SIDI: working towards amateur VLBI

Marko Cebokli S57UUU, FERAC

Pavle Reberc S57RA

ABSTRACT:

After discussing the history and motivation for attempting amateur VLBI, the paper describes the current development status of SIDI, the "SImple Digital Interferometer", and the results obtained with it so far. Next, the planned experiments, that will explore the possibility of doing VLBI with very simple hardware, using software based satellite common view synchronization techniques, are described.

1. Amateur VLBI?

Making a telescope the size of a planet is certainly a fascinating idea, and since it has been realized in the 1960's, it has generated a lot of scientific results [1]. In its canonical form, VLBI uses atomic clocks for time/frequency synchronization, which makes it rather difficult for amateurs to pursue. Nevertheless, amateur radio astronomers have long since expressed the interest in doing VLBI.

The easiest way to do some VLBI, is the intensity interferometer mode [2], which does not require precise synchronization. However, the sensitivity in this mode is very low, and with amateur-sized antennas, the Sun is probably the only source strong enough for this method. For that reason, the rest of this article is about how to do “true” coherent VLBI interferometry, using means accessible to amateurs.

2. VLBI: it is not only about the length of the baseline!

What separates a VLBI interferometer from a conventional one, is not only the length of the baseline, but the way the signals are combined. Conventional interferometer requires antennas to be physically connected by coaxial cable, optical fiber, or other type of transmission link and the data is combined in real time. In an VLBI interferometer, the signals are recorded independently at each site, and the recordings combined off-line at a later time.

So, would it make sense to try that technique even with shorter baselines? I think for amateurs, it would. Big professional observatories like VLA have enough real estate, to set up kilometer sized baselines, and run the cables on their own property. For an amateur, even a baseline of a few hundred meters might be problematic in terms of a direct cable connection. Not just the price of the cable, very few amateurs own land on that scale, and laying cables over foreign property could be an unsolvable problem.

Therefore, even if, at least in the beginning, we don't span continents, it would be very desirable, to develop a simple and cheap VLBI system.

3. SIDI, the Simple Digital Interferometer

SIDI [3][4][5] is an attempt at a contribution to the ERAC's ALLBIN project, which has the goal of linking several amateur radio telescopes into a VLBI system [6]. The main philosophical guideline behind SIDI is KISS, "Keep It Simple, Stupid!". Any unavoidable complexity should be shifted to the software side, if at all possible. This way, the hardware will be kept as simple as possible, the goal being a VLBI capable receiver for about 100 Euros, not counting the antennas, of course.

SIDI works on L band, and is currently in its third version, v1.2 [7]. It uses a couple of satellite TV tuners (DVB-S) as frequency agile front ends, which can receive between 950 and 2150 MHz. That, besides the 18 and 21cm astronomy bands, also covers the 23cm HAM band, both GPS bands, etc. The tuners are followed by simple limiting I/Q amplifiers, and a four channel single bit sampler, that supports sample rates up to 40MHz. The data is transferred to the host computer using an USB interface.
In connected mode (non-VLBI), with a 15MHz bandwidth and 100 seconds of averaging, SIDI can see single Jansky sources with a couple of 3m dishes. Averaging several scans can further improve its sensitivity. An example of a drift-scan observation at declination -10 [8] is shown in fig 1.

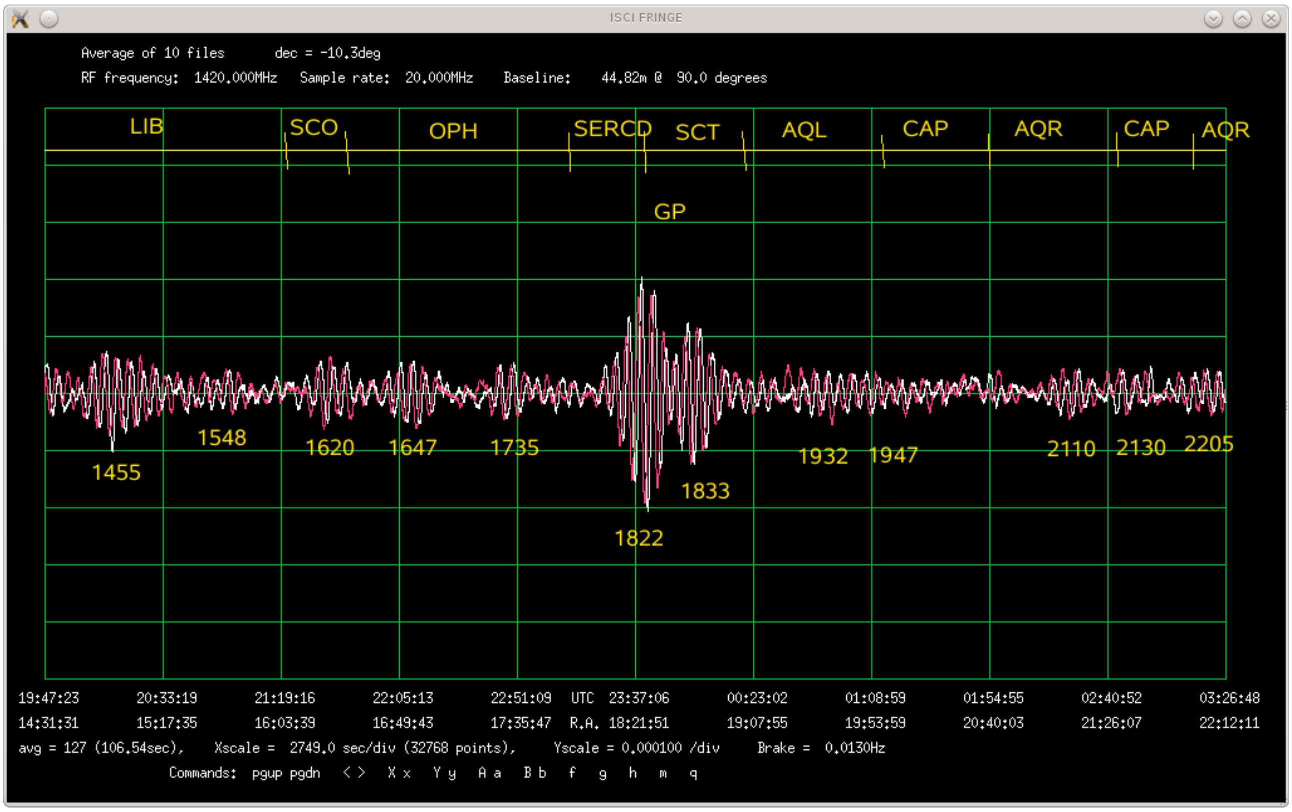

Fig 1. A drift scan at -10 degrees with SIDI 1.2

4. VLBI synchronization

In optical astronomy, a quality telescope is expected to have wavefront errors of less than 1/8 wavelength. Using the same criteria on the 21cm radio band, this translates to 45 degrees of phase on 1400MHz, which is approximately 90 picoseconds. For easier calculation we can say 100ps.

In its current configuration, SIDI needs about 100 seconds of integration, to see single Jansky sources, with a pair of 3m dishes. The required accuracy in this case is 100ps/100s = 10^{-12}, which is about what you get from a cesium clock. These occasionally come up on Ebay, and there are a few amateurs that have them (and even a couple of hydrogen masers) in their cellars [9], but it would be nice to avoid the need for them, if we want amateur VLBI to be feasible and engage more enthusiasts.gand gain

It is important to note, that we do not need absolute accuracy at that level, it is enough to achieve relative synchronization between the stations.

In the last decades, the global navigation systems (GPS, GLONASS...) have thoroughly revolutionized the art of precise time and frequency keeping.

Accordingly, many amateurs planning to do VLBI, intend to use the 1 pulse per second outputs of commercial GPS receivers to discipline their clocks and oscillators. While this will probably work OK for HF interferometry, like [10], it won't be adequate for L-band work. Commercial GPS disciplined non-atomic clocks, as used in cellular networks, are usually specified in the 10^{-11} range [11], an order of magnitude short of our requirements.

To get the required synchronization without atomic clocks, locking to a common view signal from a satellite could be a solution [12].

The plan with SIDI is to use a method from the 1960's first VLBI systems: record a reference signal along with the “astronomy” signal. For this to work, the sampling clocks and local oscillators in both channels must be derived from the same clock, but that clock does not have to be locked or very accurate. SIDI version 1.2 already fulfills this requirement.

In post processing, observation of the recorded reference signal will be used to determine the errors of the master clock, which will then be subtracted from the observed signal.

5. The SBAS (EGNOS) signals

The GPS system in its original form was not considered suitable for use in civil aviation, because there was no warning of eventual signal degradation, whether by natural causes, or by USA DoD machinations like Selective Availability.

Therefore, the civil aviation authorities decided to provide reliability augmentation systems. These consist of a number of reference ground stations, distributed over the desired coverage area, that monitor the quality of the GPS (and other GNSS) signals. Their reports are centrally collected and converted into messages, which are then broadcast from several geostationary satellites. This service is called the Satellite Based Augmentation System (SBAS) [13]. There are several such systems, covering different areas of the planet. Europe (and in future parts of Africa) are covered by EGNOS, north America by WAAS, Russia by SDCM, India by GAGAN and Japan by MSAS. While the reports in the signal messages are valid only in the areas where the ground stations are located, the signals themselves can be received over a much wider area, basically from wherever you can see the geostationary satellite transmitting the SBAS signal. For example, EGNOS can be received all over Africa and in eastern parts of both North and South America (fig.2).

Luckily (or should I say incredibly?) all these SBAS use the same format of signal [14]. It is very similar to the signal transmitted by the GPS satellites, which makes it excellent for our synchronization purposes. It even has some advantages over the signal from the GPS satellites:

- - the same satellite is visible over a very wide area
- - does not rise and set, can be locked on continuously
- - Doppler correction is much smaller and simpler than for orbiting GPS satellites
- - a simple, fixed mount directional antenna can be used, for better S/N

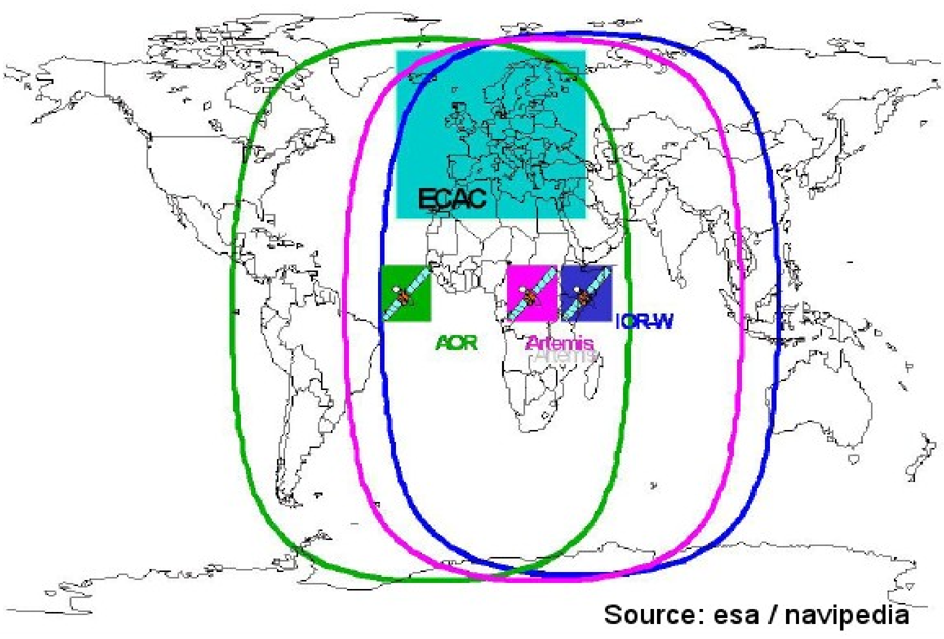

Fig 2. EGNOS signal footprints

The SBAS signals are transmitted on the same frequency as the GPS signals, but use different spread codes. The codes have the same length as the GPS codes, 1023, and the same code rate, 1023kHz. The payload data is transmitted at 250 bits per second (GPS: 50 bits per second), and is further encoded with a rate 2 convolutional FEC code, for a final rate of 500 bits per second, or two spread code lengths per bit. The payload data consists of 250bit (one second) long messages. There are many different types of messages defined, each carrying a different type of information, like date/time, satellite health statuses, satellite position ephemeris, state of ionosphere, etc. Like GPS, all timing, data and spread code, and carrier frequency, are generated coherently.

6. Doing the VLBI synchronization in software

The first step is to record reference and observed source "astro" signals in a common format. Reference signals from different sites are de-spread and demodulated, the EGNOS data from each station is written it to files, together with measured frequency offset and bit start positions in the raw file.

Next, a cross-correlation of the demodulated data bit strings (without decoding them) is enough to coarsely (to the nearest millisecond) align the two files, for timing errors up to 2.5 seconds (EGNOS messages do not repeat in less than five seconds). This is enough even for manually started recordings. Decoding the EGNOS data, and using the date and time provided there, would allow aligning over arbitrary time offsets, provided there is at least some time overlap between the recordings.

Next, the raw signal from one EGNOS channel is de-rotated by the coarse frequency difference measured in the first step, and cross-correlated with the EGNOS signal from the other station. Cross-correlating the spread codes allows alignment of the files to one sample, and provides the fine frequency and phase offset information, which is essential for VLBI.

In the last step, the frequency and phase differences determined in the previous steps, will be adjusted for the different synthesizer ratios of the "astro" channels, and used to de-rotate one astro signal before cross correlating it with the other.

When the baselines will get longer, some additional steps will be required, like delay compensations for both EGNOS and astronomy signals, etc. Further enhancements will be possible based on decoded EGNOS messages, like satellite Doppler corrections and partial ionosphere compensation.

7. Experiments with EGNOS signals using SIDI

First, we wanted to get a little familiar with the EGNOS signals, so we used the dish on the gun mount [15] and an analog spectrum analyzer, to find them. After locating the bird at 15W, we connected the dish to one channel of a SIDI receiver, and a small 6 turn helix antenna to the other channel. The result, as seen on the SIDI_FFT display, is shown in fig 3.

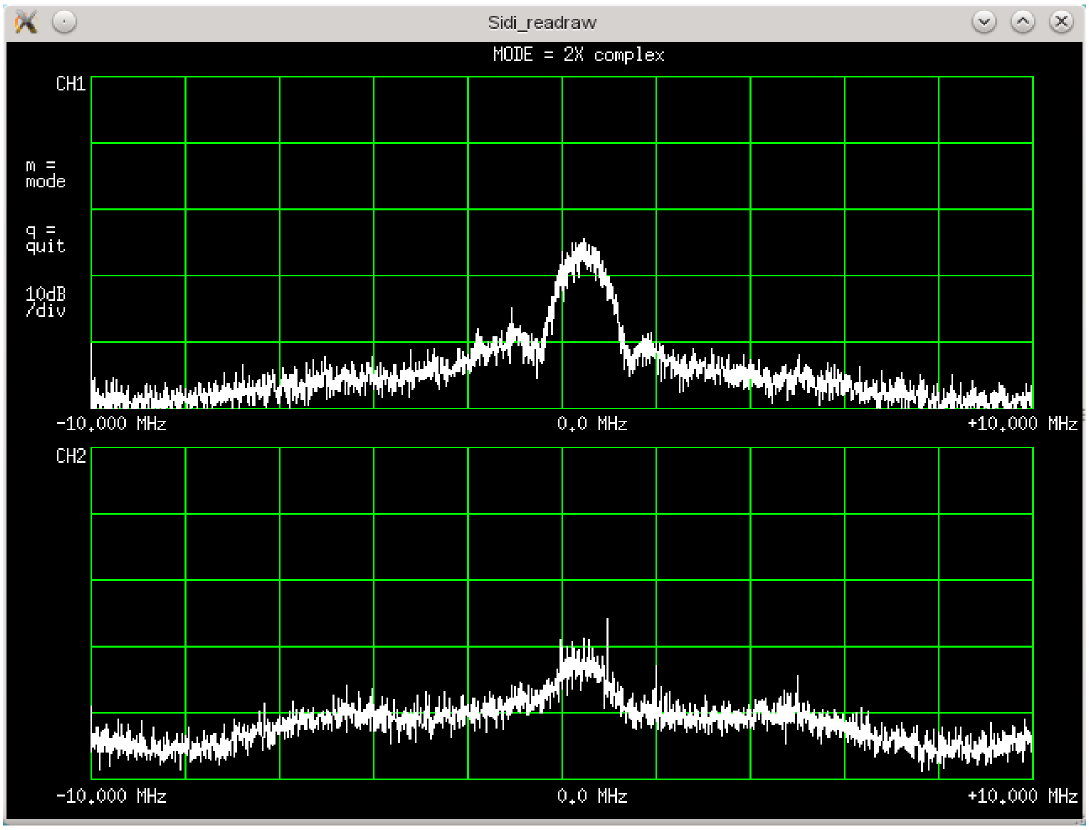

Fig 3. EGNOS signal from 15W (Inmarsat AOR), top: 3m dish, bottom: 6 turn helix

The signal from the dish is strong enough (despite the 3dB loss because of linear polarization) to allow direct demodulation of the spread code (fig 4), which of course makes no sense, it was just done as an exercise.
The signal from the helix is weaker, but still strong enough, with a lot to spare, for our purposes. After de-spreading it, the S/N of the helix signal is almost 30dB.
Next task was to demodulate the data stream. Due to some problems with the Viterbi decoder, we haven't yet decoded the messages, but the raw demodulated bit string is enough to get from one second accurate timing (manually started recordings) to about a millisecond, which significantly reduces the correlation search range needed in the next stage of processing.

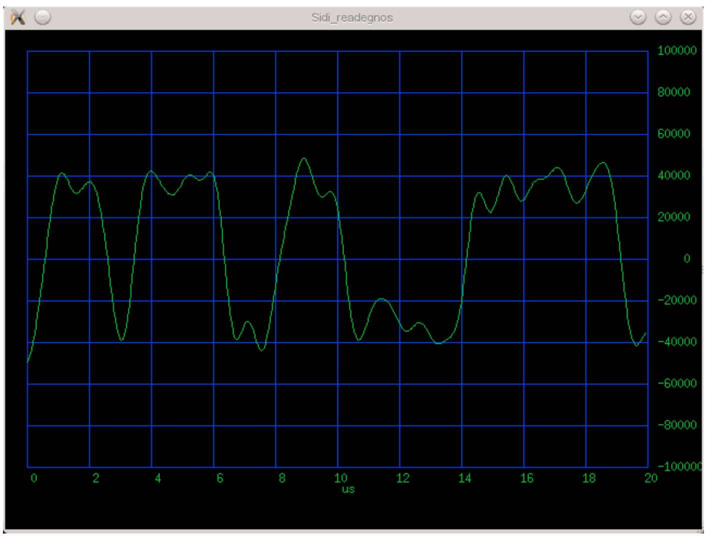

Fig 4. Directly demodulated spread code

In that next stage, the raw recorded EGNOS signals are cross correlated. This gives the timing to a fraction of the code bit length, and also the precise carrier frequency and phase offsets needed for

VLBI. It is hoped, that with a somewhat longer averaging on this cross correlation, even the ambiguity on the carrier phase might be eliminated. That is not essential for VLBI, but would be nice: a step towards absolute phase calibration.

To see how the autocorrelation of these signals looks, the dish and helix signals were cross correlated. This was done, because the autocorrelation of a single channel would have a big noise peak at zero.

The result over a longer time (+-3ms) is shown in fig 5. There is a peak every spread code length (1 ms), with the center one being the strongest, because of the 500bps quasi random payload data.

Sometimes long strings of zeros are transmitted (empty messages, reserved for future use), in this case one gets a series of equal peaks. This is not much of a problem, as the strings of zeros are never longer than a little less than a second, and the lock can be held through these periods.

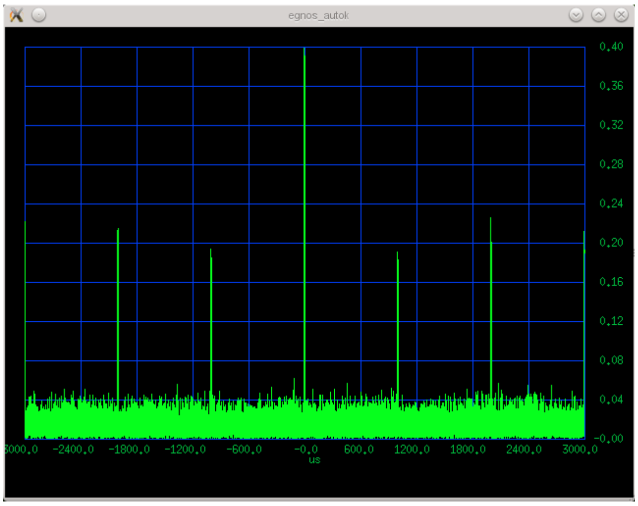

Fig 5. EGNOS signal autocorrelation, +-3ms

The same autocorrelation, close up, plotted over +-2us, is shown in fig 6. At 20MHz sample rate, the 1023kb/s code is highly oversampled, and the "square" bits make a triangular autocorrelation, two bits (1.95us) wide. The position of the peak gives the relative timing to one sample time (50ns) precision. Using curve fitting or center of gravity techniques, precision to a small fraction of that should be possible, maybe even to the level of unambiguous carrier phase (<0.5ns), ionosphere permitting.

In fig 6, the peak is slightly off center, because we did not care much about antenna positions and cable lengths in this experiment.

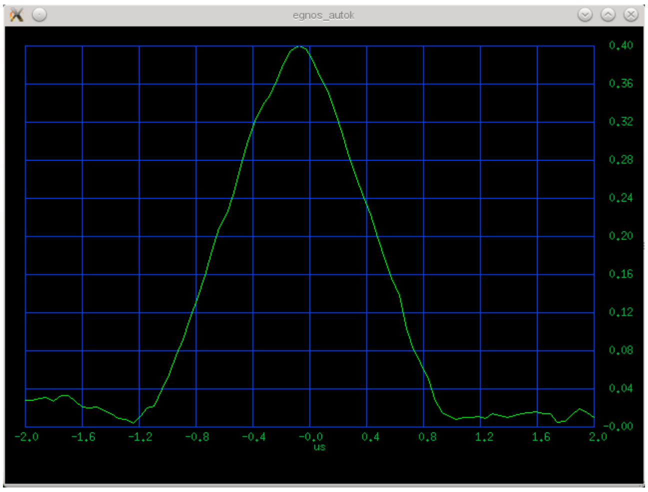

Fig 6. EGNOS signal autocorrelation, +-2us

8. Going for VLBI

End of July 2014, the first tentative recordings with separate receivers were made. We had some problems with dead LNAs and software bugs, so the current recordings are a bit clunky. The files are huge; about 40GB of data per hour is recorded at each station. Even copying them to a portable disk, takes a very long time. Transferring them over an 10Mb/s Internet link takes eight times the recording time, because the data are recorded at 80 Mb/s (20MHz sample rate times two channels times I and Q).

For the first VLBI experiments, the main antennas were left at the same positions (44m baseline) as before, to enable a comparison between the results in connected and VLBI modes.

On one side, the above mentioned six turn helix was used as the reference (EGNOS) antenna, and on the other side the reference antenna was a 90cm dish with a two turn helix feed.

The software for the post-processing is being developed now. A first version of the data demodulator is working, as is the bit stream matching. Peaks in the EGNOS signal cross correlation have been obtained.

At the time of this writing (13 aug 2014), work is continuing, and we hope to get some VLBI fringes soon!

9. Conclusion

SIDI has proven itself to be a good and versatile interferometer. Work is continuing on creating a

VLBI capability with the same very simple hardware. For news about the SIDI developments, see the ERAC_VLBI Yahoo group [16]. For observation data and pictures of the setup, check Pavle's homepage [17], and follow the links on the left side, under “Main menu”

10. References

[1] http://en.wikipedia.org/wiki/VLBI

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[7] http://lea.hamradio.si/~s57uuu/astro/sidi1_2/index.htm

[8] http://lea.hamradio.si/~s57uuu/astro/sidi1_2/obs/dec-10.htm

[9] http://www.leapsecond.com/

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[17] http://lea.hamradio.si/~s57ra/