Using Small Radio Telescopes for Very Long Baseline Interferometry

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Abstract: Throughout the summer development has continued on the next generation of the Small Radio Telescope for use as a Very Long Baseline Interferometry type interferometer. This paper discusses the difficulties with setting up this new interferometer and presents some results obtained using this small radio telescope interferometer. We used 3 small radio telescopes to form one baseline of about 5 meters and two long baselines of about 1.4 kilometers. We observed consistent strong fringes on the Sun using the short baseline and an occasional "microburst" on the long baseline. The extragalactic source Cygnus A was observed on the long baselines and a double source model was fit to the data. These test observations were carried out while developing software to make VLBI observations with the small radio telescopes easier.

Introduction

This summer we tested the newly completed small radio telescope interferometer. This system uses VLBI-type interferometry where the two systems are not connected by cables.

The goal for this summer initially was to develop some software for use with this interferometer and to take some sample data to see what was possible with the new setup. Throughout the summer we met and exceeded these goals.

We started by recording some data using the two previously completed small radio telescopes. During this time we proceeded with the production of a third small radio telescope unit. The initial short baseline tests proved that the small radio telescope interferometer worked. After overcoming several hurdles, the third unit worked and allowed us to continue data acquisition with a very narrow 3 element array. We used the three element array to look at Cygnus A and the Sun.

Building the new unit

At the outset, we expected the creation of the new small radio telescope unit to be a simple task. Computer equipment thought to have the same specifications as the original small radio telescope was purchased. The first attempt at setting up the new unit involved simply cloning the previous small radio telescope's hard disk. After cloning, we discovered that the new hardware was slightly different from the older hardware and therefore would not run the cloned system.

Next, we attempted to perform a fresh install of a new Linux distribution. The original small radio telescope runs Linux Kernel 2.4. The new distribution runs Kernel 2.6. At first glance, this upgrade was not expected to be a problem. After finally getting the system up and running with the 2.6 Kernel, we discovered that the small radio telescope software would not work properly.

After the software discovery, two parallel attempts to get the new small radio telescope unit working progressed. One attempted progression involved attempting to install a 2.4 Kernel with the appropriate functionality for the new motherboard. This attempt ultimately proved unfruitful. The second attempt involved debugging what was happening with the 2.6 Kernel to fix the software. After a week of various tests and debugging of code, we discovered that the 2.6 Kernel updated the USB interface and so the system behaved exactly as designed; however, our code did not quite work with this update.

The basic problem with the newly renovated USB interface in the 2.6 Linux Kernel involves how the software communicates over the USB port. In the old system, one could open and close the software interface at will with no ill effects. In the new system, the Kernel sends a USB control command out to the device if the software interface is opened or closed. The hardware controller we used did not have code designed to accommodate these extra control commands. Also, the Kernel did not properly reopen the interface with the code we were using in the small radio telescope software. The final solution for this problem involves changing the small radio telescope control software to simply not release the software interface for the USB device.

After solving this USB problem we continued with routine tests of the small radio telescope control hardware at the Haystack site. Once we were convinced that the new unit functioned properly we moved the unit down to the Westford site 1.4 km away.

VLBI Software Development

Throughout the summer I proceeded with development of software to make usage of the small radio telescopes for VLBI easier. This development process involved researching many functions for use in C. Many staff members at Haystack helped out in figuring out how to perform my unique tasks.

The beginning of development required simply understanding all the steps required to perform VLBI with two dishes. Before writing any code I walked through the steps required to perform recordings and processing. After following my own directions step by step several times to obtain results, I set out to carry out the entire process with a single C program.

Performing the required tasks in C did prove to be a challenge, but I overcame each setback one step at a time. The most challenging task proved to be getting multiple small radio telescopes running at the same time when started from one program. From the start I needed to learn about system calls where the C program allows the underlying operating system to perform the command passed to the system call. The underlying system is the only manner C provides for communicating with other computers unless one undertakes the task of rewriting network communication.

To run the small radio telescope with a command file requires writing a command file and getting the command file onto the small radio telescope's computer. In a similar manner, to use a catalog file requires modification of a catalog file as well as copying the file. System calls to the "scp" program adequately transfer the files. Repeated calls for the various small radio telescopes allows sequential transfers of the appropriate files as long as the command string is dynamically created for each small radio telescope. Almost all commands used to transfer files or begin executions on the remote system involve dynamic creation of the command on the local machine.

After learning to copy files in a sequential manner, I needed to start execution of the control software nearly simultaneously. After various discussions about how to accomplish this simultaneity I decided that "ssh" would be the appropriate solution. Using the ssh command with the appropriate options allows one to connect to a remote system and execute a single command on that system. After starting the ssh connection, the original program regains control while the ssh command completes executing in the background.

Once all of the pieces above are put together, the only remaining task is data retrieval before the local processing of data. Initially, “scp” seemed to be a logical choice for the data retrieval; however, one quickly realizes that copying more files than needed will be a burden on the network and will take a lot of extra time given that the data files are created at a rate of approximately 1 Megabyte per second. After a little digging by some dedicated computer staff, the “rsync” command came to my attention. This command will only copy files according to a certain criteria that are not already in the local destination folder.

With all the data files now on the processing computer, one can proceed with analysis. Alan wrote the bulk of the processing function used by the VLBI software. Over the course of the summer this processing function has received only minor modifications to accommodate adding more information to the final output and to allow integration for extended periods of time. While processing, the program performs a cross correlation by testing every possible delay to find the best correlation amplitude. The best resulting correlation amplitude, delay, and phase information is recorded to an output file.

Results

Over the course of the summer we examined two major sources in the sky, the Sun and Cygnus A. Our initial tests looked at the Sun using a five meter baseline. With this short baseline we proved that the interferometer worked; however, not much information could be gained from this test because the fringe spacing is larger than the Sun.

Cygnus A

Once the third small radio telescope unit was completed we started looking at Cygnus A using a 1.4 km baseline. While looking at Cygnus A we hoped to be able to resolve the two lobes. After a few days of only being able to obtain a couple hours of data due to the placement of the small radio telescope, we adjusted placement of the antenna so that we could obtain five or more hours of data to use for correlation. After building confidence in the data obtained for Cygnus, we performed a Monte Carlo Least Squares Fit on the data. During this fitting process we searched over right ascension, declination, and relative strength. After running some of our data through the fitting algorithm and doing some

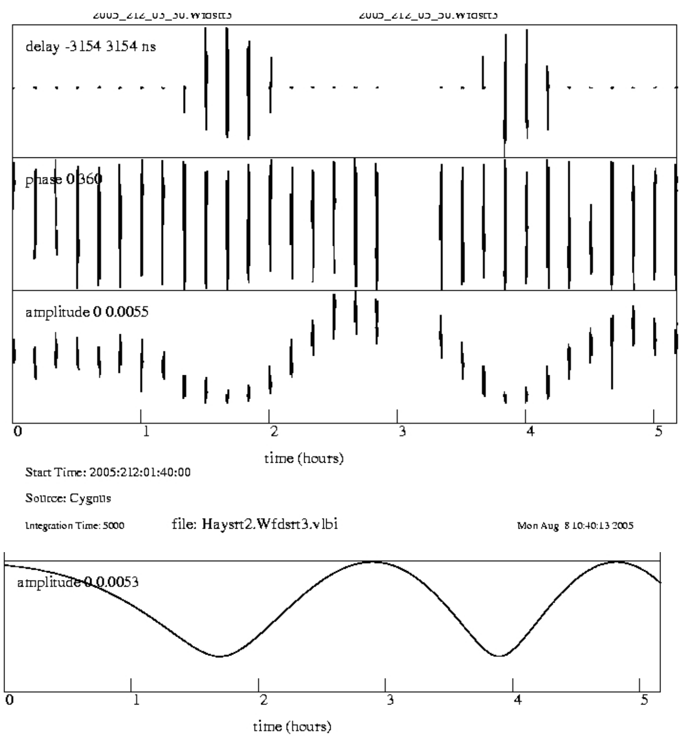

Figure 1 Cygnus Data (top) from day 212. Top graph is delay as computed by the cross correlation function. Middle graph is phase. Phase cannot be used for useful information because of a problem with the system (probably GPS related). 3rd graph shows the amplitude returned by the cross correlation. Cygnus Simulation results (bottom) shows the correlation amplitude expected for the best fit parameters.

calculations to figure out what our error level should be, we conclude that while we have identified Cygnus, our error is larger than expected for position. Also, through identifying what our expected error level is we have decided that the relative strength cannot be accurately determined using this interferometer.

Parameter	***Expected Value***	***Expected Error***	***Data Value***	***Data Error***
Right Ascension	10 seconds	±1 sec	8.7 seconds	±3 sec
Declination	1 minute	±0.25 minutes	0.0625 minutes	±1 minute

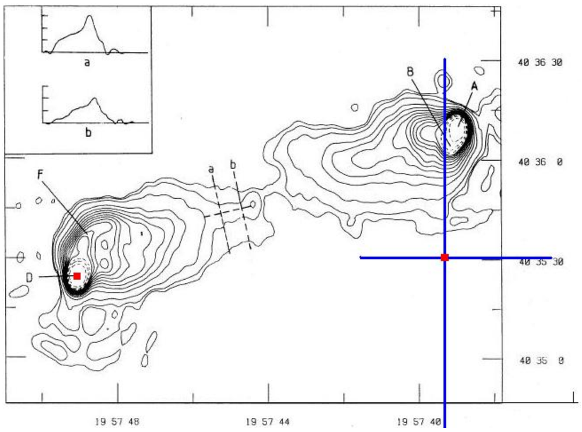

Figure 2 Cygnus A 2.4 GHz Map from Alexander et al 1984 with overlay representing results from SRT interferometer. Red dot on left indicates arbitrary origin. Blue lines represent error bars as listed above

Overall, Cygnus appeared and behaved as expected. With the ability to vary baselines one could theoretically map out Cygnus at 1.4 GHz. We could also only use 5 seconds of integration because of our problems with phase wrapping. With more than 5 seconds of integration I believe that far more accurate position results can be obtained. After correcting phase wrapping so that longer integration times can be used, other weaker radio sources will be viable candidates for study with the small radio telescope interferometer.

Sun

In addition to observing Cygnus overnight, we observed the Sun during the day. Originally, we thought that the small radio telescope interferometer could be used to identify the location of sunspots on the disk of the Sun. While we have not completely ruled out this possibility, we did not accomplish this particular task this summer. Instead of identifying sunspots, we found other solar phenomena that we did not originally anticipate.

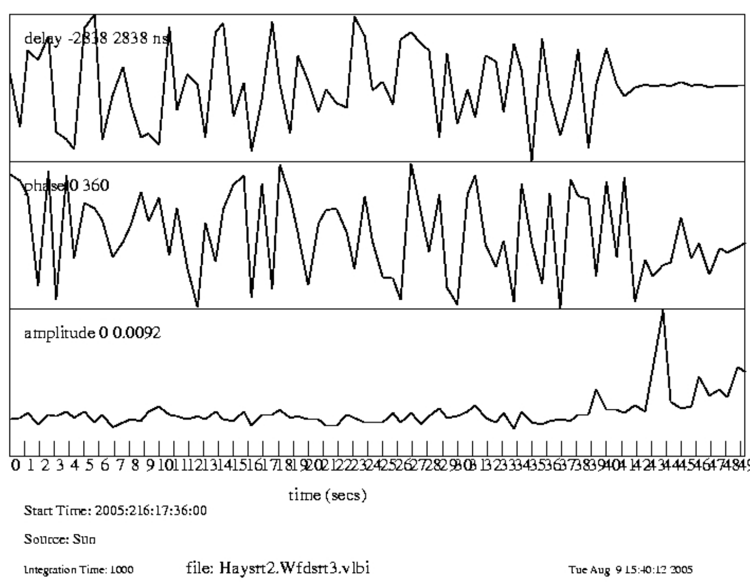

Figure 3 Sample "microburst". At the right end of the plot delay goes to nearly zero indicative of a detected signal. In the bottom graph one can see the strong spike and the surrounding raised amplitude.

According to the research we have done so far, the Sun is not widely studied in the 1 to 2 GHz frequency band. We have found a couple

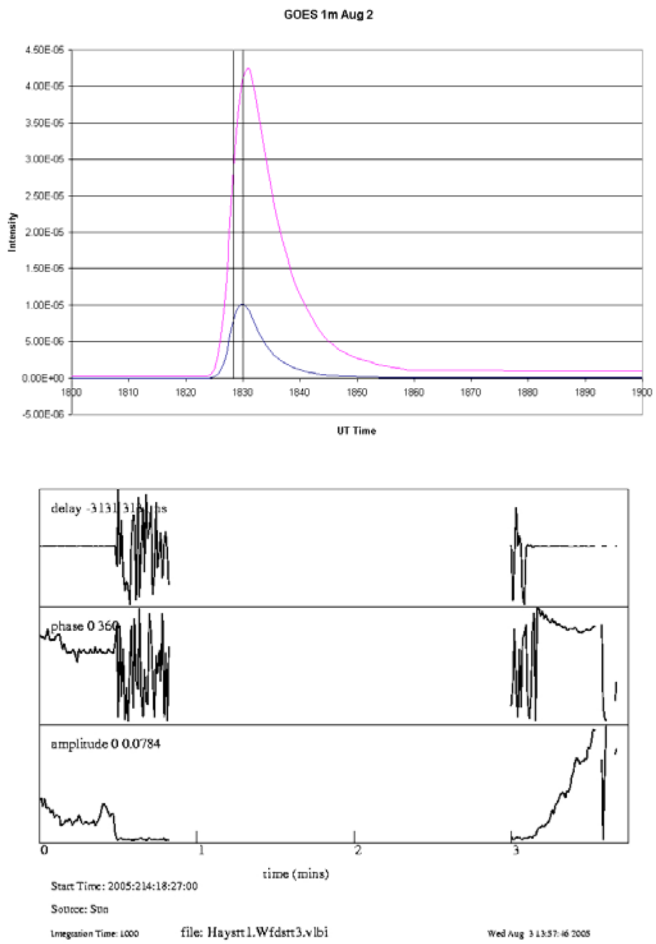

Figure 4 (Top) Hard X Ray data from the GOES Satellite. The vertical bars correspond to the times of the two segments in the bottom correlation data. (Bottom) Two bursts (end of one, beginning of next) that correspond to Hard X Ray activity on the Sun.

references to "microbursts" that could occur in this band, but aside from that, we cannot find other past research to confirm anything we might be identifying. With that said, we move on to the findings.

On July 8, Alan noticed a section of one of the recordings that produced strong correlation with more that three times the correlation amplitude of what we had been seeing on the Sun with the long baseline. This correlation equates to several spikes with lengths of a few seconds. Microbursts are the best explanation for these bursts that we have been able to find. The literature we have found describing microbursts came from the early 1990's when the VLA was used to look at the Sun (Bastian, 1991). Bastian used integration time of ten seconds and found activity that lasted a few tens of seconds. Our initial activity on July 8 could fit into this category; however, we have used integration of 1 second and therefore have a much more accurate picture of what is going on.

In the weeks since that first observation we have found other short and long bursts. When there have been active regions on the Sun facing Earth, we have found many very short duration peaks that last for only a couple seconds. Some of these very short bursts correlate with radio flares on the Sun. Other bursts do not seem to be associated with any particular activity.

Of greater interest are the longer periods of activity we have identified. To date we have found approximately half a dozen of these longer bursts. These longer bursts do not correspond to any radio activity from the Sun; however, this activity does seem to have some connection to hard X ray activity on the Sun. We have continued to look for explanations and previous studies about connections between 1.4 GHz events and hard X ray events but have found few results. We have matched up several of these events with 1 minute data from the GOES Satellite, but one minute resolution is not accurate enough to draw any highly significant conclusions about our findings (see Figure 4). So far it appears that these radio events are occurring before the peak of the hard X ray event, which is surprising because if this radio activity was caused by the same event that caused the X ray activity we expect that the lower frequency signal would occur a tiny bit later than the higher frequency X ray event.

According to Bastian, Benz, and Gary, there may be an explanation for the unexpected ordering of events. They reference some past studies that connect type III Radio bursts to Hard X Ray bursts; however, what we are seeing may not be caused by the same mechanism that causes lower frequency plasma dependent bursts. Additionally, they discuss the possibility of bidirectional electron beams causing a high and low frequency event at the same time or the possibility of an electron beam changing directions to cause a radio and hard X ray event (Bastian, Benz, and Gary, 1998). All in all, Bastian, Benz, and Gary conclude that comprehensive analysis needs to be done to better understand what is happening. We may have an opportunity to perform some of this analysis with very high time resolution using the small radio telescope interferometer.

Conclusion

During the course of the summer we met and exceeded our goals for the small radio telescope interferometer. We looked at Cygnus A and determined that the interferometer is capable of resolving the two lobes. We looked at the Sun with the anticipation of resolving a sunspot, but instead found microbursts or some other kind of solar activity.

We attempted to identify what exactly causes the solar activity. Few people have studied the Sun at 1.4 GHz and therefore we could not find well documented explanations. We believe that this activity could be to date unstudied. We hope to continue to study this solar activity in the future to identify the cause of the activity and to connect the activity to other bursts on the Sun.

With a multi-element array of small radio telescopes, the possibilities abound. This summer we have proven that the small radio telescope interferometer works and that there exists much science that can be studied with a small radio telescope interferometer. Even more exciting are the potential for studying previously unexplored aspects of the Sun and maybe other sources as well.

Works Cited

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