**EE3DSD: Digital System Design (Coursework 1)**

The following report details the first work undertaken while developing a decoder for the UK MSF and German DCF77 low frequency radio clock signals using the GNU/Linux VHDL toolchain. This beginning work is focused on analysing and decoding the received clock signals and button inputs.

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# Methodology

In the laboratory session, a Spartan-6 FPGA was connected to MSF and DCF signal receivers as inputs, and the serial port output was connected via a USB adapter to the lab computer for reading and processing output. The supplied Logic Analyser VHDL sources were built using the GHDL compiler and then synthesised and uploaded to the FPGA. The minicom modem controller was then used to record logs of the incoming signals from the FPGA to disk, in the form of plaintext files containing single entry per line data in the form:

<msf> <dcf> <unused> <right btn> <left btn> <center btn> <down btn> <up btn> <timestamp>

Where timestamp was a numerical value followed by a unit to indicate the uptime of the device. All other information is encoded in single bits. For example:

0 1 1 0 0 0 0 0 0 1504.00394 ms

0 0 1 0 0 0 0 0 0 1622.44050 ms

0 1 1 0 0 0 0 0 0 2404.29367 ms

1 1 1 0 0 0 0 0 0 2409.46444 ms

0 1 1 0 0 0 0 0 0 2602.13484 ms

0 0 1 0 0 0 0 0 0 2619.81661 ms

Two trace files were captured: ‘clocks.cap’, the purpose of which was to record incoming data from the MSF and DCF receivers over the course of several minutes, and ‘buttons.cap’, which recorded the trace generated by pressing the buttons on the FPGA over the course of 5 minutes.

-rw-r--r-- 1 chris chris 93K Oct 10 22:51 buttons.cap

-rw-r--r-- 1 chris chris 125K Oct 10 22:51 clocks.cap

With the two logs recorded, the next step was to reduce the size of the dataset and focus on particular areas of interest. In the buttons trace, a range of suitable events were chosen and their timestamps noted for future reference; for the clocks trace, a one minute slice was selected, leaving 238 events to decode and analyse, with 120 originating from the MSF source (a pair of rising and falling edge events per second), and the remaining 118 from the DCF (the DCF signal doesn’t transmit anything on the 59th second of each minute, hence there are two fewer events per minute).

The supplied radio clock test signal VHDL program was then used to analyse these logs and produce a wave file for viewing in Gtkwave. A small bash script was created in order to automate the process of computing the new wave files with different trace file inputs (see Figure 1).

#!/bin/bash

usage **()** **{**

echo "Usage: $0 <tracefile>"

**}**

**if** **[** -z $1 **]**; **then**

usage

exit 1

**fi**

**if** **[** ! -f $1 **]**; **then**

echo "Trace file '$1' not found"

exit 2

**fi**

**if** **[** -f trace.cap **]**; **then**

# Backup existing trace file so as not to overwrite

mv -v trace.cap .trace.cap~

**fi**

# Copy user trace file and simulate

cp $1 trace.cap

make clean sim view

Figure runtrace.sh script for creating and viewing traces

# Analysis of clock traces

## DCF

The DCF clock signal uses a 77.05 kHz carrier frequency and a simple pulse width modulation for encoding binary digits, with a 100ms ‘on’ pulse to dictate a binary 0 and a 200ms pulse for binary 1. The signal consist of 59 bits with the last second of every minute containing no pulse modulation to mark the start of the next minute. The DCF signal contains the date, time (with daylight savings and leap second information), civil warning and weather information, and uses even parity bits to verify integrity of the received signal.

To obtain a DCF trace, the MSF data was filtered by hand from the combined trace file, leaving 118 readings which covers a minute of DCF transmission (there are 2 readings per bit, one for the rising edge and the other for the falling). Figure 2 shows the full minute transmission, with the cursor in the first screen placed on the 59th second of the previous minute.

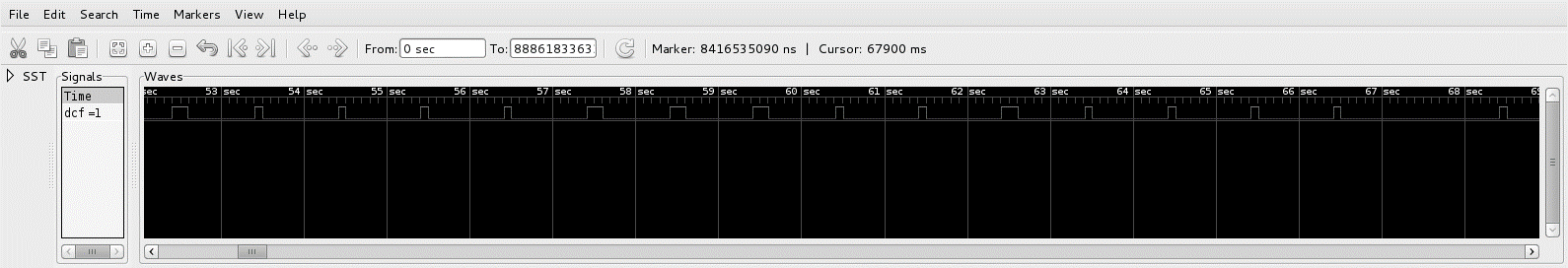
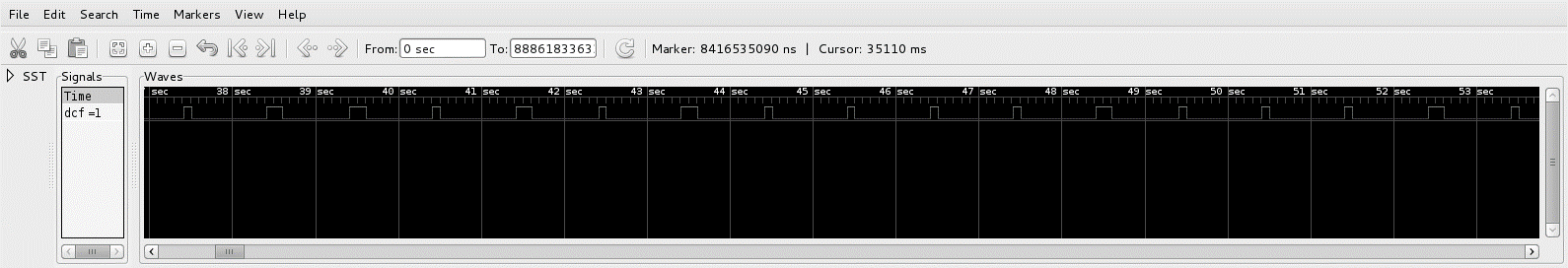
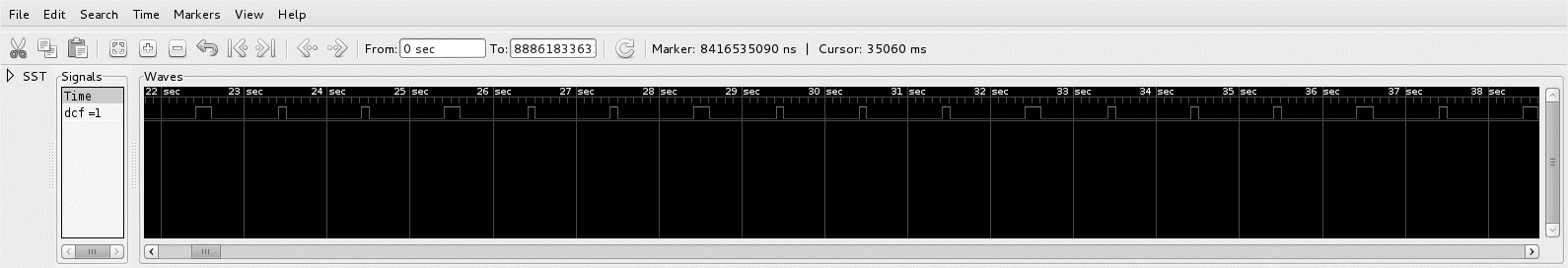
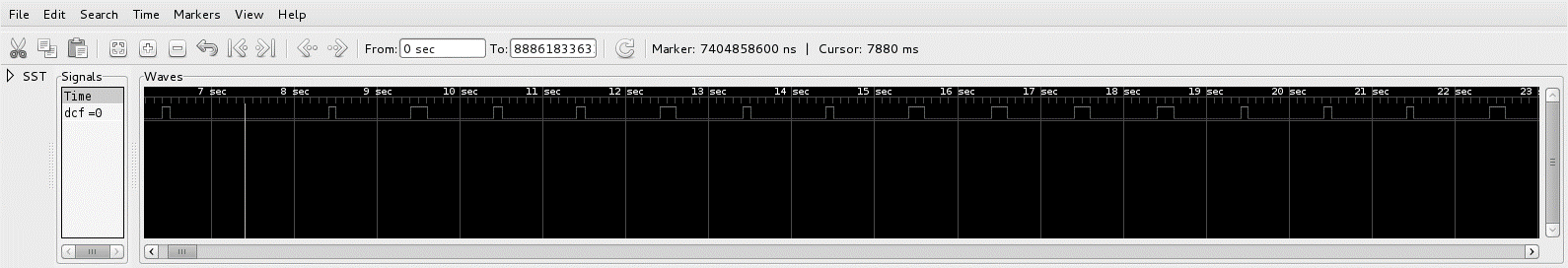


Figure A sequential series of screenshots showing a full minute of DCF transmission.

Appendix A (page 12) contains the full annotated trace file alongside information such as the bit number, pulse length and its decoded value, and the purpose of each bit. The recorded bit sequence decodes to the following message:

16:08 CEST (UTC+2), Thursday 10th October 13

### Parity Checks

The DCF transmission uses even parity bits for the minutes, hours and date message components, such that the total bit sequence always contains an even number of binary ‘1’s. Table 1 shows the parity checks for the recorded signal. If any of the rows contained a 1 in the MOD 2 column (i.e. contained an odd number of ‘1’s), we would know that there is an error in the received signal for those bits.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Bits** | **Values** | **Parity bit** | **Number of '1's** | **MOD 2** |
| Minutes (21-28) | 0 0 0 1 0 0 0 | 1 | 2 | 0 |
| Hours (29-25) | 0 1 1 0 1 0 | 1 | 4 | 0 |
| Date (36-58) | 0 0 0 0 1 0 0 0 1 0 0 0 0 1 1 1 0 0 1 0 0 0 | 0 | 6 | 0 |

Table Parity bit checks for the recorded DCF signal

## MSF

Unlike the DCF transmission, the MSF transmitter uses amplitude-shift keying to encode data by switching off the transmitter for set intervals at the beginning of the second. Each second contains ten 100 ms pieces, of which the second and third pieces (referred to as A and B, respectively) are used for transmitting two binary bits by turning off the transmitter for the allotted time to indicate a ‘1’, or leaving the transmitter on to indicate a ‘0’. The first 100 ms is always off, and the first second of each minute is denoted by 500 ms of off. This means that the MSF signal has twice the bandwidth of the DCF signal, and it is possible for up to four events to be generated in a single second, although this did not occur in our recorded trace.

To obtain an MSF trace, the DCF readings were stripped from the combined trace file (see Figure 3) so as to isolate the MSF results for analysis.

$ cp clocks.cap msf.cap

$ cat dcf.cap | \

while read entry; do

sed –i “/$entry/d” msf.cap

done

Figure Stripping DCF readings from joint trace file to leave MSF readings

Once the trace was isolated, the waveform was analysed in Gtkwave. Figure 4 shows a series of sequential screenshots showing the full minute of captured MSF signal, with the cursor in the first screenshot set at the start of the minute (the beginning of the 500 ms pulse), and cursor in the last screenshot sat at the end of the minute (the beginning of the 500 ms pulse for the next minute).

Appendix B (page 15) contains the full annotated trace file alongside information such as the bit number, the pulse widths and their decoded values, and the purpose of each bit. The MSF transmission uses three even parity bits for the minutes, hours and date message components, with the recorded bit sequence decoding to the following message:

10/10/13 15:08

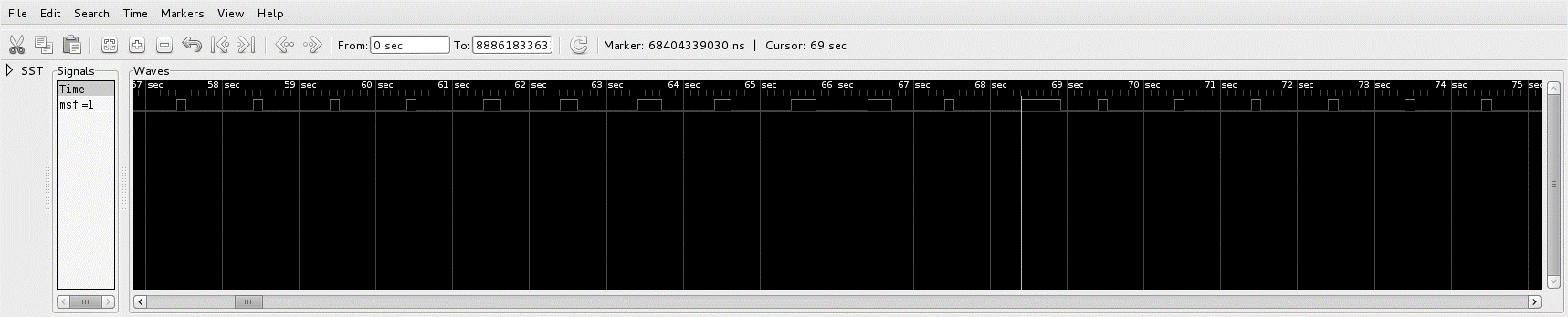
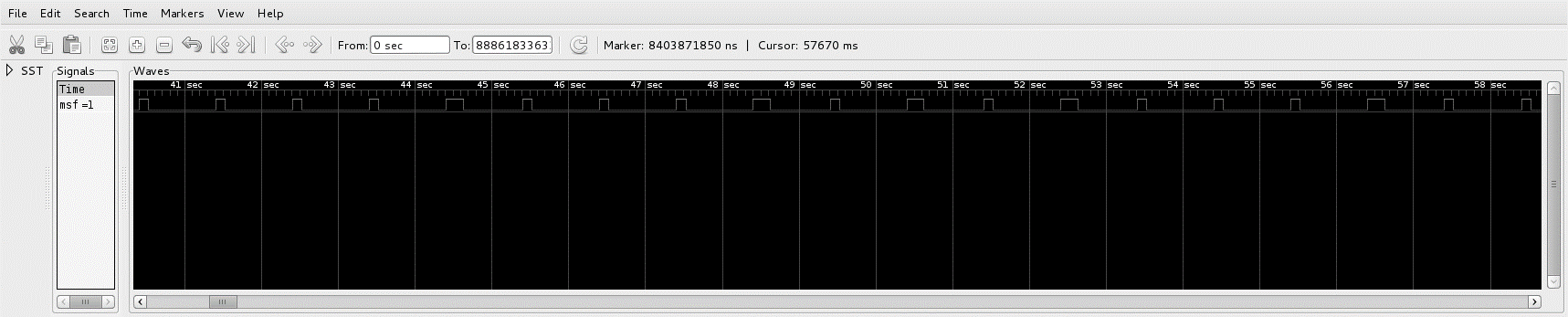
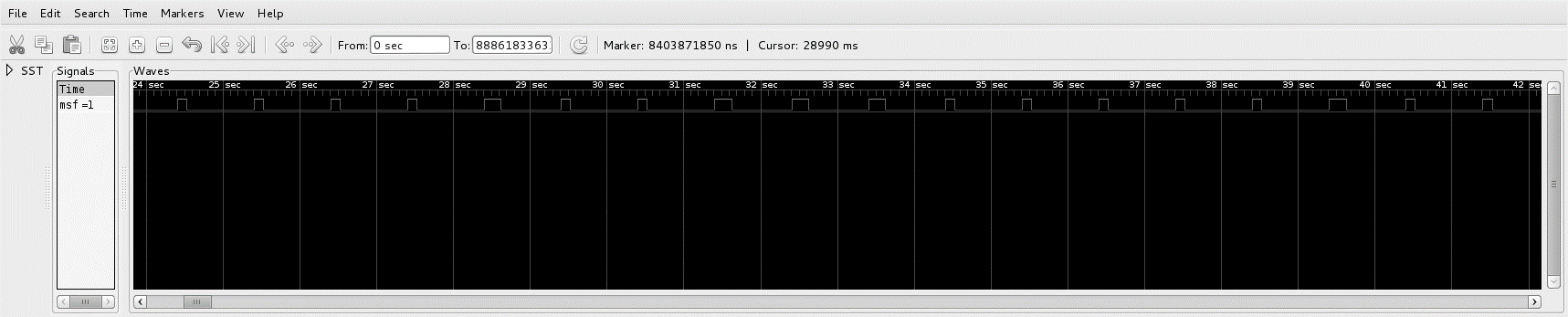
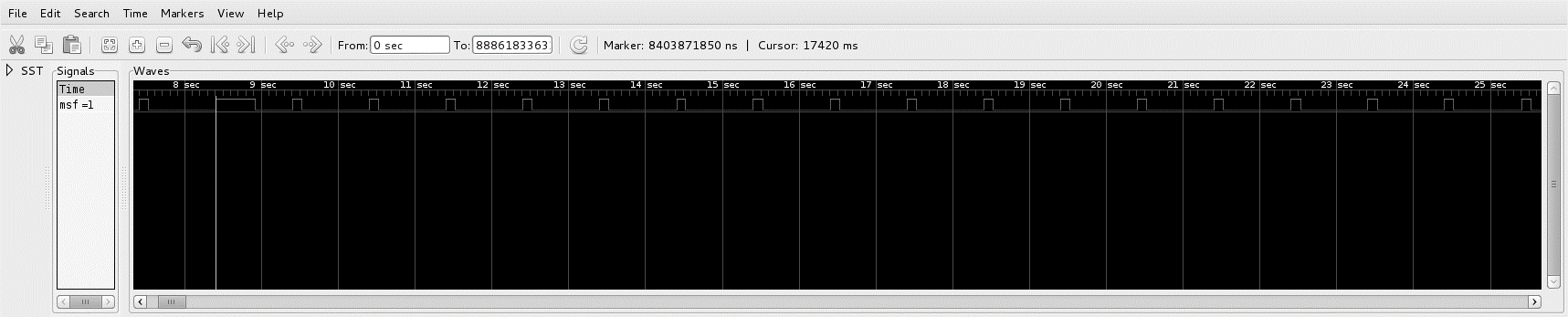


Figure A sequential series of screenshots showing a full minute of MSF transmission.

### Parity checks

Seconds 54 - 57 of the MSF signal contain four parity bits in the B (200 ms - 300 ms) bits. The MSF signal uses odd parity, so that each parity bit is set such that the number of binary 1s in any given bit sequence is always odd (including the parity bit). Table 3 shows the verified parity checks for the recorded signal. If any of the rows contained a 0 in the MOD 2 column (i.e. contained an even number of ‘1’s), we would know that there is an error in the received signal for those bits.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Bits** | **Values** | **Parity bit** | **Number of '1's** | **MOD 2** |
| Year (17A-24A) | 0 0 0 1 0 0 1 1 | 0 | 3 | 1 |
| Day (25A-35A) | 1 0 0 0 0 0 1 0 0 0 0 | 1 | 3 | 1 |
| D.O.W. (36A-38A) | 1 0 0 | 0 | 1 | 1 |
| Time (39A-51A) | 0 1 0 1 0 1 0 0 0 1 0 0 0 | 1 | 5 | 1 |

Table Parity checks for the recorded MSF signal

## Propagation times

The MSF signal is broadcast at 60 kHz (1), while the DCF77 uses a 77.5 kHz carrier signal (2), placing both signals in the Low Frequency (LF) spectrum of radio waves. At these frequencies, long wave radio propagates along the surface and sky between two points at the speed of light. At standard temperature and pressure, the speed of light is negligibly slower than in a vacuum, meaning that the theoretical propagation time can be calculated as the straight line distance between the transmitter and receiver divided by 3 × 108 m/s.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Clock** | **Transmitter** | **Receiver** | **Distance (km)** | **Propagation Time (ms)** |
| MSF | 54° 54′ 36″ N, 03° 16′ 48″ W | 52° 28′ 59″ N, 01° 53′ 37″ W | 284.9 | 0.9497 |
| DCF | 50° 00′ 56″ N, 09° 00′ 39″ E | 52° 28′ 59″ N, 01° 53′ 37″ W | 806.1 | 2.6870 |

Table Propagation times of the two clock signals (location coordinates sourced from Wikipedia)

From this we can derive an expected difference between propagation times of 1.7373 ms, or 1.7 × 108 samples on the Spartan-6 development board (at 100 MHz). To analyse the experimental data, the trace files were filtered so that just the rising edge of the per-second clock signals remained, which would act as our shared reference points for comparing the DCF and MSF signal arrival times. This left us with a set of timestamps for the DCF and MSF signals, one per second of transmission. To extract useful data from this, it was necessary to calculate the MOD 1000 of each of these values so as to remove the incrementing second component and just leave the millisecond offset as the remainder. Figure 5 shows a plot of these two sets of arrival times, with a pair of horizontal lines showing the calculated average for both clocks.

Figure A graph of the per-second arrival times of the clock signals

This showed that the MSF signal arrived at approximately 403 ms into each second, with the DCF signal arriving an average of 9 ms later. The next iteration of analysis involved subtracting the average arrival time from each of these results. This produces a per-second deviation from the average arrival time for each reading, with Figure 6 showing a plot of these results.

Figure A graph of the per-second deviation in arrival times

What is apparent from these two graphs is the difference in consistency between the arrival times of these two signals. Table 4 shows a number of different calculations based on the results, and it is apparent that in all aspects the received DCF signal shows a much greater deviation from the average arrival time than the MSF. For example, the standard deviation of the DCF signal arrival times is 332% of that of the MSF signal, and this is consistent with the increased propagation distance of 282% (Table 3). Similarly, the range of deviations is proportionally larger in the DCF arrival times than the MSF, and by extrapolating ‘per-kilometre’ values for these deviations, we can confirm that the decrease in signal quality experienced in the DCF trace is consistent with the hypothesis that this caused by the increase in signal propagation distance. See Appendix C (page 18) for a full table of the recorded and derived values.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **DCF (ms)** | **MSF (ms)** | **Difference (ms)** |
| **Average** | 412.99523 | 403.94588 | 9.04934 |
| **Standard Deviation** | 2.55910 | 0.77121 | 1.78790 |
| **Deviation range** | 9.78179 | 4.19323 | 5.58856 |
| **Median deviation** | -0.37081 | 0.06721 | 0.43801 |
| **Max deviation (early)** | -4.87598 | -1.52169 | 3.35428 |
| **Max deviation (late)** | 4.90581 | 2.67154 | 2.23428 |
| **Min deviation** | 0.01041 | 0.04465 | 0.03424 |

Table A comparison of deviations in arrival times between DCF and MSF signals

What is clear from the recorded results is that the estimated difference in arrival times between the MSF and DCF clock signals of 1.7373 ms is a lot lower than the measured difference of 9.0493 ms. The estimated value was off by a factor of 5 times, and this must be attributed to something other than purely the distance of propagation, as light in a vacuum would travel over 2700 km in that period of time. Among the possible candidates for this delay in arrival time could be the weather conditions between the DCF transmitter and our receiver, which at the time of the readings was quite severe in Europe. Other contributing factors could be a difference in the latency between the DCF and MSF receivers, or other input lag which would artificially delay the signal on one input.

## Sampling accuracy

TODO: FPGA ERROR

# Analysis of button traces

The button trace was recorded by repeatedly pressing different buttons in combination and then combing through the recorded trace to generate an average sample of events. As we were sampling the input from mechanical switches at a high frequency, contact bounce can be seen on many of the button presses, which is the phenomenon whereby the springy metals within the switch don’t immediately settle between on and off positions, instead oscillating back and forth between the two states in a seemingly random fashion for a small amount of time. The 100 MHz sampling clock of the FPGA can easily detect these bouncing events as data streams, with low pass filtering being required to remove these. See page 10 for a selection of screenshots showing these bouncing events.

The time to settle for the input buttons can be measured as the amount of time between the first change in value after pressing/releasing your finger to the end of the last bouncing oscillation. In some cases, switch bouncing does not occur, causing the switch to settle instantaneously, and

*Give typical timescales for the buttons to settle as measured from your*

*waveforms with GTKWave. Calculate the average time it takes for a button to*

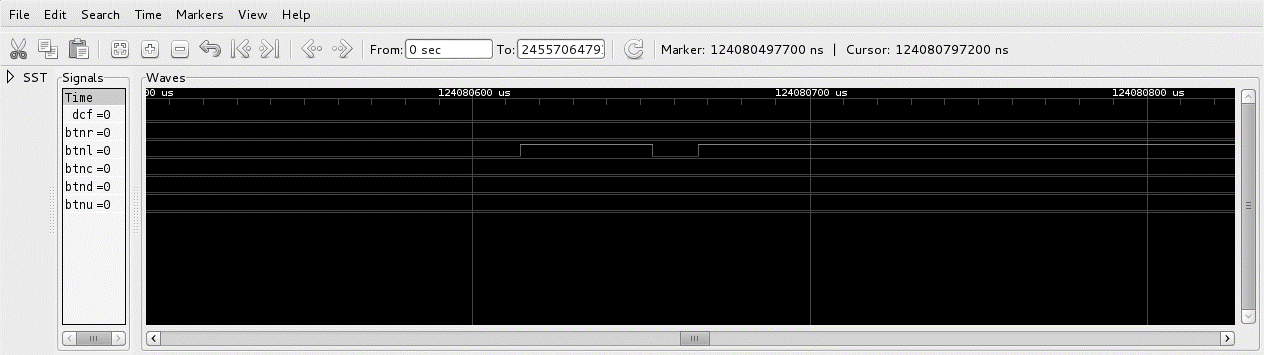
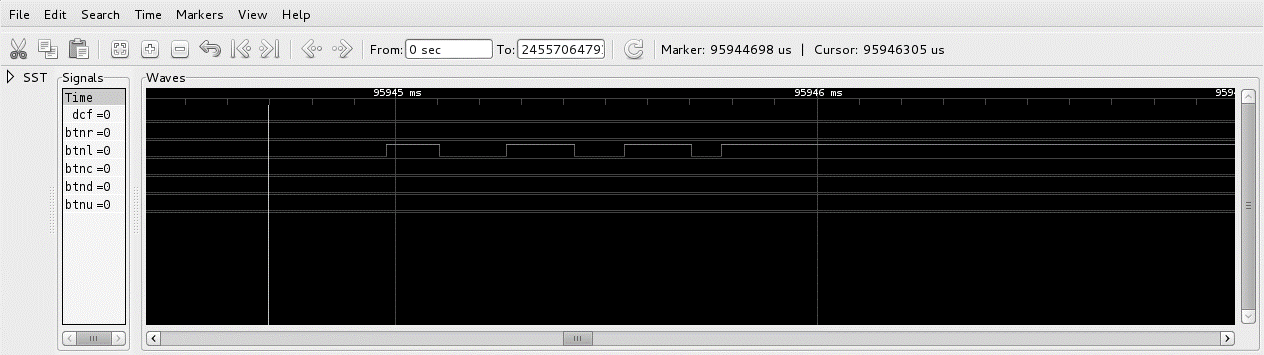
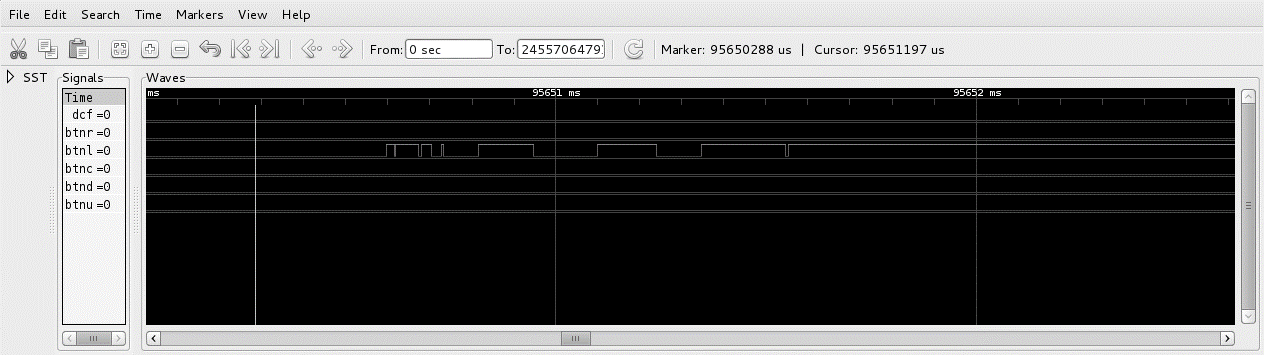
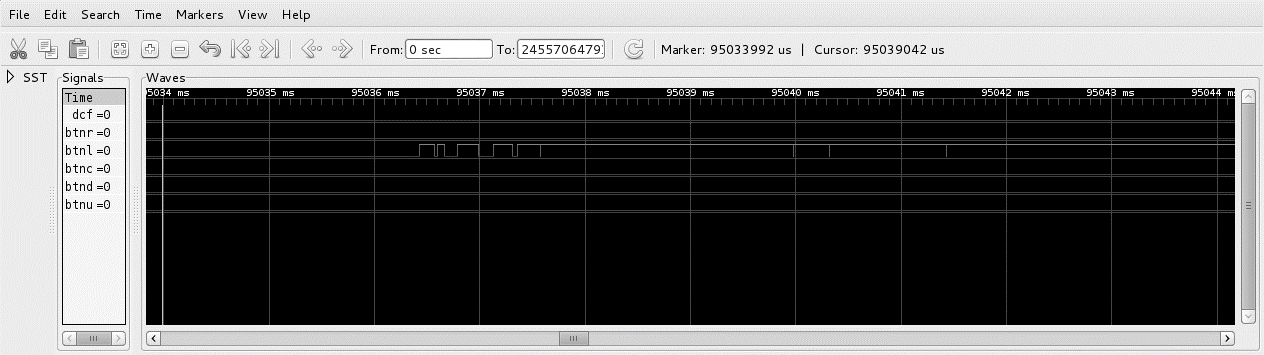
*settle with standard deviation plus minimum and maximum time. You need to*

*analyse at least 100 events to get reasonable statistics.*

## **Button bouncing**

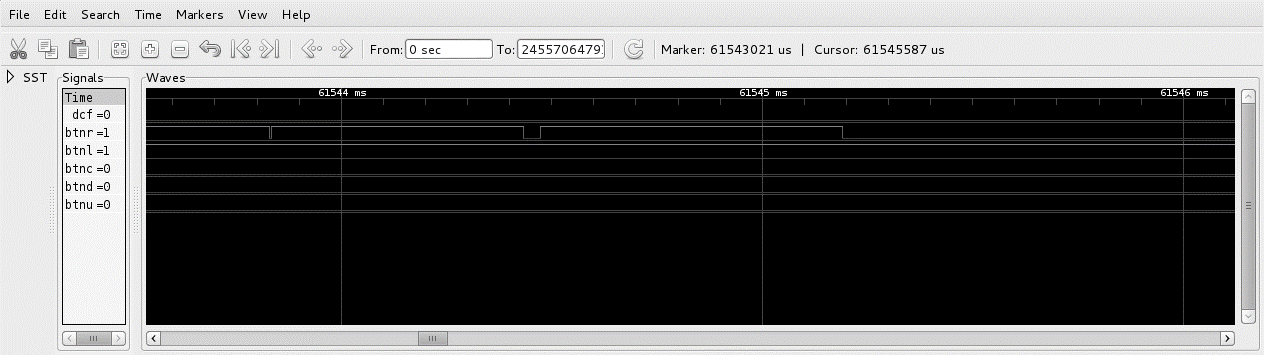
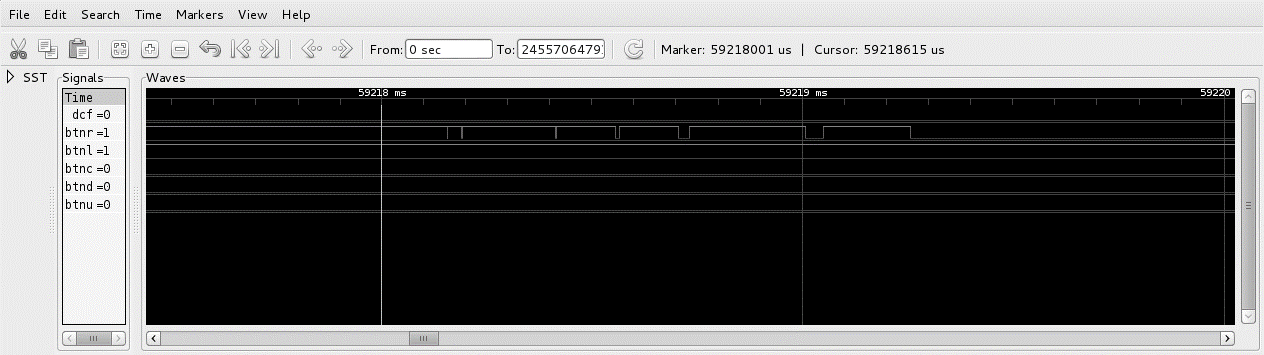
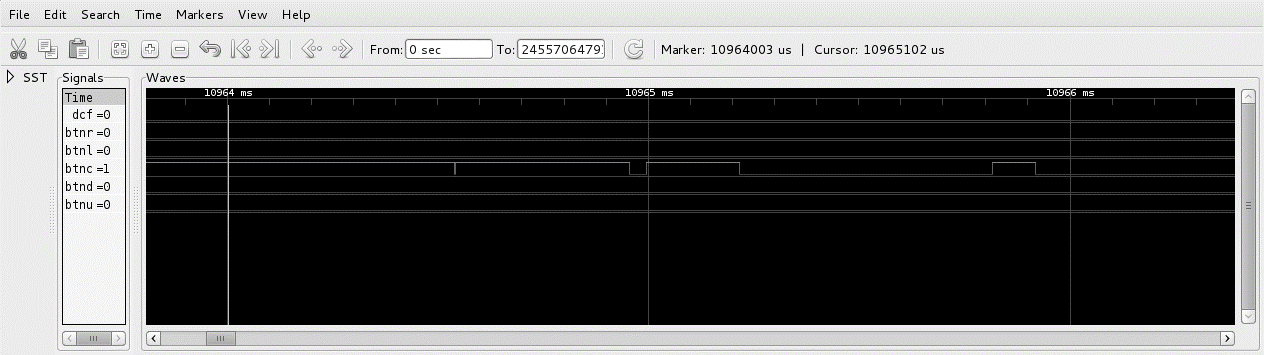
### Rising edge

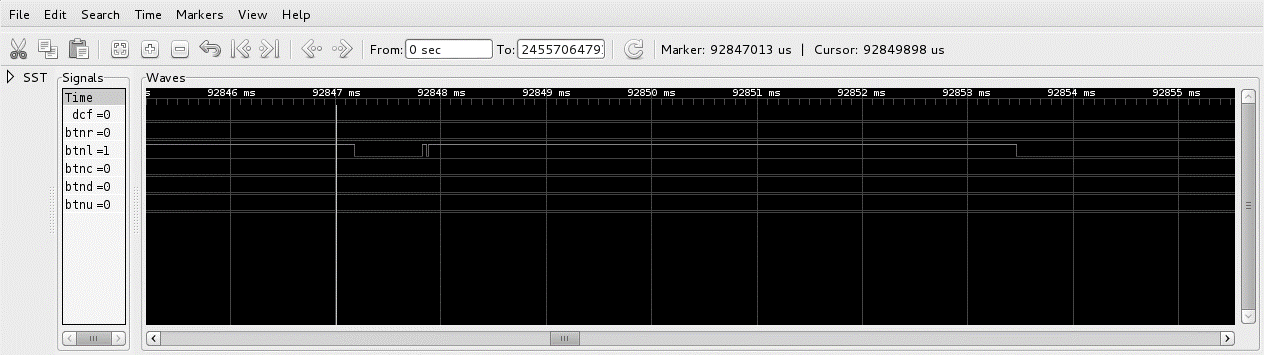
The following screenshots show four button bouncing events on the rising edge of the button press, i.e. as the button is pressed.



### Falling edge

The following screenshots show four button bouncing events on the falling edge of the button press, i.e. after the button has been released.





# Appendix A – Annotated and decoded DCF trace

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Bit** | **Pulse width (ms)** | **Value** | **Meaning** | **Weight** |
| 1 1 1 0 0 0 0 0 0 8416.53509 ms | :00 | 89.889 | **0** | Start of minute | |
| 0 1 1 0 0 0 0 0 0 8506.42440 ms |
| 1 1 1 0 0 0 0 0 0 9410.87999 ms | :01 | 196.093 | **1** | Bundesamt für Bevölkerungsschutz und Katastrophenwarnung civil warning and weather bits. | |
| 0 0 1 0 0 0 0 0 0 9606.97260 ms |
| 1 1 1 0 0 0 0 0 0 10409.72956 ms | :02 | 97.217 | **0** |
| 0 1 1 0 0 0 0 0 0 10506.94701 ms |
| 1 1 1 0 0 0 0 0 0 11408.11925 ms | :03 | 97.547 | **0** |
| 0 1 1 0 0 0 0 0 0 11505.66593 ms |
| 1 1 1 0 0 0 0 0 0 12412.53773 ms | :04 | 194.374 | **1** |
| 0 0 1 0 0 0 0 0 0 12606.91153 ms |
| 1 1 1 0 0 0 0 0 0 13413.35687 ms | :05 | 94.461 | **0** |
| 0 1 1 0 0 0 0 0 0 13507.81762 ms |
| 1 1 1 0 0 0 0 0 0 14416.62034 ms | :06 | 91.114 | **0** |
| 0 1 1 0 0 0 0 0 0 14507.73480 ms |
| 1 1 1 0 0 0 0 0 0 15409.88859 ms | :07 | 192.231 | **1** |
| 0 0 1 0 0 0 0 0 0 15602.11915 ms |
| 1 1 1 0 0 0 0 0 0 16411.74339 ms | :08 | 189.539 | **1** |
| 0 0 1 0 0 0 0 0 0 16601.28278 ms |
| 1 1 1 0 0 0 0 0 0 17411.81975 ms | :09 | 190.081 | **1** |
| 0 0 1 0 0 0 0 0 0 17601.90112 ms |
| 1 1 1 0 0 0 0 0 0 18409.60244 ms | :10 | 194.879 | **1** |
| 0 0 1 0 0 0 0 0 0 18604.48158 ms |
| 1 1 1 0 0 0 0 0 0 19415.78922 ms | :11 | 89.021 | **0** |
| 0 1 1 0 0 0 0 0 0 19504.81059 ms |
| 1 1 1 0 0 0 0 0 0 20415.81558 ms | :12 | 91.594 | **0** |
| 0 1 1 0 0 0 0 0 0 20507.40964 ms |
| 1 1 1 0 0 0 0 0 0 21414.51530 ms | :13 | 89.890 | **0** |
| 0 1 1 0 0 0 0 0 0 21504.40487 ms |
| 1 1 1 0 0 0 0 0 0 22415.59787 ms | :14 | 184.284 | **1** |
| 0 0 1 0 0 0 0 0 0 22599.88162 ms |
| 1 1 1 0 0 0 0 0 0 23414.60396 ms | :15 | 89.961 | **0** | Abnormal transmitter operation | |
| 0 1 1 0 0 0 0 0 0 23504.56446 ms |
| 1 1 1 0 0 0 0 0 0 24412.62442 ms | :16 | 92.199 | **0** | Summer time announcement | |
| 0 1 1 0 0 0 0 0 0 24504.82378 ms |
| 1 1 1 0 0 0 0 0 0 25410.82469 ms | :17 | 189.227 | **1** | CEST bit | |
| 0 0 1 0 0 0 0 0 0 25600.05206 ms |
| 1 1 1 0 0 0 0 0 0 26417.90104 ms | :18 | 88.233 | **0** | CET bit | |
| 0 1 1 0 0 0 0 0 0 26506.13445 ms |
| 1 1 1 0 0 0 0 0 0 27414.30934 ms | :19 | 93.022 | **0** | Leap second announcement | |
| 0 1 1 0 0 0 0 0 0 27507.33158 ms |
| 1 1 1 0 0 0 0 0 0 28417.63158 ms | :20 | 189.253 | **1** | Start of encoded time | |
| 0 1 1 0 0 0 0 0 0 28606.88466 ms |
| 1 1 1 0 0 0 0 0 0 29412.08879 ms | :21 | 93.192 | **0** | Minutes (0-59) | 1 |
| 0 1 1 0 0 0 0 0 0 29505.28061 ms |
| 1 1 1 0 0 0 0 0 0 30415.61355 ms | :22 | 89.810 | **0** | 2 |
| 0 1 1 0 0 0 0 0 0 30505.42330 ms |
| 1 1 1 0 0 0 0 0 0 31410.76013 ms | :23 | 97.719 | **0** | 4 |
| 0 1 1 0 0 0 0 0 0 31508.47938 ms |
| 1 1 1 0 0 0 0 0 0 32416.04544 ms | :24 | 186.735 | **1** | 8 |
| 0 1 1 0 0 0 0 0 0 32602.78078 ms |
| 1 1 1 0 0 0 0 0 0 33409.42868 ms | :25 | 97.445 | **0** | 10 |
| 0 1 1 0 0 0 0 0 0 33506.87336 ms |
| 1 1 1 0 0 0 0 0 0 34416.76350 ms | :26 | 90.498 | **0** | 20 |
| 0 1 1 0 0 0 0 0 0 34507.26182 ms |
| 1 1 1 0 0 0 0 0 0 35413.41920 ms | :27 | 94.179 | **0** | 40 |
| 0 1 1 0 0 0 0 0 0 35507.59860 ms |
| 1 1 1 0 0 0 0 0 0 36412.58461 ms | :28 | 194.701 | **1** | Parity bit for minutes | |
| 0 0 1 0 0 0 0 0 0 36607.28515 ms |
| 1 1 1 0 0 0 0 0 0 37412.79020 ms | :29 | 93.586 | **0** | Hours (0-23) | 1 |
| 0 1 1 0 0 0 0 0 0 37506.37647 ms |
| 1 1 1 0 0 0 0 0 0 38414.68335 ms | :30 | 187.826 | **1** | 2 |
| 0 0 1 0 0 0 0 0 0 38602.50950 ms |
| 1 1 1 0 0 0 0 0 0 39412.98482 ms | :31 | 195.489 | **1** | 4 |
| 0 1 1 0 0 0 0 0 0 39608.47374 ms |
| 1 1 1 0 0 0 0 0 0 40411.07808 ms | :32 | 92.371 | **0** | 8 |
| 0 1 1 0 0 0 0 0 0 40503.44868 ms |
| 1 1 1 0 0 0 0 0 0 41414.51199 ms | :33 | 189.306 | **1** | 10 |
| 0 0 1 0 0 0 0 0 0 41603.81790 ms |
| 1 1 1 0 0 0 0 0 0 42411.98859 ms | :34 | 92.753 | **0** | 20 |
| 0 1 1 0 0 0 0 0 0 42504.74114 ms |
| 1 1 1 0 0 0 0 0 0 43409.60246 ms | :35 | 193.922 | **1** | Parity bit for hours | |
| 0 0 1 0 0 0 0 0 0 43603.52495 ms |
| 1 1 1 0 0 0 0 0 0 44410.60012 ms | :36 | 97.649 | **0** | Day of month (1-31) | 1 |
| 0 1 1 0 0 0 0 0 0 44508.24911 ms |
| 1 1 1 0 0 0 0 0 0 45415.97966 ms | :37 | 86.649 | **0** | 2 |
| 0 1 1 0 0 0 0 0 0 45502.62891 ms |
| 1 1 1 0 0 0 0 0 0 46410.38667 ms | :38 | 94.852 | **0** | 4 |
| 0 1 1 0 0 0 0 0 0 46505.23869 ms |
| 1 1 1 0 0 0 0 0 0 47415.12294 ms | :39 | 89.189 | **0** | 8 |
| 0 1 1 0 0 0 0 0 0 47504.31203 ms |
| 1 1 1 0 0 0 0 0 0 48411.27513 ms | :40 | 191.798 | **1** | 10 |
| 0 1 1 0 0 0 0 0 0 48603.07266 ms |
| 1 1 1 0 0 0 0 0 0 49409.61938 ms | :41 | 96.125 | **0** | 20 |
| 0 1 1 0 0 0 0 0 0 49505.74470 ms |
| 1 1 1 0 0 0 0 0 0 50411.19757 ms | :42 | 94.749 | **0** | Day of week (Monday=1, Sunday=7) | 1 |
| 0 1 1 0 0 0 0 0 0 50505.94627 ms |
| 1 1 1 0 0 0 0 0 0 51412.42953 ms | :43 | 90.912 | **0** | 2 |
| 0 1 1 0 0 0 0 0 0 51503.34179 ms |
| 1 1 1 0 0 0 0 0 0 52412.19953 ms | :44 | 191.980 | **1** | 4 |
| 0 1 1 0 0 0 0 0 0 52604.17997 ms |
| 1 1 1 0 0 0 0 0 0 53411.11063 ms | :45 | 97.118 | **0** | Month (Junuary=1, December=12) | 1 |
| 0 1 1 0 0 0 0 0 0 53508.22833 ms |
| 1 1 1 0 0 0 0 0 0 54415.63883 ms | :46 | 89.431 | **0** | 2 |
| 0 1 1 0 0 0 0 0 0 54505.06983 ms |
| 1 1 1 0 0 0 0 0 0 55410.74412 ms | :47 | 93.990 | **0** | 4 |
| 0 1 1 0 0 0 0 0 0 55504.73368 ms |
| 1 1 1 0 0 0 0 0 0 56413.42473 ms | :48 | 90.984 | **0** | 8 |
| 0 1 1 0 0 0 0 0 0 56504.40834 ms |
| 1 1 1 0 0 0 0 0 0 57416.47699 ms | :49 | 187.405 | **1** | 10 |
| 0 0 1 0 0 0 0 0 0 57603.88238 ms |
| 1 1 1 0 0 0 0 0 0 58410.03573 ms | :50 | 192.006 | **1** | Year within century (0-99) | 1 |
| 0 0 1 0 0 0 0 0 0 58602.04190 ms |
| 1 1 1 0 0 0 0 0 0 59412.00920 ms | :51 | 191.950 | **1** | 2 |
| 0 0 1 0 0 0 0 0 0 59603.95935 ms |
|  |  |  |  |  |
| 1 1 1 0 0 0 0 0 0 60415.08350 ms | :52 | 89.909 | **0** | 4 |
| 0 1 1 0 0 0 0 0 0 60504.99266 ms |
| 1 1 1 0 0 0 0 0 0 61409.73421 ms | :53 | 98.532 | **0** | 8 |
| 0 1 1 0 0 0 0 0 0 61508.26582 ms |
| 1 1 1 0 0 0 0 0 0 62408.25061 ms | :54 | 198.685 | **1** | 10 |
| 0 1 1 0 0 0 0 0 0 62606.93558 ms |
| 1 1 1 0 0 0 0 0 0 63416.36916 ms | :55 | 90.905 | **0** | 20 |
| 0 1 1 0 0 0 0 0 0 63507.27450 ms |
| 1 1 1 0 0 0 0 0 0 64415.17233 ms | :56 | 93.909 | **0** | 40 |
| 0 1 1 0 0 0 0 0 0 64509.08096 ms |
| 1 1 1 0 0 0 0 0 0 65414.34857 ms | :57 | 95.016 | **0** | 80 |
| 0 1 1 0 0 0 0 0 0 65509.36495 ms |
| 1 1 1 0 0 0 0 0 0 66414.71985 ms | :58 | 85.762 | **0** | Parity bit for date | |
| 0 1 1 0 0 0 0 0 0 66500.48195 ms |
|  | :59 | Minute mark (no transmission) | | | |
|  |

# Appendix B – Annotated and decoded MSF trace

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Bit** | **Pulse width (ms)** | **Value** | | **Meaning** | **Weight** |
| 0 1 1 0 0 0 0 0 0 8403.87185 ms | :00 | 511.916 | **1** | **1** | Start of minute | |
| 0 0 1 0 0 0 0 0 0 8915.78745 ms |
| 0 1 1 0 0 0 0 0 0 9404.05309 ms | :01 | 117.240 | **0** | **0** | Difference between atomic and astronomical time [second bits] | |
| 1 0 1 0 0 0 0 0 0 9521.29280 ms |
| 0 1 1 0 0 0 0 0 0 10403.30498 ms | :02 | 116.572 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 10519.87661 ms |
| 0 1 1 0 0 0 0 0 0 11404.31966 ms | :03 | 117.607 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 11521.92692 ms |
| 0 1 1 0 0 0 0 0 0 12403.73795 ms | :04 | 120.473 | **0** | **0** |
| 1 0 1 0 0 0 0 0 0 12524.21140 ms |
| 0 1 1 0 0 0 0 0 0 13404.07834 ms | :05 | 119.561 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 13523.63912 ms |
| 0 1 1 0 0 0 0 0 0 14405.51386 ms | :06 | 115.902 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 14521.41579 ms |
| 0 1 1 0 0 0 0 0 0 15403.40349 ms | :07 | 120.233 | **0** | **0** |
| 1 0 1 0 0 0 0 0 0 15523.63599 ms |
| 0 1 1 0 0 0 0 0 0 16403.53274 ms | :08 | 120.686 | **0** | **0** |
| 1 0 1 0 0 0 0 0 0 16524.21878 ms |
| 0 1 1 0 0 0 0 0 0 17403.79082 ms | :09 | 119.454 | **0** | **0** |
| 1 0 1 0 0 0 0 0 0 17523.24484 ms |
| 0 1 1 0 0 0 0 0 0 18404.13745 ms | :10 | 119.664 | **0** | **0** |
| 1 0 1 0 0 0 0 0 0 18523.80126 ms |
| 0 1 1 0 0 0 0 0 0 19404.40239 ms | :11 | 119.999 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 19524.40122 ms |
| 0 1 1 0 0 0 0 0 0 20403.66107 ms | :12 | 122.973 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 20526.63417 ms |
| 0 1 1 0 0 0 0 0 0 21403.50552 ms | :13 | 118.924 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 21522.42994 ms |
| 0 1 1 0 0 0 0 0 0 22404.34025 ms | :14 | 123.228 | **0** | **0** |
| 1 0 1 0 0 0 0 0 0 22527.56826 ms |
| 0 1 1 0 0 0 0 0 0 23405.53151 ms | :15 | 120.509 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 23526.04040 ms |
| 0 1 1 0 0 0 0 0 0 24404.73271 ms | :16 | 117.901 | **0** | **0** |
| 0 0 1 0 0 0 0 0 0 24522.63352 ms |
| 0 1 1 0 0 0 0 0 0 25404.53240 ms | :17 | 120.153 | **0** | **0** | Year (0-99) [first bit] | 80 |
| 1 0 1 0 0 0 0 0 0 25524.68512 ms |
| 0 1 1 0 0 0 0 0 0 26404.11237 ms | :18 | 117.143 | **0** | **0** | 40 |
| 0 0 1 0 0 0 0 0 0 26521.25572 ms |
| 0 1 1 0 0 0 0 0 0 27404.78847 ms | :19 | 118.751 | **0** | **0** | 20 |
| 0 0 1 0 0 0 0 0 0 27523.53910 ms |
| 0 1 1 0 0 0 0 0 0 28403.29960 ms | :20 | 218.087 | **1** | **0** | 10 |
| 0 0 1 0 0 0 0 0 0 28621.38617 ms |
| 0 1 1 0 0 0 0 0 0 29404.98603 ms | :21 | 114.197 | **0** | **0** | 8 |
| 0 0 1 0 0 0 0 0 0 29519.18318 ms |
| 0 1 1 0 0 0 0 0 0 30403.99053 ms | :22 | 116.578 | **0** | **0** | 4 |
| 0 0 1 0 0 0 0 0 0 30520.56886 ms |
| 0 1 1 0 0 0 0 0 0 31402.73757 ms | :23 | 221.458 | **1** | **0** | 2 |
| 0 0 1 0 0 0 0 0 0 31624.19593 ms |
| 0 1 1 0 0 0 0 0 0 32404.04370 ms | :24 | 221.206 | **1** | **0** | 1 |
| 0 0 1 0 0 0 0 0 0 32625.24932 ms |
| 0 1 1 0 0 0 0 0 0 33404.52206 ms | :25 | 216.633 | **1** | **0** | Month (Junuary=1, December=12) [first bit] | 10 |
| 0 0 1 0 0 0 0 0 0 33621.15473 ms |
| 0 1 1 0 0 0 0 0 0 34402.98641 ms | :26 | 122.805 | **0** | **0** | 8 |
| 0 0 1 0 0 0 0 0 0 34525.79122 ms |
| 0 1 1 0 0 0 0 0 0 35402.78801 ms | :27 | 117.504 | **0** | **0** | 4 |
| 0 0 1 0 0 0 0 0 0 35520.29223 ms |
| 0 1 1 0 0 0 0 0 0 36402.42748 ms | :28 | 121.682 | **0** | **0** | 2 |
| 1 0 1 0 0 0 0 0 0 36524.10908 ms |
| 0 1 1 0 0 0 0 0 0 37403.27151 ms | :29 | 120.362 | **0** | **0** | 1 |
| 0 0 1 0 0 0 0 0 0 37523.63313 ms |
| 0 1 1 0 0 0 0 0 0 38403.79993 ms | :30 | 118.527 | **0** | **0** | Day of month (1-31) [first bit] | 20 |
| 1 0 1 0 0 0 0 0 0 38522.32689 ms |
| 0 1 1 0 0 0 0 0 0 39404.28279 ms | :31 | 218.140 | **1** | **0** | 10 |
| 0 0 1 0 0 0 0 0 0 39622.42251 ms |
| 0 1 1 0 0 0 0 0 0 40403.26730 ms | :32 | 121.058 | **0** | **0** | 8 |
| 0 0 1 0 0 0 0 0 0 40524.32520 ms |
| 0 1 1 0 0 0 0 0 0 41404.08546 ms | :33 | 120.392 | **0** | **0** | 4 |
| 1 0 1 0 0 0 0 0 0 41524.47723 ms |
| 0 1 1 0 0 0 0 0 0 42404.74387 ms | :34 | 116.341 | **0** | **0** | 2 |
| 0 0 1 0 0 0 0 0 0 42521.08473 ms |
| 0 1 1 0 0 0 0 0 0 43404.07292 ms | :35 | 120.663 | **0** | **0** | 1 |
| 1 0 1 0 0 0 0 0 0 43524.73613 ms |
| 0 1 1 0 0 0 0 0 0 44403.74363 ms | :36 | 219.743 | **1** | **0** | Day of week (Sunday=0, Saturday=6) [first bit] | 4 |
| 0 0 1 0 0 0 0 0 0 44623.48674 ms |
| 0 1 1 0 0 0 0 0 0 45403.56600 ms | :37 | 122.408 | **0** | **0** | 2 |
| 0 0 1 0 0 0 0 0 0 45525.97427 ms |
| 0 1 1 0 0 0 0 0 0 46404.52919 ms | :38 | 116.216 | **0** | **0** | 1 |
| 0 0 1 0 0 0 0 0 0 46520.74478 ms |
| 0 1 1 0 0 0 0 0 0 47404.55663 ms | :39 | 122.231 | **0** | **0** | Hour (0-23) [first bit] | 20 |
| 0 0 1 0 0 0 0 0 0 47526.78751 ms |
| 0 1 1 0 0 0 0 0 0 48402.42419 ms | :40 | 220.335 | **1** | **0** | 10 |
| 0 0 1 0 0 0 0 0 0 48622.75960 ms |
| 0 1 1 0 0 0 0 0 0 49403.31116 ms | :41 | 119.284 | **0** | **0** | 8 |
| 0 0 1 0 0 0 0 0 0 49522.59521 ms |
| 0 1 1 0 0 0 0 0 0 50403.04044 ms | :42 | 216.917 | **1** | **0** | 4 |
| 0 0 1 0 0 0 0 0 0 50619.95766 ms |
| 0 1 1 0 0 0 0 0 0 51403.34427 ms | :43 | 119.292 | **0** | **0** | 2 |
| 0 0 1 0 0 0 0 0 0 51522.63615 ms |
| 0 1 1 0 0 0 0 0 0 52403.66275 ms | :44 | 223.783 | **1** | **0** | 1 |
| 0 0 1 0 0 0 0 0 0 52627.44613 ms |
| 0 1 1 0 0 0 0 0 0 53406.61742 ms | :45 | 117.309 | **0** | **0** | Minute (0-59) [first bit] | 40 |
| 0 0 1 0 0 0 0 0 0 53523.92594 ms |
| 0 1 1 0 0 0 0 0 0 54404.01701 ms | :46 | 116.630 | **0** | **0** | 20 |
| 0 0 1 0 0 0 0 0 0 54520.64675 ms |
| 0 1 1 0 0 0 0 0 0 55404.03588 ms | :47 | 118.762 | **0** | **0** | 10 |
| 0 0 1 0 0 0 0 0 0 55522.79830 ms |
| 0 1 1 0 0 0 0 0 0 56404.53851 ms | :48 | 216.369 | **1** | **0** | 8 |
| 0 0 1 0 0 0 0 0 0 56620.90784 ms |
| 0 1 1 0 0 0 0 0 0 57403.61524 ms | :49 | 119.707 | **0** | **0** | 4 |
| 1 0 1 0 0 0 0 0 0 57523.32185 ms |
| 0 1 1 0 0 0 0 0 0 58404.59686 ms | :50 | 118.685 | **0** | **0** | 2 |
| 1 0 1 0 0 0 0 0 0 58523.28222 ms |
| 0 1 1 0 0 0 0 0 0 59402.87444 ms | :51 | 123.304 | **0** | **0** | 1 |
| 1 0 1 0 0 0 0 0 0 59526.17809 ms |
|  |  |  |  |  |  |  |
| 0 1 1 0 0 0 0 0 0 60403.17447 ms | :52 | 120.556 | **0** | **0** | Minute marker [first bits: 01111110] | |
| 0 0 1 0 0 0 0 0 0 60523.73041 ms |
| 0 1 1 0 0 0 0 0 0 61403.23465 ms | :53 | 217.388 | **1** | **0** | Summer time warning [second bit] | |
| 0 0 1 0 0 0 0 0 0 61620.62223 ms |
| 0 1 1 0 0 0 0 0 0 62404.82368 ms | :54 | 217.114 | **1** | **0** | Parity bit for year [second bit] | |
| 0 0 1 0 0 0 0 0 0 62621.93731 ms |
| 0 1 1 0 0 0 0 0 0 63404.00917 ms | :55 | 316.747 | **1** | **1** | Parity bit for day [second bit] | |
| 0 0 1 0 0 0 0 0 0 63720.75587 ms |
| 0 1 1 0 0 0 0 0 0 64404.48939 ms | :56 | 217.008 | **1** | **0** | Parity bit for DOW [second bit] | |
| 0 0 1 0 0 0 0 0 0 64621.49705 ms |
| 0 1 1 0 0 0 0 0 0 65404.09733 ms | :57 | 319.278 | **1** | **1** | Parity bit for time [second bit] | |
| 0 0 1 0 0 0 0 0 0 65723.37542 ms |
| 0 1 1 0 0 0 0 0 0 66403.27600 ms | :58 | 313.312 | **1** | **1** | Summer time in effect [second bit] | |
| 0 0 1 0 0 0 0 0 0 66716.58800 ms |
| 0 1 1 0 0 0 0 0 0 67404.51864 ms | :59 | 117.783 | **0** | **0** | Unused | |
| 0 0 1 0 0 0 0 0 0 67522.30132 ms |

# Appendix C – Clock signal arrival times

A comparison of signal arrival times per second between DCF and MSF clocks (all units in ms).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Bit** | **DCF** | | | **MSF** | | |
| **Time** | **MOD 1000** | **Deviation** | **Time** | **MOD 1000** | **Deviation** |
| :00 | 8416.53509 | 416.53509 | 3.53986 | 8403.87185 | 403.87185 | -0.07403 |
| :01 | 9410.87999 | 410.87999 | -2.11524 | 9404.05309 | 404.05309 | 0.10721 |
| :02 | 10409.72956 | 409.72956 | -3.26567 | 10403.30498 | 403.30498 | -0.64090 |
| :03 | 11408.11925 | 408.11925 | -4.87598 | 11404.31966 | 404.31966 | 0.37378 |
| :04 | 12412.53773 | 412.53773 | -0.45750 | 12403.73795 | 403.73795 | -0.20793 |
| :05 | 13413.35687 | 413.35687 | 0.36164 | 13404.07834 | 404.07834 | 0.13246 |
| :06 | 14416.62034 | 416.62034 | 3.62511 | 14405.51386 | 405.51386 | 1.56798 |
| :07 | 15409.88859 | 409.88859 | -3.10664 | 15403.40349 | 403.40349 | -0.54239 |
| :08 | 16411.74339 | 411.74339 | -1.25184 | 16403.53274 | 403.53274 | -0.41314 |
| :09 | 17411.81975 | 411.81975 | -1.17548 | 17403.79082 | 403.79082 | -0.15506 |
| :10 | 18409.60244 | 409.60244 | -3.39279 | 18404.13745 | 404.13745 | 0.19157 |
| :11 | 19415.78922 | 415.78922 | 2.79399 | 19404.40239 | 404.40239 | 0.45651 |
| :12 | 20415.81558 | 415.81558 | 2.82035 | 20403.66107 | 403.66107 | -0.28481 |
| :13 | 21414.51530 | 414.51530 | 1.52007 | 21403.50552 | 403.50552 | -0.44036 |
| :14 | 22415.59787 | 415.59787 | 2.60264 | 22404.34025 | 404.34025 | 0.39437 |
| :15 | 23414.60396 | 414.60396 | 1.60873 | 23405.53151 | 405.53151 | 1.58563 |
| :16 | 24412.62442 | 412.62442 | -0.37081 | 24404.73271 | 404.73271 | 0.78683 |
| :17 | 25410.82469 | 410.82469 | -2.17054 | 25404.53240 | 404.53240 | 0.58652 |
| :18 | 26417.90104 | 417.90104 | 4.90581 | 26404.11237 | 404.11237 | 0.16649 |
| :19 | 27414.30934 | 414.30934 | 1.31411 | 27404.78847 | 404.78847 | 0.84259 |
| :20 | 28417.63158 | 417.63158 | 4.63635 | 28403.29960 | 403.29960 | -0.64628 |
| :21 | 29412.08879 | 412.08879 | -0.90644 | 29404.98603 | 404.98603 | 1.04015 |
| :22 | 30415.61355 | 415.61355 | 2.61832 | 30403.99053 | 403.99053 | 0.04465 |
| :23 | 31410.76013 | 410.76013 | -2.23510 | 31402.73757 | 402.73757 | -1.20831 |
| :24 | 32416.04544 | 416.04544 | 3.05021 | 32404.04370 | 404.04370 | 0.09782 |
| :25 | 33409.42868 | 409.42868 | -3.56655 | 33404.52206 | 404.52206 | 0.57618 |
| :26 | 34416.76350 | 416.76350 | 3.76827 | 34402.98641 | 402.98641 | -0.95947 |
| :27 | 35413.41920 | 413.41920 | 0.42397 | 35402.78801 | 402.78801 | -1.15787 |
| :28 | 36412.58461 | 412.58461 | -0.41062 | 36402.42748 | 402.42748 | -1.51840 |
| :29 | 37412.79020 | 412.79020 | -0.20503 | 37403.27151 | 403.27151 | -0.67437 |
| :30 | 38414.68335 | 414.68335 | 1.68812 | 38403.79993 | 403.79993 | -0.14595 |
| :31 | 39412.98482 | 412.98482 | -0.01041 | 39404.28279 | 404.28279 | 0.33691 |
| :32 | 40411.07808 | 411.07808 | -1.91715 | 40403.26730 | 403.26730 | -0.67858 |
| :33 | 41414.51199 | 414.51199 | 1.51676 | 41404.08546 | 404.08546 | 0.13958 |
| :34 | 42411.98859 | 411.98859 | -1.00664 | 42404.74387 | 404.74387 | 0.79799 |
| :35 | 43409.60246 | 409.60246 | -3.39277 | 43404.07292 | 404.07292 | 0.12704 |
| :36 | 44410.60012 | 410.60012 | -2.39511 | 44403.74363 | 403.74363 | -0.20225 |
| :37 | 45415.97966 | 415.97966 | 2.98443 | 45403.56600 | 403.56600 | -0.37988 |
| :38 | 46410.38667 | 410.38667 | -2.60856 | 46404.52919 | 404.52919 | 0.58331 |
| :39 | 47415.12294 | 415.12294 | 2.12771 | 47404.55663 | 404.55663 | 0.61075 |
| :40 | 48411.27513 | 411.27513 | -1.72010 | 48402.42419 | 402.42419 | -1.52169 |
| :41 | 49409.61938 | 409.61938 | -3.37585 | 49403.31116 | 403.31116 | -0.63472 |
| :42 | 50411.19757 | 411.19757 | -1.79766 | 50403.04044 | 403.04044 | -0.90544 |
| :43 | 51412.42953 | 412.42953 | -0.56570 | 51403.34427 | 403.34427 | -0.60161 |
| :44 | 52412.19953 | 412.19953 | -0.79570 | 52403.66275 | 403.66275 | -0.28313 |
| :45 | 53411.11063 | 411.11063 | -1.88460 | 53406.61742 | 406.61742 | 2.67154 |
| :46 | 54415.63883 | 415.63883 | 2.64360 | 54404.01701 | 404.01701 | 0.07113 |
| :47 | 55410.74412 | 410.74412 | -2.25111 | 55404.03588 | 404.03588 | 0.09000 |
| :48 | 56413.42473 | 413.42473 | 0.42950 | 56404.53851 | 404.53851 | 0.59263 |
| :49 | 57416.47699 | 416.47699 | 3.48176 | 57403.61524 | 403.61524 | -0.33064 |
| :50 | 58410.03573 | 410.03573 | -2.95950 | 58404.59686 | 404.59686 | 0.65098 |
| :51 | 59412.00920 | 412.00920 | -0.98603 | 59402.87444 | 402.87444 | -1.07144 |
| :52 | 60415.08350 | 415.08350 | 2.08827 | 60403.17447 | 403.17447 | -0.77141 |
| :53 | 61409.73421 | 409.73421 | -3.26102 | 61403.23465 | 403.23465 | -0.71123 |
| :54 | 62408.25061 | 408.25061 | -4.74462 | 62404.82368 | 404.82368 | 0.87780 |
| :55 | 63416.36916 | 416.36916 | 3.37393 | 63404.00917 | 404.00917 | 0.06329 |
| :56 | 64415.17233 | 415.17233 | 2.17710 | 64404.48939 | 404.48939 | 0.54351 |
| :57 | 65414.34857 | 414.34857 | 1.35334 | 65404.09733 | 404.09733 | 0.15145 |
| :58 | 66414.71985 | 414.71985 | 1.72462 | 66403.27600 | 403.27600 | -0.66988 |
| :59 |  |  |  | 67404.51864 | 404.51864 | 0.57276 |

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