

Observing at the GBT with VLBA+Mark5A and VLBA+S2 backends

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Abstract

We have tested GBT observing with VLBA+Mark5A and VLBA+S2 backends. Observing with VLBA+Mark5A does not require any additional steps during set up in comparison with standard GBT observing in the VLBA mode. Observing with VLBA+S2 requires some re-cabling as well as manual simple configuration of the S2 terminal. Both backends have produced high quality data. Results of data processing are presented and discussed. We conclude that both Mark5A and S2 recording systems can be successfully used in experiments which require high temporal resolution.

1 Introduction

Both Mark5A and S2 backends are standard VLBI recording systems which are available in many radio observatories around the world. This makes the use of them relatively easy and reliable. They can be utilized not only for VLBI experiments but for any kind of experiment which calls for high temporal resolution. Particularly, for pulsar observing.

We have performed a test with GBT (February 5, 2005, 16:45 – 20:00 UTC, observations of two strong pulsars with well known parameters, B1937+21 and Crab pulsar) in order to check reliability of use in a single dish mode of available VLBA+Mark5A and VLBA+S2 GBT backends. We have chosen to use pulsars in this test because they provide an accurate check of parameters of the system used for high temporal resolution observing.

2 Set-up, observing, and data transfer

2.1 Mark5A

We have produced a VLBI card file using the NRAO sched software package (Walker 2005). The card file is a standard set of commands which is used to set-up and control VLBI observations. The key-in and catalog files used to produce the card file may be found on the Wiki page¹. This procedure is standard for VLBI observing and is routinely performed by every VLBI observer.

The card file was used in a standard way (exactly the same as done for any other standard GBT VLBI experiment) in order to produce all the needed GBT setup and control files for the observing as well as to directly setup and control the VLBA backend. This is supposed to be a routine procedure for the GBT support staff.

¹<http://wiki.gb.nrao.edu/bin/view/Data/HowToObserveReduceMark5AandS2Data>

The Mark5A disk pack was installed in the Mark5A computer and turned on (in case of standard tape VLBI recording one would have to install the tape in the VLBA tape recorder instead).

Please refer to Appendix A for Mark5 procedures.

GBT frontend and VLBA backend setup as well as observing were done in the same routine way as for any other standard GBT VLBA experiment.

We have recorded on Mark5A both RCP and LCP, upper and lower sidebands for 2100 and 2068 MHz, 8 channels in total, 16 MHz per channel, Nyquist sampling, 2 bits. This have produced 512 Mbps of pure data flow. B1937+21 was observed for about 110 minutes, and Crab pulsar for 15 minutes.

We have transfered the data from Mark5 disk pack to a Linux PC after observing. The continuous Mark5 data were split into individual pieces of 10^9 bytes. The size of pieces was determined taking into account storage capacity for optimal processing.

The transfer (if needed to be performed right after observing, in Green Bank) may be done by a visiting observer. Please refer to Appendix B for Mark5 data transfer notes.

2.2 S2

We have performed a re-cabling in order to connect the S2 recording system to the VLBA backend, have manually entered time, recording mode (32x4-2), as well as loaded 8 S2 tapes. Start and stop of S2 recording was also managed manually. S2 recording was done in this test in parallel to the Mark5A recording.

Please refer to Appendix C for the S2 observing procedures

We have used S2 to record LCP signal only, upper and lower sidebands for 2100 MHz, 2 channels in total, 16 MHz per channel, Nyquist sampling, 2 bits. This gave as 128 Mbps of pure data flow.

Eight tapes with data recorded using S2 backend were directly sent to the Astro Space Center (Moscow, Russia) for further processing. By means of S2-RDR interface (improved S2-TCI, developed in the Astro Space Center) the data from S2 tapes were transferred to a standard disk in a piecewise manner, the size or duration of each piece of data stream being limited by the disk storage capacity. We took 10-sec pieces of data stream when played data back.

3 Data Reduction

3.1 Decoding the data

3.1.1 Mark5A

The Mark5A data appear as if they have been recorded to VLBA tapes. The VLBA tape format and recording modes are described in details in Mark4 memos (Whitney 2000, 1998). The first memo (Whitney 2000) is just the newest version but both are the same in part concerning the VLBA data

format. We have used these memos and also the Mark5A memo #005.2 (Whitney 2001) to go into Mark5A data recording, investigate Mark5A data format and then decode our data.

Doing our decoding we have found that

- all parity bits were removed in our data, contrary to information given in Whitney (2001). Parity bits are described to be removed in Mark5B system only rather than Mark5A in use;
- all pure data (excluding header and auxiliary information in track frames) were modulated by a fixed pseudo-random sequence. In memos Whitney (2000, 1998) it is only said that data *may, optionally, be modulated* and nothing about are they usually really modulated, and what is a default option;
- barrel-roll was not used. In log information it was stated that the barrel-roll is set to an auto-mode, the header information of sequential data frames shows that there was no changes of track numbers for all bit-streams;
- digits A11, A12 and A13 (see memos Whitney 2000, 1998 for explanation) in the auxiliary data field were set wrong in our data. Fan-out mode 1:4 was used in our data, so sequential data bits from one data stream are distributed over 4 tracks. In the first track digits mentioned above were correct, but not the same for other 3 tracks.

Taking into account all mentioned above the program `mk5decode` for decoding our Mark5A data recorded in “512-8-2” mode was written. This program is available at the Wiki-page. A short description of available options is obtained by typing `mk5decode` (or see the code of `mk5decode.cpp`). This program uses standard VLBA bit-correspondence scheme +3, +1, -1, -3 rather than +3.3359, +1, -1, -3.3359 which gives better results as noted in the VLBA memo 5 (Kogan 1993). However, in our subsequent processing we changed the decoding values through the data records from ± 1 and ± 3 to real values that correspond to the current $\pm 1\sigma$ levels in accordance with the technique developed by Jenet & Anderson (1998).

3.1.2 S2

We used S2 backend in our earlier pulsar baseband observations, so we were familiar with data stream format after S2 tapes were played back using S2-RDR interface. S2-RDR is a special interface for playing back S2 tapes and coping them to a disk storage. It was developed in the Astro Space Center based on the standard S2-TCI interface. RDR is a more advanced interface, allowing writing of data from tapes to disk in one pass whereas TCI uses 5–6 passes. The record mode for S2-RT in our observations was “32x4-2”, mode “16x8-2” was used to playback our data from tapes to disk volume. To decode these data we use our program `decoder` which one can also find in the Wiki-page². As in case of `mk5decode` a short description of options is available by typing `decoder`. File “`bit.info`” should be present which describes the bit placement within data word. The bit placement is determined by record and playback S2 modes. All corresponding descriptions about S2

²Programs for checking the bit statistics in the data (percentage of bit-couples that give +3, +1, -1 or -3 values in decode data) and correcting for it and program for visualization binary data are also available in the Wiki-page.

itself, available modes and other were available earlier at an ftp site of Space Geodynamics Laboratory (SGL) of CRESSTech. SGL does not exist now, so all descriptions, S2 data formats, modes, manuals, etc., are available at our Wiki-page.

3.2 Signal Processing

Having investigated the Mark5A data format, or just played back S2 data from tapes to disk storage, we further processed our raw data by decoding them into 2-bit data streams for every sideband and polarization. Note, that S2 data contain only two sidebands near the central frequency 2100 MHz in left circular polarization. Then we applied technique suggested by Jenet & Anderson (1998) to correct our decoding values according with current $\pm 1\sigma$ -level. After that coherent dispersion removal procedure developed by Hankins (1971) was used to compensate our data for dispersion smearing of pulsar signal within each of 16-MHz bands. This processing routine was applied together with amplitude corrections for non-uniform receiver frequency bandpass and removing of interferences. In more details all of these processing steps are described in Popov et al. (2002a,b).

4 Data Analysis

Here we shortly describe system parameters, such as receiver bandpass, phase-cal and noise diode signals, and also report on successful detection of giant pulses from Mark5A and S2 data.

4.1 System Parameters

4.1.1 Receiver Bandpass

Receiver bandpass of the baseband channels obtained from Mark5A data is shown in Figure 1. The bandpass looks good, RFI contribution to total power is less than 1%.

4.1.2 Phase-calibration signal

We have recorded a 2-min scan with phase-calibration signal turned on. The amplitude of phase-calibration signal versus frequency is presented in Figure 2.

The relative change of amplitude of phase-cal harmonics obtained from S2 data looks almost the same as for phase-cal signal obtained from Mark5A data. The fine structure of phase-cal harmonics is shown in Figure 3. It is clearly seen that the phase-cal signal represents a number of harmonics in the power spectrum, located in a frequency range of about 4 kHz. This takes place in every sideband in both left and right circular polarizations.

We also folded the average noise diode signal in the data with phase-cal and noise diode signals turned on. The periods of phase-cal (1 μ s) and noise diode (12.5 ms) signals are divisible by each other. So, having the folded noise diode signal we also have the folded phase-cal signal. However,

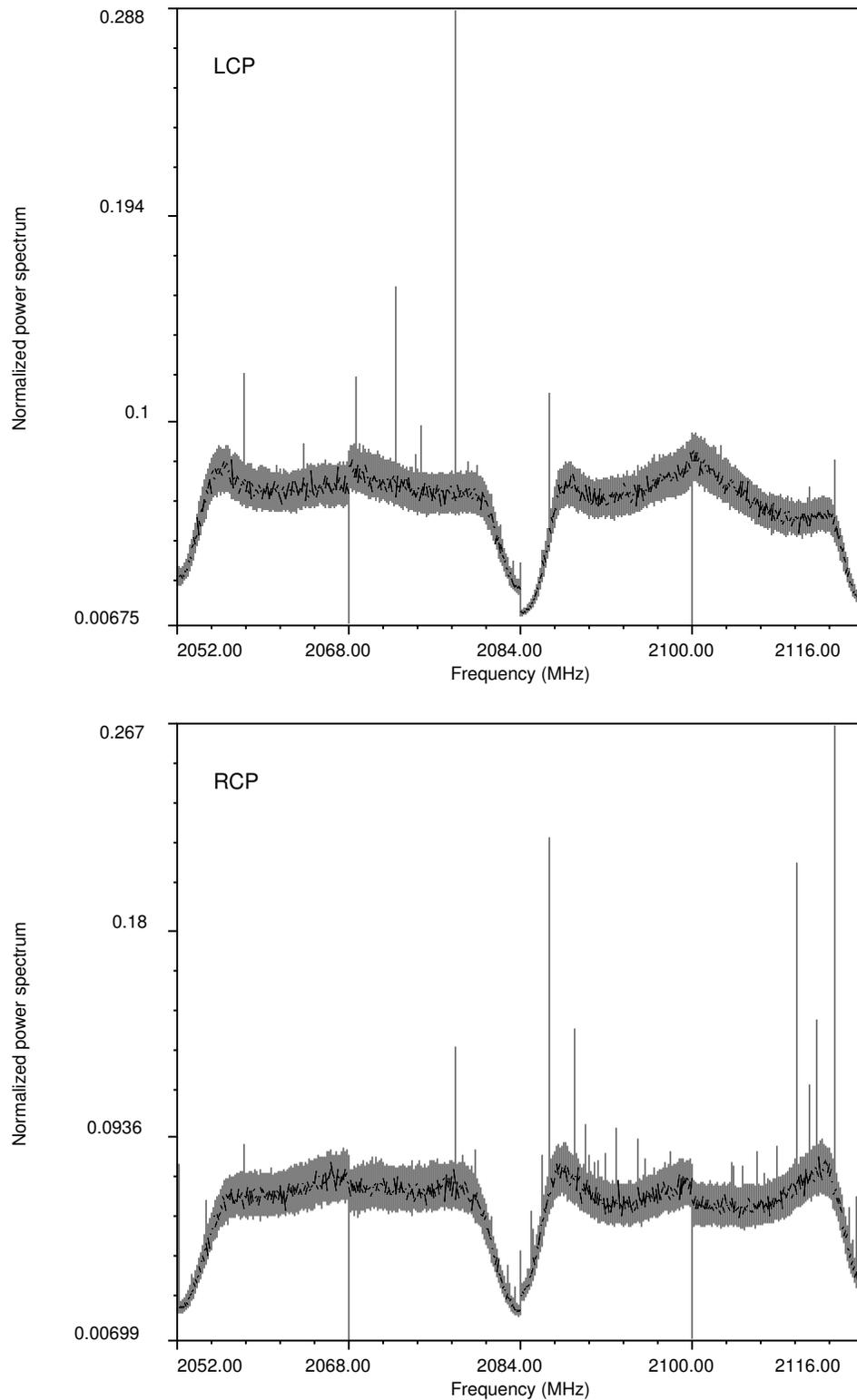


Figure 1: The receiver bandpass in all channels in both circular polarizations. These average spectra were built using Mark5A data for 50.8375 sec. The number of individual samples averaged is 774. The frequency resolution in these plots is 15.26 Hz.

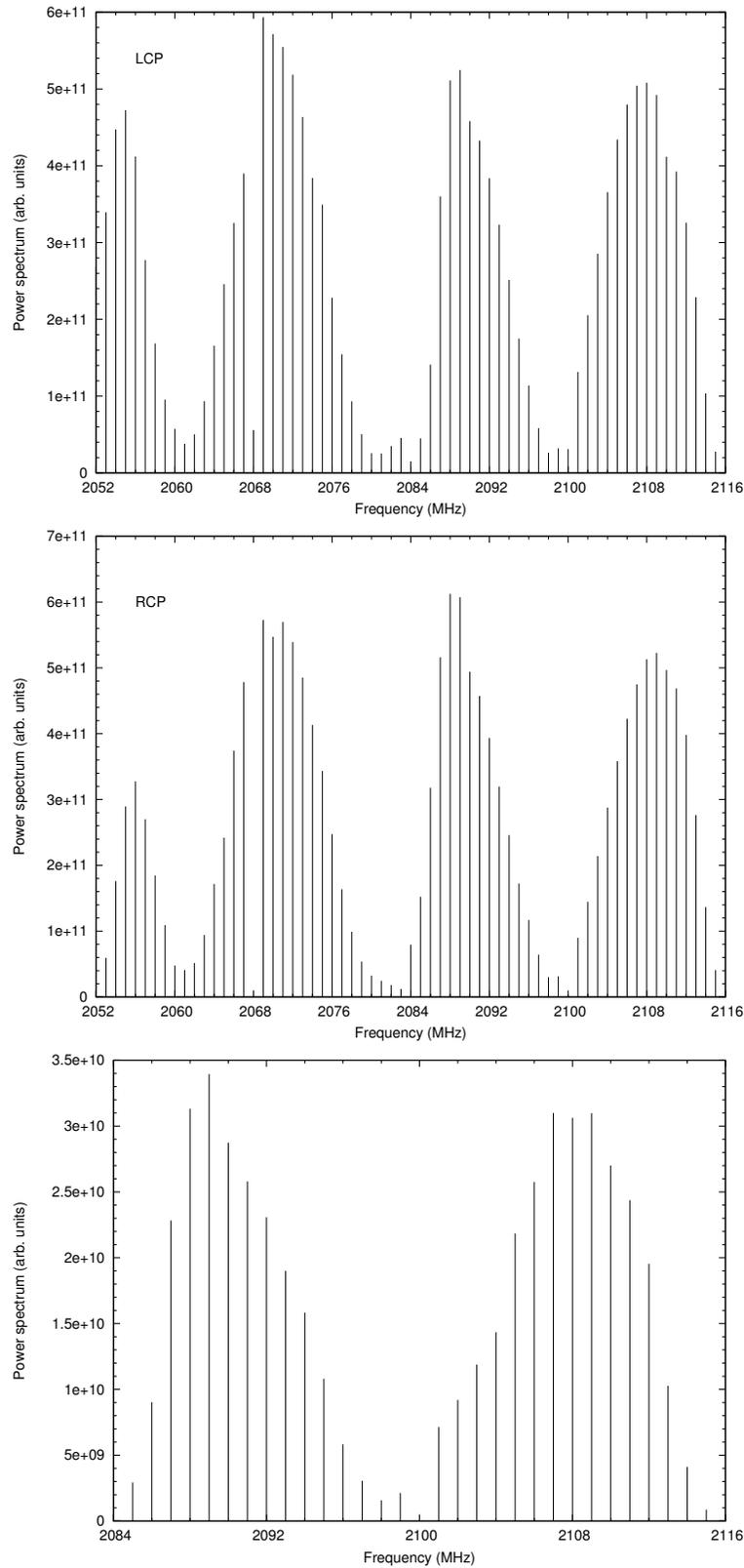


Figure 2: The amplitude of phase-calibration signal in the receiver bandpass. Two upper plots represent average power spectrum obtained from Mark5A data for left and right circular polarization, and the lowest one — obtained from S2 data.

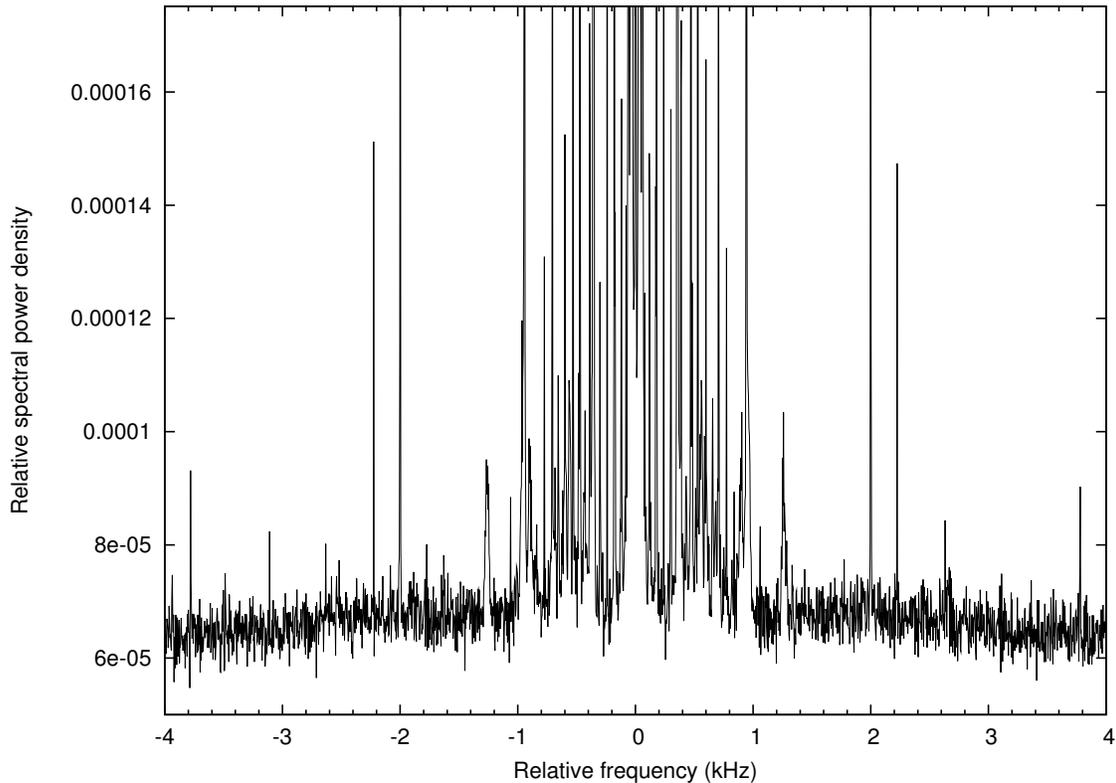


Figure 3: The average fine structure of one of the phase-cal signals in left circular polarization. The value 0 of relative frequency represents the frequency of 2070 MHz. The number of individual samples averaged is 422. The frequency resolution is 3.81 Hz. Maximum amplitude of satellite harmonics is below -25 dB of the main tone amplitude, which is overscaled in the figure.

the profiles of phase-calibration pulses are not single, but double and triple, so the time of arrival for phase-calibration signal fluctuates within ± 1 sample relative to the expected value (± 31.25 ns).

For each frequency channel both for Mark5A data and S2 data the dependence of phase of harmonics versus frequency was constructed. This phase curves are shown in Figure 4. During processing we have corrected the data only for bandpass amplitude irregularities but not for phase irregularities.

4.1.3 Noise diode signal

We had the noise diode signal turned on during the most part of our observations. Its switching frequency was set to 80 Hz and controlled by the VLBA backend (the period is 12.5 ms) which is standard for VLBA observations. Examples of the average noise diode signal folded during of about 15.5 s are shown in Figure 5.

For simplicity, in our further processing we use the system temperature value $T_{\text{sys}} = 23$ K for every frequency channel in both circular polarizations. It is an average of the system temperature measurements performed by the VLBA backend if the noise diode temperature $T_{\text{cal}} = 2.0$ K.

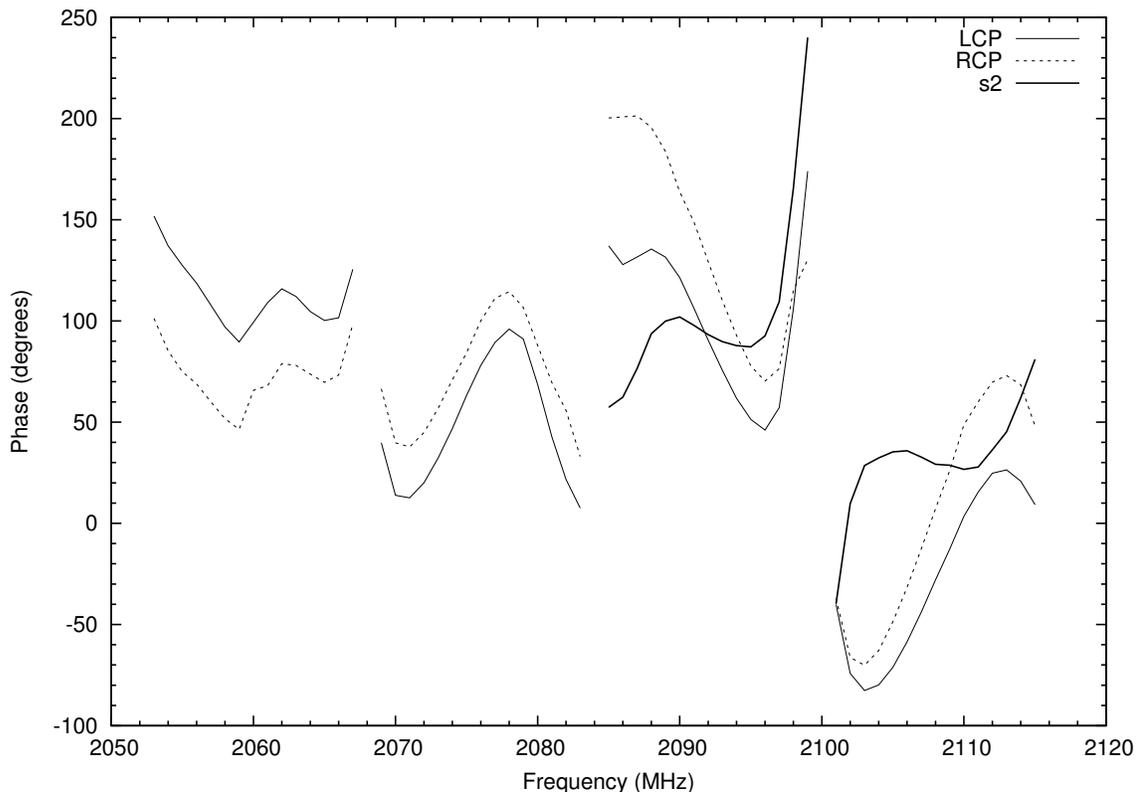


Figure 4: The phase versus frequency dependence for our receiver bandpass in both circular polarizations obtained from Mark5A data as well as from S2 data.

It was found that the noise diode signal for every frequency channel has an anomalous significant peak at the rise edge of up to $2 \times T_{\text{sys}}$ (see Figure 6 with a 29 K peak amplitude for both RCP and LCP). The full-width at half-maximum is of about 120 ns.

Having noise diode signal turned on did not affect the search for giant pulses (see § 4.2). However, it can distort slightly the integrated profile. So, it is desirable to turn on the noise diode signal before and after pulsar observations to calibrate the data, but to have noise diode signal turned off during observing.

4.2 Mark5A vs. S2: data comparison

We have successfully decoded and processed Mark5A and S2 data, and have detected giant pulses from the millisecond pulsar B1937+21 as well as from the Crab pulsar. The threshold for searching giant pulses within the pulsar period was set to the value of 20σ for both pulsars. The examples of detected giant pulses from both pulsars are shown in Figures 7, 8. The S2 and Mark5A profiles look very similar. This means that the backends as well as our decoding software work well.

Small differences in pulse profiles are probably due to different functions used to correct receiver bandpass for amplitude bandpass irregularities. Full set of these detected giant pulses in all Mark5A

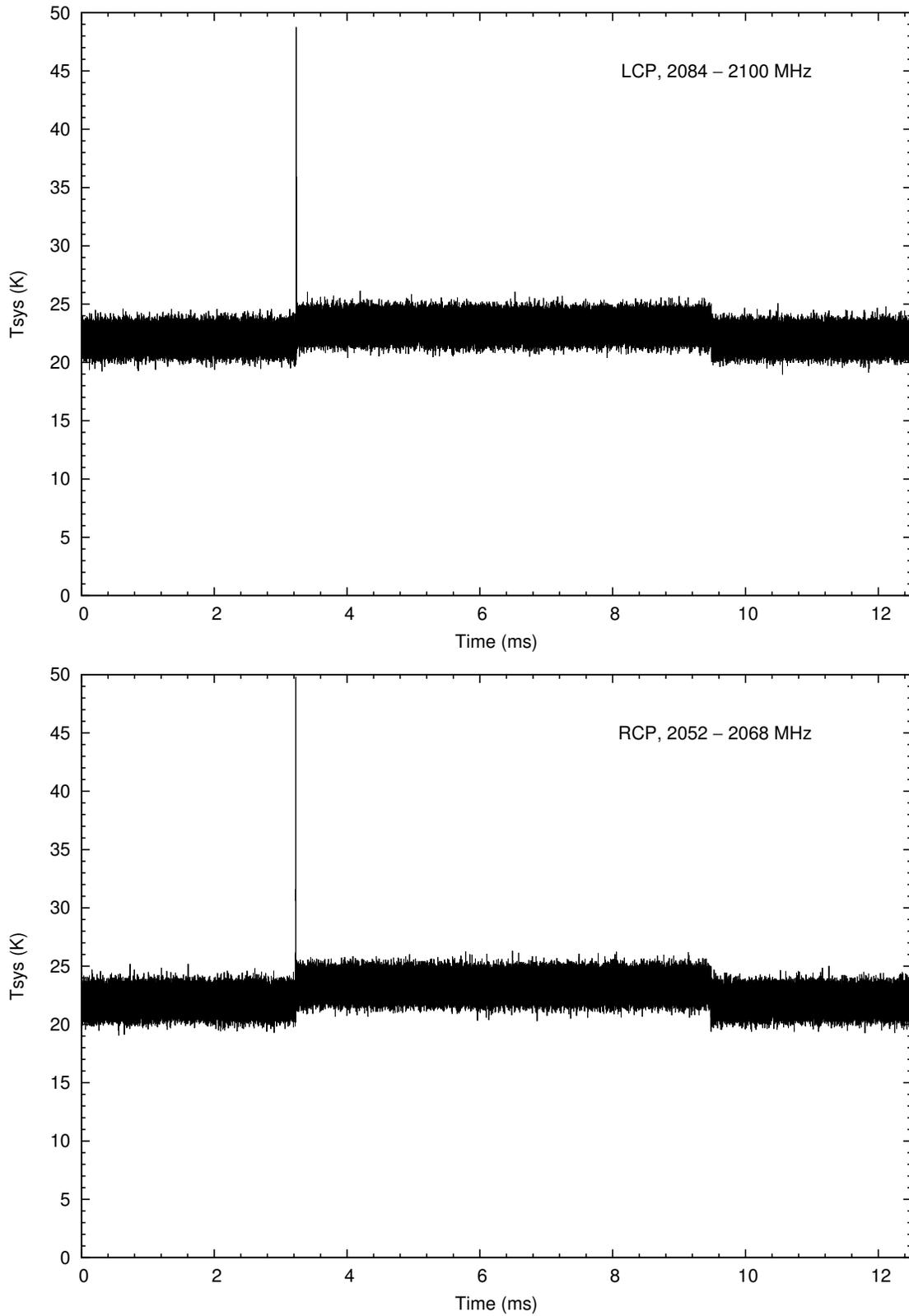


Figure 5: The average noise diode signal folded during of ≈ 15.5 s (1239 individual noise diode periods) in two frequency channels: 2084 –2100 MHz in left circular polarization (upper plot) and 2052 – 2068 MHz in right circular polarization (lower plot).

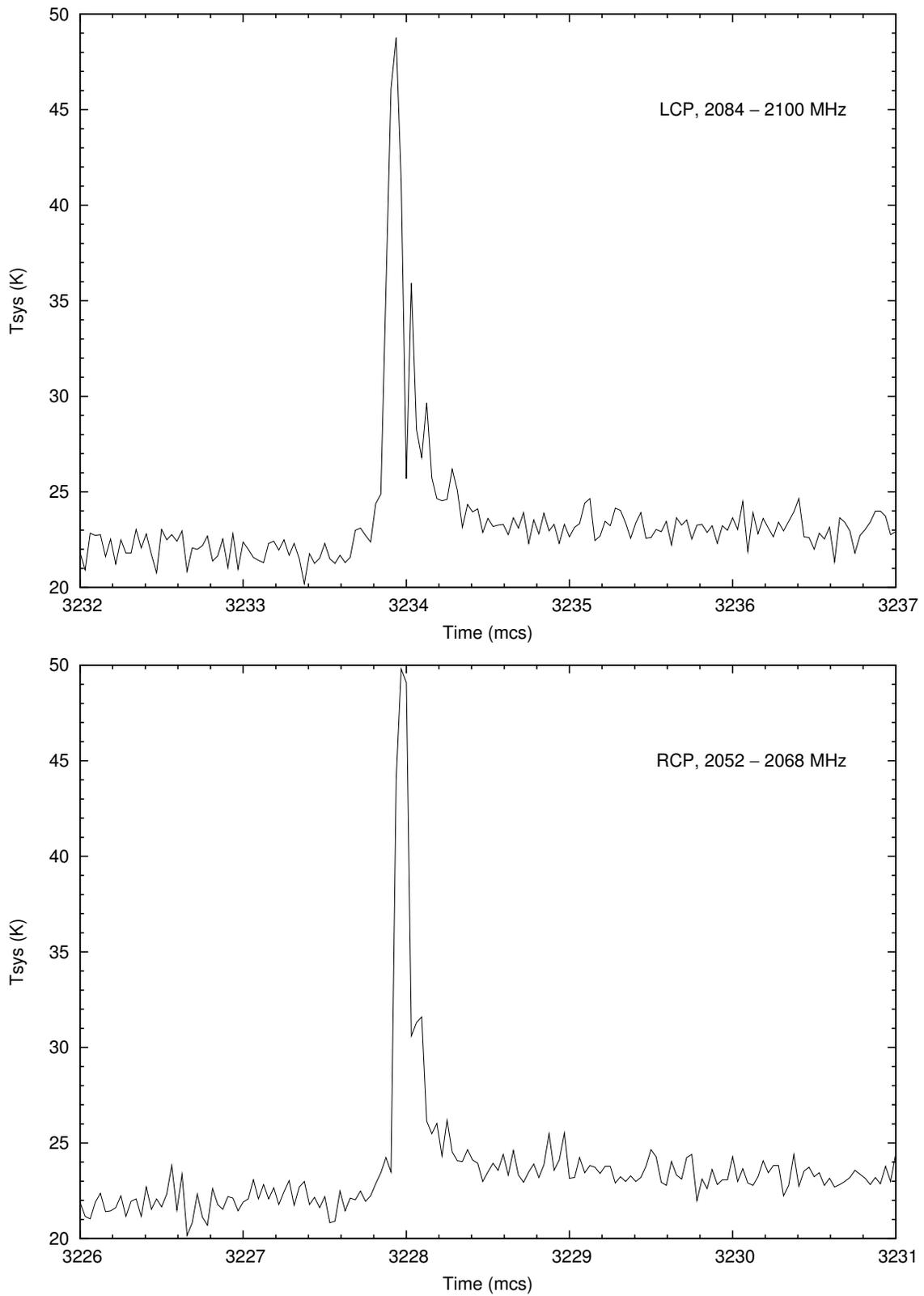


Figure 6: The fine structure of the noise diode signal in its rise edge for corresponding examples from Figure 5 in two frequency channels: 2084 –2100 MHz in left circular polarization (upper plot) and 2052 – 2068 MHz in right circular polarization (lower plot).

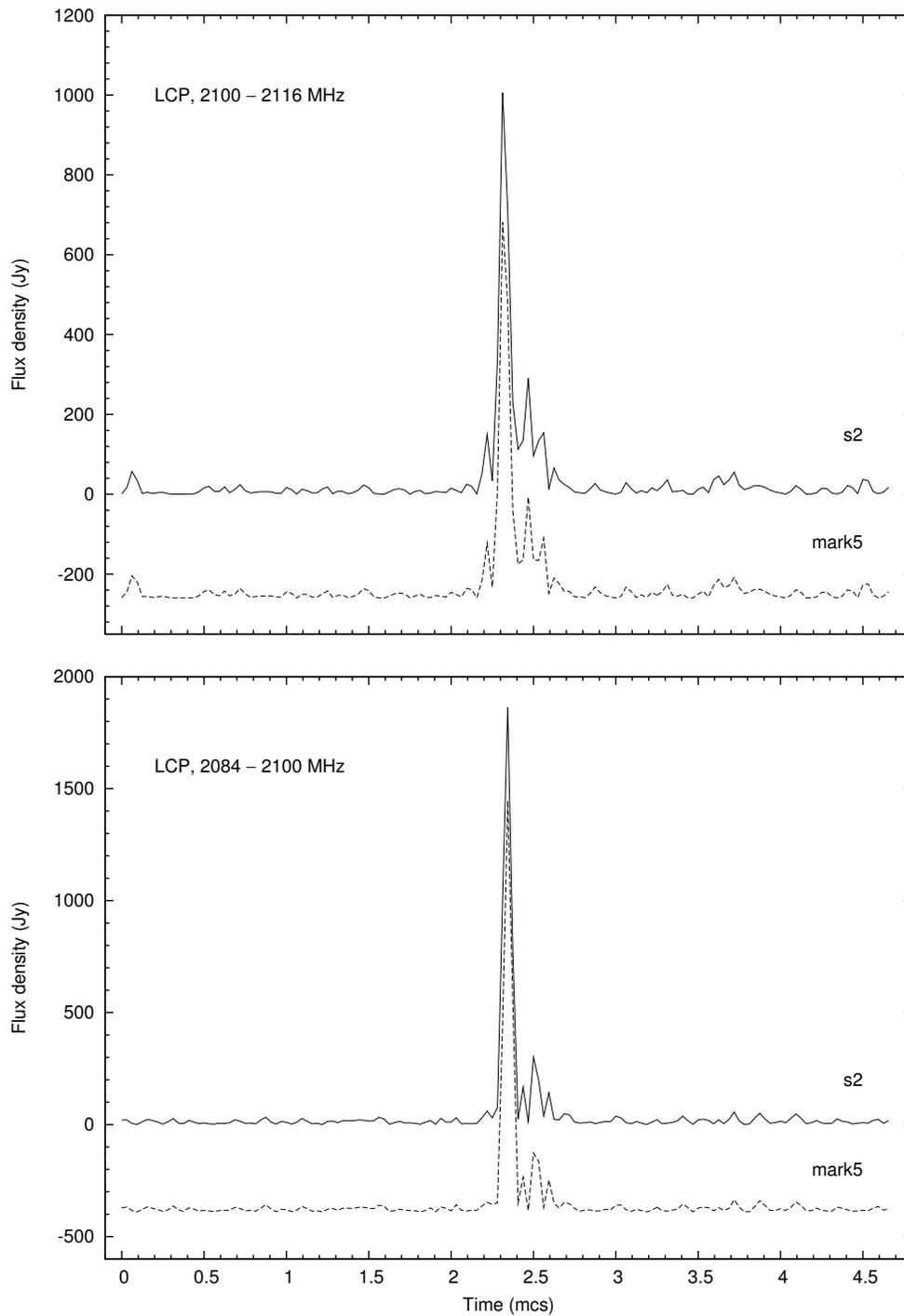


Figure 7: The strongest giant pulse of the millisecond pulsar B1937+21 up to 2000 Jy which occurred during the observing run. Two plots represent giant pulse profile in two sidebands near the central frequency 2100 MHz in left circular polarization. Dispersion smearing and dispersion delay are removed. The upper curves in each plot are profiles obtained from S2 data, and lower ones are profiles from the Mark5A data. It is clearly seen that S2 and Mark5A profiles are almost identical. Small differences appeared due to different functions used to correct the receiver bandpass for amplitude irregularities. Profiles are shown with original time resolution of 31.25 ns. The values of flux density are based on system temperature of 23 K and the GBT gain value for S-band.

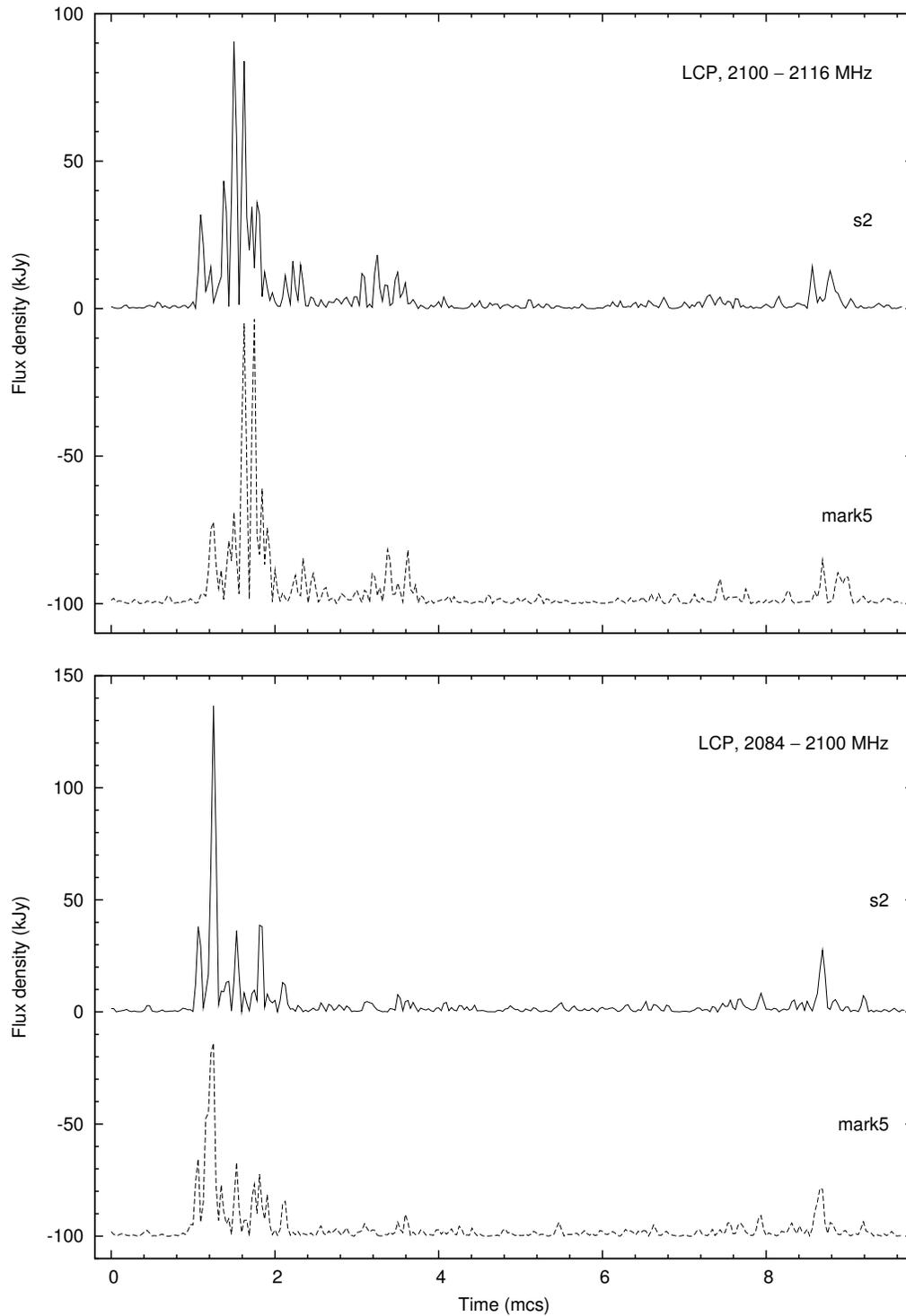


Figure 8: Example of the Crab giant pulse in frequency channels recorded using both Mark5A and S2 backends (left circular polarization, 2084 – 2100 and 2100 – 2116 MHz). Dispersion smearing and dispersion delay are removed. The upper curves in each plot are profiles obtained from S2 data, and lower ones are profiles from the Mark5A data. Profiles are shown with original time resolution of 31.25 ns. The flux density scale is determined here by Crab Nebula background emission which was taken as 710 Jy (from Kostyuk et al. 2003 for the frequency 2228 MHz).

frequency channels is presented in Figures 9, 10.

We have processed all the S2 data. Altogether we have found 37 giant pulses for the Crab pulsar and 8 for the millisecond pulsar B1937+21 with the flux densities greater than 30σ , the strongest one about 2000 Jy for B1937+21. Processing of Mark5A data continues. So far, we have processed about 10 min of Mark5 data for B1937+21 and 2.5 min for Crab pulsar. We have found in RCP and/or LCP 15 giant pulses for B1937+21 and 10 for the Crab pulsar with flux densities greater than 20σ . The average profile of regular pulses for the millisecond pulsar B1937+21 is shown in Figure 11. Flux density of average regular profile for the B1937+21 was found to be of about 65 mJy. The same value was obtained by Popov & Stappers (2003) at the frequency 2300 MHz using the WSRT.

4.3 Mark5A frequency channels: extra time delay

We have found an extra time delay in Mark5A data between frequency channels centered at 2068 and 2100 MHz. The difference is equal to about $6 \mu\text{s}$ and is based on measurements of time of arrivals of detected giant pulses relative to the time marks in the data. This delay is system intrinsic rather than connected with other value of dispersion measure of observed pulsars because a corresponding difference in dispersion measure of $0.2 \text{ pc}/\text{cm}^3$ is too big. Cognard et al. (1995) have found variations of dispersion measure for this pulsar of about $0.005 \text{ pc}/\text{cm}^3$ within 4 years.

During the most part of observations we have noise diode signal turned on. We have folded the average noise diode signal with its period of 12.5 ms during the time of about 15.5 s (1239 individual noise diode periods) in each frequency channel for every polarization. We have found a time shift of $6 \mu\text{s}$ (192 counts) for noise diode signals between frequency channels centered at 2068 and 2100 MHz. Hence, the found extra time delay is system specific rather than pulsar specific.

4.4 Mark5A vs. S2: time discrepancy

Time discrepancy of more than 1 s is present between Mark5A and S2 data. As in the previous § 4.3 this difference was obtained from time of arrivals of detected giant pulses. The main bulk of this time of exactly 1 s is unambiguously connected with the manual setting of time in the S2 terminal. It is very easy to make a mistake of 1 s setting the time, and we often dealt with this in our observations with S2 backend. However, the extra time shift of about 198 ms remained after removing 1 sec, which is believed to be system specific. This time discrepancy is not critical for observing with Mark5A and S2 backends.

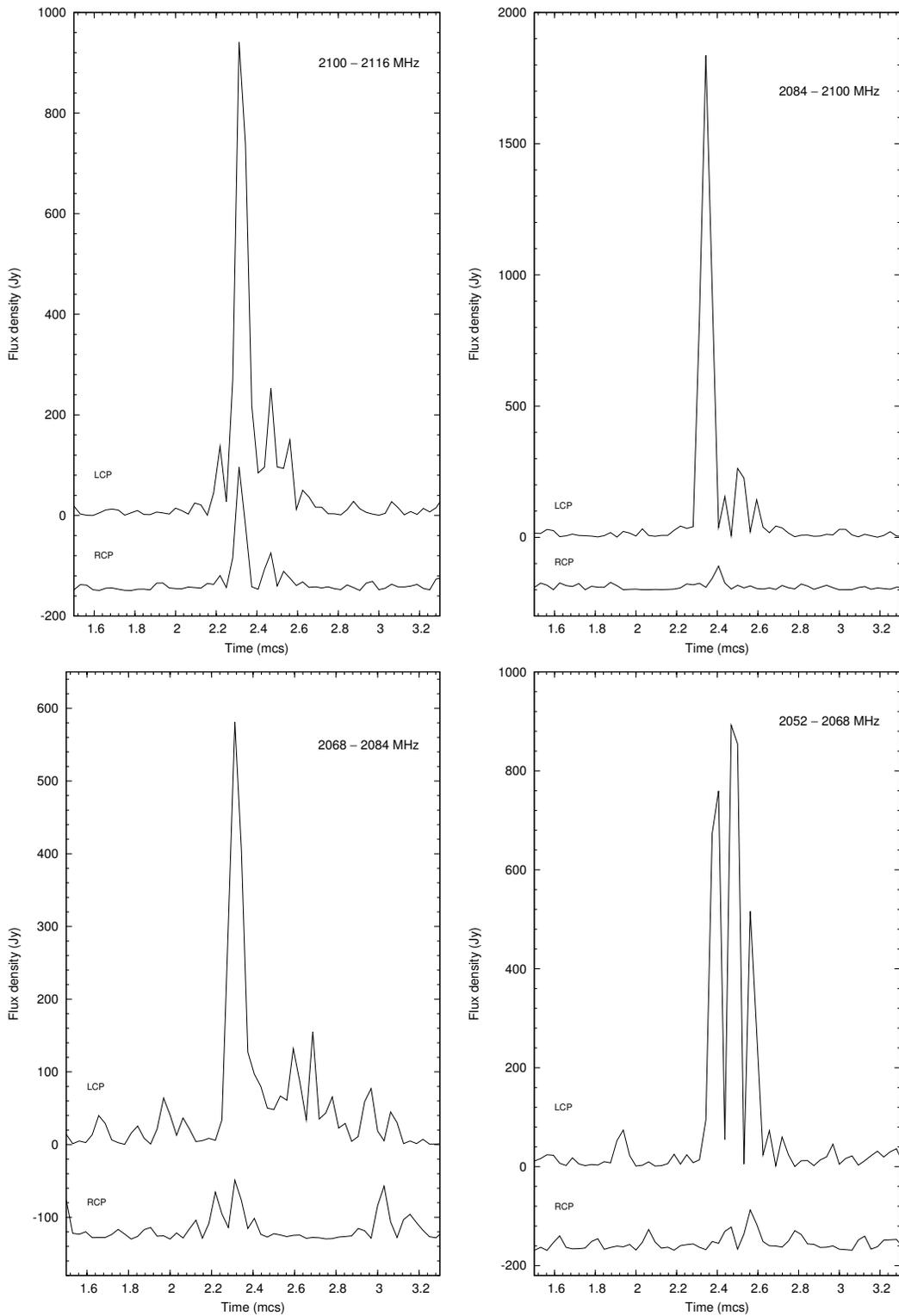


Figure 9: The strongest giant pulse of the B1937+21 in all Mark5A channels in both circular polarizations. Upper curves in each plot are in LCP, and the lower ones are in RCP. The pulsar signal is detected only in 2100–2116 MHz frequency channel for RCP. Dispersion smearing and dispersion delay are removed. Profiles are shown with original time resolution of 31.25 ns.

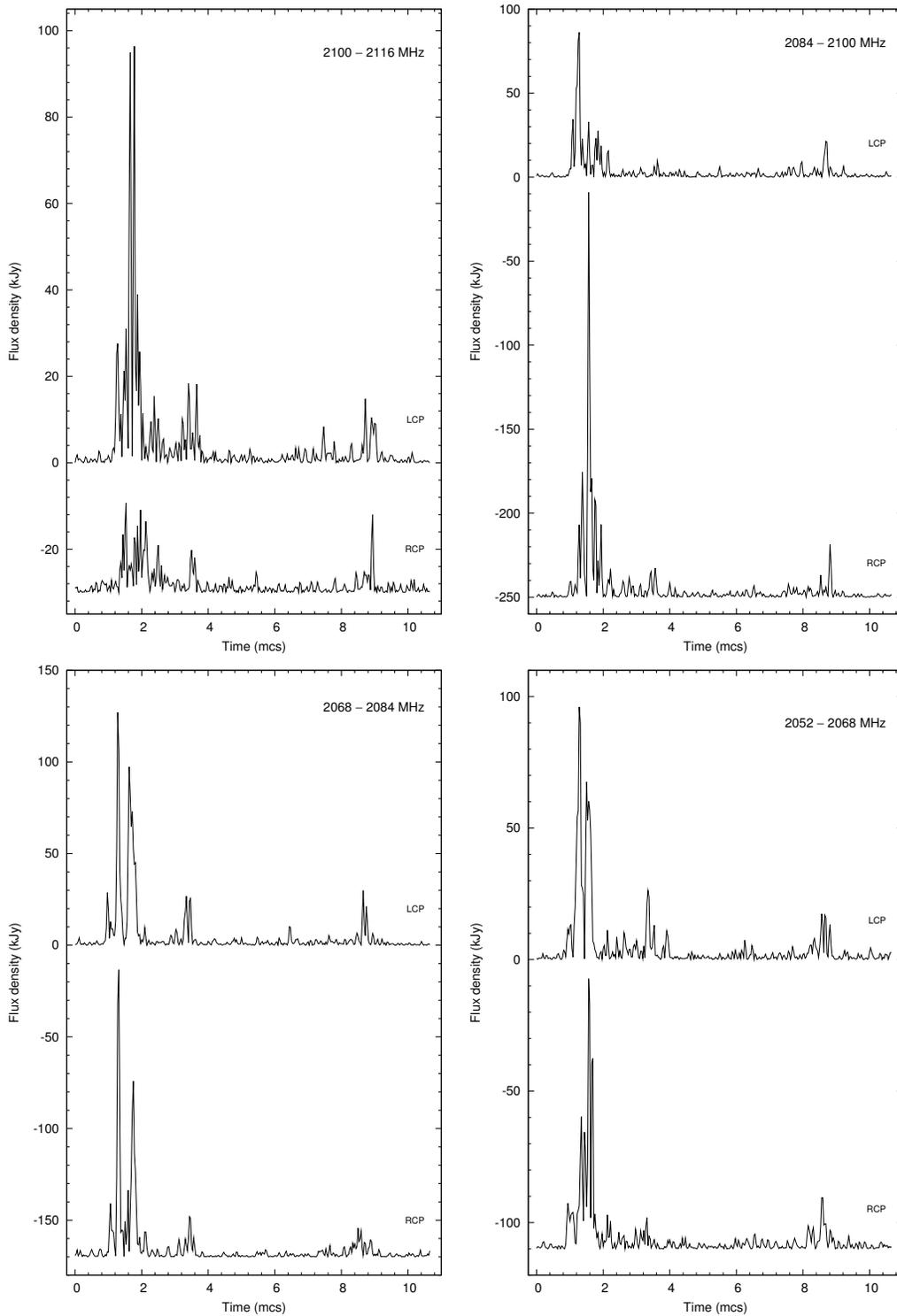


Figure 10: Full set of frequency channels from Mark5A data for Crab giant pulse presented in Figure 8. Upper curves in each plot are in LCP, and the lower ones are in RCP. Dispersion smearing and dispersion delay are removed. Profiles are shown with original time resolution of 31.25 ns. The flux density scale is determined here by Crab Nebula background emission which was taken as 710 Jy (from Kostyuk et al. 2003 for the frequency 2228 MHz).

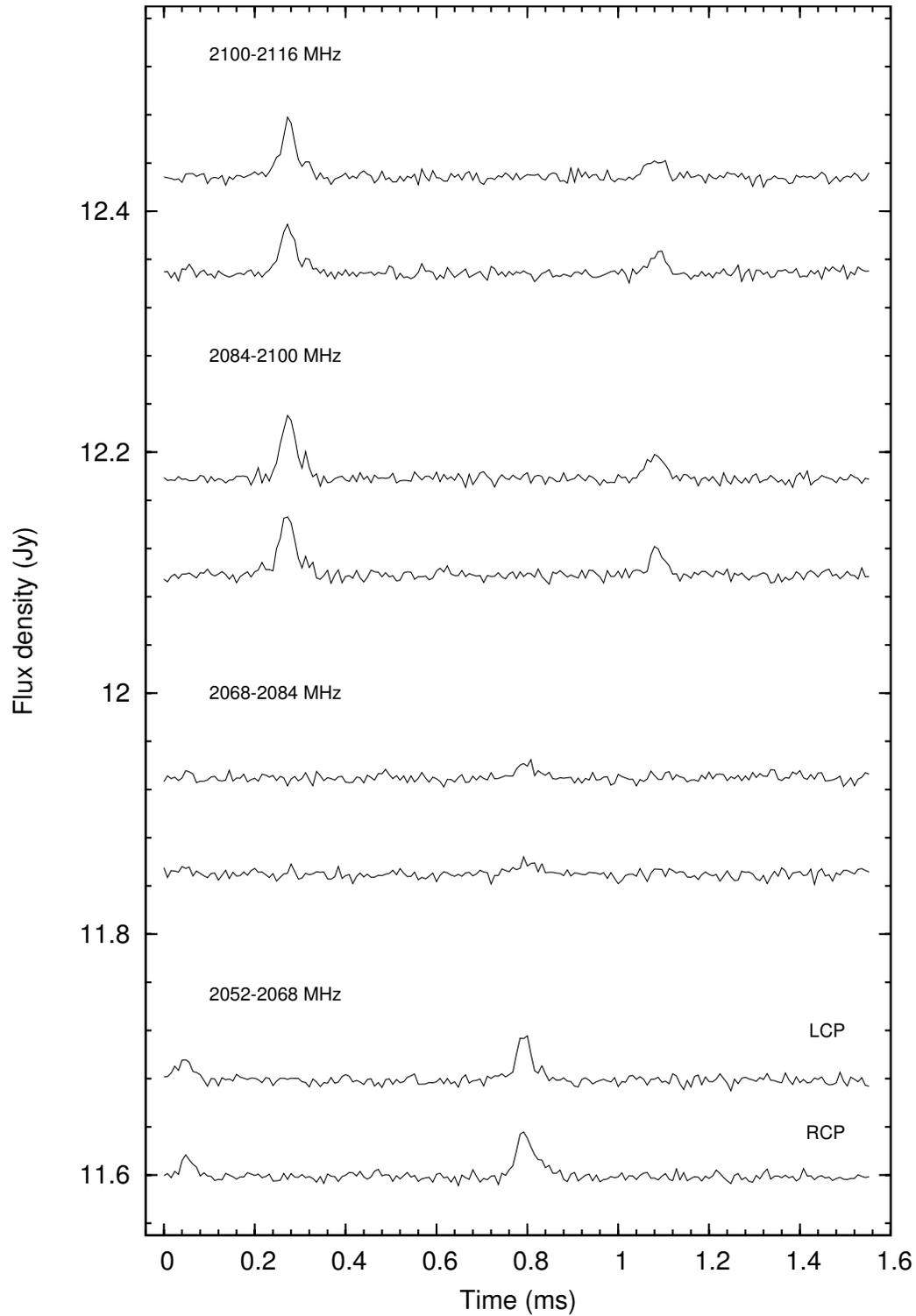


Figure 11: Profile of regular pulses for the millisecond pulsar B1937+21 in all Mark5A frequency channels in both circular polarizations. The folded time is about 210 sec. Upper curves in each set are in LCP, and the lower ones are in RCP. Dispersion smearing is removed. Dispersion delay between frequency channels centered at 2068 and 2100 MHz is not removed. Profiles are shown with time constant of $8 \mu\text{s}$. The absence of signal in frequency channel of 2068–2084 MHz is connected with interstellar scintillations.

5 Conclusions

We confirmed reliability of use of the VLBA+Mark5A and VLBA+S2 GBT backends for GBT observing with high temporal resolution. All the found features are not critical and can be taken into account in data processing.

We acknowledge Walter Brisken for helping us with data format decoding especially with demodulating pure data using pseudo-random modulation pattern.

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Appendix A: Mark5A procedures

Refer to the Mark5 memo Whitney (2004).

1. Shipping of disks is managed in the same way as for VLBA tapes:
the TRACK system is used to record when we receive a disk pack and when we ship one out.
2. Receiving disks:
Unpack the disk unit from the packing box and remove its metal covers. The disk VSN number and CRCC code is usually found on a label on the rear of the unit. Enter it in the TRACK system.
3. Shipping disks:
Put the metal covers back on, and pack it in its box, give it to Sherry to ship out. Enter the VSN and CRCC and the waybill number in the TRACK system.
4. Inserting a disk pack into the Mark5:
 - turn off the key,
 - insert the disk pack gently,
 - engage the locking handle (thing at lower left of disk pack),
 - turn on the key,
 - the lights on the disk pack should flash, and eventually all 4 lights above the disk should come on.
5. Erasing the disk:
 - if the disk has a green dot on the front, it has already been erased and there is nothing more to do,
 - if the disk has a yellow dot, it means it has been read at the correlator and is ready to be erased,
 - To erase, bring up the “rscreen” window, go to DISC/DISC/ select the desired disk pack and push the “erase” button.
6. Removing a disk pack from the Mark5:
turn off the key, pull down the locking handle, and gently pull the disk pack out of the Mark5.
7. Running an experiment:
The schedule file (`...crd.gb` file) has the commands for writing to the disk, so there is no difference in running an experiment between using tapes and using disks.

Appendix B: Transferring data between Mark5 and another Linux box

We present here notes on file transfer from Mark5 disk pack to external Raid array (see Whitney & Ball 2004 for useful Mark5 commands).

Example of doing a data transfer from Mark5 to a Raid (in this case we are going from “mark5gb” to raid array on “fourier”):

1. Take the Mark5 disk offline using “rscreen” window go to DISC/DISC and push “offline”.
2. On fourier:


```
$ cd /export/raid/scratch/ykovalev
$ Net2file -r 8388608 -f GBTtest_Feb5_2005_Mark5A_scan1
Net2file terminates itself when the transfer is done with the message Net2file: The End.
```
3. On mark5gb:


```
$ tstMark5A
> net_protocol=tcp:8388608:2097152
> disk2net=connect:fourier
> disk2net=on:<startbyte>:<endbyte>
> disk2net? (get status)
> disk2net=disconnect (disconnects the connection).
```
4. On mark5gb after data transfer finishes:


```
> disk2net=disconnect (this stops Net2file).
```

Example of doing a data transfer from a Raid to Mark5 (in this case we are going from raid array on “fourier” to “mark5gb”):

1. Take the Mark5 disk offline using “rscreen” window go to DISC/DISC and push “offline”.
2. On mark5gb:


```
$ tstMark5A
> net_protocol=tcp:8388608:2097152
> net2disk=open:newscanname
```
3. On fourier:


```
$ cd /export/raid/scratch/ykovalev
File2net -c mark5gb -f test2.data -s 8388608
The whole file “test2.data” is transferred to the mark5, apparently starting at the current write pointer location. File2net terminates itself when the transfer is done.
```
4. On mark5gb:


```
> net2disk=close
```

Source code and short description of Net2file and File2net can be found in <http://web.haystack.edu/Mark5/>

Appendix C: S2 Procedures

At this time we do not support regular VLBI schedules using the VEX schedule files. We can only support projects in which the S2 recorder is run manually. Thus we will not run a project requiring that the S2 recording be started and stopped on time scales of a few minutes. We can support a mode in which the recording is continuous for an hour or more.

S2 recording:

1. Connect the S2 data input cable to the output of sampler 1 at the back of the VLBA DAR. If the DAR is to be used in parallel with the S2, connect the S2 data output cable to the VLBA formatter sampler input 1.

Note that if the DAR is used in parallel, one can only use BBCs 1-4.

2. Insert a set of 8 S2 data VCR tapes.
3. Bring up the S2 control screen by typing: `telnet s2`
4. Make sure the S2 is in the right clock mode by:
 - > `scpll mode refclk`

Set the S2 clock to the nearest UT second. Use

 - > `time DOY-HH-MM-SS,`
 - > `time s+1,`
 - > `time s-1,`
 - > `time validate.`
5. Set the tape speed:
 - > `speed lp` gives 4 hours for tapes ST126/SE180,
 - > `speed slp` gives 6 hours for tapes ST126/SE180 and 1.5 times more for ST182/SE260.
6. Set the tape type code which is used by S2 to determine transport write-current levels:
 - > `tapetype 1` (1 — Scotch, 2 — Maxwell, 3 — Ampex, 4 — Fuji).
7. Set the tape header (optional):
 - > `Tape ID` (ID — up to 20 characters tape identifier),
 - > `User info 1 field`, > `User info 2 field`, > `User info 3 field`. In the three info fields (up to 16 characters) one can enter the telescope name, source name, band, polarization, etc.
8. Set the S2 recording mode (to be suggested by a proposer), for example:
 - > `mode 32x4-2.`
9. Start and stop recording with the > `record` and > `stop` commands.
10. When the experiment is over, remove the tapes and ship to wherever they will be processed.
11. Restore the cables to the original state.