049 \times 10^{-23}\text{ J/K}\), FAST L-band receiver has a sensitivity
\(A_{\text{eff}}/T_{\text{sys}} \approx 2000\text{ K/m}^2\) when its system temperature is 20K, hence
\(\text{SEFD} \approx 1.7326 \times 10^{-26}\text{ J/m}^2 \text{ s} \approx 1.7326\text{ Jy}\). Let us define flux un-
certainty \(\Delta F = SEFD/\sqrt{\eta_{\text{pol}}\Delta v\Delta\eta}\), where \(\eta\) is polarization,
\(\Delta v\) is frequency resolution, \(\Delta\) is the total integration time of a single DLA,
we can deduce the SNR formula theoretically(Yu et al. 2014):

\[
\text{SNR} = \frac{F}{\Delta F} = \frac{F\sqrt{\eta_{\text{pol}}\Delta v\Delta\eta}}{\text{SEFD}}. \tag{7}
\]

If we make stringent assumptions that (1) original spectrum has to
meet the SNR of 10; (2) frequency resolution needs to reach the level
of 0.1 Hz over one decade; (3) the depth of the signal peak is 0.02 Jy;
consequently, a 2-polarizations observation for a single DLA requires
integration time of \(3.839 \times 10^{6} \text{ s} \approx 1060\text{ h}\). But we would add some
actual considerations from data processing in the following section
that (1) raw spectra often have SNR<5, after appropriate processing
it can easily exceed 10; (2) using raw spectra to measure cosmic
acceleration is out of reality, which necessitates long observations,
huge data process, and precise error analysis, so it can be simplified
by Gaussian profiles fitting of those processed spectra so we can relax
frequency resolution to 10 Hz; (3) a supposed narrower and deeper
DLA is found within FAST coverage, let the depth be 0.05 Jy. As a
realistic and achievable medium-term goal, we have a more friendly
time 3600 s = 1 h.

2.4.2 The Uncertainty of Velocity Measurement

Fitting Gaussian profiles to extract spectral features, where we use the
mean to denote cosmic acceleration peak location and the standard
deviation to depict the narrowness of the profile, proposes a new
question: what uncertainty(accuracy and precision) the fitting can
give, or how many significant digits the results would present. In
this paper, we introduce two indicators as temporary solutions and
employ them simultaneously.

We regard the result of Fouque et al. (1990) as a reasonable way,
in which they deduced the velocity uncertainty of a Gaussian profile
as theoretically as possible(with some inevitable numerical results).
We rewrite their final formula as follow:

\[
\sigma_{V_1} = 0.797885 \frac{\sqrt{RA}}{SVh} \text{ (km s}^{-1}\text{)}, \tag{8}
\]

where \(R\) is velocity resolution(km s\(^{-1}\)), \(A\) is the area enclosed by
the profile and coordinate axis(Jy km s\(^{-1}\)), \(S\) is the SNR, \(h\) is the peak signal(Jy).

Meanwhile, as a more widely spread and semi-empirical approach,
we use what Koribalski et al. (2004) proposed and Zhang et al. (2021)
We cut off the 10 MHz-width band containing the expected absorption from the 500MHz baseband data and draw its waterfall to roughly judge whether we detect the absorption peak, 1142.5-1152.5MHz for PKS0952 and 1135.0-1145.0 MHz for PKS1413. In the waterfall of PKS1413 we can see a clear horizontal absorption line near 1139 MHz in the left part. In diode stripes there exist narrower dark vertical stripes explained in Figure 4.

Then we divide the states of source-ON/OFF and diode-on/off counterparts, thus are abandoned from date process out of caution. From TEST data including source-ON only (Figure 3), we find distinct regularity of the diode modes in the shape of high and low impulses. As for REAL data (Figure 4), we utilize the same regularity to classify the upper part data as on/off, while the left higher part denotes source-ON mode. Curiously, at the lower part of Figure 4, we find a faint absorption line near 1139 MHz in the left part. In diode stripes there exist narrower dark vertical stripes explained in Figure 4.

The next step is calibrating temperature spectra from power ones. We first convert them into source-ON/OFF system-temperature spectra through the formula:

\[
\sigma T = \sqrt{PR} \frac{\nu}{S}
\]

(9)

where \( R \) is velocity resolution (km s\(^{-1}\)), \( \psi_{20} \) indicates the profile width at 20% peak value, \( P = 0.5 (\psi_{20} - \psi_{50}) \) is defined to express the slope of the profile, \( S \) is the SNR.

### Table 1. selected DLAs in FAST coverage

| Name          | RA Dec     | \( z_{\text{HI}} \) | Type | \( S_{1.4 \text{GHz}} \) (Jy) \( d \) | Literature | Optical depth | FWHM (km s\(^{-1}\)) |
|---------------|------------|---------------------|------|--------------------------------------|------------|---------------|---------------------|
| PKS 0952+179a| 09 54 56.824 +17 43 31.22 | 0.237806 | I    | 1.007                               | K01        | 0.013         | 20                  |
| PKS 1413+135  | 14 15 58.818 +13 20 23.71 | 0.246079 | A    | 1.142                               | C92        | 0.34          | 18                  |
| B2 0738+313 A | 07 41 10.703 +31 12 00.23 | 0.091235 | I    | 2.051                               | L00        | 0.08          | 13                  |
| B2 0738+313 B | 07 41 10.703 +31 12 00.23 | 0.220999 | I    | 9.192                               | L98        | 0.042         | 8                   |
| B3 0839+458   | 08 43 07.095 +45 37 42.90 | 0.192225 | A    | 0.259                               | G15        | 0.26          | 80                  |
| J1120+2736    | 11 20 30.079 +27 36 10.83 | 0.111720 | A    | 0.152                               | G15        | 0.15          | 60                  |
| J0849+5108    | 08 49 57.977 +51 08 29.02 | 0.311991 | I    | 0.344                               | G13        | 0.06          | 4                   |
| J1124+1919    | 11 24 43.693 +19 19 28.11 | 0.165161 | A    | 0.877                               | G06        | 0.09          | 13                  |

\( a \) The bold DLAs in the first four lines are observed by Darling (2012). \( b \) The italic DLAs in the last two lines have obvious multi-peak structure in the reference spectra. \( c \) Redshifts of DLAs in the third column and the type of DLAs in fourth column are given in Curran et al. (2016), what we abbreviate are I(intervening) and A(associated). \( d \) The peak flux at 1.4GHz in fifth column refers to the VLA FIRST survey (Becker et al. 1995). The sixth column contains the literature of these original spectra, providing the information in the last two columns. \( e \) K01(Kanekar & Chengalur 2001), C92(Carilli et al. 1992), L00(Lane et al. 2000), L98(Lane et al. 1998), G15(Geréb et al. 2015), G13(Gupta et al. 2013), G06(Gupta et al. 2006).

### Table 2. relative decade-drifts versus redshift

| \( z \) | \( \Delta z_{10} \) | \( \Delta V_{10} \) (Hz) | \( \Delta V_{10} \) (cm s\(^{-1}\)) |
|------|-----------------|-----------------|-----------------|
| 0.05 | 1.749 x 10\(^{-11}\) | 0.023 | 0.525 |
| 0.15 | 3.777 x 10\(^{-11}\) | 0.040 | 1.012 |
| 0.20 | 4.883 x 10\(^{-11}\) | 0.052 | 1.464 |
| 0.25 | 6.269 x 10\(^{-11}\) | 0.062 | 1.879 |
| 0.30 | 7.537 x 10\(^{-11}\) | 0.069 | 2.260 |
| 0.35 | 8.691 x 10\(^{-11}\) | 0.073 | 2.606 |
| 0.40 | 9.733 x 10\(^{-11}\) | 0.076 | 2.918 |

Figure 2. The waterfall of REAL data (PKS1413) with about 10 kHz resolution, the abcissa is a time sequence but may be discontinuous. With narrow vertical stripes suggesting diode states, the left pale portion is source-ON, and the right dark is source-OFF. We can find a faint absorption line near 1139 MHz in the left part. In diode stripes there exist narrower dark vertical stripes explained in Figure 4.
First attempt of cosmic acceleration with FAST

- **Figure 3.** The RMS noise behavior of TEST data (only including source-ON data). The diode effect is distinguishable in the time direction. The higher data points covered by the green block represent diode-on, while the lower in the yellow block is diode-off.

- **Figure 4.** The RMS noise behavior of REAL data. At the upper part of the graph, we can see two arrays in the color blocks with a similar pattern to Figure 3. But at the lower part, noise behavior is different, descending periodically, covering all the observational time, and indicating some systematics in the instruments.

\[ T_1 = \frac{T_{\text{sys}}^{\text{on}}}{T_{\text{sys}}^{\text{off}}} = \frac{\sigma_{\text{on}}}{\sigma_{\text{off}}} T_{\text{cal}} - T_{\text{cal}}, \quad (10) \]
\[ T_2 = \frac{T_{\text{sys}}^{\text{off}}}{T_{\text{sys}}^{\text{on}}} = \frac{\sigma_{\text{off}}}{\sigma_{\text{on}}} T_{\text{cal}} - T_{\text{cal}}, \quad (11) \]

where \( T_{\text{cal}} \) is the diode temperature (\( \approx 10 \) K). To reduce the glitch-interference in baseline fitting require data smoothing. Avoiding flattening the peaks, we refer to Zhang et al. (2021) and only make Gaussian smooth of the denominator every 0.5 MHz considering Nyquist sampling and 1 MHz baseline ripple of the FAST receiver system.

With a reasonable assumption that similar RMS noise levels exist in the divided two sets of data (source-ON and -OFF), we obtain an RMS(\( \sigma \)) weighted spectrum to minimize the merged RMS noise level:

\[ w_i = \frac{\sigma_i^2}{(\sigma_i^2 + \sigma_j^2)}, \quad i, j = 1, 2, \quad i \neq j, \quad (12) \]
\[ T_{\text{sys}} = w_1 T_1 + w_2 T_2. \quad (13) \]

For TEST data only has ON spectrum, we will concern NO-OFF fitting of REAL data. We compare 3 baseline fittings: (1) cubic polynomial plus sine (com), (2) Chebyshev polynomial (cheb), (3) asymmetric reweighted Penalty Least Square (arPLS, Baek et al. 2015) in the HiFAST pipeline (Jing et al., preparation). In a low resolution (10 kHz), three means have comparable results in RMS noise, while at higher resolution (5 kHz, 2 kHz, 1 kHz), the arPLS surpasses the others (Figure 5). So we use arPLS fitting in a low-res group (from 10 kHz to 1 kHz). However, in a finer group (5 hundred Hz, 2 Hz, 1 Hz), the arPLS is abnormal around the peak due to the noticeable sensitivity and continuous differentiability (Figure 6). Therefore, we use cheb fitting in the high-res group (higher than 1 kHz). After baseline correction, we divided by the antenna gain of \( G(1150 \text{ MHz})=16.48 \text{ K Jy} \) (Jiang et al. 2020) around the targeted frequency and cut 1 MHz-width flux density-frequency data for the last Gaussian fitting.

We make a frequency Gaussian fitting to the truncated data (Figure 7) with a custom Gaussian function and the optimize_curve_fit function in the python3 package scipy. Transforming the frequency to barycentric velocity via PyAstronomy module (Czesla et al. 2019) un-
3.3 Data Analysis: Results

We cut off some bands of different widths to fit the baseline with several frequency resolutions but always fit the Gaussian profile in 1.0 MHz band, and list some essential fitted parameters in Table 3. The consistency of fitted central frequency and radial velocity was manifested remarkably in all the cases, where the corrected barycentric radial velocities locate in 73958.928848-73958.954755 km s$^{-1}$ with 0.03 km s$^{-1}$ range. To guarantee a persuasive result, we discard the data with SNR<14.50 in the following analysis.

Various resolutions smooth distinct data points, different wide-bands retain unequal data amount, both may slightly change the data distribution and naturally make the results fluctuate. It is hard to choose a best value among them, considering all varying conditions. Therefore we take a simple mean with the smaller uncertainty $\sigma_{V1}$: the corrected barycentric radial velocity $V_M = 73958.939571 \pm 0.057922$ km s$^{-1}$, corrected redshift $z_M = 0.24670047 \pm 0.00000019$, corrected frequency $f_M = 1139332.009531 \pm 0.173637$ kHz.

3.4 Discussions

As for the absent absorption features of PKS0952, we find a reason: its absorption depth is less than 0.02 Jy obtained by 5 h source-ON integration(Kanekar & Chengalur 2001). We have only about 5 min ON time, and 2/3 of the data are accidentally damaged.

Referring to the literature spectrum of PKS1413(Carilli et al. 1992), we reach a stricter redshift constrain(where it gives $z = 0.24671 \pm 0.00001$), a more Gaussian profile, and a less notable extended wing. According to Darling (2012), the DLA in the PKS1413 spectrum should be a steady one free of noticeable frequency shift with redshift $z_{HI} = 0.24670374(30)$ based on a decade observation. However, in Curran et al. (2016), it has the redshift of $z_{HI} = 0.246079$. A 0.0006 difference exists in the two redshift values, and our result supports Darling’s redshift still have a redshift difference of 0.00003. Restricted by the shortage of observation time, at a similar resolution(10 kHz), we only achieve an RMS noise of 0.008 Jy, worse than the literature. But all of these finished in a twelve-minute observation already proved the great power of FAST.

Comparing the two indicators of velocity uncertainty, we find that they all decrease when resolution improves, matching our presentative assumptions. $\sigma_{V2}$ is one time larger than $\sigma_{V1}$, which we consider as more reasonable gives a stricter constraint. To some extent, however, the two evaluators originate from certain features in spectra and ignore the undergoing physics and systematics discussed in Liske et al. (2008). Due to their potential drawbacks, we use them out of expediency and still need to build a widely accepted definition of uncertainty.

Aiming to trace cosmic acceleration, the most serious question we encounter is how to improve spectral resolution and decrease the velocity uncertainty at the same time. High-resolved data demand more observation time, while the current uncertainty is still three magnitudes larger than the theoretically predicted acceleration and does not halve when the resolution improves by two orders of magnitude. It is necessary to prolong the integration time per DLAbecause the 10 min is too short and can not help us reach the limitation of velocity uncertainty that FAST baseband data can offer.

The biggest technical problem is the process of massive data. Though a 10 MHz band would satisfy our need, the FAST baseband provides 500 MHz data before Fourier Transform, raising a rigorous demand on the computational capacity in the FAST site and the potential optimization of our FFT program.

Figure 7. Frequency Gaussian fittings of REAL data with 10 MHz-band. There are 1, 2, 5, 10 kHz resolutions from top to bottom. The cyan line is realistic data, the magenta curve is the Gaussian profile we fit, the black line is the offseted error of Gaussian fitting. The vertical blue dashed line is the fitted peak location.

Figure 8. Velocity Gaussian fittings of REAL data with 10 MHz-band. There are 0.326, 0.562, 1.629, 3.259 km s$^{-1}$ resolutions from top to bottom.

under the online instruction(the function: radial velocity correction$^2$) of the astropy module(Astropy Collaboration 2013), ultimately, we take a velocity Gaussian fitting(Figure 8) and analyze the results by the former two indicators in sec 2.4.2.

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$^2$ https://docs.astropy.org/en/stable/api/astropy.coordinates.SkyCoord.html
Without adequate integration time, the fluctuations in lines rise with the increase of resolution. In this case, com and cheb are not good, while arPLS is invalid for its abnormal behavior near the peak. We should update the model parameters in arPLS at the different scenarios or find a finer baseline fitting against the multiplied amount of data. The new method must take apart global subtle baseline variations from local trivial and sharp interference, where their boundary gradually blurs.

We perform barycentric radial velocity correction via PyAstronomy and astropy with the same input. But the outputs they produce have a difference of about 6 m s\(^{-1}\). We adopt the PyAstronomy outcome for it can present detailed information which can be verified conveniently. The uncertainty we obtain is one order of magnitude larger than 6 m s\(^{-1}\), three to four orders larger than 0.01 m s\(^{-1}\) decade\(^{-1}\). More accurate astrometric techniques are still in urgent need.

Moreover, the values we process in a python3 program are operated in the form of floating-point numbers. With its accuracy to fifteen decimal places, this data type could cause the stochastic fluctuating in intermediate results, which would lead to a wrong outcome, especially in a high-precision case. The round function or decimal module both are unfit to process massive data in an array or matrix.

For the first attempt, we have been learning from some flaws. The most irreparable is that we document the sequence numbers of the FFT data but neglect exact time information. After removing corrupted data, the timeline becomes discontinuous, preventing us from improving the precision of radial velocity correction. Besides, since our critical concern is peak location(velocity), we could prolong the diode-off time during the observation.

### 4 CONCLUSION

By observing two DLAs in the FAST commissioning progress, we manage to attain an H i 21cm absorption line feature and prove the consistency of Gaussian fitting results at different baseline lengths and resolutions, validating the correctness of our processing. Constrained by the observation time, the spectra we generate have a deficiency in RMS noise level than the literature spectrum(Carilli et al. 1992), but have higher precision and better Gaussian shape, providing convincing feasibility of Gaussian fitting. Under the demand for precise velocity measurement, we establish an analytical framework with a relativistic receding velocity, combined with two phenomenological evaluators from spectral features to represent velocity uncertainty.

Combining all the values to obtain their means, we take these final parameters of DLA in the sightline of PKS1413+135: barycentric corrected radial velocity \( V_{\text{c}} \) = 73958.939571 \pm 0.057922 km s\(^{-1}\), corrected redshift \( z_{\text{c}} = 0.24670047 \pm 0.00000019 \). The redshift we derive is more precise than the original literature(Carilli et al. 1992), but a bit different (0.000003 larger in redshift, 2.74 kHz in frequency) with Darling (2012), and three magnitudes larger than the theoretical drift of cosmic acceleration over a decade. Although Darling claimed the frequency stability of DLA in PKS1413 by the long-span observations, we notice that Curran et al. (2016) classified the DLA as an associated one, which is more likely to be affected by the host galaxy. Consequently, the difference in redshifts is reasonable, justifying the significance of persistent concern about DLAs, and requires more observations to explain.

Approaching radio cosmic acceleration raises some crucial necessities. (1) an accurate barycentric radial velocity correction with the accuracy of cm s\(^{-1}\) decade\(^{-1}\). Now the results given by PyAstronomy and astropy still have a difference about 6 m s\(^{-1}\). (2) a precise timing standard to establish and verify the long-term frequency stability of the telescope system and DLAs at the same time; (3) a statistical sample set of DLAs diminishing the bias. (4) a recognized and analytical velocity uncertainty to show us the numerical gap between theory and observation. With intimate and comprehensive collaboration across the community, cosmic acceleration and SL cosmology will be no longer far away.

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### Table 3. key fitted parameters from the DLA in PKS1413+135 spectrum

| Band start\(^a\) (MHz) | Band end\(^a\) (MHz) | SNR | \( \text{RES}_{V} \) (km s\(^{-1}\)) | Fitted \( \sigma^{b} \) (Jy) | Fitted \( \mu^{b} \) (km s\(^{-1}\)) | Fitted \( \sigma^{c} \) (km s\(^{-1}\)) | \( \sigma_{V1} \) (km s\(^{-1}\)) | \( \sigma_{V2} \) (km s\(^{-1}\)) |
|------------------------|------------------------|-----|----------------------------------|------------------|------------------|------------------|------------------|------------------|
| 1135.0                 | 1145.0                 | 20.40 | 0.325869 | -0.421436 | 73958.934152 | 9.291219 | 0.107763 | 0.200977 |
| 28.17                  | 0.651738               | -0.422289 | 73958.930277 | 9.346801 | 0.110673 | 0.206402 |
| 42.83                  | 1.629340               | -0.423126 | 73958.94238 | 9.429868 | 0.115607 | 0.215605 |
| 52.80                  | 3.525866               | -0.421004 | 73958.942622 | 9.431026 | 0.132643 | 0.247377 |
| 1137.4                 | 1141.4                 | 8.02  | 0.032587 | -0.424130 | 73958.944865 | 9.432015 | 0.087344 | 0.162896 |
| 10.63                  | 0.061517               | -0.424105 | 73958.944803 | 9.432133 | 0.093140 | 0.173705 |
| 15.09                  | 0.162935               | -0.42159 | 73958.94705 | 9.429936 | 0.103748 | 0.193489 |
| 20.38                  | 0.325866               | -0.421748 | 73958.935633 | 9.306787 | 0.111669 | 0.208260 |
| 27.93                  | 0.651738               | -0.422654 | 73958.928848 | 9.353615 | 0.111669 | 0.208260 |
| 40.78                  | 1.629351               | -0.424213 | 73958.949153 | 9.433751 | 0.121457 | 0.226516 |
| 55.43                  | 3.525868               | -0.422642 | 73958.936749 | 9.472499 | 0.126613 | 0.236131 |
| 1138.4                 | 1140.4                 | 8.17  | 0.032587 | -0.423461 | 73958.936090 | 9.403024 | 0.085586 | 0.159657 |
| 10.46                  | 0.061517               | -0.423455 | 73958.935864 | 9.402322 | 0.094502 | 0.176290 |
| 14.50                  | 0.162935               | -0.423502 | 73958.936884 | 9.402301 | 0.107775 | 0.201052 |
| 19.91                  | 0.325866               | -0.422381 | 73958.937650 | 9.339416 | 0.110645 | 0.206401 |
| 27.99                  | 0.651737               | -0.421653 | 73958.949495 | 9.327674 | 0.112311 | 0.207494 |
| 40.76                  | 1.629346               | -0.422737 | 73958.943395 | 9.405579 | 0.121286 | 0.226261 |
| 52.78                  | 3.525870               | -0.420929 | 73958.954755 | 9.448312 | 0.123759 | 0.247684 |

\( ^a \) The diverse cut-bands are only used in baseline correction. \(^b \) The columns from the fifth to seventh are the three parameters of a Gaussian profile \( f(x) = \frac{a}{\sigma \sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \). The fifth column is the fit absorption depth, the sixth is the fit barycentric corrected radial velocity, and the seventh is the fit standard deviation.
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DATA AVAILABILITY

The preprocessed data analysed by this work are from the FAST baseband observation project and can be accessed by sending request to the corresponding authors of this paper. However, the original baseband data are not open in the FAST Data Centre according to the relative regulations.

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