An introduction to SIDI,
the simple digital interferometer

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ABSTRACT: The ERAC (European Radio Astronomy Club) has a project to build an amateur VLBI system called ALLBIN [1]. I found it interesting, and decided to try to contribute something. It seemed to me, that a simple working digital interferometer wold be the best, since it could serve as a base for further developments, and a testbed for different ideas. This paper is a short description of what I have done so far, and the results obtained with the first versions, for now working in the connected (non-VLBI) mode.

1. Why simple?

While it is perfectly OK to strive for lofty goals, when trying to reach them too fast and directly, one can easily get frustrated by some high hurdle on the way, or the fact that after a lot of work, the results are still elusive.
If you are doing something as an amateur (= for the fun of it), it should better be fun all along the way. So it is important to get some results early, which will give you the motivation to improve and upgrade. I am quite sure, that the Wright brothers DID dream about flying 500 people half way around the globe. But they did not start by trying to collect the parts for an A380 - rather they took a few planks and wires and built a gizmo that just barely got off the ground. But what is most important, it DID get off the ground, and what followed we all know!
Incidentally, the first versions of SIDI have almost identical technical characteristics (sampling at a few hundred kHz with one bit) as the first professional digital VLBI system in 1967 [2]!
Most importantly, SIDI is modular, so the evolutionary path to a more complex system is fully open. Improvements can be made step by step, keeping it functional all the while.
And last but not least, being simple and cheap will make it accessible to more people.

2. Why digital?

In the 21st century it is probably not necessary to explain the advantages of going digital, but because a radio astronomy interferometer is quite an exotic beast, let's look a little deeper into this.
Amateurs have produced excellent results using analog techniques [3],[4]. So what could be the advantages of going digital?
The sensitivity of an radio interferometer depends mostly on its bandwidth. Using simple analog techniques, like the phase switching interferometer, amateurs can easily achieve bandwidths in the hundreds of MHz [5],[6]. In contrast, the current (2007) generation of PC hardware, without expensive add-ons, can achieve bandwidths somewhere in the tens of MHz, an order of magnitude less. This would imply that going digital makes no sense. But this holds only for connected (single site) interferometry, where the signals can be directly brought together and correlated in real time.
In VLBI, the signals have to be recorded for later offline correlation. If we compare the bandwidths of analog and digital recording possibilities, the situation is the other way around. The analog recording technique with the biggest bandwidth, available to amateurs, are analog video recorders. A VHS tape has a little more than 2MHz of bandwidth. Compared to the PC's tens of MHz, the order of magnitude advantage is now on the digital side! Not even mentioning the clumsiness of analog recording, and the fact that digital hardware is getting faster and faster. In contrast, the bandwidth of analog VCRs is going nowhere, and in ten years it will be difficult to even find a working analog VCR!
Another reason for going digital is that in VLBI, many additional processing steps have to be done, like delay equalization, fringe stopping, phase calibration, correlation search... These things are very difficult and expensive with analog circuits, but surprisingly simple when you have the signals in the digital domain.

3. Why interferometer?

Because an interferometer is a great toy, offering countless possibilities for experimentation.

4. So, how does it look like?

The block diagram of a basic two channel SIDI is shown below. As the name suggests, it is very simple. The signals from the antennas are fed to the inputs of two digital satellite TV tuners, which convert them down to complex (I and Q) baseband. These baseband signals are then sent to two simple dual channel limiting IF amplifiers. The limiting is equivalent to an one bit A/D conversion, and removes the need for AGC, keeping everything extremely simple. The outputs of the IF amps go through an digital interface (LPT or USB) into the PC, which does all of the subsequent interferometric processing in software.
An TCXO feeds the synthesizer reference to both tuners, and a simple I2C interface serves for tuner synthesizer programming.
The block diagram is shown below, in fig. 1:

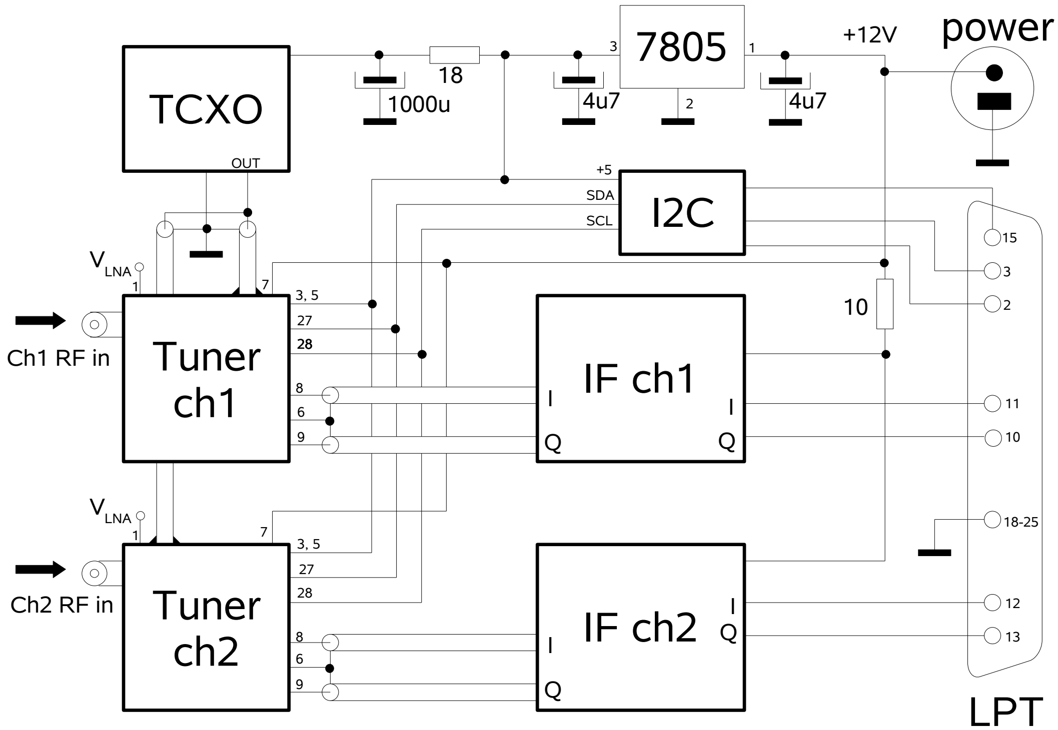

Fig 1. Block diagram of SIDI v1.1 (LPT interface)

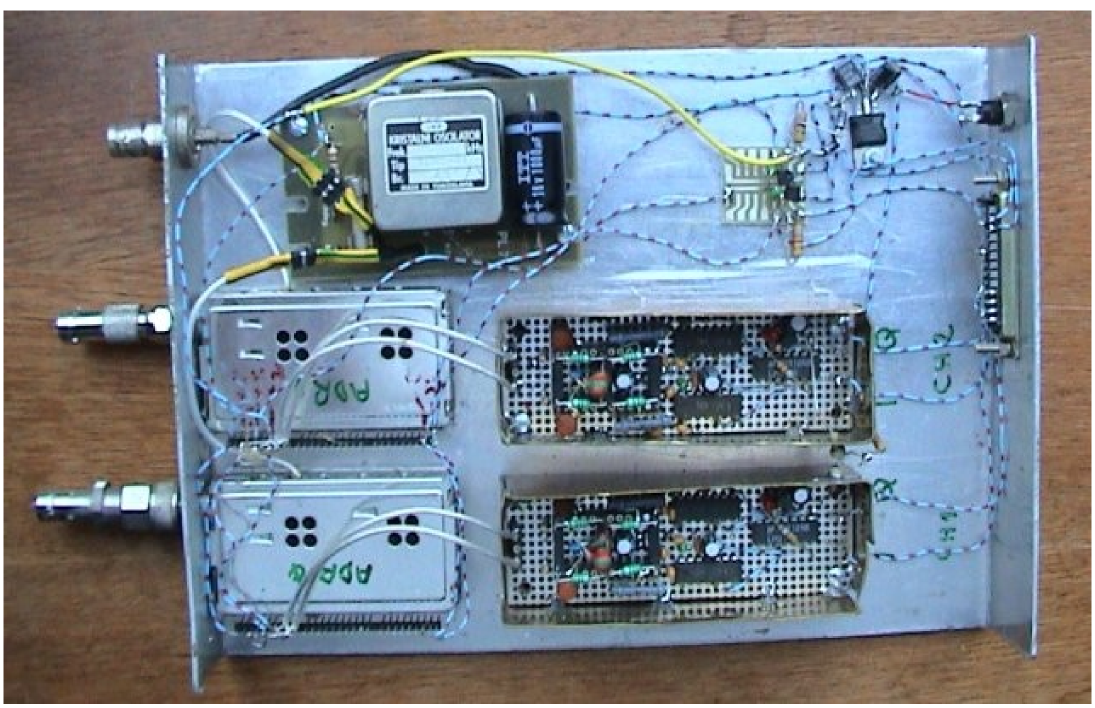

Fig 2. SIDI v1.1 (LPT interface)

5. Single bit A/D

I know that single bit sampling looks like a "brutal oversimplification that will most certainly incur a huge penalty in performance", but it is simply not so. An interferometer designed for below-noise signals is just so much different than any "normal" radio receiver, that a very different set of design criteria has to be used. In realistic radio astronomy situations, single bit sampling can be the optimum in more ways than just in the sense of simplicity!
It all depends on where the bandwidth limit is.

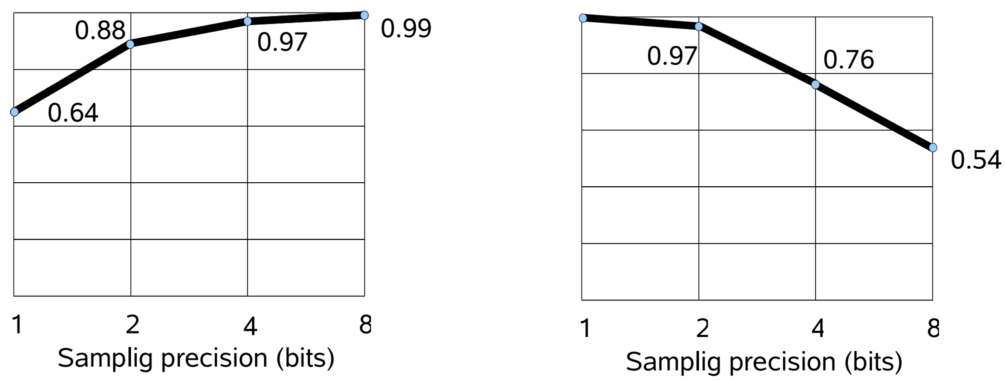

Fig 3. Sensitivity loss Left: bw limited by source Right: bw limited by hardware

The left diagram in fig. 3 shows the situation when the "sky is the limit". That is the situation when the maximum possible bandwidth is determined not by the hardware capabilities, but by external factors, like the available clear spectrum between RFI, especially on 408MHz and below, or when the observed source is inherently narrowband (a spectral line for example).
In that case, we want to pull maximum information from the available bandwidth, so sampling with a higher precision does make some sense. However, sampling with 1 bit gives us 64% of the theoretical sensitivity [7], so the gain of multi bit sampling is not that impressive, considering the simplicity of single bit sampling hardware (no gain control!), and that the lost sensitivity can be reclaimed by longer integration times.
The right hand diagram shows the situation when the sky can provide as much bandwidth as we can swallow, and the limit is our hardware, like the amount of bits per second that the hard disk can continuously record. In that case, the bandwidth we can record is inversely proportional to the number of bits per sample. Because the sensitivity is proportional to the square root of the bandwidth, the sensitivity decreases as we increase the number of bits! Since 0.64 is more than 0.88 divided by sqrt(2) etc., the single bit scheme is the most sensitive.
This is a bit counter intuitive, but the fact is that for low S/N signals, bandwidth is more valuable than sampling precision.

6. The RF part (the receiver)

These days, we are drowning in digital RF stuff (cellular, DVBx, GPS navigation, WIFI, WIMAX, Bluetooth, Zigbee...) so it was easy to find a suitable solution.
For the front end, I decided to use the tuners from digital satellite TV receivers. They cover the 950....2150MHz band, which includes A LOT of interesting frequencies. I found their synthesizers

stable enough, and the direct conversion types are easy to synchronize (only a single LO). Most will require some slight modifications, as described on my webpage.
The IF part of SIDI has to be home made, but it is very simple. Currently I use the ancient TBA120S FM IF chips as the limiters (single bit A/D is essentially a limiting process, keeping just the sign of the signal) and LM319 comparators as TTL converters.
Also under development is a front end for cca 400...450 MHz, which I hope to publish soon.
I have decided against using commercial "general purpose communications receivers", like Icom R7000 and similar, because their lack of bandwidth (in the end, we want at least tens of MHz!). Their complicated multiple conversion schemes would also make VLBI synchronization difficult.

7. The digital part (processing and recording)

There is not really much to choose here - the ubiquitous PC has become so cheap and powerful, that it beats any alternative by a big margin. I did think about DV camcorders for the recording, but came to the conclusion that PC hard disk recording will be simpler and offer a higher performance.
All we must do, is to somehow get the bits into the PC.
Sound cards are very popular with amateurs, but they lack the desired bandwidth by orders of magnitude.
For my first experiments, described below, I have used the parallel (LPT) port. It can give a few hundred kHz of bandwidth, and with the software running under DOS, virtually no additional interfacing hardware is needed, because software loops can do the timing.
This solution, of course, has its problems: relatively low bandwidth, and the severe DOS memory limits.
Therefore, one of the first upgrades of SIDI will be a better interface, which will allow bigger bandwidth, externally controlled sampling clock, and a more comfortable operating system.
I have already developed an USB2 interface board [8], and the sampling circuits are under development. This should give the desired tens of MHz bandwidth.
Once the data is inside the PC, it can easily be recorded, or processed on the fly for single site interferometry, all in software.

8. The software part (some dirty code)

The software is written in plain old C (Borland C for the DOS/LPT versions and GCC (GNU C) for the USB/Linux versions).
It is available in source form on my website. It consists of many programs, some for (hardware) debugging and some for different kinds of interferometric experiments.
Most of the programs are "highly experimental" and not very user friendly. Here I hope for some help! I enjoy writing the DSP part, but the user interfaces kill me...
The correlation is done using a simple fast table lookup algorithm, and the data will be saved in the DataX format, as defined by ERAC [9].

9. The VLBI part (synchronization)

I have not yet realized anything in this direction, so let me just describe the idea, how I plan to try to do my first VLBI experiments with SIDI.

The current ALLBIN station proposal (Fig 4) is to lock all timing & frequency sensitive circuits to a common clock derived from a GPS timing receiver. This requires quite a bit of sophisticated frequency synthesis circuits, which will be relatively costly and difficult to get working by an amateur.
So I was thinking if something could be done along the SIDI guidelines, especially how the complexity could be moved from the hardware into the software.
Looking at how VLBI was done in the beginning (Fig 5) gave me an idea. In the first VLBI experiments, analog tape recorders were used, which have horrible timing errors in the tape transport mechanism. The solution was to record a reference signal along with the source signal. Because they were recorded on the same tape, their relative phase/timing was fixed, so multiple tapes could be exactly synchronized on playback.
The idea is just to replace the tape recorder with a digital recording device (the PC), and use the GPS (or some other satellite) signal as the recorded reference.

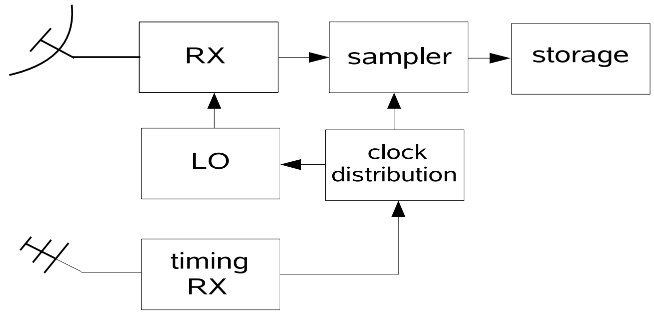

Fig 4. Current ALBIN proposal

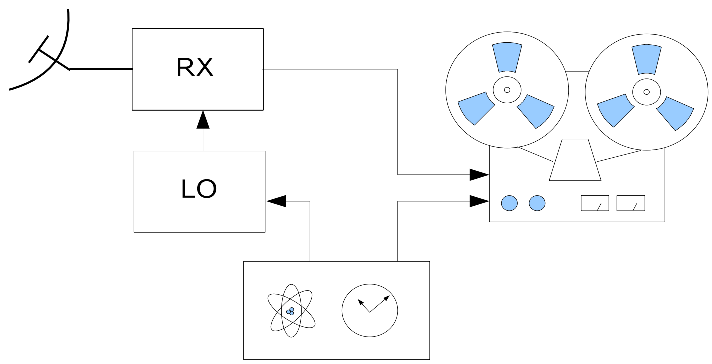

Fig 5. A "Traditional" analog VLBI station

Fig 6 shows the block diagram of such an unlocked digital VLBI station. It is virtually identical to the basic two channel SIDI receiver! The second channel simply records the whole GPS bandwidth (cca 1MHz), which contains signals from all the visible satellites, from a small GPS antenna.
On playback, the recorded reference can be used to decode the GPS signals in software, to determine the phase/frequency/time offsets of the free-running oscillators in the SIDI receivers and correct for them. (Fig 7).
With this scheme, each station would be extremely simple - a basic SIDI receiver, whose components cost less than 200 euro, and requires almost no RF skills to build.

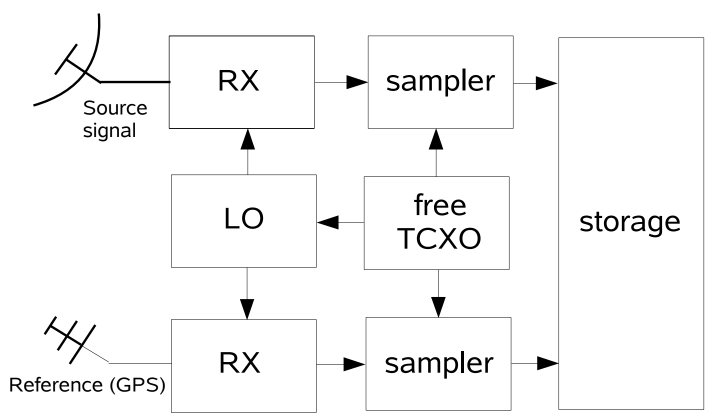

Fig 6. A free running SIDI based VLBI station

All of the complex stuff is carried out in software, and even that software needs only to be run at the central correlation station. On the other hand, anybody interested in doing the complex stuff only needs to download the "central station" software, so this solution has a lot of potential for decentralized processing, etc.
Joint operation of such stations with the traditional locked stations is possible too, all that is needed is adequate "central station" software.
Some other advantages are:

- much simpler hardware
- common view GPS possible
- can use other sats than GPS
- precise historic GPS ephemeris can be used
- backwards in time GPS processing is possible

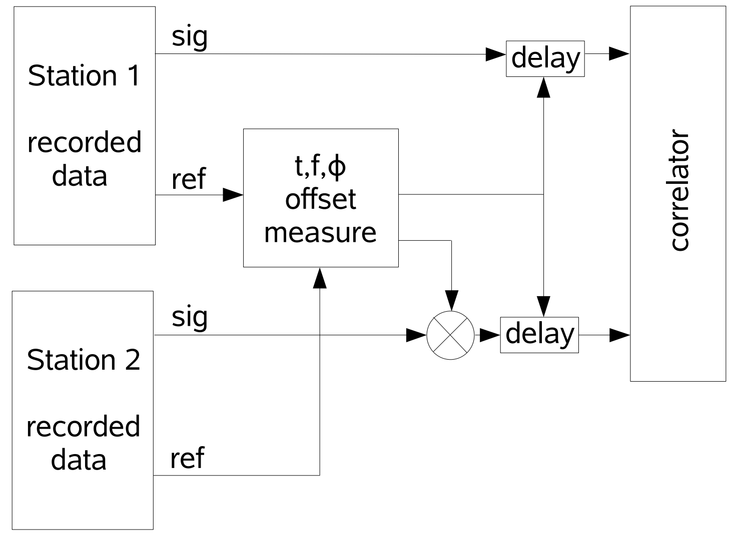

Fig 7. VLBI signal processing of recorded data

10. Antennas and preamps

I have not designed any special antennas or LNAs for SIDI. Anything suitable for the desired frequency will do - feel free to experiment.
With good LNAs, SIDI is sensitive enough to detect the Sun with simple dipole antennas!
SIDI can supply 12V through the center conductor for the LNA, since this is a built-in feature of the sat TV tuners, for the LNB supply.
I have on purpose chosen/designed the front ends so that their coverage includes the HAM radio bands, hoping that existing EME antenna systems could be used.

11. The cost

Not counting the PC, antennas, LNAs and cables, the total cost of the material for the first (LPT based) version of SIDI, if you buy new SkyStar cards (cca 70 euros a piece) for the tuners, is less than 200 euros.
If you can get them used, or buy only the tuners, or even find the tuners at a flea market, the total parts cost can be as low as 50 euros or less!
For the USB2 version, add maybe 50 euros extra, for the interface.

12. The results obtained so far

So far, all experiments have been done in “connected” mode, no VLBI. As expected, the biggest problem in practice has shown to be QRM/RFI, which is hard to avoid in a society, where even the toilet bowl has to be wireless to sell well!
SIDI was tested at a rural location, at a friends house, whose nearest neighbor is a few km away, but still encountered problems. The culprits were a leaky satellite TV installation and (of course...) the very PC used to run SIDI software.

After sorting these out, the fringes from the Sun, using 16dBi antennas on 23cm, came out quite pretty (Fig 8)
By changing the length of the baseline, the first minimum in the visibility function was easy to see, and in good agreement with the known angular diameter of the solar disk. SIDI was working well!
Next, we went for the famous radio source in Cygnus. Because of the small antennas, and the relatively low bandwidth (few 100 kHz) of the LPT version, the fringes were not directly visible, but could be pulled out using FFT (Fig 9).
The desired signal is the small peak to the left of the central DC residue spike.

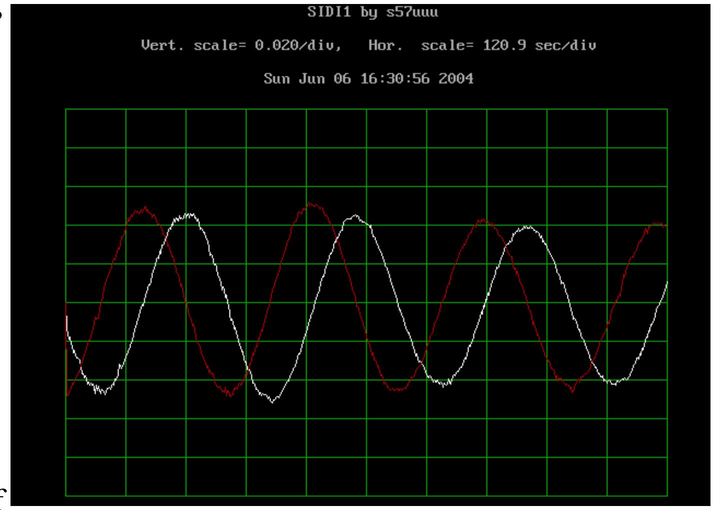

Fig 8. Fringes from the Sun

To check the feasibility of GPS reception with SIDI, and to try out some imaging concepts, two small active GPS antennas were connected next. After letting SIDI run over the whole night, the resulting fringe pattern, drawn as a "waterfall" spectrogram, is shown in fig 10. Individual satellites can be resolved, because their different positions in the sky give them different fringe frequencies.
Next day, moving one of the antennas in a 16x16 pattern, and integrating for two seconds at each position, it was possible to reconstruct an image of the GPS constellation in the sky (Fig 11).
Note that this was done without using the known GPS spread sequences, just using the GPS satellites as point noise sources.
All of the above experiments are described in detail at my homepage [10],[11],[12].

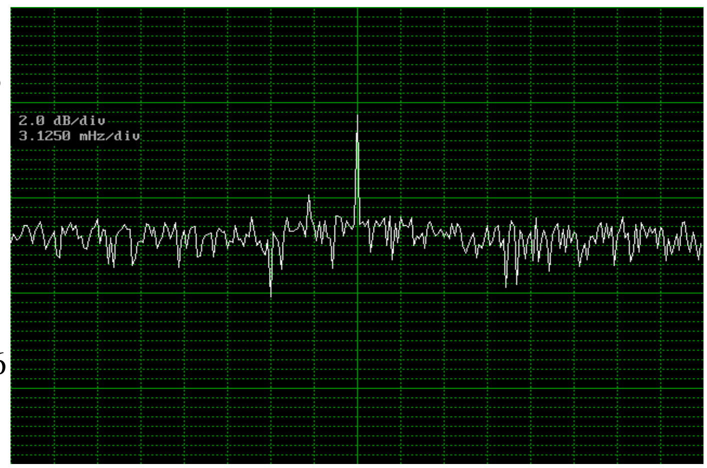

Fig 9. Detection of the Cygnus source

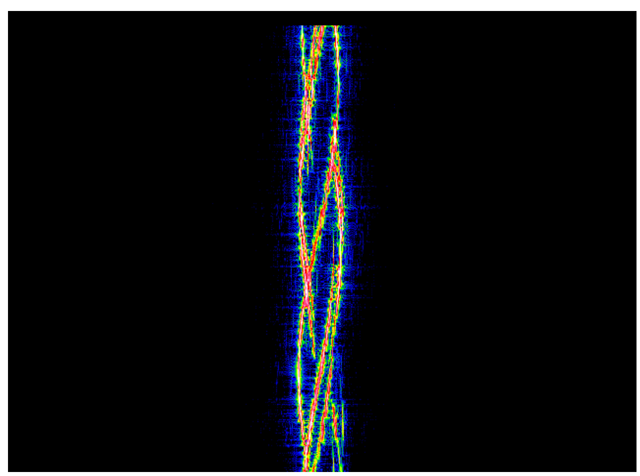

Fig 10. A spectrogram of GPS fringes

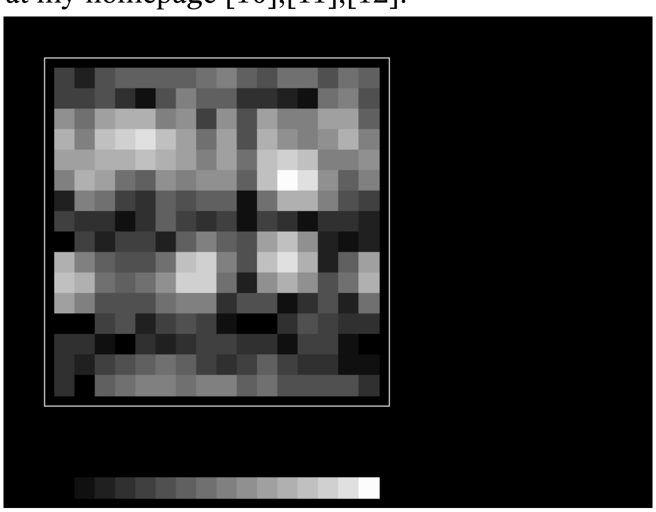

Fig 11. A 16x16 pixel image of the GPS constellation

13. How to join in on the fun

If you are interested in these things, and would like to join ERAC, check the official ERAC web site [13].
If you are lucky enough to live in a place, where it would be possible to set up a radio telescope (space for a, say, 2..3m dish and a low, "rural" level of interference), you might consider signing in to set up an ERAC ALLBIN station [14].
If you would just like to read a little more about SIDI, check my webpage [15], where all versions of SIDI are described in full detail, with complete schematics and software sources.
There is also the "erac-vlbi" discussion group on Yahoo [16], where new developments are discussed. It is a quite low traffic list, and has a publicly accessible archive.

14. Conclusion

The results obtained with SIDI show, that it is possible to make a working digital radio interferometer at a very low cost, and have a lot of fun with it.

15. References

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