Report on the First Year of Operations of the ESA-Haystack Radio Telescope at ISU

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September 2010

1. Installation and initial operations

After its mounting on the roof in summer 2008, the laying of the 120 m long cables, extensive technical tests as well as major modifications and extensions of the software, the ESA-Haystack radio telescope saw “First Light” on an evening in June 2009 by observing the emission of the Milky Way’s atomic hydrogen gas.

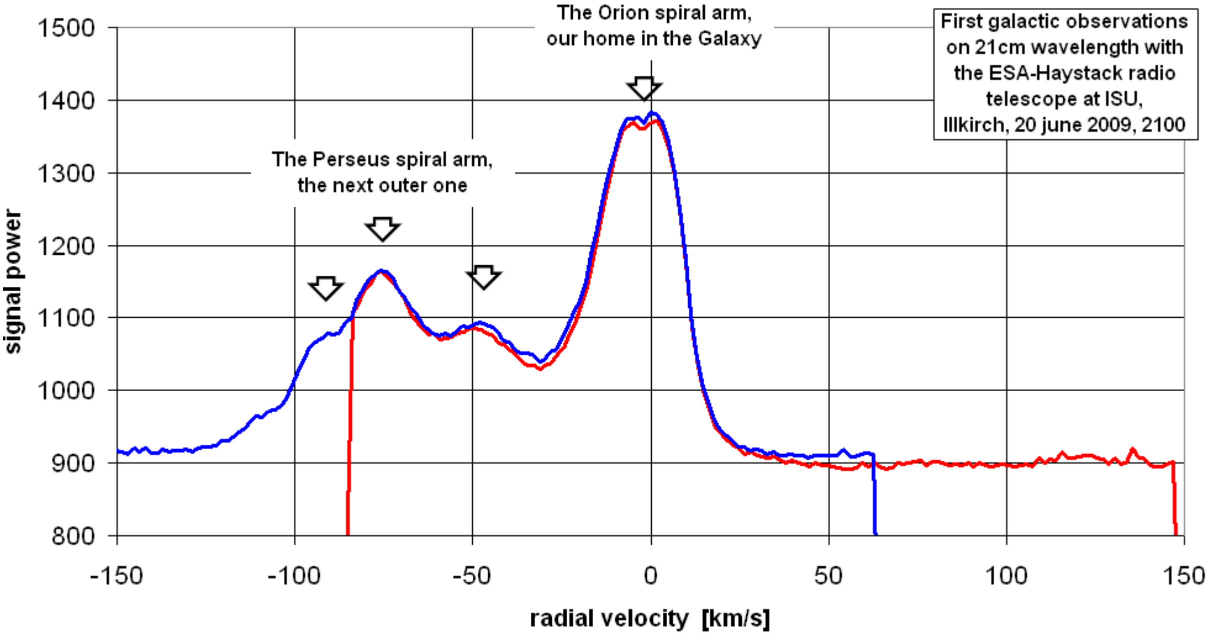


Fig.1: *The first observation of Galactic hydrogen emission by the ESA-Haystack telescope*

In July, observations in the galactic plane demonstrated the feasibility of determining the Galactic rotation curve with data taken at ISU. The experience gained during extensive manual observations permitted to further update the telescope software and adapt it to our needs.

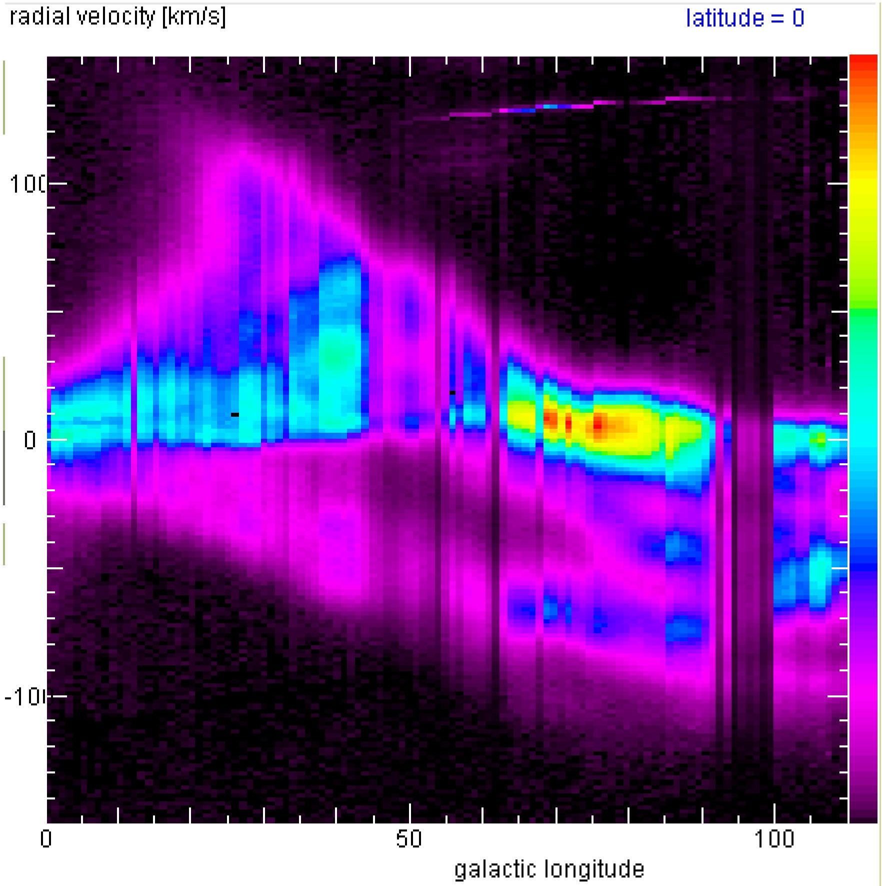


Fig.2: *A first complete observation of the inner Galactic Plane (15 July 2009). In this map of Galactic longitude and radial velocity the measured power is coded as false rainbow-like colours, with red representing high intensity. The fine trace at the top is an interference signal. The vertical stripes and gaps seen in the Milky Way emission are also caused by interference.*

However, in autumn it was noticed that the observations were strongly upset by interference, so that data finally became completely useless. Evidently, the transmissions of a mobile phone tower in only 400m distance caused an overload of the telescope's preamplifier. To counter this blocking, narrow band filters were constructed. However, their first application in January 2020 did not yet result in the improvement I had hoped for.

2. Use during Personal Assignments in Masters Program

During the Masters 2010 program at ISU, the telescope was used by Marissa Rosenberg in her personal assignment work (60 hours of work, during January to March). She studied the thickness of the galactic disk of hydrogen gas by observing how the intensity of the emission decreases with distance from the galactic plane. As during this time we continued to suffer from the strong interference, we had to learn how to obtain observational data despite these severe restrictions. Her observations showed clearly that interference was strongest when the receiver gave low values for the signal. This proved that interference essentially blocked the preamplifier and made the instrument insensitive.

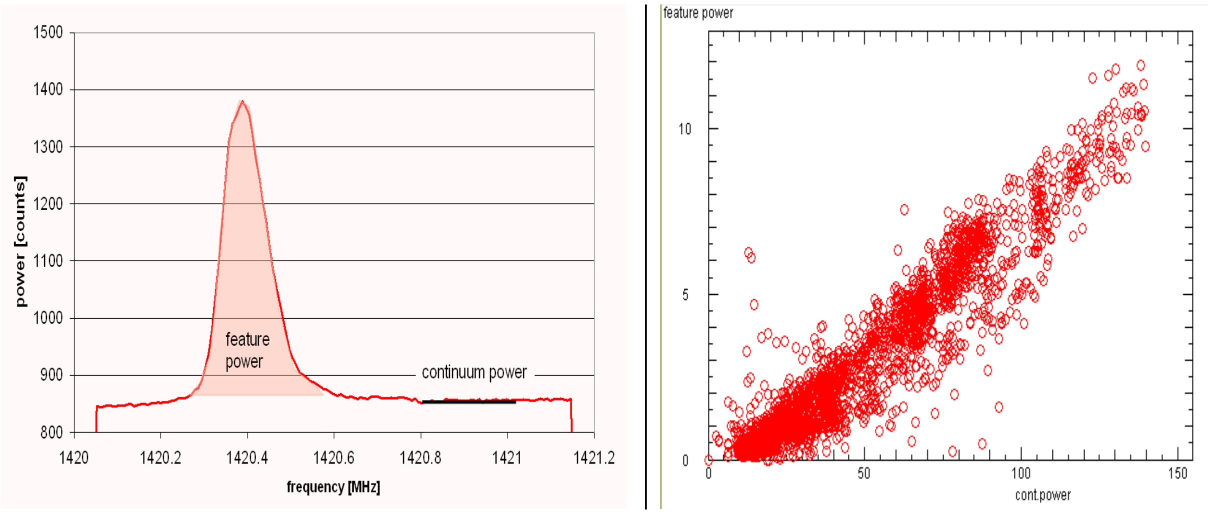


Fig.3: *Monitoring the Galactic anti-centre – normal spectrum shown at left – over a long period with low and high interference reveals that the measured power of the Galactic is well correlated with the level of the near-by continuum (right). Since the true power of the Galactic feature is constant, this proves that interference causes a reduction of the telescope's sensitivity by overloading the pre-amplifier.*

By judiciously selecting data from times of low interference or times of nearly constant interference, she was able to secure useful data which could even be confronted with simple models. The data had to undergo substantial and careful reduction. To learn and appreciated this was one most important lesson!

The basic result is that the intensity of the hydrogen emission declines as one moves away from the Galactic Plane. Her data, taken at several longitudinal directions, show that the Galactic Disk has a thickness (full width at half maximum) of almost 20 degrees. If one compares these results with a simple model in which the gas is distributed smoothly in the Galactic Disk, one would obtain a true thickness of 1 kpc.

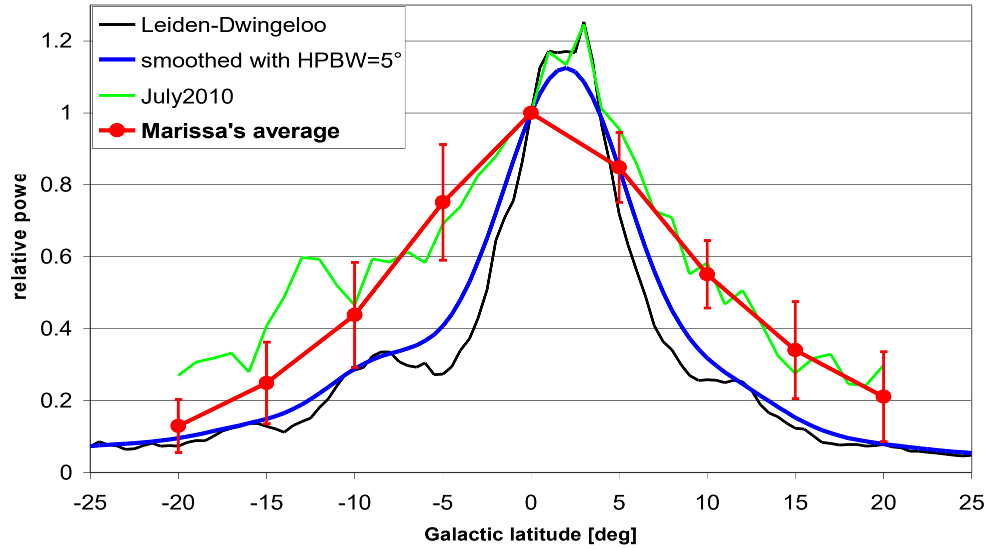


Fig.3: *The vertical profile at 90° Galactic latitude: Marissa's observations, done despite interference, agree well with data taken under interference-free conditions later. However, both give a broader profile than had been obtained by the (professional) 25m diameter Leiden-Dwingeloo telescope – even smoothed to the antenna beam width of ESA-Haystack. This indicates that our background subtraction method calls for further refinement!*

However, this is substantially larger than the value of 0.14 kpc which proper Galactic models use. Should we be disappointed? Certainly not …

- The somewhat limited quality of her data, which are not free from the effects of interference, could not be blamed, as follow-up observations done after suppression of the interference prove
- Instead, the determination and subtraction of the background due to the receiver noise leads to a systematic overestimation of weak signals. This needs improvement!
- But there is another, more fundamental aspect, because professional data also show the rather extended profiles: We are located within a spiral arm and thus we are surrounded by emission extending to high latitudes. This aspect stimulated the follow-up studies described below.

Apart from completing her observational and data reducing work, this personal assignment resulted in

- her comprehensive design of a workshop activity which was offered in the SSP10 physics department
- her presentation of her work and of the telescope during several visits of ISU by high school students from France, Italy, Sweden, and Germany.

2.1 Follow-up studies

After the completion of Marissa's project, the interference problems could be resolved by improved shielding and use of upgraded filters. Since a period of complete absence of any interference effects could be enjoyed, a survey of hydrogen gas in the Milky Way was started. This permitted to separate the emission by local gas from those of other spiral arms, and to address the second aspect of the discrepancy Marissa had found. In that first attempt, we had considered at every position the total emission, integrated over all radial velocities. However, a closer look at the data shows that the emission at zero radial velocity – hence the emission from gas in our close neighbourhood – is present at all latitudes from the Galactic Plane: We are located within a spiral arm and thus we are surrounded in this emission.

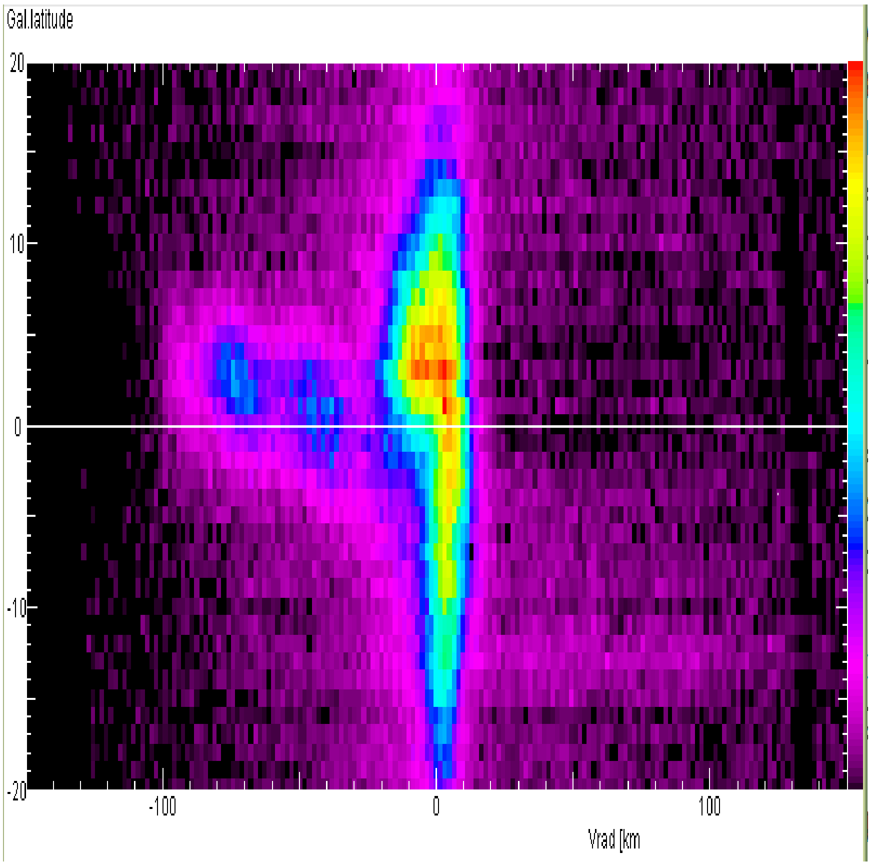


Fig.5a: *False colour map of the data from a vertical cut at 90° Galactic longitude, done by ESA-Haystack. Despite its lower spatial resolution and its poorer system temperature giving a noisier background, the essential features are clearly captured: the emission of the local spiral arm (at zero radial velocity) extends up to latitudes of 20°, and the next outer spiral arms (the two blobs left of the local emission) are above the Galactic Plane: Our Milky Way's disk is warped!*

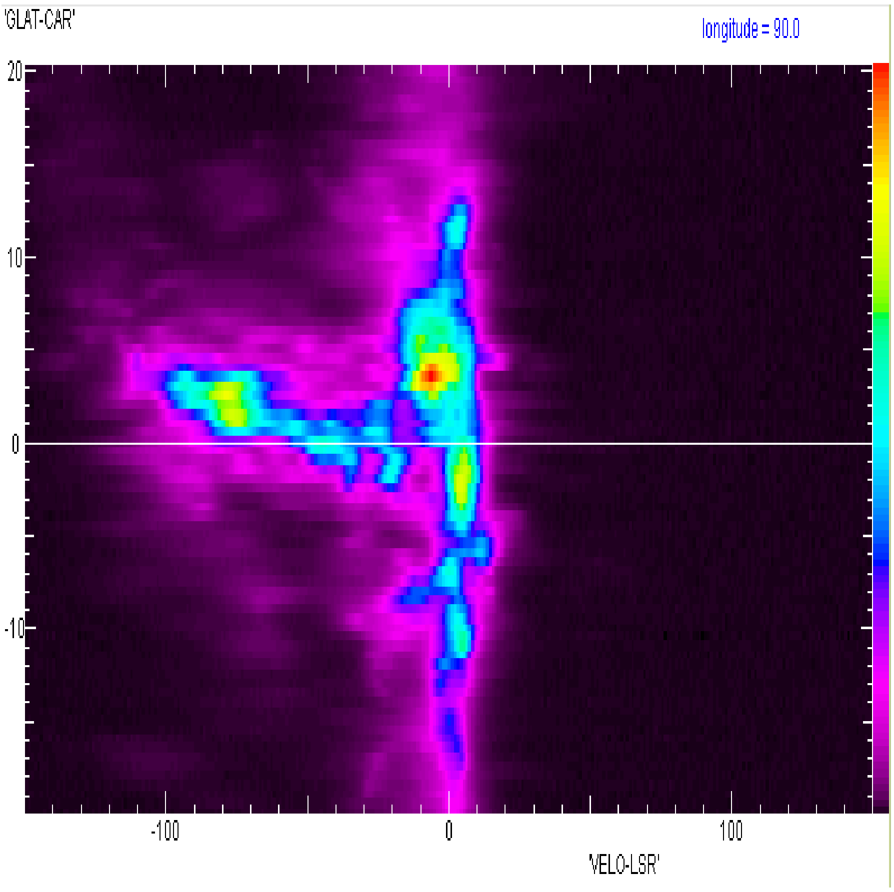


Fig.5b: *The same region as in Fig.5a, but observed with the Leiden-Dwingeloo telescope with ten times better spatial resolution and much cleaner background. It shows the same features, only in greater detail.*

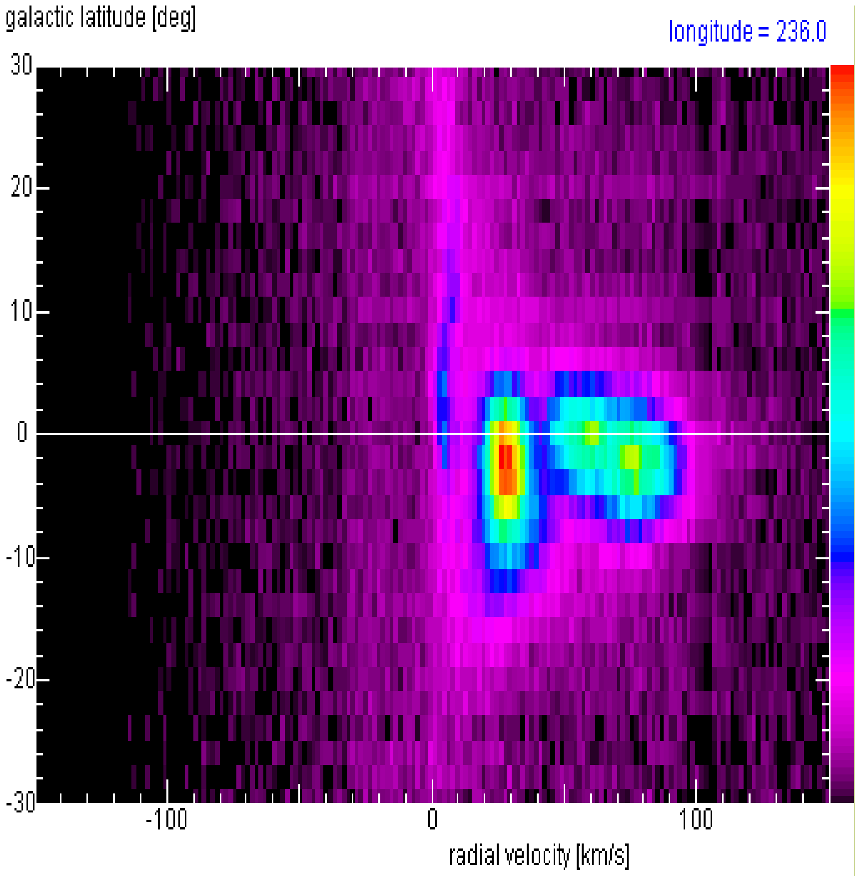


Fig.6a: *The other side of the warp seen with ESA-Haystack: at 236° longitude the outer spiral arms (the two blobs to the right of the strong local emission) show a tendency downwards*

It would be interesting to be able to observe at longitude 270°... This would be possible with an instrument in the southern hemisphere!

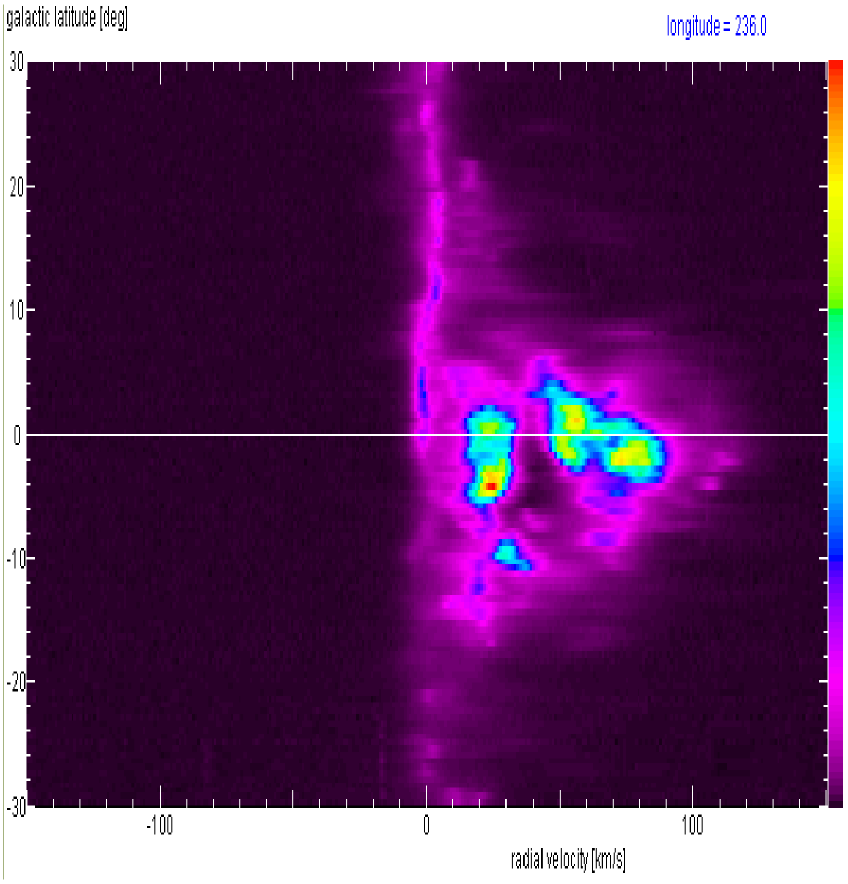


Fig.6b: *Same as Fig. 6a, but obtained with the Leiden-Dwingeloo telescope. Many details are apparent, but the essential features are identical.*

Subsequent improvements have motivated to repeat this survey in summer. By now, all the emission within 30° of the Galactic Plane has been mapped with the same quality, albeit with an unsatisfactorily high system temperature of 900 K. Examples are shown above, in Figs.5a and 6a. Essential findings are

- Spiral arms can be identified. The data are good enough to de-project the observations and construct the true spatial map of the spiral arms in the Plane (cf. Fig.11 below)
- Spiral arms do not stay in the Galactic Plane: there is clear evidence that the Disk is warped and distorted
- As we have the complete data in steps of 2° in longitude and latitude, it would seem feasible to reconstruct the spiral arms in 3D – this will be proposed as a personal assignment for 2011
- The data from the present survey are sufficiently good to serve as observational material for exercises and workshops on (astronomical) data analysis, or on the structure of the Milky Way, at a level suitable for Master2 education in astronomy.
- The survey data may be inspected on the Internet by an interactive JAVA applet at http://astro.u-strasbg.fr/~koppen/ISGH/ .

3. Use during SSP10

In 2010 the summer school (SSP) was held at the ISU's main campus in Strasbourg, thus it offered the use of both telescopes to the students of the Physics Department. In two workshops, the nine participants were given introductions to radio astronomy in general and the two instruments. That all thermal sources – such as human beings – emit radio waves, was demonstrated with a small satellite TV dish. Since the ESA-Dresden telescope requires the observer to be present at the controls and to interact closely, direct observations of the Sun and the Moon were scheduled. At that evening's run for the Moon, however, thick rain clouds assembled in the sky, and gave the students the experience that sometimes even in radio astronomy one is dependent on the weather! At a more favourable time, I secured a few lunar observations.

In another workshop, the students analysed their own dataset or other, previously obtained data. They were given the raw data, and performed all the necessary steps of data reduction, calibration, and interpretation, as any professional observer would have to do. Finally each participant was rewarded with the temperature on the surface of the Sun or the Moon.

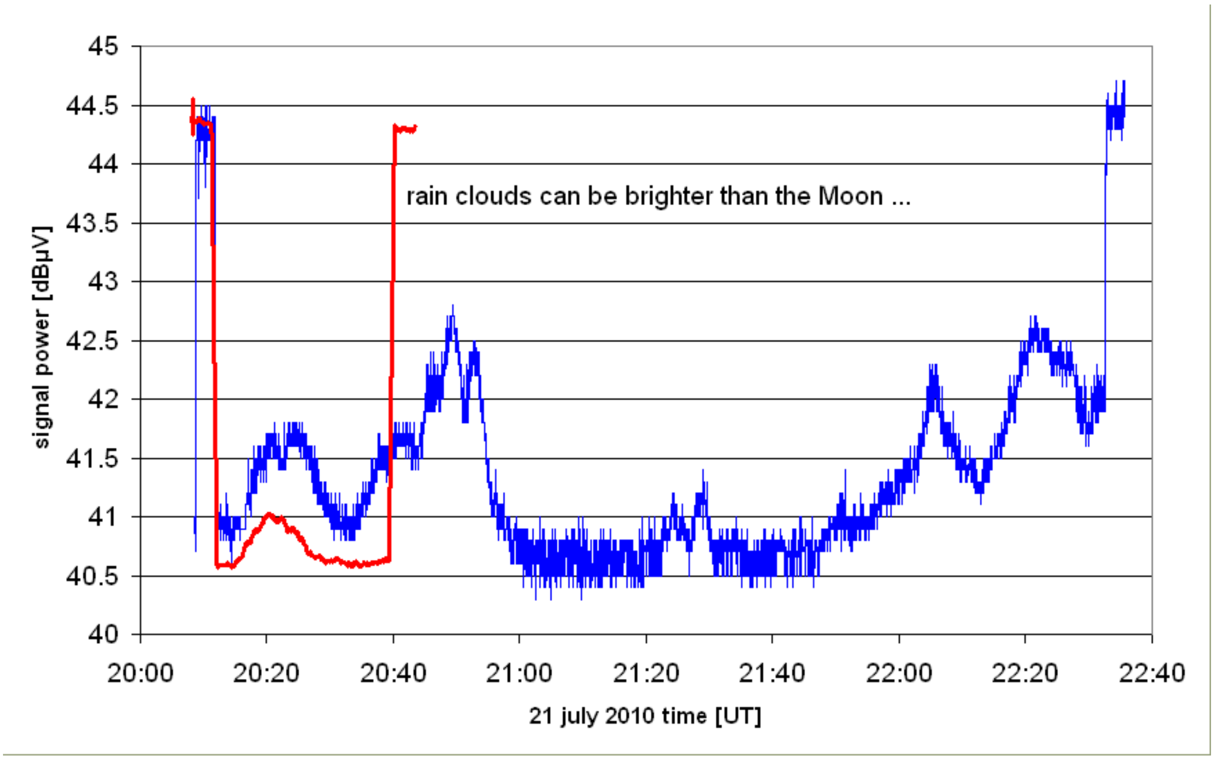


Fig.7: *Our attempt to observe with the ESA-Dresden telescope the Moon on an evening when clouds invaded the sky. The red curve depicts a proper lunar observation under more favourable conditions some days later. In each tracing the parts at a high value of about 44dBµV are the flux calibration measurements.*

Since the ESA-Haystack telescope allows batch operations, it was run continuously during the departmental time, observing the Galactic Plane and also taking profiles perpendicular to the Plane. This was also necessary, since in summer the inner part of the Milky Way is only observable late at night! Nonetheless, one student team took observations of the inner part of the Plane one evening. Another student took measurements of the Sun.

In a further workshop the students reduced either their data or the data chosen from what the telescope had executed. Because of the more complex nature of the spectrometric data, the rather limited available time during this summer school did not permit to treat all aspects of a detailed analysis. The team who had done their own observations successfully determined the rotation curve of the Milky Way and confirmed its flat shape, which is the indicator for the presence of Dark Matter. Furthermore, the temperature of the Sun seen at 1420 MHz turned out to be ten times higher than the one deduced from 11 GHz, which shows the temperature increase to the corona. All other participants analysed data from the Galactic Plane, so that despite the restraint by the short time, everyone came up with results that were worth to be looked at, to be discussed, and to be further explained!

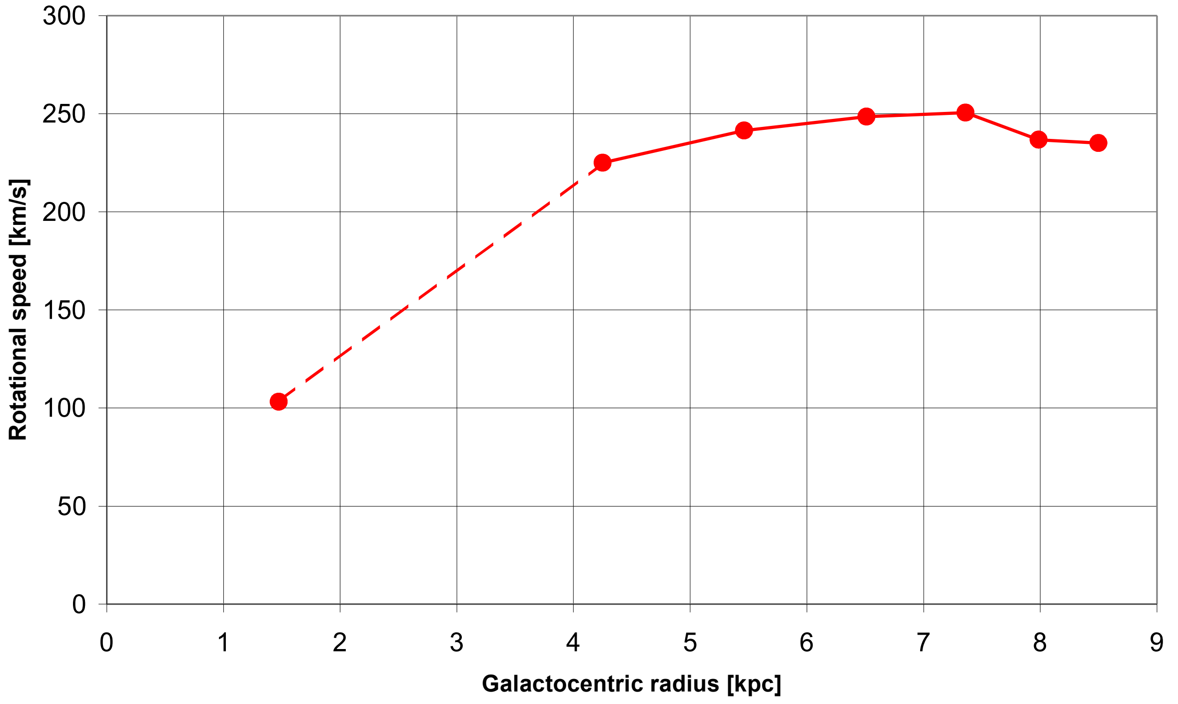


Fig.8: *The rotation curve of the Milky Way, from observations by Jagruti Pankhania and Konstaninos Kaskavelis, similar to those shown in Fig.2. The innermost datum is not representative for the Galactic Disk, because its measurement is already affected by the emission from the Galactic Centre, which has its own particular gas kinematics.*

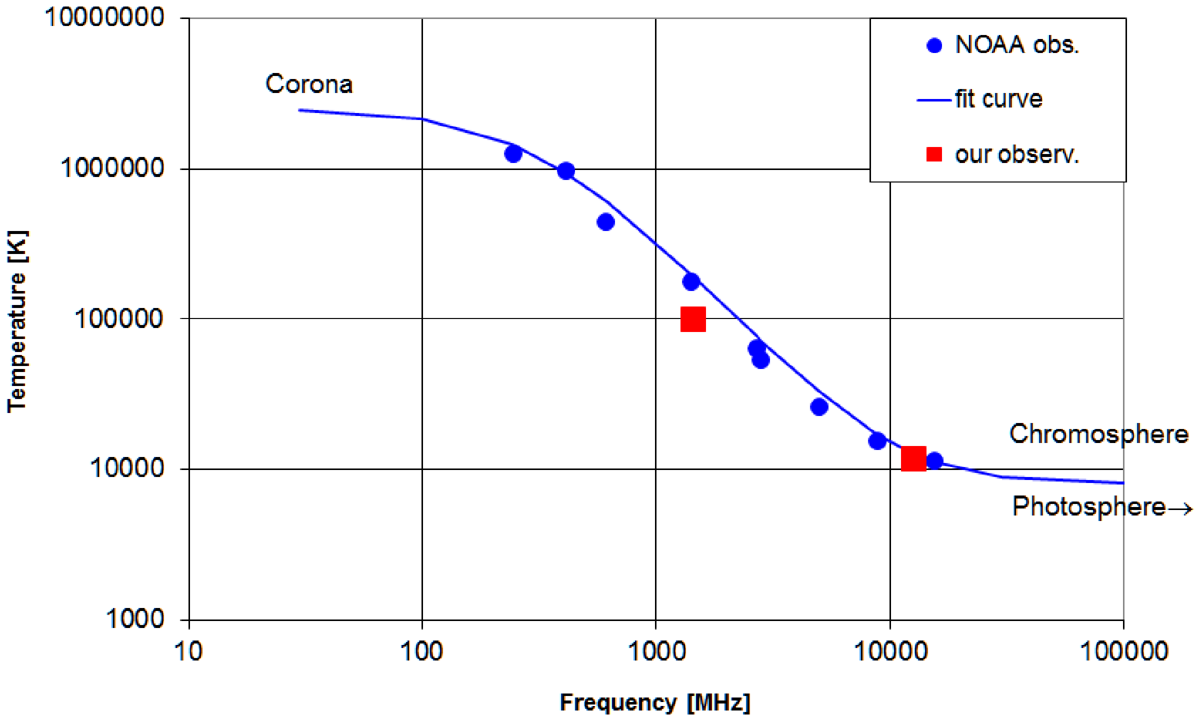


Fig.9: *The run of temperature in the outer solar atmosphere: G.Regikumar observed the Sun with ESA-Haystack (left red square) and ESA-Dresden (right). His results, which show directly the increase towards the corona, are in good agreement with the measurements by professional solar observatories taken at the same day.*

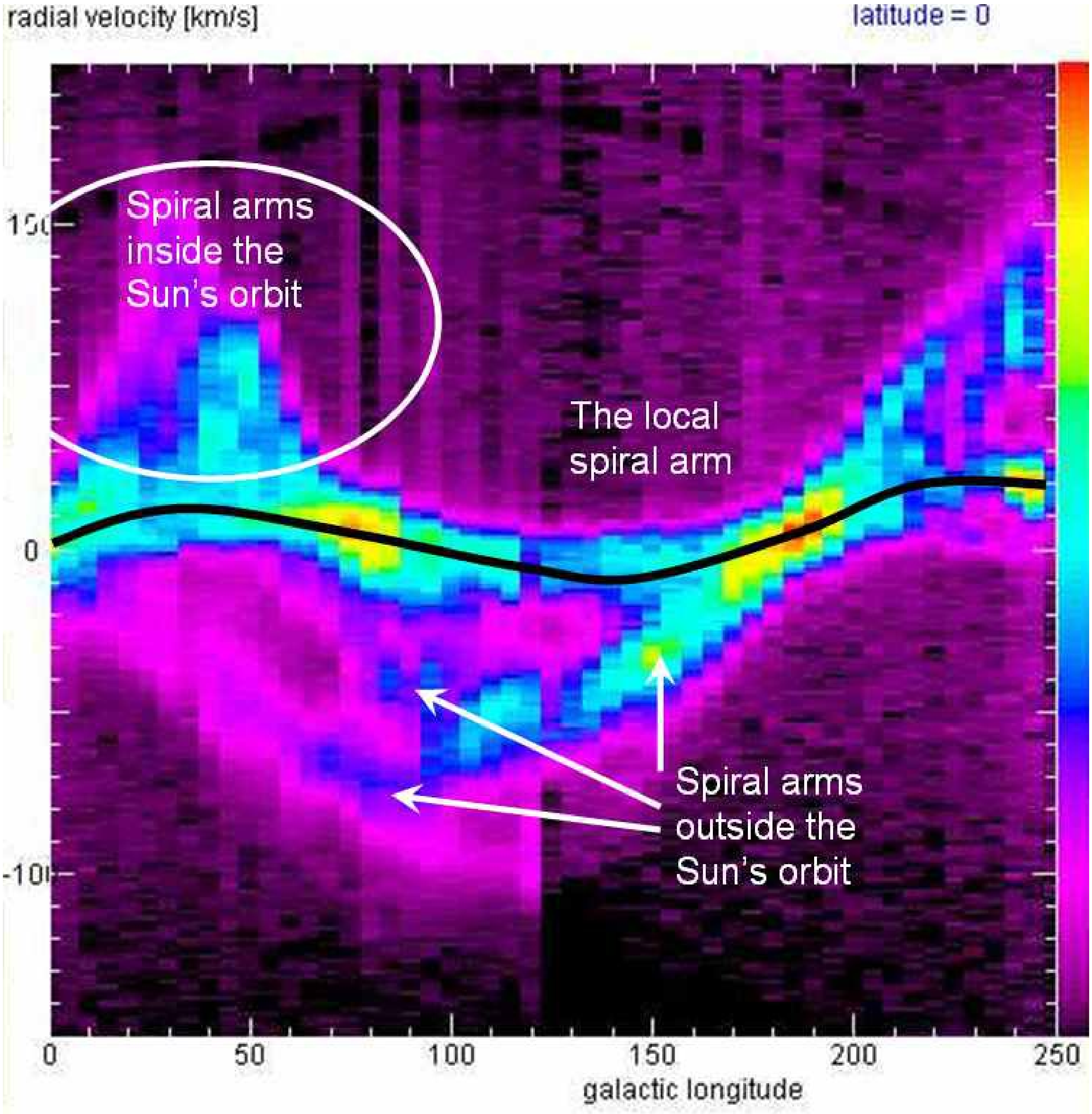


Fig.10: *During one entire day in SSP10 the Galactic Plane was observed. From the Northern Hemisphere, we can cover about three quarters. The hydrogen emission can be seen being organized in separate features, such as the local spiral arm, and the arms inside and outside the Sun's orbit around the Galactic Centre.*

Fig.11: *Deprojection of the observed data allows production of a view onto the Galactic Plane, with the Sun and its orbit about the Centre. A number of spiral arms of hydrogen gas can be distinguished. However, these arms are not simple, neat spirals … as had been found by the first professional studies 50 years ago …*

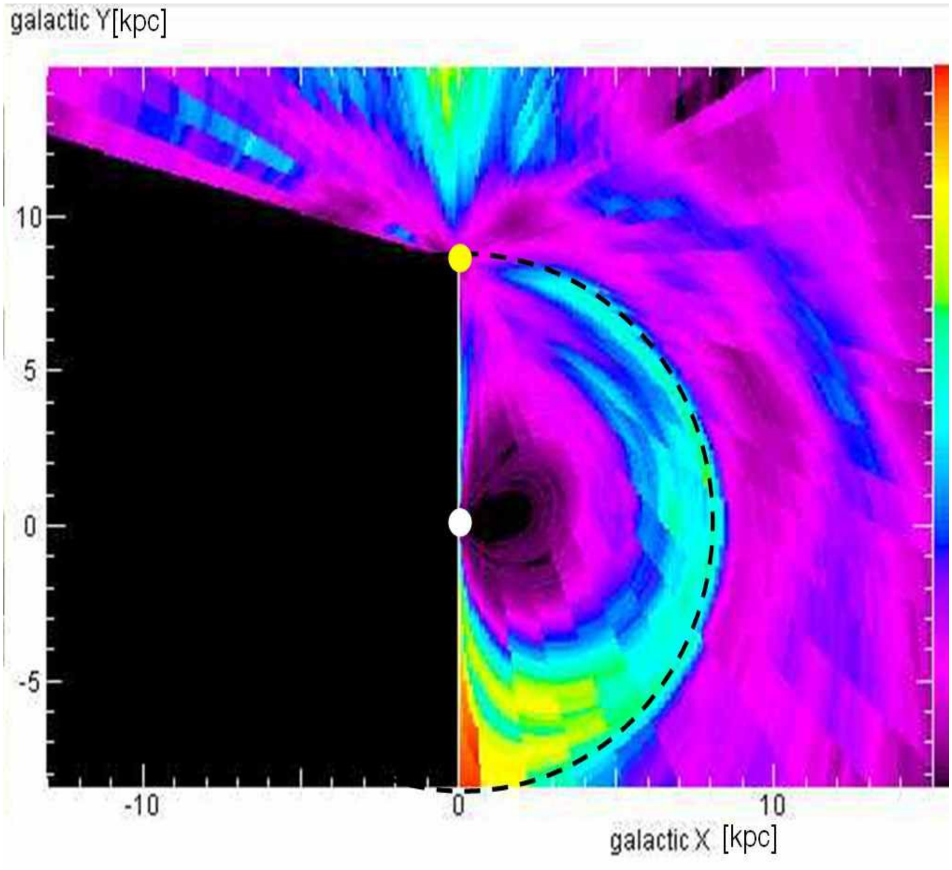
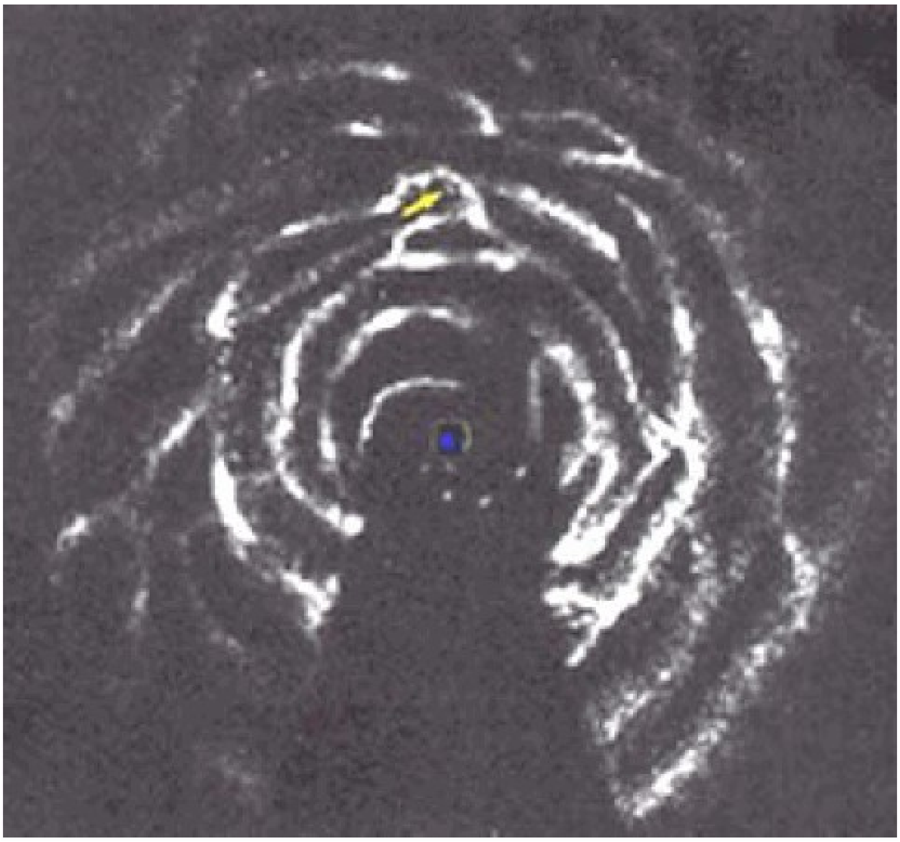


Fig.12: *View of the spiral arms of the Milky Way, obtained in the 1960s by Dutch and Australian radio astronomers. The prominent outer spiral arm on the right hand side forks into two branches at lower right – just as is clearly evident in the ESA-Haystack data depicted in Fig.11.*

Note that the region towards the Galactic Centre is not shown here because of confusion problems.



4. Relation to the ESA-Dresden telescope

The ESA-Dresden telescope complements the Haystack instrument:

- As it measures only the intensity of the radiation, its functionality is easier to understand by a beginner, and thus it serves well as an introduction to radio astronomy.
- It operates on a higher frequency – 11 GHz – at which solar radiation comes from the cooler layers, just below the corona. Hence combining observations of the two instruments gives direct evidence of the temperature structure of the outer solar atmosphere (Fig.9).
- Despite its smaller size, it is able to pick up radiation from the Moon, which is beyond the reach of the ESA-Haystack. This faint source provides an excellent example for the treatment of weak signals.

Since its installation in 2006, ESA-Dresden had been used in personal assignment work: by 3 students in 2006, three in 2007, and one in 2008. Data secured with this instrument has been used in data analysis workshops in SSP08, Masters08, SSP09, Masters09, and will be used in Masters10. In addition, three topics will be proposed for personal assignment projects.

5. Experiences

We may summarize our impressions from the Masters and SSP programs:

- **ESA-Dresden is the ideal instrument for the beginner,** as its working and the meaning of the results are clear and easy to grasp.
    - It is primarily a radiometer, i.e. to measure absolute fluxes. It can observe the Sun, the Moon, and TV satellites. It may be employed to take spectra, but there is no astrophysically relevant line observable in that frequency range.
    - The limited accuracy and stability of the positioning system requires the presence of and direct control by the observer. It rules out any operation in batch mode or by remote control.
    - One person is quite enough to operate it, in a team of two there is always one who has to remain inactive.
    - After an initial brief demonstration with a small satellite TV dish that all thermal bodies emit radio radiation, it is straightforward to use this instrument.
    - For a complete solar drift scan one needs about 30 minutes, hence actual observations cannot be done as a class-room activity.
    - In the SSP workshops, the instructor was always present. But once the participants because familiar with the instrument, only casual assistance was needed.
    - As had been experienced in previous personal assignments, this is a very good instrument for project work, and it is suitable for non-science individuals, provided they are interested in the measurements.

- **ESA-Haystack and its data require a deeper understanding,**
    - It is primarily a spectrometer, i.e. to measure the radial velocities of hydrogen gas in the Milky Way. It can also observe the Sun. At the present time, nothing else is accessible from our site, such as the Andromeda galaxy. It can also furnish calibrated fluxes (to be developed).
    - The stable and reliable positioning system allows faultless programmable operations. This was an enormous advantage for the summer school, as the entire Galactic Plane could be observed during one full day, even during class hours and night time. Likewise, it makes it easy to conduct systematic observations of selected sources
    - Ideally, it is operated by an individual or by small teams of two and maybe three persons. For the SSP students there was always an instructor present.
    - The seemingly complicated kinematics in the rotating disk of our Galaxy needs quite a bit of explanatory preparations! Nonetheless even within the restricted time frame of a summer school, it proved possible that everyone can take something home … provided that the number of participants is sufficiently small, so that there is enough opportunity to discuss and explain with every one.
    - The output of the telescope is more complex than from ESA-Dresden, because of the spectral information. This requires proper explanation of the file format and how to analyze the data, as well as it demands a greater effort by the students. In the summer school, we concentrated on the kinematical information, thus it was not necessary to perform a careful subtraction of the background. During project work of a longer duration this can be addressed and therefore the participant can also make quantitative use of the recorded intensities (such as in Marissa's project)
    - Students can easily write their own batch files, if they have e.g. one entire week to work with this telescope. In view of the tight schedule, we did not use this option at SSP.
    - The instrument is best used in projects work lasting at least one or two weeks. Operations for demonstration are possible, but as reliable data are only obtained by accumulation over many data sets, it is better employed in batch mode. The main target is the hydrogen gas in the Milky Way. This offers a variety of challenging questions of how to interpret the data and its fine structure. Since this instrument still is in its 'commissioning' phase, there is also the desire to improve the performance and make it possible to detect weaker sources!

6. Current plans

Based on the presently achievable performance of the telescope and the results so far obtained, the following developments are foreseen:

6.1 Technical

- The present system temperature – a measure of sensitivity – is about 900 K, which is still substantially higher than the 200 K one should expect from the technical data of the preamplifier. It is necessary to identify the reason, and hopefully to take measures to bring the system temperature down to more acceptable values.

- Construction and development of a sensitive but more interference-immune front-end for 1420 MHz. This is already in progress. The objective would be to reach a system temperature of 200 K.
- Construction of a front-end for the 1666 MHz lines of the OH molecule, whose emission would be detectable in maser sources around late-type stars.
- Installation of a satellite TV front-end in the focus of the dish. This would permit lunar observations with substantially better quality than with the smaller ESA-Dresden instrument.
- Development of client-server software to allow remote-control operations via the Internet

6.2 Educational

- For the coming Masters10 program, three topics will be proposed for personal assignment projects, and available data will be used in optional workshops offered.
- From the Northern Hemisphere one can observe about two-thirds of the Galactic Plane. Astronomical institutes in the Southern Hemisphere which operate the same type of telescope for student training, have already been contacted for exchange of data and developing collaborations
- Develop specific observational exercises for students at various levels – from beginner and non-science students to astronomy students.
- In the long run, the telescope(s) will be made available to the other educational institutions in Strasbourg, in particular to the Astronomical Observatory (for the students in their Master2 program)

7. Available resources

On this website

https://portia.astrophysik.uni-kiel.de/~koeppen/Haystack/index.html

we have collected all relevant material for the operation of the ESA-Haystack telescope. Here, instructions for the use of the instrument, descriptions of observational projects and the necessary data reduction, and the results obtained with the telescope can be found. A fully functional simulation, very similar to the telescope software, accessible on the internet, allows a student to learn how to operate the instrument by performing simulated observations:

https://portia.astrophysik.uni-kiel.de/~koeppen/JS/RSM/ESAdresden.html

Furthermore, the results of the Illkirch Survey of Galactic Hydrogen can be inspected interactively at

https://portia.astrophysik.uni-kiel.de/~koeppen/JS/FITSviewerISGH5.html