On the Local Standard of Rest

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Abstract

This article deals with the Local Standard of Rest (LSR) which is the commonly used reference frame for giving velocities in particular for spectral measurements in our own galaxy. Such a reference frame is of importance when observations from different observatories, different times, or towards different directions are compared. This article explains the background and demonstrates why this is important also for amateur observations. Code is provided to do the necessary calculations.

What is the issue?

Velocities can be measured when an astronomical object emits (or absorbs) radiation from a well-known transition between different energy levels. This manifests itself in the occurrence of a distinct spectral lines. The most prominent example in radio astronomy is the 21-cm line (1420.405 MHz). But many other lines are also observable in the radio regime and the study of these give detailed information of the dynamics involved. For the amateur radio astronomer, observations of the 21-cm line of neutral hydrogen can easily be achieved. But amateurs have also been successful in observing maser emission lines from OH, methanol and water. With larger instruments radio recombination lines of hydrogen and carbon become observable.

The velocity of the observed objects become apparent by the Doppler shift of the line, i.e. a deviation of the observed frequency from the frequency of the transition, the so-called rest frequency.

The amount of the Doppler shift is determined by the velocity between the observed object and the observer. This immediately shows that there is an issue: The observer itself moves as the earth rotates around the sun and around itself. This will result in different Doppler shifts at different times and even between different observatories. This makes observations difficult to compare to each other. Furthermore, observational results are difficult to interpret with respect to the motions of the observed regions when the observer motion is included in the data. The solution to this problem is to define a standard reference frame, to which all observations are related. By using such a reference frame, observational results become independent of time and location of the observations.

Reference frames: ICRS

In order to provide a common ground, the International Astronomical Union (IAU) [1] has defined a reference frame, the International Celestial Reference Frame (ICRS) [2]. This reference frame is centered at the barycenter of the solar system. The exact definition is refined from time to time. Some links to this subject matter which may be of interest are [3][4][5].

The position of the earth and other objects of our solar system with respect to this reference frame is represented by a solar system ephemeris. A widely adopted ephemeris are the JPL DE430/DE431 models [6]. With this ephemeris, the position and velocity of the earth with respect of the ICRS frame can be calculated for any point in time. Then of course, the motion of the observer location in respect to the center of the earth due to the rotation of the earth needs to be considered as well. Referencing all observations to the ICRS reference frame will eliminate all such variations caused by the motion of the observatory in the solar system.

Reference frames: From ICRS to the Local Standard of Rest

The ICRS reference frame is used for many observations as the standard reference frame. There is one limitation of this standard, though: It takes the solar system barycenter as the point of reference. Obviously, our solar system will also move within our milky way. So, any observation which is intended to learn about the dynamics of our galaxy will be influenced by this motion. It has been found, that our solar system has a peculiar motion with respect to the stars in the local vicinity, the so-called Local Group. In order to eliminate this motion, an

additional correction is introduced which accounts for this. This reference frame is called Local Standard of Rest (LSR).
Determining the peculiar motion of the sun, however, depends on which stars in the neighborhood are taken into account and how the measurements are done. Therefore, over time several different results have been achieved and consequently different definitions have bee drafted. Fortunately, it seems that in the radio astronomy community there is a common ground which is using the following definition based on work by Gordon [7]:

The peculiar solar motion is 20 km/s in direction RA 18 h , Dec +30° at epoch 1900.
This is equivalent to the definition at epoch 2000:
20.0 km/sec towards RA 18h03m50.29s, Dec +30°00'16.8"

This definition is also called the kinematic LSR. It has been verified that this definition is in use at the observatories Effelsberg[8], Jodrell Bank[9], Green Bank[10] and the ATNF telescopes [11]. Since our (Stockert) data using this definition agrees with data from the Nancay telescope it can safely be assumed that the same definition has been adopted there. Therefore, it is highly recommended that this definition should also be applied in the amateur community.

How to calculate the LSR correction

Calculating the LSR correction is a complex task as it needs to take the various motions into account. Fortunately, there are now routines available as part of the AstroPy package. However, there is a big caveat: Astropy routines do not use the kinematic LSR as defined above as default. Therefore, it is required to set the parameters to override the default settings of Astropy.
With this article I am providing Python code to implement the kinematic LSR calculation based on Astropy. The code with the file name lsr_calc.py contains a function vlsr_calc which does all the needed calculations based on the coordinates of the telescope, the equatorial coordinates of the observed sky location and the time of observation. It provides both the Local Standard of Rest velocity and the barycentric velocity. The code also contains examples how to use this function. These examples are:

- Calculate the observer’s velocity with respect to the Local Standard of Rest and Barycenter for a given observatory, sky coordinate and time
- Calculate the frequency of the Hydrogen line at rest for the observing parameters as above. This is useful for determining to which frequency the receiver must be set in order to record directly in the LSR frame
- Calculate the LSR-velocity for an observed hydrogen line for the observing parameters as above.

Please note that using this code requires Python 3 and a fairly recent version of Astropy. It has been tested with Astropy 4.2. The code is available on https://github.com/Astropeiler/vlsr_calc.

There is some other code available from Tammo Jan Dijkema on gitlab [12] which works fine and is using the kinematic LSR standard. This code is also based on Astropy.

How about online-calculators? There is one available at [13] which is based on previous work by Steve Olney from the HawkRAO observatory. He himself does no longer provide an online calculator. There used to be a few more around in the past. At the time of writing these seemed to have disappeared or are not functional any more. Any hints to the author about additional calculators are welcome.

Correction applied during data capture or post processing?

One of the questions inevitably come up: Should one correct for the LSR immediately when recording the data or should one record topocentric data and then correct it later in the further process? Both options are viable. The typical approach at professional observatories is to record data in the LSR reference frame. The main argument is that one should take out any observatory specifics and provide data which is independent of the location and time. One can always convert this data into other reference frames without any additional information required. The only thing which needs to be known what reference frame has been used for recording.

In contrast to this, any recording in a local reference frame will need to keep additional information such as location of the observatory and time of observation in order to be able to convert this to other reference frames later on.

In certain cases, when very high-resolution data is recorded with very long integration times (weak maser sources for example) it may be needed to adjust the frequency during the observation. The Doppler shift might vary during the observation time enough to broaden the recorded line. In this case, this can only be avoided by adjusting the frequency of observation from time to time. This is only doable when recording directly in the LSR frame. This scenario, however, will hardly ever occur in an amateur observatory so may be not so relevant here. In particular, it is not required for any Hydrogen line observations as these lines are fairly broad.

Does it matter for the amateur community?

The simple answer is, yes it does. The difference between an uncorrected spectrum and a spectrum referenced to the Local Standard of Rest can be quite significant. Below in fig. 1 are examples of the Hydrogen spectra at galactic latitude 90° / galactic longitude 0°. One spectrum (black) is referenced to the local standard of rest whereas the other (red) is without correction.

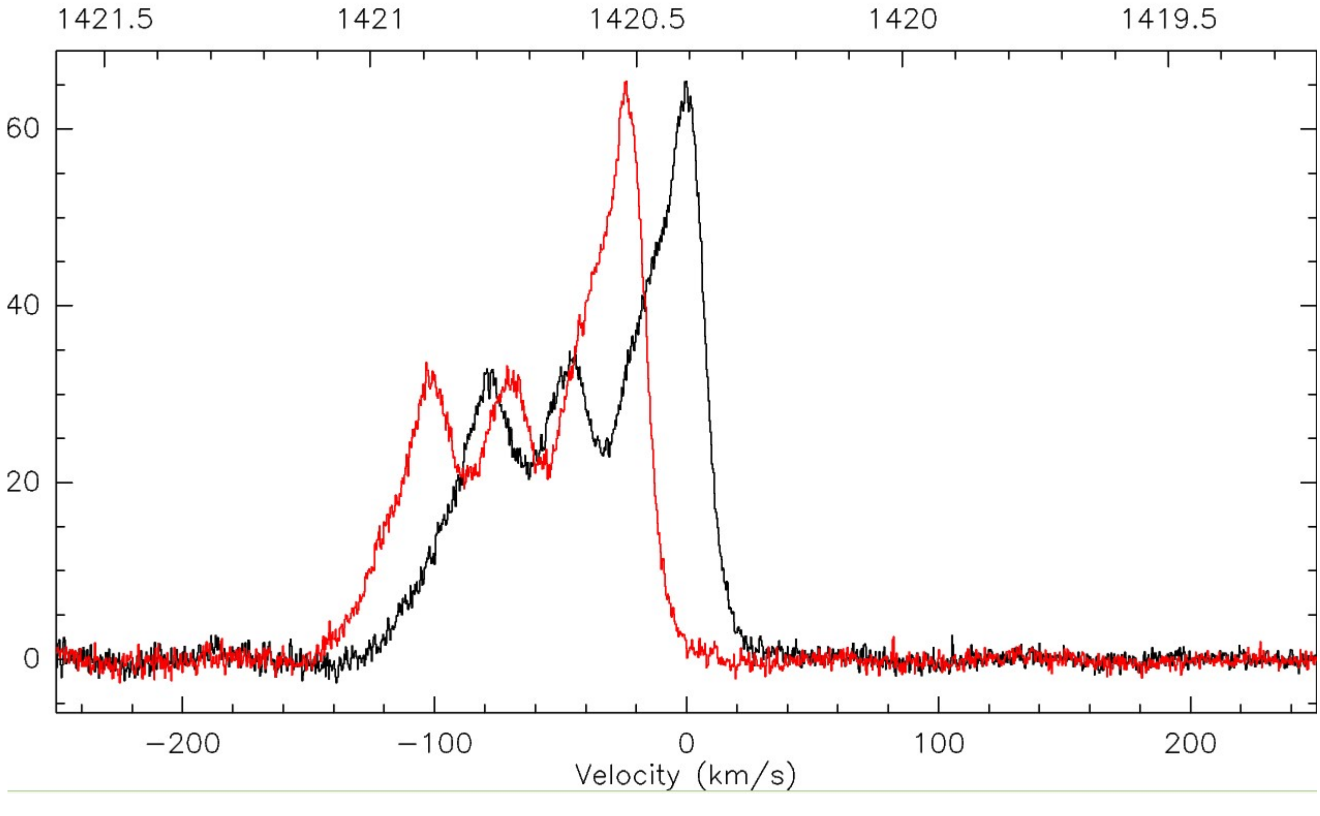

Figure 1: Hydrogen Spectra at l=90°, b=0° with and without LSR correction

The spectra were taken with one of the smaller instruments of our observatory, a 2.3-m dish. Data was recorded at Aug. 6th at approx. 16:07 UTC with 20 seconds integration time each. The difference in velocity at that time was 23.5 km/s km/s. This is certainly a significant difference which cannot be neglected.

A frequent experiment done by amateurs is to record the spectra at various galactic latitudes in the galactic plane and derive the rotation curve from that data. The result will be erroneous if the spectra are not referenced to the LSR as an additional Doppler shift is introduced due to the motion of the observer.

In conclusion, it is recommended that also amateurs adopt the practice to record data in the LSR reference frame.

References

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[10] https://www.gb.nrao.edu/~fghigo/gbtdoc/doppler.html
[11] https://www.narrabri.atnf.csiro.au/observing/obstools/velo.html
[12] https://gitlab.camras.nl/dijkema/HPIB/blob/185d241ad9bd7507ed90c9fa91fe0a63009d3eee/vlsr.py
[13] http://f4klo.ampr.org/vlsrKLO.php

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He received his PhD in Physics from the University of Bonn. He has spent most of his professional career in the telecommunication industry. At retirement age, he now enjoys learning as much as possible about radio astronomy, doing observations and improving the instruments at Astropeiler.

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