Digital Signal Processing Lab Report

Novel Approach to Real-Time Digital Signal Processing of Stereo Audio

Tarig Mustafa[1], Haseeb Malik[1], Jakub Mandula[1], Kevin Golan[1]

April 5, 2019

Abstract

The following report is composed of two main sections. Real-time audio processing with software, and a proposed high-level hardware design for real-time stereo audio processing. The software section of this report includes sample code to exercise the real-time performance of the Analog Devices ADSP-BF706 device. Applications explored include fractional channel gain manipulation, volume control, 16-bit bandpass and 32-bit stopband finite impulse response filtration, with corresponding coefficients, and sinusoidal generation. The aim of the hardware design is to create a stand-alone system capable of supporting the bandwidth requirements of studio-quality music; outlining key components, high-level connectivity and data flow.

[1]University of Manchester, School of EEE

Contents

1 Lab exercises

1.1 Exercises 1

Listing 1: *ex1-gain1.asm* - Multiplies the left cannel by 3.7

```
/*
Program gain1 is a simple inout program but multiplies the left channel by 3.7
Author: Patrick Gaydecki (modified by Haseeb Malik, Jakub Mandula, Tarig Mustafa, Kevin Golan)
Date  : 12.10.2017 (modified 5/3/19)
*/

.section program;
.align 4;
.global _main;
#include <defBF706.h>

_main:
call codec_configure;
call sport_configure;

R3.H=0.925r;              // Setting constant value to intially multiply sample with (0.925 =
    3.7/2^(2))

get_audio:
wait_left:
// Wait left flag in and read
R0=[REG_SPORT0_CTL_B]; CC=BITTST(R0, 31); if !CC jump wait_left;
R0=[REG_SPORT0_RXPRI_B];

// Left channel code added for Excersise 1
R0 <<= 0x02;              // Multiplying sample value by 4 via bit shifting
R2=R0*R3;               // Multiplying resultant value by 0.925

// Write left out, R2=3.7*R0
[REG_SPORT0_TXPRI_A]=R2;
wait_right:
// Wait right flag in and read
R0=[REG_SPORT0_CTL_B]; CC=BITTST(R0, 31); if !CC jump wait_right;
// Write right out
R0=[REG_SPORT0_RXPRI_B]; [REG_SPORT0_TXPRI_A]=R0;
jump get_audio;
rts;
._main.end:

// Function codec_configure initialises the ADAU1761 codec. Refer to the control register
// descriptions, page 51 onwards of the ADAU1761 data sheet.

codec_configure:
[--SP] = RETS; // Push stack (only for nested calls)
R1=0x01(X); R0=0x4000(X); call TWI_write; // Enable master clock, disable PLL
R1=0x7f(X); R0=0x40f9(X); call TWI_write; // Enable all clocks
R1=0x03(X); R0=0x40fa(X); call TWI_write; // Enable all clocks
R1=0x01(X); R0=0x4015(X); call TWI_write; // Set serial port master mode
R1=0x13(X); R0=0x4019(X); call TWI_write; // Set ADC to on, both channels
R1=0x21(X); R0=0x401c(X); call TWI_write; // Enable left channel mixer
R1=0x41(X); R0=0x401e(X); call TWI_write; // Enable right channel mixer
R1=0x03(X); R0=0x4029(X); call TWI_write; // Turn on power, both channels
R1=0x03(X); R0=0x402a(X); call TWI_write; // Set both DACs on
R1=0x01(X); R0=0x40f2(X); call TWI_write; // DAC gets L, R input from serial port
R1=0x01(X); R0=0x40f3(X); call TWI_write; // ADC sends L, R input to serial port
R1=0x0b(X); R0=0x400a(X); call TWI_write; // Set left line-in gain to 0 dB
R1=0x0b(X); R0=0x400c(X); call TWI_write; // Set right line-in gain to 0 dB
R1=0xe7(X); R0=0x4023(X); call TWI_write; // Set left headphone volume to 0 dB
R1=0xe7(X); R0=0x4024(X); call TWI_write; // Set right headphone volume to 0 dB
R1=0x00(X); R0=0x4017(X); call TWI_write; // Set codec default sample rate, 48 kHz
nop;
RETS = [SP++];                          // Pop stack (only for nested calls)
rts;
codec_configure.end:

// Function sport_configure initialises the SPORT0. Refer to pages 26-59, 26-67,
// 26-75 and 26-76 of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
```

```
sport_configure:
R0=0x3F0(X); [REG_PORTC_FER]=R0;          // Set up Port C in peripheral mode
R0=0x3F0(X); [REG_PORTC_FER_SET]=R0;      // Set up Port C in peripheral mode
R0=0x2001973; [REG_SPORT0_CTL_A]=R0;      // Set up SPORT0 (A) as TX to codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_A]=R0;      // 64 bits per frame, clock divisor of 1
R0=0x1973(X); [REG_SPORT0_CTL_B]=R0;      // Set up SPORT0 (B) as RX frm codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_B]=R0;      // 64 bits per frame, clock divisor of 1
rts;
sport_configure.end:

// Function TWI_write is a simple driver for the TWI. Refer to page 24-15 onwards
// of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
TWI_write:
R3=R0 <<0x8; R0=R0 >>>0x8; R2=R3|R0;      // Reverse low order and high order bytes
R0=0x3232(X); [REG_TWI0_CLKDIV]=R0;       // Set duty cycle
R0=0x008c(X); [REG_TWI0_CTL]=R0;          // Set pre-scale and enable TWI
R0=0x0038(X); [REG_TWI0_MSTRADDR]=R0;     // Address of codec
[REG_TWI0_TXDATA16]=R2;                   // Address of register to set, LSB then MSB
R0=0x00c1(X); [REG_TWI0_MSTRCTL]=R0;      // Command to send three bytes and enable TX
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
[REG_TWI0_TXDATA8]=R1;                    // Data to write
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x050; [REG_TWI0_ISTAT]=R0;            // Clear TXERV interrupt
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x010; [REG_TWI0_ISTAT]=R0;            // Clear MCOMP interrupt
rts;
TWI_write.end:

// Function delay introduces a delay to allow TWI communication
delay:
p0=0x8000;
loop lc0=p0;
nop; nop; nop;
loop_end;
rts;
delay.end:
```

1.2 Exercises 2

Listing 2: *ex2-gain2.asm* - Reduce the left channel by 4dB by configuring the codec

```
/*
Program gain2 is a simple inout program but reduces the gain on the left channel by 4 dB, (i.e. 0.631)
using a command to the codec

Author: Patrick Gaydecki (modified by Haseeb Malik, Jakub Mandula, Tarig Mustafa, Kevin Golan - Modied line 48)
Date  : 15.10.2017 (modified 5/3/19)
*/

.section program;
.align 4;
.global _main;
#include <defBF706.h>

_main:
call codec_configure;
call sport_configure;
get_audio:
wait_left:
// Wait left flag in and read
R0=[REG_SPORT0_CTL_B]; CC=BITTST(R0, 31); if !CC jump wait_left;
// Write left out
R0=[REG_SPORT0_RXPRI_B]; [REG_SPORT0_TXPRI_A]=R0;
wait_right:
// Wait right flag in and read
R0=[REG_SPORT0_CTL_B]; CC=BITTST(R0, 31); if !CC jump wait_right;
// Write right out
R0=[REG_SPORT0_RXPRI_B]; [REG_SPORT0_TXPRI_A]=R0;
jump get_audio;
._main.end:

// Function codec_configure initialises the ADAU1761 codec. Refer to the control register
// descriptions, page 51 onwards of the ADAU1761 data sheet.
codec_configure:
[--SP] = RETS; // Push stack (only for nested calls)
R1=0x01(X); R0=0x4000(X); call TWI_write; // Enable master clock, disable PLL
R1=0x7f(X); R0=0x40f9(X); call TWI_write; // Enable all clocks
R1=0x03(X); R0=0x40fa(X); call TWI_write; // Enable all clocks
R1=0x01(X); R0=0x4015(X); call TWI_write; // Set serial port master mode
R1=0x13(X); R0=0x4019(X); call TWI_write; // Set ADC to on, both channels
R1=0x21(X); R0=0x401c(X); call TWI_write; // Enable left channel mixer
R1=0x41(X); R0=0x401e(X); call TWI_write; // Enable right channel mixer
R1=0x03(X); R0=0x4029(X); call TWI_write; // Turn on power, both channels
R1=0x03(X); R0=0x402a(X); call TWI_write; // Set both DACs on
R1=0x01(X); R0=0x40f2(X); call TWI_write; // DAC gets L, R input from serial port
R1=0x01(X); R0=0x40f3(X); call TWI_write; // ADC sends L, R input to serial port
R1=0x0b(X); R0=0x400a(X); call TWI_write; // Set left line-in gain to 0 dB
R1=0x0b(X); R0=0x400c(X); call TWI_write; // Set right line-in gain to 0 dB
R1=0xd7(X); R0=0x4023(X); call TWI_write; // Set left headphone volume to -4 dB
R1=0xe7(X); R0=0x4024(X); call TWI_write; // Set right headphone volume to 0 dB
R1=0x00(X); R0=0x4017(X); call TWI_write; // Set codec default sample rate, 48 kHz
nop;
RETS = [SP++];                            // Pop stack (only for nested calls)
rts;
codec_configure.end:

// Function sport_configure initialises the SPORT0. Refer to pages 26-59, 26-67,
// 26-75 and 26-76 of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
sport_configure:
R0=0x3F0(X); [REG_PORTC_FER]=R0;          // Set up Port C in peripheral mode
R0=0x3F0(X); [REG_PORTC_FER_SET]=R0;      // Set up Port C in peripheral mode
R0=0x2001973; [REG_SPORT0_CTL_A]=R0;      // Set up SPORT0 (A) as TX to codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_A]=R0;      // 64 bits per frame, clock divisor of 1
R0=0x1973(X); [REG_SPORT0_CTL_B]=R0;      // Set up SPORT0 (B) as RX frm codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_B]=R0;      // 64 bits per frame, clock divisor of 1
rts;
sport_configure.end:

// Function TWI_write is a simple driver for the TWI. Refer to page 24-15 onwards
// of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
TWI_write:
```

```
R3=R0 <<0x8; R0=R0 >>>0x8; R2=R3|R0;      // Reverse low order and high order bytes
R0=0x3232(X); [REG_TWI0_CLKDIV]=R0;       // Set duty cycle
R0=0x008c(X); [REG_TWI0_CTL]=R0;          // Set pre-scale and enable TWI
R0=0x0038(X); [REG_TWI0_MSTRADDR]=R0;     // Address of codec
[REG_TWI0_TXDATA16]=R2;                   // Address of register to set, LSB then MSB
R0=0x00c1(X); [REG_TWI0_MSTRCTL]=R0;      // Command to send three bytes and enable TX
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
[REG_TWI0_TXDATA8]=R1;                    // Data to write
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x050; [REG_TWI0_ISTAT]=R0;            // Clear TXERV interrupt
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x010; [REG_TWI0_ISTAT]=R0;            // Clear MCOMP interrupt
rts;
TWI_write.end:

// Function delay introduces a delay to allow TWI communication
delay:
p0=0x8000;
loop lc0=p0;
nop; nop; nop;
loop_end;
rts;
delay.end:
```

1.3 Exercises 3

Listing 3: *ex3-modulate.asm* - Produces pure and double side band amplitude modulation of right channel with left channel.

```
/*
Program modulate takes data from both codec input channels and generates the following ouputs:
Right channel out = left x right (pure modulation)
Left channel out =  right + (left x right) (double sideband amplitude modulation, or DSBAM

Author: Patrick Gaydecki (modified by Haseeb Malik, Jakub Mandula, Tarig Mustafa, Kevin Golan)
Date  : 28.09.2017 (modified 5/3/19)
*/

.section program;
.align 4;
.global _main;
#include <defBF706.h>

_main:
call codec_configure;
call sport_configure;

get_audio:
wait_left:
// Wait left flag in
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_left;
// Read and modulate. Note codec is 24-bit;
R0=[REG_SPORT0_RXPRI_B];

// Left channel Code added for Excersise 3
R2=R0*R1;     // Left in * Right in (to excercise spec)
R2<<=0x08;      // Shifting as DAC is 24 Bit(32-24=8)
R2=R1+R2;       // Setting output to (Right in + (Left in * Right in))

// Write left out
[REG_SPORT0_TXPRI_A]=R2;
wait_right:
// Wait right flag in
R1=[REG_SPORT0_CTL_B];
CC=BITTST(R1, 31);
if !CC jump wait_right;
// Read and modulate. Note codec is 24-bit;
// Also add carrier
R1=[REG_SPORT0_RXPRI_B];

// Right channel code added
R2=R0*R1;     // Left in * Right in (to excercise spec)
R2<<=0x08;      // Setting output to (Left in * Right in) and Shifting as DAC is 24 Bit

[REG_SPORT0_TXPRI_A]=R2; // Write right out
jump get_audio;
._main.end:

// Function codec_configure initialises the ADAU1761 codec. Refer to the control register
// descriptions, page 51 onwards of the ADAU1761 data sheet.
codec_configure:
[--SP] = RETS; // Push stack (only for nested calls)
R1=0x01(X); R0=0x4000(X); call TWI_write; // Enable master clock, disable PLL
R1=0x7f(X); R0=0x40f9(X); call TWI_write; // Enable all clocks
R1=0x03(X); R0=0x40fa(X); call TWI_write; // Enable all clocks
R1=0x01(X); R0=0x4015(X); call TWI_write; // Set serial port master mode
R1=0x13(X); R0=0x4019(X); call TWI_write; // Set ADC to on, both channels
R1=0x21(X); R0=0x401c(X); call TWI_write; // Enable left channel mixer
R1=0x41(X); R0=0x401e(X); call TWI_write; // Enable right channel mixer
R1=0x03(X); R0=0x4029(X); call TWI_write; // Turn on power, both channels
R1=0x03(X); R0=0x402a(X); call TWI_write; // Set both DACs on
R1=0x01(X); R0=0x40f2(X); call TWI_write; // DAC gets L, R input from serial port
R1=0x01(X); R0=0x40f3(X); call TWI_write; // ADC sends L, R input to serial port
R1=0x0b(X); R0=0x400a(X); call TWI_write; // Set left line-in gain to 0 dB
R1=0x0b(X); R0=0x400c(X); call TWI_write; // Set right line-in gain to 0 dB
R1=0xe7(X); R0=0x4023(X); call TWI_write; // Set left headphone volume to 0 dB
R1=0xe7(X); R0=0x4024(X); call TWI_write; // Set right headphone volume to 0 dB
```

```
R1=0x00(X); R0=0x4017(X); call TWI_write; // Set codec default sample rate, 48 kHz
nop;
RETS = [SP++];                            // Pop stack (only for nested calls)
rts;
codec_configure.end:

// Function sport_configure initialises the SPORT0. Refer to pages 26-59, 26-67,
// 26-75 and 26-76 of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
sport_configure:
R0=0x3F0(X); [REG_PORTC_FER]=R0;          // Set up Port C in peripheral mode
R0=0x3F0(X); [REG_PORTC_FER_SET]=R0;      // Set up Port C in peripheral mode
R0=0x2001973; [REG_SPORT0_CTL_A]=R0;      // Set up SPORT0 (A) as TX to codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_A]=R0;      // 64 bits per frame, clock divisor of 1
R0=0x1973(X); [REG_SPORT0_CTL_B]=R0;      // Set up SPORT0 (B) as RX frm codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_B]=R0;      // 64 bits per frame, clock divisor of 1
rts;
sport_configure.end:

// Function TWI_write is a simple driver for the TWI. Refer to page 24-15 onwards
// of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
TWI_write:
R3=R0 <<0x8; R0=R0 >>>0x8; R2=R3|R0;      // Reverse low order and high order bytes
R0=0x3232(X); [REG_TWI0_CLKDIV]=R0;       // Set duty cycle
R0=0x008c(X); [REG_TWI0_CTL]=R0;          // Set pre-scale and enable TWI
R0=0x0038(X); [REG_TWI0_MSTRADDR]=R0;     // Address of codec
[REG_TWI0_TXDATA16]=R2;                   // Address of register to set, LSB then MSB
R0=0x00c1(X); [REG_TWI0_MSTRCTL]=R0;      // Command to send three bytes and enable TX
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
[REG_TWI0_TXDATA8]=R1;                    // Data to write
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x050; [REG_TWI0_ISTAT]=R0;            // Clear TXERV interrupt
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x010; [REG_TWI0_ISTAT]=R0;            // Clear MCOMP interrupt
rts;
TWI_write.end:

// Function delay introduces a delay to allow TWI communication
delay:
p0=0x8000;
loop lc0=p0;
nop; nop; nop;
loop_end;
rts;
delay.end:
```

1.4 Exercises 4

Listing 4: *ex4-filter1.asm* - Applies a FIR filter to the output signal coefficients created by Signal Wizard.

```
/*
Program filter1 is a single MAC FIR filtering program. It reads in a file of coefficients created by
    Signal Wizard.

Author: Patrick Gaydecki (modified by Haseeb Malik, Jakub Mandula, Tarig Mustafa, Kevin Golan)
Date  : 29.09.2017 (modified 5/3/19)
*/

.section L1_data_b;                    // Linker places data starting at 0x11900000
.BYTE2 filter[] = "filter1.txt";    // Importing co-efficients file as a byte array
.section program;
.global _main;
.align 4;
# include <defBF706.h>

_main:
call codec_configure;
call sport_configure;
P0=length(filter)*2;
// Set up circular buffers

I0=0x11800000; B0=I0; L0=P0;
I1=0x11900000; B1=I1; L1=P0;

P0 = length(filter)-1;                  // Sets P0 to the number of coeffs in the filter minus 1 (one
    n-1 are done in the loop)

get_audio:
wait_left:
// Wait for left data then read
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_left;
R0=[REG_SPORT0_RXPRI_B];
// Convolution kernel

//Setting up Circular buffer for FIR Filter and Filtering
A0 = 0 || W[I0++]= R0.H|| R1.H = W[I1++];       // Retrieving the first sample and filter coeff
LOOP LC0=P0;                          // Starting of iterator (iterating through coeffs and previous
    samples - to carry out convolution)
A0+= R0.H * R1.H || R0.H = W[I0++] || R1.H = W[I1++];   // Filtering the Input (.H used as 16 bit
    FIR in excercise spec)
LOOP_END;                          // Concluding iterator
A0+= R0.H * R1.H||I0-=2;                // Backtracking 2 bytes due to overshoot

//Writing left out
R0=A0; [REG_SPORT0_TXPRI_A]=R0;

wait_right:
// Wait for right data then read
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_right;
R0=[REG_SPORT0_RXPRI_B];
//Write right out
[REG_SPORT0_TXPRI_A]=R0;
jump get_audio;
rts;
._main.end:

// Function codec_configure initialises the ADAU1761 codec. Refer to the control register
// descriptions, page 51 onwards of the ADAU1761 data sheet.
codec_configure:
[--SP] = RETS;                             // Push stack (only for nested calls)
R1=0x01(X); R0=0x4000(X); call TWI_write; // Enable master clock, disable PLL
R1=0x7f(X); R0=0x40f9(X); call TWI_write; // Enable all clocks
R1=0x03(X); R0=0x40fa(X); call TWI_write; // Enable all clocks
R1=0x01(X); R0=0x4015(X); call TWI_write; // Set serial port master mode
R1=0x13(X); R0=0x4019(X); call TWI_write; // Set ADC to on, both channels
R1=0x21(X); R0=0x401c(X); call TWI_write; // Enable left channel mixer
```

```
R1=0x41(X); R0=0x401e(X); call TWI_write; // Enable right channel mixer
R1=0x03(X); R0=0x4029(X); call TWI_write; // Turn on power, both channels
R1=0x03(X); R0=0x402a(X); call TWI_write; // Set both DACs on
R1=0x01(X); R0=0x40f2(X); call TWI_write; // DAC gets L, R input from serial port
R1=0x01(X); R0=0x40f3(X); call TWI_write; // ADC sends L, R input to serial port
R1=0x0b(X); R0=0x400a(X); call TWI_write; // Set left line-in gain to 0 dB
R1=0x0b(X); R0=0x400c(X); call TWI_write; // Set right line-in gain to 0 dB
R1=0xe7(X); R0=0x4023(X); call TWI_write; // Set left headphone volume to 0 dB
R1=0xe7(X); R0=0x4024(X); call TWI_write; // Set right headphone volume to 0 dB
R1=0x00(X); R0=0x4017(X); call TWI_write; // Set codec default sample rate, 48 kHz
NOP;
RETS = [SP++];                            // Pop stack (only for nested calls)
RTS;
codec_configure.end:

// Function sport_configure initialises the SPORT0. Refer to pages 26-59, 26-67,
// 26-75 and 26-76 of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
sport_configure:
R0=0x3F0(X); [REG_PORTC_FER]=R0;          // Set up Port C in peripheral mode
R0=0x3F0(X); [REG_PORTC_FER_SET]=R0;      // Set up Port C in peripheral mode
R0=0x2001973; [REG_SPORT0_CTL_A]=R0;      // Set up SPORT0 (A) as TX to codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_A]=R0;      // 64 bits per frame, clock divisor of 1
R0=0x1973(X); [REG_SPORT0_CTL_B]=R0;      // Set up SPORT0 (B) as RX from codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_B]=R0;      // 64 bits per frame, clock divisor of 1
RTS;
sport_configure.end:

// Function TWI_write is a simple driver for the TWI. Refer to page 24-15 onwards
// of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
TWI_write:
R3=R0 <<0x8; R0=R0 >>>0x8; R2=R3|R0;      // Reverse low order and high order bytes
R0=0x3232(X); [REG_TWI0_CLKDIV]=R0;       // Set duty cycle
R0=0x008c(X); [REG_TWI0_CTL]=R0;          // Set prescale and enable TWI
R0=0x0038(X); [REG_TWI0_MSTRADDR]=R0;     // Address of codec
[REG_TWI0_TXDATA16]=R2;                   // Address of register to set, LSB then MSB
R0=0x00c1(X); [REG_TWI0_MSTRCTL]=R0;      // Command to send three bytes and enable tx
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
[REG_TWI0_TXDATA8]=R1;                    // Data to write
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x050; [REG_TWI0_ISTAT]=R0;            // Clear TXERV interrupt
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x010; [REG_TWI0_ISTAT]=R0;            // Clear MCOMP interrupt
rts;
TWI_write.end:

// Function delay introduces a delay to allow TWI communication
delay:
P0=0x8000;
loop LC0=P0;
NOP; NOP; NOP;
loop_end;
RTS;
delay.end:
```

Listing 5: Filter coefficinets for filter 1 generated using Signal Wizard. The file is available at: https://github.com/mandulaj/2019DSPLabCode/blob/master/code/filter1.txt

```
 0.000000000r, -0.000000000r, -0.000000001r, -0.000000003r, -0.000000004r, -0.000000006r,
    -0.000000007r, -0.000000007r, -0.000000005r, -0.000000000r,  0.000000006r,  0.000000016r,
    0.000000027r,  0.000000038r,  0.000000049r,  0.000000059r,  0.000000064r,  0.000000065r,
    0.000000059r,  0.000000047r,  0.000000028r,  0.000000002r, -0.000000028r, -0.000000062r,
    -0.000000096r, -0.000000128r, -0.000000154r, -0.000000171r, -0.000000178r, -0.000000170r,
    -0.000000149r, -0.000000113r, -0.000000065r, -0.000000006r,  0.000000060r,  0.000000127r,
    0.000000192r,  0.000000248r,  0.000000291r,  0.000000316r,  0.000000320r,  0.000000300r,
    0.000000257r,  0.000000192r,  0.000000108r,  0.000000011r, -0.000000093r, -0.000000198r,
    -0.000000294r, -0.000000374r, -0.000000433r, -0.000000463r, -0.000000462r, -0.000000428r,
    -0.000000362r, -0.000000268r, -0.000000150r, -0.000000017r,  0.000000122r,  0.000000257r,
    0.000000379r,  0.000000478r,  0.000000547r,  0.000000579r,  0.000000572r,  0.000000525r,
    0.000000440r,  0.000000323r,  0.000000181r,  0.000000025r, -0.000000135r, -0.000000288r,
    -0.000000422r, -0.000000527r, -0.000000597r, -0.000000626r, -0.000000612r, -0.000000556r,
    -0.000000462r, -0.000000338r, -0.000000191r, -0.000000033r,  0.000000124r,  0.000000270r,
    0.000000393r,  0.000000487r,  0.000000545r,  0.000000564r,  0.000000543r,  0.000000487r,
    0.000000400r,  0.000000291r,  0.000000168r,  0.000000042r, -0.000000077r, -0.000000181r,
    -0.000000264r, -0.000000319r, -0.000000347r, -0.000000346r, -0.000000321r, -0.000000276r,
    -0.000000220r, -0.000000158r, -0.000000100r, -0.000000051r, -0.000000017r, -0.000000000r,
    -0.000000001r, -0.000000018r, -0.000000045r, -0.000000076r, -0.000000103r, -0.000000118r,
```

```
-0.000000114r, -0.000000084r, -0.000000026r,  0.000000060r,  0.000000171r,  0.000000301r,
0.000000437r,  0.000000568r,  0.000000678r,  0.000000752r,  0.000000777r,  0.000000741r,
0.000000638r,  0.000000464r,  0.000000226r, -0.000000068r, -0.000000399r, -0.000000746r,
-0.000001081r, -0.000001377r, -0.000001605r, -0.000001738r, -0.000001755r, -0.000001641r,
-0.000001391r, -0.000001010r, -0.000000512r,  0.000000074r,  0.000000713r,  0.000001362r,
0.000001972r,  0.000002494r,  0.000002880r,  0.000003090r,  0.000003091r,  0.000002866r,
0.000002414r,  0.000001749r,  0.000000902r, -0.000000078r, -0.000001128r, -0.000002178r,
-0.000003150r, -0.000003967r, -0.000004558r, -0.000004863r, -0.000004839r, -0.000004467r,
-0.000003748r, -0.000002710r, -0.000001409r,  0.000000079r,  0.000001658r,  0.000003222r,
0.000004654r,  0.000005845r,  0.000006692r,  0.000007115r,  0.000007056r,  0.000006492r,
0.000005432r,  0.000003924r,  0.000002050r, -0.000000076r, -0.000002317r, -0.000004520r,
-0.000006524r, -0.000008175r, -0.000009338r, -0.000009901r, -0.000009794r, -0.000008989r,
-0.000007507r, -0.000005418r, -0.000002840r,  0.000000069r,  0.000003119r,  0.000006099r,
0.000008797r,  0.000011005r,  0.000012545r,  0.000013275r,  0.000013106r,  0.000012006r,
0.000010010r,  0.000007218r,  0.000003792r, -0.000000057r, -0.000004074r, -0.000007985r,
-0.000011508r, -0.000014378r, -0.000016363r, -0.000017287r, -0.000017038r, -0.000015583r,
-0.000012976r, -0.000009350r, -0.000004919r,  0.000000039r,  0.000005196r,  0.000010199r,
0.000014689r,  0.000018330r,  0.000020834r,  0.000021979r,  0.000021632r,  0.000019759r,
0.000016434r,  0.000011834r,  0.000006233r, -0.000000014r, -0.000006494r, -0.000012760r,
-0.000018366r, -0.000022896r, -0.000025992r, -0.000027387r, -0.000026922r, -0.000024564r,
-0.000020410r, -0.000014687r, -0.000007742r, -0.000000018r,  0.000007974r,  0.000015682r,
0.000022559r,  0.000028097r,  0.000031865r,  0.000033539r,  0.000032935r,  0.000030019r,
0.000024920r,  0.000017922r,  0.000009453r,  0.000000057r, -0.000009641r, -0.000018975r,
-0.000027281r, -0.000033951r, -0.000038467r, -0.000040449r, -0.000039682r, -0.000036135r,
-0.000029972r, -0.000021544r, -0.000011369r, -0.000000105r,  0.000011498r,  0.000022640r,
0.000032535r,  0.000040458r,  0.000045800r,  0.000048118r,  0.000047164r,  0.000042912r,
0.000035566r,  0.000025551r,  0.000013489r,  0.000000161r, -0.000013540r, -0.000026674r,
-0.000038313r, -0.000047608r, -0.000053852r, -0.000056531r, -0.000055364r, -0.000050334r,
-0.000041688r, -0.000029933r, -0.000015806r, -0.000000226r,  0.000015763r,  0.000031062r,
0.000044594r,  0.000055375r,  0.000062591r,  0.000065654r,  0.000064250r,  0.000058369r,
0.000048310r,  0.000034671r,  0.000018311r,  0.000000300r, -0.000018153r, -0.000035781r,
-0.000051344r, -0.000063715r, -0.000071967r, -0.000075433r, -0.000073766r, -0.000066966r,
-0.000055390r, -0.000039732r, -0.000020986r, -0.000000383r,  0.000020694r,  0.000040796r,
0.000058512r,  0.000072565r,  0.000081907r,  0.000085791r,  0.000083837r,  0.000076057r,
0.000062869r,  0.000045074r,  0.000023809r,  0.000000473r, -0.000023363r, -0.000046061r,
-0.000066031r, -0.000081840r, -0.000092314r, -0.000096626r, -0.000094360r, -0.000085546r,
-0.000070669r, -0.000050642r, -0.000026750r, -0.000000572r,  0.000026128r,  0.000051516r,
0.000073816r,  0.000091433r,  0.000103067r,  0.000107809r,  0.000105210r,  0.000095320r,
0.000078694r,  0.000056364r,  0.000029771r,  0.000000677r, -0.000028954r, -0.000057088r,
-0.000081760r, -0.000101211r, -0.000114015r, -0.000119181r, -0.000116230r, -0.000105235r,
-0.000086827r, -0.000062157r, -0.000032827r, -0.000000788r,  0.000031797r,  0.000062689r,
0.000089736r,  0.000111017r,  0.000124979r,  0.000130554r,  0.000127236r,  0.000115124r,
0.000094927r,  0.000067919r,  0.000035866r,  0.000000903r, -0.000034604r, -0.000068217r,
-0.000097597r, -0.000120666r, -0.000135751r, -0.000141711r, -0.000138014r, -0.000124793r,
-0.000102833r, -0.000073536r, -0.000038825r, -0.000001021r,  0.000037315r,  0.000073551r,
0.000105172r,  0.000129946r,  0.000146092r,  0.000152399r,  0.000148320r,  0.000134018r,
0.000110362r,  0.000078874r,  0.000041635r,  0.000001140r, -0.000039862r, -0.000078559r,
-0.000112267r, -0.000138620r, -0.000155732r, -0.000162336r, -0.000157875r, -0.000142549r,
-0.000117306r, -0.000083786r, -0.000044216r, -0.000001257r,  0.000042171r,  0.000083090r,
0.000118669r,  0.000146419r,  0.000164370r,  0.000171209r,  0.000166376r,  0.000150109r,
0.000123436r,  0.000088107r,  0.000046482r,  0.000001371r, -0.000044156r, -0.000086978r,
-0.000124139r, -0.000153052r, -0.000171677r, -0.000178672r, -0.000173484r, -0.000156393r,
-0.000128501r, -0.000091658r, -0.000048339r, -0.000001480r,  0.000045726r,  0.000090044r,
0.000128422r,  0.000158199r,  0.000177295r,  0.000184352r,  0.000178837r,  0.000161073r,
0.000132231r,  0.000094244r,  0.000049684r,  0.000001579r, -0.000046784r, -0.000092095r,
-0.000131239r, -0.000161519r, -0.000180838r, -0.000187848r, -0.000182043r, -0.000163796r,
-0.000134335r, -0.000095660r, -0.000050407r, -0.000001667r,  0.000047225r,  0.000092923r,
0.000132296r,  0.000162647r,  0.000181899r,  0.000188735r,  0.000182691r,  0.000164190r,
0.000134507r,  0.000095685r,  0.000050394r,  0.000001741r, -0.000046937r, -0.000092311r,
-0.000131283r, -0.000161203r, -0.000180050r, -0.000186566r, -0.000180347r, -0.000161863r,
-0.000132426r, -0.000094093r, -0.000049524r, -0.000001798r,  0.000045806r,  0.000090033r,
0.000127878r,  0.000156789r,  0.000174844r,  0.000180879r,  0.000174562r,  0.000156413r,
0.000127760r,  0.000090645r,  0.000047674r,  0.000001835r, -0.000043712r, -0.000085856r,
-0.000121748r, -0.000148996r, -0.000165826r, -0.000171199r, -0.000164875r, -0.000147424r,
-0.000120171r, -0.000085102r, -0.000044717r, -0.000001850r,  0.000040534r,  0.000079542r,
0.000112556r,  0.000137409r,  0.000152530r,  0.000157043r,  0.000150821r,  0.000134477r,
0.000109314r,  0.000077219r,  0.000040526r,  0.000001839r, -0.000036150r, -0.000070852r,
-0.000099961r, -0.000121610r, -0.000134490r, -0.000137930r, -0.000131932r, -0.000117153r,
-0.000094847r, -0.000066754r, -0.000034973r, -0.000001801r,  0.000030436r,  0.000059546r,
0.000083626r,  0.000101186r,  0.000111244r,  0.000113379r,  0.000107746r,  0.000095039r,
0.000076432r,  0.000053466r,  0.000027934r,  0.000001733r, -0.000023273r, -0.000045392r,
-0.000063220r, -0.000075732r, -0.000082342r, -0.000082927r, -0.000077814r, -0.000067733r,
-0.000053741r, -0.000037125r, -0.000019288r, -0.000001634r,  0.000014545r,  0.000028164r,
0.000038424r,  0.000044858r,  0.000047351r,  0.000046125r,  0.000041706r,  0.000034848r,
0.000026461r,  0.000017509r,  0.000008921r,  0.000001503r, -0.000004140r, -0.000007648r,
-0.000008937r, -0.000008197r, -0.000005861r, -0.000002554r,  0.000000983r,  0.000003973r,
```

```
0.000005700r,  0.000005587r,  0.000003273r, -0.000001337r, -0.000008044r, -0.000016356r,
-0.000025522r, -0.000034593r, -0.000042504r, -0.000048175r, -0.000050623r, -0.000049063r,
-0.000043010r, -0.000032351r, -0.000017391r,  0.000001139r,  0.000022101r,  0.000044026r,
0.000065204r,  0.000083816r,  0.000098080r,  0.000106407r,  0.000107544r,  0.000100713r,
0.000085705r,  0.000062948r,  0.000033516r, -0.000000906r, -0.000038115r, -0.000075521r,
-0.000110328r, -0.000139737r, -0.000161160r, -0.000172437r, -0.000172029r, -0.000159172r,
-0.000133985r, -0.000097517r, -0.000051720r,  0.000000641r,  0.000056153r,  0.000110970r,
0.000161076r,  0.000202573r,  0.000231980r,  0.000246509r,  0.000244306r,  0.000224639r,
0.000188008r,  0.000136166r,  0.000072057r, -0.000000344r, -0.000076272r, -0.000150476r,
-0.000217586r, -0.000272490r, -0.000310719r, -0.000328798r, -0.000324539r, -0.000297259r,
-0.000247887r, -0.000178973r, -0.000094563r,  0.000000018r,  0.000098508r,  0.000194106r,
0.000279949r,  0.000349592r,  0.000397487r,  0.000419413r,  0.000412828r,  0.000377113r,
0.000313685r,  0.000225975r,  0.000119256r,  0.000000334r, -0.000122880r, -0.000241892r,
-0.000348204r, -0.000433921r, -0.000492323r, -0.000518388r, -0.000509197r, -0.000464216r,
-0.000385407r, -0.000277175r, -0.000146133r, -0.000000710r,  0.000149389r,  0.000293826r,
0.000422334r,  0.000525448r,  0.000595188r,  0.000625673r,  0.000613592r,  0.000558513r,
0.000463003r,  0.000332531r,  0.000175169r,  0.000001106r, -0.000178014r, -0.000349860r,
-0.000502264r, -0.000624073r, -0.000705963r, -0.000741138r, -0.000725876r, -0.000659875r,
-0.000546360r, -0.000391957r, -0.000206316r, -0.000001517r,  0.000208710r,  0.000409902r,
0.000587854r,  0.000729619r,  0.000824440r,  0.000864558r,  0.000845828r,  0.000768094r,
0.000635303r,  0.000455325r,  0.000239501r,  0.000001938r, -0.000241412r, -0.000473815r,
-0.000678905r, -0.000841832r, -0.000950328r, -0.000995624r, -0.000973136r, -0.000882884r,
-0.000729590r, -0.000522457r, -0.000274629r, -0.000002364r,  0.000276030r,  0.000541417r,
0.000775150r,  0.000960377r,  0.001083244r,  0.001133928r,  0.001107400r,  0.001003877r,
0.000828914r,  0.000593131r,  0.000311580r,  0.000002789r, -0.000312450r, -0.000612479r,
-0.000876258r, -0.001084838r, -0.001222715r, -0.001278973r, -0.001248131r, -0.001130626r,
-0.000932903r, -0.000667078r, -0.000350209r, -0.000003208r,  0.000350536r,  0.000686727r,
0.000981832r,  0.001214722r,  0.001368182r,  0.001430171r,  0.001394749r,  0.001262605r,
0.001041120r,  0.000743982r,  0.000390348r,  0.000003613r, -0.000390127r, -0.000763841r,
-0.001091411r, -0.001349457r, -0.001518997r, -0.001586841r, -0.001546592r, -0.001399210r,
-0.001153065r, -0.000823484r, -0.000431805r, -0.000003999r,  0.000431041r,  0.000843459r,
0.001204475r,  0.001488394r,  0.001674430r,  0.001748219r,  0.001702910r,  0.001539762r,
0.001268178r,  0.000905183r,  0.000474368r,  0.000004360r, -0.000473074r, -0.000925176r,
-0.001320444r, -0.001630817r, -0.001833672r, -0.001913458r, -0.001862880r, -0.001683516r,
-0.001385842r, -0.000988636r, -0.000517803r, -0.000004690r,  0.000515999r,  0.001008550r,
0.001438682r,  0.001775940r,  0.001995839r,  0.002081639r,  0.002025604r,  0.001829660r,
0.001505389r,  0.001073366r,  0.000561859r,  0.000004982r, -0.000559576r, -0.001093100r,
-0.001558508r, -0.001922920r, -0.002159984r, -0.002251771r, -0.002190120r, -0.001977325r,
-0.001626105r, -0.001158865r, -0.000606268r, -0.000005231r,  0.000603542r,  0.001178318r,
0.001679192r,  0.002070858r,  0.002325099r,  0.002422806r,  0.002355410r,  0.002125593r,
0.001747236r,  0.001244593r,  0.000650747r,  0.000005432r, -0.000647625r, -0.001263666r,
-0.001799969r, -0.002218814r, -0.002490128r, -0.002593645r, -0.002520408r, -0.002273505r,
-0.001867993r, -0.001329991r, -0.000695004r, -0.000005581r,  0.000691537r,  0.001348585r,
0.001920045r,  0.002365807r,  0.002653975r,  0.002763151r,  0.002684010r,  0.002420067r,
0.001987563r,  0.001414481r,  0.000738737r,  0.000005673r, -0.000734984r, -0.001432498r,
-0.002038601r, -0.002510833r, -0.002815517r, -0.002930156r, -0.002845087r, -0.002564263r,
-0.002105115r, -0.001497473r, -0.000781638r, -0.000005706r,  0.000777662r,  0.001514818r,
0.002154803r,  0.002652870r,  0.002973611r,  0.003093477r,  0.003002494r,  0.002705068r,
0.002219808r,  0.001578372r,  0.000823398r,  0.000005678r, -0.000819267r, -0.001594954r,
-0.002267815r, -0.002790890r, -0.003127111r, -0.003251926r, -0.003155083r, -0.002841450r,
-0.002330803r, -0.001656582r, -0.000863708r, -0.000005586r,  0.000859493r,  0.001672315r,
0.002376799r,  0.002923870r,  0.003274876r,  0.003404323r,  0.003301716r,  0.002972391r,
0.002437267r,  0.001731517r,  0.000902265r,  0.000005431r, -0.000898039r, -0.001746317r,
-0.002480933r, -0.003050803r, -0.003415786r, -0.003549510r, -0.003441276r, -0.003096892r,
-0.002538387r, -0.001802604r, -0.000938773r, -0.000005213r,  0.000934608r,  0.001816392r,
0.002579415r,  0.003170710r,  0.003548751r,  0.003686364r,  0.003572683r,  0.003213987r,
0.002633376r,  0.001869287r,  0.000972946r,  0.000004933r, -0.000968916r, -0.001881992r,
-0.002671472r, -0.003282650r, -0.003672727r, -0.003813808r, -0.003694899r, -0.003322751r,
-0.002721485r, -0.001931040r, -0.001004514r, -0.000004594r,  0.001000690r,  0.001942594r,
0.002756373r,  0.003385732r,  0.003786725r,  0.003930824r,  0.003806950r,  0.003422315r,
0.002802008r,  0.001987369r,  0.001033225r,  0.000004198r, -0.001029673r, -0.001997711r,
-0.002833433r, -0.003479124r, -0.003889824r, -0.004036467r, -0.003907929r, -0.003511873r,
-0.002874294r, -0.002037817r, -0.001058846r, -0.000003752r,  0.001055629r,  0.002046893r,
0.002902022r,  0.003562062r,  0.003981183r,  0.004129873r,  0.003997009r,  0.003590692r,
0.002937750r,  0.002081972r,  0.001081168r,  0.000003258r, -0.001078343r, -0.002089733r,
-0.002961576r, -0.003633863r, -0.004060047r, -0.004210271r, -0.004073457r, -0.003658122r,
-0.002991853r, -0.002119469r, -0.001100009r, -0.000002724r,  0.001097625r,  0.002125875r,
0.003011598r,  0.003693929r,  0.004125761r,  0.004276993r,  0.004136635r,  0.003713603r,
0.003036154r,  0.002149998r,  0.001115212r,  0.000002156r, -0.001113312r, -0.002155016r,
-0.003051668r, -0.003741758r, -0.004177774r, -0.004329481r, -0.004186016r, -0.003756670r,
-0.003070282r, -0.002173305r, -0.001126652r, -0.000001560r,  0.001125271r,  0.002176908r,
0.003081449r,  0.003776946r,  0.004215649r,  0.004367292r,  0.004221185r,  0.003786962r,
0.003093953r,  0.002189195r,  0.001134236r,  0.000000944r, -0.001133397r, -0.002191364r,
-0.003100688r, -0.003799194r, -0.004239064r, -0.004390108r, -0.004241844r, -0.003804225r,
-0.003106968r, -0.002197537r, -0.001137901r, -0.000000316r,  0.001137620r,  0.002198261r,
0.003109219r,  0.003808314r,  0.004247821r,  0.004397735r,  0.004247821r,  0.003808314r,
```

```
    0.003109219r,  0.002198261r,  0.001137620r, -0.000000316r, -0.001137901r, -0.002197537r,
    -0.003106968r, -0.003804225r, -0.004241844r, -0.004390108r, -0.004239064r, -0.003799194r,
    -0.003100688r, -0.002191364r, -0.001133397r,  0.000000944r,  0.001134236r,  0.002189195r,
    0.003093953r,  0.003786962r,  0.004221185r,  0.004367292r,  0.004215649r,  0.003776946r,
    0.003081449r,  0.002176908r,  0.001125271r, -0.000001560r, -0.001126652r, -0.002173305r,
    -0.003070282r, -0.003756670r, -0.004186016r, -0.004329481r, -0.004177774r, -0.003741758r,
    -0.003051668r, -0.002155016r, -0.001113312r,  0.000002156r,  0.001115212r,  0.002149998r,
    0.003036154r,  0.003713603r,  0.004136635r,  0.004276993r,  0.004125761r,  0.003693929r,
    0.003011598r,  0.002125875r,  0.001097625r, -0.000002724r, -0.001100009r, -0.002119469r,
    -0.002991853r, -0.003658122r, -0.004073457r, -0.004210271r, -0.004060047r, -0.003633863r,
    -0.002961576r, -0.002089733r, -0.001078343r,  0.000003258r,  0.001081168r,  0.002081972r,
    0.002937750r,  0.003590692r,  0.003997009r,  0.004129873r,  0.003981183r,  0.003562062r,
    0.002902022r,  0.002046893r,  0.001055629r, -0.000003752r, -0.001058846r, -0.002037817r,
    -0.002874294r, -0.003511873r, -0.003907929r, -0.004036467r, -0.003889824r, -0.003479124r,
    -0.002833433r, -0.001997711r, -0.001029673r,  0.000004198r,  0.001033225r,  0.001987369r,
    0.002802008r,  0.003422315r,  0.003806950r,  0.003930824r,  0.003786725r,  0.003385732r,
    0.002756373r,  0.001942594r,  0.001000690r, -0.000004594r, -0.001004514r, -0.001931040r,
    -0.002721485r, -0.003322751r, -0.003694899r, -0.003813808r, -0.003672727r, -0.003282650r,
    -0.002671472r, -0.001881992r, -0.000968916r,  0.000004933r,  0.000972946r,  0.001869287r,
    0.002633376r,  0.003213987r,  0.003572683r,  0.003686364r,  0.003548751r,  0.003170710r,
    0.002579415r,  0.001816392r,  0.000934608r, -0.000005213r, -0.000938773r, -0.001802604r,
    -0.002538387r, -0.003096892r, -0.003441276r, -0.003549510r, -0.003415786r, -0.003050803r,
    -0.002480933r, -0.001746317r, -0.000898039r,  0.000005431r,  0.000902265r,  0.001731517r,
    0.002437267r,  0.002972391r,  0.003301716r,  0.003404323r,  0.003274876r,  0.002923870r,
    0.002376799r,  0.001672315r,  0.000859493r, -0.000005586r, -0.000863708r, -0.001656582r,
    -0.002330803r, -0.002841450r, -0.003155083r, -0.003251926r, -0.003127111r, -0.002790890r,
    -0.002267815r, -0.001594954r, -0.000819267r,  0.000005678r,  0.000823398r,  0.001578372r,
    0.002219808r,  0.002705068r,  0.003002494r,  0.003093477r,  0.002973611r,  0.002652870r,
    0.002154803r,  0.001514818r,  0.000777662r, -0.000005706r, -0.000781638r, -0.001497473r,
    -0.002105115r, -0.002564263r, -0.002845087r, -0.002930156r, -0.002815517r, -0.002510833r,
    -0.002038601r, -0.001432498r, -0.000734984r,  0.000005673r,  0.000738737r,  0.001414481r,
    0.001987563r,  0.002420067r,  0.002684010r,  0.002763151r,  0.002653975r,  0.002365807r,
    0.001920045r,  0.001348585r,  0.000691537r, -0.000005581r, -0.000695004r, -0.001329991r,
    -0.001867993r, -0.002273505r, -0.002520408r, -0.002593645r, -0.002490128r, -0.002218814r,
    -0.001799969r, -0.001263666r, -0.000647625r,  0.000005432r,  0.000650747r,  0.001244593r,
    0.001747236r,  0.002125593r,  0.002355410r,  0.002422806r,  0.002325099r,  0.002070858r,
    0.001679192r,  0.001178318r,  0.000603542r, -0.000005231r, -0.000606268r, -0.001158865r,
    -0.001626105r, -0.001977325r, -0.002190120r, -0.002251771r, -0.002159984r, -0.001922920r,
    -0.001558508r, -0.001093100r, -0.000559576r,  0.000004982r,  0.000561859r,  0.001073366r,
    0.001505389r,  0.001829660r,  0.002025604r,  0.002081639r,  0.001995839r,  0.001775940r,
    0.001438682r,  0.001008550r,  0.000515999r, -0.000004690r, -0.000517803r, -0.000988636r,
    -0.001385842r, -0.001683516r, -0.001862880r, -0.001913458r, -0.001833672r, -0.001630817r,
    -0.001320444r, -0.000925176r, -0.000473074r,  0.000004360r,  0.000474368r,  0.000905183r,
    0.001268178r,  0.001539762r,  0.001702910r,  0.001748219r,  0.001674430r,  0.001488394r,
    0.001204475r,  0.000843459r,  0.000431041r, -0.000003999r, -0.000431805r, -0.000823484r,
    -0.001153065r, -0.001399210r, -0.001546592r, -0.001586841r, -0.001518997r, -0.001349457r,
    -0.001091411r, -0.000763841r, -0.000390127r,  0.000003613r,  0.000390348r,  0.000743982r,
    0.001041120r,  0.001262605r,  0.001394749r,  0.001430171r,  0.001368182r,  0.001214722r,
    0.000981832r,  0.000686727r,  0.000350536r, -0.000003208r, -0.000350209r, -0.000667078r,
    -0.000932903r, -0.001130626r, -0.001248131r, -0.001278973r, -0.001222715r, -0.001084838r,
    -0.000876258r, -0.000612479r, -0.000312450r,  0.000002789r,  0.000311580r,  0.000593131r,
    0.000828914r,  0.001003877r,  0.001107400r,  0.001133928r,  0.001083244r,  0.000960377r,
    0.000775150r,  0.000541417r,  0.000276030r, -0.000002364r, -0.000274629r, -0.000522457r,
    -0.000729590r, -0.000882884r, -0.000973136r, -0.000995624r, -0.000950328r, -0.000841832r,
    -0.000678905r, -0.000473815r, -0.000241412r,  0.000001938r,  0.000239501r,  0.000455325r,
    0.000635303r,  0.000768094r,  0.000845828r,  0.000864558r,  0.000824440r,  0.000729619r,
    0.000587854r,  0.000409902r,  0.000208710r, -0.000001517r, -0.000206316r, -0.000391957r,
    -0.000546360r, -0.000659875r, -0.000725876r, -0.000741138r, -0.000705963r, -0.000624073r,
    -0.000502264r, -0.000349860r, -0.000178014r,  0.000001106r,  0.000175169r,  0.000332531r,
    0.000463003r,  0.000558513r,  0.000613592r,  0.000625673r,  0.000595188r,  0.000525448r,
    0.000422334r,  0.000293826r,  0.000149389r, -0.000000710r, -0.000146133r, -0.000277175r,
    -0.000385407r, -0.000464216r, -0.000509197r, -0.000518388r, -0.000492323r, -0.000433921r,
    -0.000348204r, -0.000241892r, -0.000122880r,  0.000000334r,  0.000119256r,  0.000225975r,
    0.000313685r,  0.000377113r,  0.000412828r,  0.000419413r,  0.000397487r,  0.000349592r,
    0.000279949r,  0.000194106r,  0.000098508r,  0.000000018r, -0.000094563r, -0.000178973r,
    -0.000247887r, -0.000297259r, -0.000324539r, -0.000328798r, -0.000310719r, -0.000272490r,
    -0.000217586r, -0.000150476r, -0.000076272r, -0.000000344r,  0.000072057r,  0.000136166r,
    0.000188008r,  0.000224639r,  0.000244306r,  0.000246509r,  0.000231980r,  0.000202573r,
    0.000161076r,  0.000110970r,  0.000056153r,  0.000000641r, -0.000051720r, -0.000097517r,
    -0.000133985r, -0.000159172r, -0.000172029r, -0.000172437r, -0.000161160r, -0.000139737r,
    -0.000110328r, -0.000075521r, -0.000038115r, -0.000000906r,  0.000033516r,  0.000062948r,
    0.000085705r,  0.000100713r,  0.000107544r,  0.000106407r,  0.000098080r,  0.000083816r,
    0.000065204r,  0.000044026r,  0.000022101r,  0.000001139r, -0.000017391r, -0.000032351r,
    -0.000043010r, -0.000049063r, -0.000050623r, -0.000048175r, -0.000042504r, -0.000034593r,
    -0.000025522r, -0.000016356r, -0.000008044r, -0.000001337r,  0.000003273r,  0.000005587r,
    0.000005700r,  0.000003973r,  0.000000983r, -0.000002554r, -0.000005861r, -0.000008197r,
```

```
    -0.000008937r, -0.000007648r, -0.000004140r,  0.000001503r,  0.000008921r,  0.000017509r,
    0.000026461r,  0.000034848r,  0.000041706r,  0.000046125r,  0.000047351r,  0.000044858r,
    0.000038424r,  0.000028164r,  0.000014545r, -0.000001634r, -0.000019288r, -0.000037125r,
    -0.000053741r, -0.000067733r, -0.000077814r, -0.000082927r, -0.000082342r, -0.000075732r,
    -0.000063220r, -0.000045392r, -0.000023273r,  0.000001733r,  0.000027934r,  0.000053466r,
    0.000076432r,  0.000095039r,  0.000107746r,  0.000113379r,  0.000111244r,  0.000101186r,
    0.000083626r,  0.000059546r,  0.000030436r, -0.000001801r, -0.000034973r, -0.000066754r,
    -0.000094847r, -0.000117153r, -0.000131932r, -0.000137930r, -0.000134490r, -0.000121610r,
    -0.000099961r, -0.000070852r, -0.000036150r,  0.000001839r,  0.000040526r,  0.000077219r,
    0.000109314r,  0.000134477r,  0.000150821r,  0.000157043r,  0.000152530r,  0.000137409r,
    0.000112556r,  0.000079542r,  0.000040534r, -0.000001850r, -0.000044717r, -0.000085102r,
    -0.000120171r, -0.000147424r, -0.000164875r, -0.000171199r, -0.000165826r, -0.000148996r,
    -0.000121748r, -0.000085856r, -0.000043712r,  0.000001835r,  0.000047674r,  0.000090645r,
    0.000127760r,  0.000156413r,  0.000174562r,  0.000180879r,  0.000174844r,  0.000156789r,
    0.000127878r,  0.000090033r,  0.000045806r, -0.000001798r, -0.000049524r, -0.000094093r,
    -0.000132426r, -0.000161863r, -0.000180347r, -0.000186566r, -0.000180050r, -0.000161203r,
    -0.000131283r, -0.000092311r, -0.000046937r,  0.000001741r,  0.000050394r,  0.000095685r,
    0.000134507r,  0.000164190r,  0.000182691r,  0.000188735r,  0.000181899r,  0.000162647r,
    0.000132296r,  0.000092923r,  0.000047225r, -0.000001667r, -0.000050407r, -0.000095660r,
    -0.000134335r, -0.000163796r, -0.000182043r, -0.000187848r, -0.000180838r, -0.000161519r,
    -0.000131239r, -0.000092095r, -0.000046784r,  0.000001579r,  0.000049684r,  0.000094244r,
    0.000132231r,  0.000161073r,  0.000178837r,  0.000184352r,  0.000177295r,  0.000158199r,
    0.000128422r,  0.000090044r,  0.000045726r, -0.000001480r, -0.000048339r, -0.000091658r,
    -0.000128501r, -0.000156393r, -0.000173484r, -0.000178672r, -0.000171677r, -0.000153052r,
    -0.000124139r, -0.000086978r, -0.000044156r,  0.000001371r,  0.000046482r,  0.000088107r,
    0.000123436r,  0.000150109r,  0.000166376r,  0.000171209r,  0.000164370r,  0.000146419r,
    0.000118669r,  0.000083090r,  0.000042171r, -0.000001257r, -0.000044216r, -0.000083786r,
    -0.000117306r, -0.000142549r, -0.000157875r, -0.000162336r, -0.000155732r, -0.000138620r,
    -0.000112267r, -0.000078559r, -0.000039862r,  0.000001140r,  0.000041635r,  0.000078874r,
    0.000110362r,  0.000134018r,  0.000148320r,  0.000152399r,  0.000146092r,  0.000129946r,
    0.000105172r,  0.000073551r,  0.000037315r, -0.000001021r, -0.000038825r, -0.000073536r,
    -0.000102833r, -0.000124793r, -0.000138014r, -0.000141711r, -0.000135751r, -0.000120666r,
    -0.000097597r, -0.000068217r, -0.000034604r,  0.000000903r,  0.000035866r,  0.000067919r,
    0.000094927r,  0.000115124r,  0.000127236r,  0.000130554r,  0.000124979r,  0.000111017r,
    0.000089736r,  0.000062689r,  0.000031797r, -0.000000788r, -0.000032827r, -0.000062157r,
    -0.000086827r, -0.000105235r, -0.000116230r, -0.000119181r, -0.000114015r, -0.000101211r,
    -0.000081760r, -0.000057088r, -0.000028954r,  0.000000677r,  0.000029771r,  0.000056364r,
    0.000078694r,  0.000095320r,  0.000105210r,  0.000107809r,  0.000103067r,  0.000091433r,
    0.000073816r,  0.000051516r,  0.000026128r, -0.000000572r, -0.000026750r, -0.000050642r,
    -0.000070669r, -0.000085546r, -0.000094360r, -0.000096626r, -0.000092314r, -0.000081840r,
    -0.000066031r, -0.000046061r, -0.000023363r,  0.000000473r,  0.000023809r,  0.000045074r,
    0.000062869r,  0.000076057r,  0.000083837r,  0.000085791r,  0.000081907r,  0.000072565r,
    0.000058512r,  0.000040796r,  0.000020694r, -0.000000383r, -0.000020986r, -0.000039732r,
    -0.000055390r, -0.000066966r, -0.000073766r, -0.000075433r, -0.000071967r, -0.000063715r,
    -0.000051344r, -0.000035781r, -0.000018153r,  0.000000300r,  0.000018311r,  0.000034671r,
    0.000048310r,  0.000058369r,  0.000064250r,  0.000065654r,  0.000062591r,  0.000055375r,
    0.000044594r,  0.000031062r,  0.000015763r, -0.000000226r, -0.000015806r, -0.000029933r,
    -0.000041688r, -0.000050334r, -0.000055364r, -0.000056531r, -0.000053852r, -0.000047608r,
    -0.000038313r, -0.000026674r, -0.000013540r,  0.000000161r,  0.000013489r,  0.000025551r,
    0.000035566r,  0.000042912r,  0.000047164r,  0.000048118r,  0.000045800r,  0.000040458r,
    0.000032535r,  0.000022640r,  0.000011498r, -0.000000105r, -0.000011369r, -0.000021544r,
    -0.000029972r, -0.000036135r, -0.000039682r, -0.000040449r, -0.000038467r, -0.000033951r,
    -0.000027281r, -0.000018975r, -0.000009641r,  0.000000057r,  0.000009453r,  0.000017922r,
    0.000024920r,  0.000030019r,  0.000032935r,  0.000033539r,  0.000031865r,  0.000028097r,
    0.000022559r,  0.000015682r,  0.000007974r, -0.000000018r, -0.000007742r, -0.000014687r,
    -0.000020410r, -0.000024564r, -0.000026922r, -0.000027387r, -0.000025992r, -0.000022896r,
    -0.000018366r, -0.000012760r, -0.000006494r, -0.000000014r,  0.000006233r,  0.000011834r,
    0.000016434r,  0.000019759r,  0.000021632r,  0.000021979r,  0.000020834r,  0.000018330r,
    0.000014689r,  0.000010199r,  0.000005196r,  0.000000039r, -0.000004919r, -0.000009350r,
    -0.000012976r, -0.000015583r, -0.000017038r, -0.000017287r, -0.000016363r, -0.000014378r,
    -0.000011508r, -0.000007985r, -0.000004074r, -0.000000057r,  0.000003792r,  0.000007218r,
    0.000010010r,  0.000012006r,  0.000013106r,  0.000013275r,  0.000012545r,  0.000011005r,
    0.000008797r,  0.000006099r,  0.000003119r,  0.000000069r, -0.000002840r, -0.000005418r,
    -0.000007507r, -0.000008989r, -0.000009794r, -0.000009901r, -0.000009338r, -0.000008175r,
    -0.000006524r, -0.000004520r, -0.000002317r, -0.000000076r,  0.000002050r,  0.000003924r,
    0.000005432r,  0.000006492r,  0.000007056r,  0.000007115r,  0.000006692r,  0.000005845r,
    0.000004654r,  0.000003222r,  0.000001658r,  0.000000079r, -0.000001409r, -0.000002710r,
    -0.000003748r, -0.000004467r, -0.000004839r, -0.000004863r, -0.000004558r, -0.000003967r,
    -0.000003150r, -0.000002178r, -0.000001128r, -0.000000078r,  0.000000902r,  0.000001749r,
    0.000002414r,  0.000002866r,  0.000003091r,  0.000003090r,  0.000002880r,  0.000002494r,
    0.000001972r,  0.000001362r,  0.000000713r,  0.000000074r, -0.000000512r, -0.000001010r,
    -0.000001391r, -0.000001641r, -0.000001755r, -0.000001738r, -0.000001605r, -0.000001377r,
    -0.000001081r, -0.000000746r, -0.000000399r, -0.000000068r,  0.000000226r,  0.000000464r,
    0.000000638r,  0.000000741r,  0.000000777r,  0.000000752r,  0.000000678r,  0.000000568r,
    0.000000437r,  0.000000301r,  0.000000171r,  0.000000060r, -0.000000026r, -0.000000084r,
    -0.000000114r, -0.000000118r, -0.000000103r, -0.000000076r, -0.000000045r, -0.000000018r,
```

```
    -0.000000001r, -0.000000000r, -0.000000017r, -0.000000051r, -0.000000100r, -0.000000158r,
    -0.000000220r, -0.000000276r, -0.000000321r, -0.000000346r, -0.000000347r, -0.000000319r,
    -0.000000264r, -0.000000181r, -0.000000077r,  0.000000042r,  0.000000168r,  0.000000291r,
    0.000000400r,  0.000000487r,  0.000000543r,  0.000000564r,  0.000000545r,  0.000000487r,
    0.000000393r,  0.000000270r,  0.000000124r, -0.000000033r, -0.000000191r, -0.000000338r,
    -0.000000462r, -0.000000556r, -0.000000612r, -0.000000626r, -0.000000597r, -0.000000527r,
    -0.000000422r, -0.000000288r, -0.000000135r,  0.000000025r,  0.000000181r,  0.000000323r,
    0.000000440r,  0.000000525r,  0.000000572r,  0.000000579r,  0.000000547r,  0.000000478r,
    0.000000379r,  0.000000257r,  0.000000122r, -0.000000017r, -0.000000150r, -0.000000268r,
    -0.000000362r, -0.000000428r, -0.000000462r, -0.000000463r, -0.000000433r, -0.000000374r,
    -0.000000294r, -0.000000198r, -0.000000093r,  0.000000011r,  0.000000108r,  0.000000192r,
    0.000000257r,  0.000000300r,  0.000000320r,  0.000000316r,  0.000000291r,  0.000000248r,
    0.000000192r,  0.000000127r,  0.000000060r, -0.000000006r, -0.000000065r, -0.000000113r,
    -0.000000149r, -0.000000170r, -0.000000178r, -0.000000171r, -0.000000154r, -0.000000128r,
    -0.000000096r, -0.000000062r, -0.000000028r,  0.000000002r,  0.000000028r,  0.000000047r,
    0.000000059r,  0.000000065r,  0.000000064r,  0.000000059r,  0.000000049r,  0.000000038r,
    0.000000027r,  0.000000016r,  0.000000006r, -0.000000000r, -0.000000005r, -0.000000007r,
    -0.000000007r, -0.000000006r, -0.000000004r, -0.000000003r, -0.000000001r, -0.000000000r,
    0.000000000r
```

1.5 Exercises 5

Listing 6: *ex5-filter2.asm* - 32-bit version of FIR filter from execercise 4

```
/*
Program filter2 is a single MAC FIR filtering program similar to filter1. However, this is a 32-bit version, requiring
a combined A1:A0 72-bit accumulator register. It can handle up to 8050 coefficients, although the available memory
limits this to 7680 (unless using an L2 to L1 transfer).

Author: Patrick Gaydecki (modified by Haseeb Malik, Jakub Mandula, Tarig Mustafa, Kevin Golan)
Date  : 29.09.2017 (modified 5/3/19)
*/

.section L1_data_b;                 // Linker places data starting at 0x11900000
.BYTE4/r32 filter[] = "filter2.txt";      // Importing the file containing Coefficients

.section program;
.global _main;
.align 4;
# include <defBF706.h>

_main:
call codec_configure;
call sport_configure;

// Setting up circular buffers
P0=length(filter)*4;                // Setting length of circular buffer to Byte length of filter
I1=filter;
B1=I1;
L1=P0;
I0=0x11800000;
B0=I0;
L0=P0;

P0 = length(filter)-1;                // Sets P0 back to the number of coeffs in the filter minus 1 (one n-1 are done in the loop)

get_audio:
wait_left:
// Wait for left data then read
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_left;
R0=[REG_SPORT0_RXPRI_B];              // Reads the sample

// Convolution kernel
A0 = 0;
A1 = 0 || [I0++]= R0 || R1 = [I1++];        // Retrieving the first sample and filter coeff
LOOP LC0=P0;                    // Iterating through the coeffs and previous samples (to carry out convolution)
A1:0+= R0 * R1||R0= [I0++]||R1=[I1++];        // Doing the 32 bit Filtering
LOOP_END;                     // Concluding Iterator
A1:0+= R0 * R1 || I0-=4;              // Backtracking 4 bytes due to overshoot

//Write out left
R0=A1:0; [REG_SPORT0_TXPRI_A]=R0;

wait_right:
// Wait for left data then dummy read
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_right;
R0=[REG_SPORT0_RXPRI_B];
// Copy from left to write
R0=A1:0;
// Write right out
[REG_SPORT0_TXPRI_A]=R0;
jump get_audio;
rts;
._main.end:

// Function codec_configure initialises the ADAU1761 codec. Refer to the control register
// descriptions, page 51 onwards of the ADAU1761 data sheet.
codec_configure:
```

```
[--SP] = RETS;                              // Push stack (only for nested calls)
R1=0x01(X); R0=0x4000(X); call TWI_write; // Enable master clock, disable PLL
R1=0x7f(X); R0=0x40f9(X); call TWI_write; // Enable all clocks
R1=0x03(X); R0=0x40fa(X); call TWI_write; // Enable all clocks
R1=0x01(X); R0=0x4015(X); call TWI_write; // Set serial port master mode
R1=0x13(X); R0=0x4019(X); call TWI_write; // Set ADC to on, both channels
R1=0x21(X); R0=0x401c(X); call TWI_write; // Enable left channel mixer
R1=0x41(X); R0=0x401e(X); call TWI_write; // Enable right channel mixer
R1=0x03(X); R0=0x4029(X); call TWI_write; // Turn on power, both channels
R1=0x03(X); R0=0x402a(X); call TWI_write; // Set both DACs on
R1=0x01(X); R0=0x40f2(X); call TWI_write; // DAC gets L, R input from serial port
R1=0x01(X); R0=0x40f3(X); call TWI_write; // ADC sends L, R input to serial port
R1=0x0b(X); R0=0x400a(X); call TWI_write; // Set left line-in gain to 0 dB
R1=0x0b(X); R0=0x400c(X); call TWI_write; // Set right line-in gain to 0 dB
R1=0xe7(X); R0=0x4023(X); call TWI_write; // Set left headphone volume to 0 dB
R1=0xe7(X); R0=0x4024(X); call TWI_write; // Set right headphone volume to 0 dB
R1=0x00(X); R0=0x4017(X); call TWI_write; // Set codec default sample rate, 48 kHz
NOP;
RETS = [SP++];                              // Pop stack (only for nested calls)
RTS;
codec_configure.end:

// Function sport_configure initialises the SPORT0. Refer to pages 26-59, 26-67,
// 26-75 and 26-76 of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
sport_configure:
R0=0x3F0(X); [REG_PORTC_FER]=R0;          // Set up Port C in peripheral mode
R0=0x3F0(X); [REG_PORTC_FER_SET]=R0;      // Set up Port C in peripheral mode
R0=0x2001973; [REG_SPORT0_CTL_A]=R0;      // Set up SPORT0 (A) as TX to codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_A]=R0;      // 64 bits per frame, clock divisor of 1
R0=0x1973(X); [REG_SPORT0_CTL_B]=R0;      // Set up SPORT0 (B) as RX from codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_B]=R0;      // 64 bits per frame, clock divisor of 1
RTS;
sport_configure.end:

// Function TWI_write is a simple driver for the TWI. Refer to page 24-15 onwards
// of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
TWI_write:
R3=R0 <<0x8; R0=R0 >>>0x8; R2=R3|R0;      // Reverse low order and high order bytes
R0=0x3232(X); [REG_TWI0_CLKDIV]=R0;       // Set duty cycle
R0=0x008c(X); [REG_TWI0_CTL]=R0;          // Set prescale and enable TWI
R0=0x0038(X); [REG_TWI0_MSTRADDR]=R0;     // Address of codec
[REG_TWI0_TXDATA16]=R2;                   // Address of register to set, LSB then MSB
R0=0x00c1(X); [REG_TWI0_MSTRCTL]=R0;      // Command to send three bytes and enable tx
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
[REG_TWI0_TXDATA8]=R1;                    // Data to write
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x050; [REG_TWI0_ISTAT]=R0;            // Clear TXERV interrupt
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x010; [REG_TWI0_ISTAT]=R0;            // Clear MCOMP interrupt
rts;
TWI_write.end:

// Function delay introduces a delay to allow TWI communication
delay:
P0=0x8000;
loop LC0=P0;
NOP; NOP; NOP;
loop_end;
RTS;
delay.end:
```

Listing 7: Filter coefficinets for filter 2 generated using Signal Wizard. The file is available at: https://github.com/mandulaj/2019DSPLabCode/blob/master/code/filter2.txt

```
-0.000000000r,  0.000000001r,  0.000000002r,  0.000000002r, -0.000000001r, -0.000000009r,
    -0.000000019r, -0.000000031r, -0.000000040r, -0.000000042r, -0.000000037r, -0.000000025r,
    -0.000000009r,  0.000000002r,  0.000000000r, -0.000000021r, -0.000000067r, -0.000000134r,
    -0.000000215r, -0.000000296r, -0.000000360r, -0.000000390r, -0.000000375r, -0.000000309r,
    -0.000000199r, -0.000000060r,  0.000000086r,  0.000000212r,  0.000000296r,  0.000000324r,
    0.000000294r,  0.000000218r,  0.000000119r,  0.000000027r, -0.000000026r, -0.000000017r,
    0.000000065r,  0.000000213r,  0.000000406r,  0.000000610r,  0.000000786r,  0.000000898r,
    0.000000922r,  0.000000849r,  0.000000691r,  0.000000475r,  0.000000240r,  0.000000025r,
    -0.000000137r, -0.000000225r, -0.000000240r, -0.000000194r, -0.000000115r, -0.000000034r,
    0.000000025r,  0.000000047r,  0.000000034r,  0.000000003r, -0.000000021r, -0.000000010r,
    0.000000054r,  0.000000174r,  0.000000333r,  0.000000499r,  0.000000627r,  0.000000678r,
    0.000000624r,  0.000000464r,  0.000000225r, -0.000000042r, -0.000000268r, -0.000000389r,
```

```
-0.000000360r, -0.000000173r,  0.000000131r,  0.000000469r,  0.000000727r,  0.000000782r,
0.000000530r, -0.000000078r, -0.000001025r, -0.000002215r, -0.000003481r, -0.000004619r,
-0.000005421r, -0.000005719r, -0.000005432r, -0.000004586r, -0.000003317r, -0.000001860r,
-0.000000495r,  0.000000501r,  0.000000921r,  0.000000677r, -0.000000169r, -0.000001405r,
-0.000002702r, -0.000003678r, -0.000003974r, -0.000003335r, -0.000001677r,  0.000000882r,
0.000004027r,  0.000007293r,  0.000010153r,  0.000012118r,  0.000012834r,  0.000012171r,
0.000010249r,  0.000007437r,  0.000004279r,  0.000001396r, -0.000000640r, -0.000001430r,
-0.000000836r,  0.000000980r,  0.000003575r,  0.000006305r,  0.000008454r,  0.000009381r,
0.000008654r,  0.000006158r,  0.000002128r, -0.000002878r, -0.000008078r, -0.000012614r,
-0.000015720r, -0.000016875r, -0.000015918r, -0.000013079r, -0.000008946r, -0.000004353r,
-0.000000212r,  0.000002667r,  0.000003741r,  0.000002847r,  0.000000236r, -0.000003476r,
-0.000007429r, -0.000010699r, -0.000012486r, -0.000012281r, -0.000009977r, -0.000005891r,
-0.000000710r,  0.000004652r,  0.000009229r,  0.000012202r,  0.000013056r,  0.000011687r,
0.000008412r,  0.000003900r, -0.000000962r, -0.000005257r, -0.000008217r, -0.000009372r,
-0.000008634r, -0.000006294r, -0.000002948r,  0.000000643r,  0.000003723r,  0.000005699r,
0.000006260r,  0.000005433r,  0.000003557r,  0.000001197r, -0.000000992r, -0.000002414r,
-0.000002658r, -0.000001579r,  0.000000683r,  0.000003758r,  0.000007138r,  0.000010307r,
0.000012852r,  0.000014552r,  0.000015403r,  0.000015586r,  0.000015396r,  0.000015128r,
0.000014977r,  0.000014967r,  0.000014929r,  0.000014541r,  0.000013421r,  0.000011241r,
0.000007847r,  0.000003340r, -0.000001908r, -0.000007302r, -0.000012143r, -0.000015789r,
-0.000017816r, -0.000018148r, -0.000017104r, -0.000015367r, -0.000013842r, -0.000013460r,
-0.000014940r, -0.000018587r, -0.000024158r, -0.000030846r, -0.000037396r, -0.000042331r,
-0.000044256r, -0.000042176r, -0.000035754r, -0.000025448r, -0.000012493r,  0.000001293r,
0.000013835r,  0.000023206r,  0.000028040r,  0.000027833r,  0.000023099r,  0.000015310r,
0.000006630r, -0.000000513r, -0.000003927r, -0.000002150r,  0.000005199r,  0.000017271r,
0.000032091r,  0.000046902r,  0.000058697r,  0.000064829r,  0.000063573r,  0.000054536r,
0.000038797r,  0.000018764r, -0.000002250r, -0.000020656r, -0.000033291r, -0.000038062r,
-0.000034388r, -0.000023351r, -0.000007511r,  0.000009582r,  0.000024093r,  0.000032681r,
0.000033191r,  0.000025125r,  0.000009774r, -0.000009998r, -0.000030318r, -0.000047061r,
-0.000056698r, -0.000057017r, -0.000047609r, -0.000029980r, -0.000007287r,  0.000016260r,
0.000036227r,  0.000048821r,  0.000051646r,  0.000044174r,  0.000027851r,  0.000005796r,
-0.000017823r, -0.000038626r, -0.000052895r, -0.000058306r, -0.000054370r, -0.000042501r,
-0.000025695r, -0.000007888r,  0.000006865r,  0.000015229r,  0.000015265r,  0.000006810r,
-0.000008505r, -0.000027613r, -0.000046644r, -0.000061720r, -0.000069719r, -0.000068880r,
-0.000059103r, -0.000041908r, -0.000020070r,  0.000002993r,  0.000023927r,  0.000040102r,
0.000050081r,  0.000053820r,  0.000052549r,  0.000048397r,  0.000043840r,  0.000041110r,
0.000041696r,  0.000046050r,  0.000053542r,  0.000062672r,  0.000071475r,  0.000078003r,
0.000080784r,  0.000079130r,  0.000073238r,  0.000064060r,  0.000053000r,  0.000041494r,
0.000030623r,  0.000020830r,  0.000011842r,  0.000002804r, -0.000007401r, -0.000019727r,
-0.000034563r, -0.000051452r, -0.000069029r, -0.000085218r, -0.000097651r, -0.000104222r,
-0.000103647r, -0.000095888r, -0.000082318r, -0.000065561r, -0.000049008r, -0.000036114r,
-0.000029600r, -0.000030756r, -0.000039016r, -0.000051924r, -0.000065532r, -0.000075182r,
-0.000076517r, -0.000066519r, -0.000044332r, -0.000011679r,  0.000027257r,  0.000066497r,
0.000099376r,  0.000119879r,  0.000123944r,  0.000110429r,  0.000081537r,  0.000042557r,
0.000000954r, -0.000035053r, -0.000058135r, -0.000063397r, -0.000049482r, -0.000018996r,
0.000021886r,  0.000064562r,  0.000099707r,  0.000119195r,  0.000117843r,  0.000094624r,
0.000053054r,  0.000000662r, -0.000052397r, -0.000095313r, -0.000118801r, -0.000117044r,
-0.000088989r, -0.000038718r,  0.000025218r,  0.000091373r,  0.000147612r,  0.000183497r,
0.000192377r,  0.000172753r,  0.000128620r,  0.000068708r,  0.000004764r, -0.000050806r,
-0.000087441r, -0.000098576r, -0.000083008r, -0.000045172r,  0.000005728r,  0.000057554r,
0.000097696r,  0.000115632r,  0.000105089r,  0.000065358r,  0.000001487r, -0.000076671r,
-0.000156376r, -0.000224492r, -0.000270036r, -0.000286280r, -0.000271981r, -0.000231501r,
-0.000173806r, -0.000110565r, -0.000053745r, -0.000013203r,  0.000005231r,  0.000000803r,
-0.000022173r, -0.000055377r, -0.000088323r, -0.000110612r, -0.000114093r, -0.000094511r,
-0.000052306r,  0.000007577r,  0.000076791r,  0.000145341r,  0.000203607r,  0.000244194r,
0.000263237r,  0.000260915r,  0.000241091r,  0.000210220r,  0.000175780r,  0.000144612r,
0.000121520r,  0.000108438r,  0.000104315r,  0.000105685r,  0.000107774r,  0.000105827r,
0.000096339r,  0.000077895r,  0.000051436r,  0.000019900r, -0.000012631r, -0.000042050r,
-0.000065306r, -0.000081161r, -0.000090433r, -0.000095642r, -0.000100171r, -0.000107142r,
-0.000118338r, -0.000133442r, -0.000149854r, -0.000163156r, -0.000168165r, -0.000160334r,
-0.000137160r, -0.000099244r, -0.000050677r,  0.000001402r,  0.000048046r,  0.000080328r,
0.000091363r,  0.000078060r,  0.000042182r, -0.000009610r, -0.000066808r, -0.000117065r,
-0.000148776r, -0.000153691r, -0.000128980r, -0.000078259r, -0.000011254r,  0.000057887r,
0.000113381r,  0.000141143r,  0.000131977r,  0.000083933r,  0.000003264r, -0.000096306r,
-0.000195936r, -0.000275243r, -0.000316399r, -0.000307917r, -0.000247318r, -0.000142061r,
-0.000008477r,  0.000131170r,  0.000252946r,  0.000336013r,  0.000366914r,  0.000342488r,
0.000270754r,  0.000169526r,  0.000062961r, -0.000023292r, -0.000067392r, -0.000055976r,
0.000012792r,  0.000128452r,  0.000269976r,  0.000409711r,  0.000518763r,  0.000572775r,
0.000556906r,  0.000469010r,  0.000320311r,  0.000133422r, -0.000061950r, -0.000234744r,
-0.000358618r, -0.000417091r, -0.000406739r, -0.000337769r, -0.000231849r, -0.000117621r,
-0.000024808r,  0.000021890r,  0.000007883r, -0.000068292r, -0.000194619r, -0.000347988r,
-0.000498823r, -0.000617016r, -0.000677936r, -0.000667320r, -0.000584048r, -0.000440273r,
-0.000258907r, -0.000069005r,  0.000099980r,  0.000223895r,  0.000288390r,  0.000291328r,
0.000242682r,  0.000161981r,  0.000073925r,  0.000003092r, -0.000031133r, -0.000018368r,
0.000040943r,  0.000136035r,  0.000248426r,  0.000356037r,  0.000437885r,  0.000478349r,
0.000470140r,  0.000415397r,  0.000324772r,  0.000214795r,  0.000104172r,  0.000009865r,
```

```
-0.000056174r, -0.000088965r, -0.000090775r, -0.000069790r, -0.000037559r, -0.000005904r,
0.000015953r,  0.000023378r,  0.000016989r,  0.000001907r, -0.000014131r, -0.000023278r,
-0.000020009r, -0.000002836r,  0.000025151r,  0.000057055r,  0.000084072r,  0.000098007r,
0.000093744r,  0.000070979r,  0.000034705r, -0.000005758r, -0.000039030r, -0.000054732r,
-0.000046577r, -0.000014700r,  0.000033453r,  0.000084044r,  0.000119505r,  0.000122449r,
0.000080003r, -0.000012458r, -0.000149101r, -0.000313624r, -0.000481631r, -0.000625052r,
-0.000717779r, -0.000741344r, -0.000689371r, -0.000569733r, -0.000403786r, -0.000222630r,
-0.000061057r,  0.000049672r,  0.000088707r,  0.000050647r, -0.000052463r, -0.000192754r,
-0.000331654r, -0.000427562r, -0.000444607r, -0.000360668r, -0.000172935r,  0.000100282r,
0.000422043r,  0.000743234r,  0.001011818r,  0.001183069r,  0.001228700r,  0.001142982r,
0.000944470r,  0.000672856r,  0.000381446r,  0.000126681r, -0.000043218r, -0.000098183r,
-0.000032718r,  0.000132566r,  0.000354756r,  0.000577083r,  0.000740399r,  0.000795374r,
0.000712945r,  0.000490841r,  0.000154791r, -0.000245911r, -0.000647675r, -0.000984893r,
-0.001202771r, -0.001268137r, -0.001176009r, -0.000950587r, -0.000640423r, -0.000308746r,
-0.000020865r,  0.000168779r,  0.000227331r,  0.000149815r, -0.000040226r, -0.000295862r,
-0.000556597r, -0.000760851r, -0.000858556r, -0.000821308r, -0.000648032r, -0.000365062r,
-0.000020694r,  0.000324625r,  0.000610402r,  0.000788020r,  0.000830056r,  0.000735175r,
0.000527682r,  0.000251986r, -0.000036799r, -0.000284069r, -0.000446437r, -0.000499754r,
-0.000442904r, -0.000296746r, -0.000098616r,  0.000106299r,  0.000274773r,  0.000374446r,
0.000389993r,  0.000325371r,  0.000201878r,  0.000052621r, -0.000085215r, -0.000178526r,
-0.000205085r, -0.000157557r, -0.000044026r,  0.000114886r,  0.000291436r,  0.000457338r,
0.000589898r,  0.000676311r,  0.000715214r,  0.000715296r,  0.000691489r,  0.000659837r,
0.000632451r,  0.000613872r,  0.000599807r,  0.000578547r,  0.000534694r,  0.000454179r,
0.000329227r,  0.000161877r, -0.000035017r, -0.000239709r, -0.000426134r, -0.000570091r,
-0.000655548r, -0.000679437r, -0.000653579r, -0.000602999r, -0.000560735r, -0.000560123r,
-0.000626223r, -0.000768396r, -0.000975914r, -0.001217923r, -0.001448142r, -0.001613621r,
-0.001665890r, -0.001572152r, -0.001324014r, -0.000941618r, -0.000471907r,  0.000018981r,
0.000457957r,  0.000779482r,  0.000939346r,  0.000924722r,  0.000758129r,  0.000494123r,
0.000209059r, -0.000014261r, -0.000104031r, -0.000015387r,  0.000258592r,  0.000683380r,
0.001188052r,  0.001678206r,  0.002054378r,  0.002232327r,  0.002161046r,  0.001834675r,
0.001295631r,  0.000628006r, -0.000057714r, -0.000645752r, -0.001037789r, -0.001172764r,
-0.001039596r, -0.000680067r, -0.000181061r,  0.000342472r,  0.000770519r,  0.001002399r,
0.000977586r,  0.000688655r,  0.000183590r, -0.000443156r, -0.001069195r, -0.001568655r,
-0.001837668r, -0.001815691r, -0.001498330r, -0.000938968r, -0.000238802r,  0.000472756r,
0.001063413r,  0.001423945r,  0.001489558r,  0.001252333r,  0.000762293r,  0.000116920r,
-0.000558709r, -0.001137073r, -0.001513535r, -0.001626721r, -0.001469888r, -0.001091090r,
-0.000582269r, -0.000059647r,  0.000360459r,  0.000585397r,  0.000564692r,  0.000299647r,
-0.000157750r, -0.000716149r, -0.001263847r, -0.001691417r, -0.001913254r, -0.001883672r,
-0.001604441r, -0.001122521r, -0.000518811r,  0.000109417r,  0.000668527r,  0.001086700r,
0.001326614r,  0.001390220r,  0.001315013r,  0.001163047r,  0.001005420r,  0.000905845r,
0.000906905r,  0.001021884r,  0.001233626r,  0.001500305r,  0.001766367r,  0.001975876r,
0.002085036r,  0.002071032r,  0.001935326r,  0.001700943r,  0.001404764r,  0.001086999r,
0.000780679r,  0.000503850r,  0.000256473r,  0.000022730r, -0.000221966r, -0.000501178r,
-0.000827600r, -0.001195925r, -0.001580593r, -0.001939350r, -0.002222082r, -0.002382951r,
-0.002392883r, -0.002249160r, -0.001979365r, -0.001638175r, -0.001297125r, -0.001029247r,
-0.000891885r, -0.000911651r, -0.001075335r, -0.001329414r, -0.001589015r, -0.001755025r,
-0.001736073r, -0.001470728r, -0.000944897r, -0.000200112r,  0.000669843r,  0.001534070r,
0.002248996r,  0.002687399r,  0.002766030r,  0.002465781r,  0.001839602r,  0.001005764r,
0.000127055r, -0.000620407r, -0.001082719r, -0.001160782r, -0.000832949r, -0.000162516r,
0.000712199r,  0.001603841r,  0.002313307r,  0.002670998r,  0.002573579r,  0.002008432r,
0.001060227r, -0.000102369r, -0.001257814r, -0.002174821r, -0.002658982r, -0.002593435r,
-0.001965037r, -0.000870273r,  0.000500831r,  0.001900073r,  0.003068961r,  0.003789643r,
0.003928598r,  0.003464064r,  0.002491370r,  0.001204725r, -0.000141149r, -0.001282044r,
-0.001997708r, -0.002156878r, -0.001744666r, -0.000866535r,  0.000272120r,  0.001406870r,
0.002267456r,  0.002632590r,  0.002375272r,  0.001489394r,  0.000092216r, -0.001597827r,
-0.003303512r, -0.004742824r, -0.005683657r, -0.005988186r, -0.005638075r, -0.004735587r,
-0.003480654r, -0.002128827r, -0.000938881r, -0.000120841r,  0.000205000r,  0.000029964r,
-0.000544359r, -0.001329938r, -0.002093275r, -0.002604767r, -0.002686147r, -0.002246327r,
-0.001298586r,  0.000043924r,  0.001592790r,  0.003123372r,  0.004419754r,  0.005316092r,
0.005725971r,  0.005654162r,  0.005189115r,  0.004478696r,  0.003695123r,  0.002997153r,
0.002497818r,  0.002244397r,  0.002214347r,  0.002327163r,  0.002468586r,  0.002520921r,
0.002392114r,  0.002036849r,  0.001465074r,  0.000736558r, -0.000056529r, -0.000814153r,
-0.001453605r, -0.001928852r, -0.002239201r, -0.002425172r, -0.002552847r, -0.002690949r,
-0.002886915r, -0.003148613r, -0.003437101r, -0.003673092r, -0.003756311r, -0.003593428r,
-0.003127759r, -0.002362902r, -0.001373443r, -0.000298621r,  0.000681281r,  0.001381712r,
0.001656115r,  0.001433996r,  0.000745245r, -0.000276373r, -0.001413346r, -0.002405677r,
-0.003005676r, -0.003034937r, -0.002430751r, -0.001270582r,  0.000232714r,  0.001766251r,
0.002977659r,  0.003549447r,  0.003271935r,  0.002098735r,  0.000171445r, -0.002194013r,
-0.004559183r, -0.006444569r, -0.007425489r, -0.007222927r, -0.005769930r, -0.003238104r,
-0.000016343r,  0.003356477r,  0.006293312r,  0.008275893r,  0.008963272r,  0.008268966r,
0.006389152r,  0.003773685r,  0.001043215r, -0.001132947r, -0.002174796r, -0.001717643r,
0.000300334r,  0.003608761r,  0.007642507r,  0.011641110r,  0.014792459r,  0.016393238r,
0.015994136r,  0.013499735r,  0.009201137r,  0.003732304r, -0.002043696r, -0.007197861r,
-0.010916479r, -0.012664326r, -0.012296332r, -0.010093605r, -0.006714346r, -0.003067145r,
-0.000130095r,  0.001249202r,  0.000532858r, -0.002385655r, -0.007143552r, -0.012964403r,
-0.018798694r, -0.023523269r, -0.026161114r, -0.026077973r, -0.023115925r, -0.017635820r,
```

```
-0.010458157r, -0.002712115r,  0.004378938r,  0.009733893r,  0.012625547r,  0.012824824r,
0.010647711r,  0.006893983r,  0.002688308r, -0.000746014r, -0.002336459r, -0.001384305r,
0.002283708r,  0.008266460r,  0.015653580r,  0.023193328r,  0.029531268r,  0.033473289r,
0.034221063r,  0.031532964r,  0.025777728r,  0.017869139r,  0.009093547r,  0.000863397r,
-0.005555052r, -0.009286170r, -0.010013011r, -0.008035309r, -0.004205323r,  0.000246306r,
0.003960683r,  0.005727448r,  0.004733397r,  0.000733426r, -0.005890515r, -0.014194675r,
-0.022850624r, -0.030399681r, -0.035534668r,  0.962646484r, -0.035534668r, -0.030399681r,
-0.022850624r, -0.014194675r, -0.005890515r,  0.000733426r,  0.004733397r,  0.005727448r,
0.003960683r,  0.000246306r, -0.004205323r, -0.008035309r, -0.010013011r, -0.009286170r,
-0.005555052r,  0.000863397r,  0.009093547r,  0.017869139r,  0.025777728r,  0.031532964r,
0.034221063r,  0.033473289r,  0.029531268r,  0.023193328r,  0.015653580r,  0.008266460r,
0.002283708r, -0.001384305r, -0.002336459r, -0.000746014r,  0.002688308r,  0.006893983r,
0.010647711r,  0.012824824r,  0.012625547r,  0.009733893r,  0.004378938r, -0.002712115r,
-0.010458157r, -0.017635820r, -0.023115925r, -0.026077973r, -0.026161114r, -0.023523269r,
-0.018798694r, -0.012964403r, -0.007143552r, -0.002385655r,  0.000532858r,  0.001249202r,
-0.000130095r, -0.003067145r, -0.006714346r, -0.010093605r, -0.012296332r, -0.012664326r,
-0.010916479r, -0.007197861r, -0.002043696r,  0.003732304r,  0.009201137r,  0.013499735r,
0.015994136r,  0.016393238r,  0.014792459r,  0.011641110r,  0.007642507r,  0.003608761r,
0.000300334r, -0.001717643r, -0.002174796r, -0.001132947r,  0.001043215r,  0.003773685r,
0.006389152r,  0.008268966r,  0.008963272r,  0.008275893r,  0.006293312r,  0.003356477r,
-0.000016343r, -0.003238104r, -0.005769930r, -0.007222927r, -0.007425489r, -0.006444569r,
-0.004559183r, -0.002194013r,  0.000171445r,  0.002098735r,  0.003271935r,  0.003549447r,
0.002977659r,  0.001766251r,  0.000232714r, -0.001270582r, -0.002430751r, -0.003034937r,
-0.003005676r, -0.002405677r, -0.001413346r, -0.000276373r,  0.000745245r,  0.001433996r,
0.001656115r,  0.001381712r,  0.000681281r, -0.000298621r, -0.001373443r, -0.002362902r,
-0.003127759r, -0.003593428r, -0.003756311r, -0.003673092r, -0.003437101r, -0.003148613r,
-0.002886915r, -0.002690949r, -0.002552847r, -0.002425172r, -0.002239201r, -0.001928852r,
-0.001453605r, -0.000814153r, -0.000056529r,  0.000736558r,  0.001465074r,  0.002036849r,
0.002392114r,  0.002520921r,  0.002468586r,  0.002327163r,  0.002214347r,  0.002244397r,
0.002497818r,  0.002997153r,  0.003695123r,  0.004478696r,  0.005189115r,  0.005654162r,
0.005725971r,  0.005316092r,  0.004419754r,  0.003123372r,  0.001592790r,  0.000043924r,
-0.001298586r, -0.002246327r, -0.002686147r, -0.002604767r, -0.002093275r, -0.001329938r,
-0.000544359r,  0.000029964r,  0.000205000r, -0.000120841r, -0.000938881r, -0.002128827r,
-0.003480654r, -0.004735587r, -0.005638075r, -0.005988186r, -0.005683657r, -0.004742824r,
-0.003303512r, -0.001597827r,  0.000092216r,  0.001489394r,  0.002375272r,  0.002632590r,
0.002267456r,  0.001406870r,  0.000272120r, -0.000866535r, -0.001744666r, -0.002156878r,
-0.001997708r, -0.001282044r, -0.000141149r,  0.001204725r,  0.002491370r,  0.003464064r,
0.003928598r,  0.003789643r,  0.003068961r,  0.001900073r,  0.000500831r, -0.000870273r,
-0.001965037r, -0.002593435r, -0.002658982r, -0.002174821r, -0.001257814r, -0.000102369r,
0.001060227r,  0.002008432r,  0.002573579r,  0.002670998r,  0.002313307r,  0.001603841r,
0.000712199r, -0.000162516r, -0.000832949r, -0.001160782r, -0.001082719r, -0.000620407r,
0.000127055r,  0.001005764r,  0.001839602r,  0.002465781r,  0.002766030r,  0.002687399r,
0.002248996r,  0.001534070r,  0.000669843r, -0.000200112r, -0.000944897r, -0.001470728r,
-0.001736073r, -0.001755025r, -0.001589015r, -0.001329414r, -0.001075335r, -0.000911651r,
-0.000891885r, -0.001029247r, -0.001297125r, -0.001638175r, -0.001979365r, -0.002249160r,
-0.002392883r, -0.002382951r, -0.002222082r, -0.001939350r, -0.001580593r, -0.001195925r,
-0.000827600r, -0.000501178r, -0.000221966r,  0.000022730r,  0.000256473r,  0.000503850r,
0.000780679r,  0.001086999r,  0.001404764r,  0.001700943r,  0.001935326r,  0.002071032r,
0.002085036r,  0.001975876r,  0.001766367r,  0.001500305r,  0.001233626r,  0.001021884r,
0.000906905r,  0.000905845r,  0.001005420r,  0.001163047r,  0.001315013r,  0.001390220r,
0.001326614r,  0.001086700r,  0.000668527r,  0.000109417r, -0.000518811r, -0.001122521r,
-0.001604441r, -0.001883672r, -0.001913254r, -0.001691417r, -0.001263847r, -0.000716149r,
-0.000157750r,  0.000299647r,  0.000564692r,  0.000585397r,  0.000360459r, -0.000059647r,
-0.000582269r, -0.001091090r, -0.001469888r, -0.001626721r, -0.001513535r, -0.001137073r,
-0.000558709r,  0.000116920r,  0.000762293r,  0.001252333r,  0.001489558r,  0.001423945r,
0.001063413r,  0.000472756r, -0.000238802r, -0.000938968r, -0.001498330r, -0.001815691r,
-0.001837668r, -0.001568655r, -0.001069195r, -0.000443156r,  0.000183590r,  0.000688655r,
0.000977586r,  0.001002399r,  0.000770519r,  0.000342472r, -0.000181061r, -0.000680067r,
-0.001039596r, -0.001172764r, -0.001037789r, -0.000645752r, -0.000057714r,  0.000628006r,
0.001295631r,  0.001834675r,  0.002161046r,  0.002232327r,  0.002054378r,  0.001678206r,
0.001188052r,  0.000683380r,  0.000258592r, -0.000015387r, -0.000104031r, -0.000014261r,
0.000209059r,  0.000494123r,  0.000758129r,  0.000924722r,  0.000939346r,  0.000779482r,
0.000457957r,  0.000018981r, -0.000471907r, -0.000941618r, -0.001324014r, -0.001572152r,
-0.001665890r, -0.001613621r, -0.001448142r, -0.001217923r, -0.000975914r, -0.000768396r,
-0.000626223r, -0.000560123r, -0.000560735r, -0.000602999r, -0.000653579r, -0.000679437r,
-0.000655548r, -0.000570091r, -0.000426134r, -0.000239709r, -0.000035017r,  0.000161877r,
0.000329227r,  0.000454179r,  0.000534694r,  0.000578547r,  0.000599807r,  0.000613872r,
0.000632451r,  0.000659837r,  0.000691489r,  0.000715296r,  0.000715214r,  0.000676311r,
0.000589898r,  0.000457338r,  0.000291436r,  0.000114886r, -0.000044026r, -0.000157557r,
-0.000205085r, -0.000178526r, -0.000085215r,  0.000052621r,  0.000201878r,  0.000325371r,
0.000389993r,  0.000374446r,  0.000274773r,  0.000106299r, -0.000098616r, -0.000296746r,
-0.000442904r, -0.000499754r, -0.000446437r, -0.000284069r, -0.000036799r,  0.000251986r,
0.000527682r,  0.000735175r,  0.000830056r,  0.000788020r,  0.000610402r,  0.000324625r,
-0.000020694r, -0.000365062r, -0.000648032r, -0.000821308r, -0.000858556r, -0.000760851r,
-0.000556597r, -0.000295862r, -0.000040226r,  0.000149815r,  0.000227331r,  0.000168779r,
-0.000020865r, -0.000308746r, -0.000640423r, -0.000950587r, -0.001176009r, -0.001268137r,
```

```
-0.001202771r, -0.000984893r, -0.000647675r, -0.000245911r,  0.000154791r,  0.000490841r,
0.000712945r,  0.000795374r,  0.000740399r,  0.000577083r,  0.000354756r,  0.000132566r,
-0.000032718r, -0.000098183r, -0.000043218r,  0.000126681r,  0.000381446r,  0.000672856r,
0.000944470r,  0.001142982r,  0.001228700r,  0.001183069r,  0.001011818r,  0.000743234r,
0.000422043r,  0.000100282r, -0.000172935r, -0.000360668r, -0.000444607r, -0.000427562r,
-0.000331654r, -0.000192754r, -0.000052463r,  0.000050647r,  0.000088707r,  0.000049672r,
-0.000061057r, -0.000222630r, -0.000403786r, -0.000569733r, -0.000689371r, -0.000741344r,
-0.000717779r, -0.000625052r, -0.000481631r, -0.000313624r, -0.000149101r, -0.000012458r,
0.000080003r,  0.000122449r,  0.000119505r,  0.000084044r,  0.000033453r, -0.000014700r,
-0.000046577r, -0.000054732r, -0.000039030r, -0.000005758r,  0.000034705r,  0.000070979r,
0.000093744r,  0.000098007r,  0.000084072r,  0.000057055r,  0.000025151r, -0.000002836r,
-0.000020009r, -0.000023278r, -0.000014131r,  0.000001907r,  0.000016989r,  0.000023378r,
0.000015953r, -0.000005904r, -0.000037559r, -0.000069790r, -0.000090775r, -0.000088965r,
-0.000056174r,  0.000009865r,  0.000104172r,  0.000214795r,  0.000324772r,  0.000415397r,
0.000470140r,  0.000478349r,  0.000437885r,  0.000356037r,  0.000248426r,  0.000136035r,
0.000040943r, -0.000018368r, -0.000031133r,  0.000003092r,  0.000073925r,  0.000161981r,
0.000242682r,  0.000291328r,  0.000288390r,  0.000223895r,  0.000099980r, -0.000069005r,
-0.000258907r, -0.000440273r, -0.000584048r, -0.000667320r, -0.000677936r, -0.000617016r,
-0.000498823r, -0.000347988r, -0.000194619r, -0.000068292r,  0.000007883r,  0.000021890r,
-0.000024808r, -0.000117621r, -0.000231849r, -0.000337769r, -0.000406739r, -0.000417091r,
-0.000358618r, -0.000234744r, -0.000061950r,  0.000133422r,  0.000320311r,  0.000469010r,
0.000556906r,  0.000572775r,  0.000518763r,  0.000409711r,  0.000269976r,  0.000128452r,
0.000012792r, -0.000055976r, -0.000067392r, -0.000023292r,  0.000062961r,  0.000169526r,
0.000270754r,  0.000342488r,  0.000366914r,  0.000336013r,  0.000252946r,  0.000131170r,
-0.000008477r, -0.000142061r, -0.000247318r, -0.000307917r, -0.000316399r, -0.000275243r,
-0.000195936r, -0.000096306r,  0.000003264r,  0.000083933r,  0.000131977r,  0.000141143r,
0.000113381r,  0.000057887r, -0.000011254r, -0.000078259r, -0.000128980r, -0.000153691r,
-0.000148776r, -0.000117065r, -0.000066808r, -0.000009610r,  0.000042182r,  0.000078060r,
0.000091363r,  0.000080328r,  0.000048046r,  0.000001402r, -0.000050677r, -0.000099244r,
-0.000137160r, -0.000160334r, -0.000168165r, -0.000163156r, -0.000149854r, -0.000133442r,
-0.000118338r, -0.000107142r, -0.000100171r, -0.000095642r, -0.000090433r, -0.000081161r,
-0.000065306r, -0.000042050r, -0.000012631r,  0.000019900r,  0.000051436r,  0.000077895r,
0.000096339r,  0.000105827r,  0.000107774r,  0.000105685r,  0.000104315r,  0.000108438r,
0.000121520r,  0.000144612r,  0.000175780r,  0.000210220r,  0.000241091r,  0.000260915r,
0.000263237r,  0.000244194r,  0.000203607r,  0.000145341r,  0.000076791r,  0.000007577r,
-0.000052306r, -0.000094511r, -0.000114093r, -0.000110612r, -0.000088323r, -0.000055377r,
-0.000022173r,  0.000000803r,  0.000005231r, -0.000013203r, -0.000053745r, -0.000110565r,
-0.000173806r, -0.000231501r, -0.000271981r, -0.000286280r, -0.000270036r, -0.000224492r,
-0.000156376r, -0.000076671r,  0.000001487r,  0.000065358r,  0.000105089r,  0.000115632r,
0.000097696r,  0.000057554r,  0.000005728r, -0.000045172r, -0.000083008r, -0.000098576r,
-0.000087441r, -0.000050806r,  0.000004764r,  0.000068708r,  0.000128620r,  0.000172753r,
0.000192377r,  0.000183497r,  0.000147612r,  0.000091373r,  0.000025218r, -0.000038718r,
-0.000088989r, -0.000117044r, -0.000118801r, -0.000095313r, -0.000052397r,  0.000000662r,
0.000053054r,  0.000094624r,  0.000117843r,  0.000119195r,  0.000099707r,  0.000064562r,
0.000021886r, -0.000018996r, -0.000049482r, -0.000063397r, -0.000058135r, -0.000035053r,
0.000000954r,  0.000042557r,  0.000081537r,  0.000110429r,  0.000123944r,  0.000119879r,
0.000099376r,  0.000066497r,  0.000027257r, -0.000011679r, -0.000044332r, -0.000066519r,
-0.000076517r, -0.000075182r, -0.000065532r, -0.000051924r, -0.000039016r, -0.000030756r,
-0.000029600r, -0.000036114r, -0.000049008r, -0.000065561r, -0.000082318r, -0.000095888r,
-0.000103647r, -0.000104222r, -0.000097651r, -0.000085218r, -0.000069029r, -0.000051452r,
-0.000034563r, -0.000019727r, -0.000007401r,  0.000002804r,  0.000011842r,  0.000020830r,
0.000030623r,  0.000041494r,  0.000053000r,  0.000064060r,  0.000073238r,  0.000079130r,
0.000080784r,  0.000078003r,  0.000071475r,  0.000062672r,  0.000053542r,  0.000046050r,
0.000041696r,  0.000041110r,  0.000043840r,  0.000048397r,  0.000052549r,  0.000053820r,
0.000050081r,  0.000040102r,  0.000023927r,  0.000002993r, -0.000020070r, -0.000041908r,
-0.000059103r, -0.000068880r, -0.000069719r, -0.000061720r, -0.000046644r, -0.000027613r,
-0.000008505r,  0.000006810r,  0.000015265r,  0.000015229r,  0.000006865r, -0.000007888r,
-0.000025695r, -0.000042501r, -0.000054370r, -0.000058306r, -0.000052895r, -0.000038626r,
-0.000017823r,  0.000005796r,  0.000027851r,  0.000044174r,  0.000051646r,  0.000048821r,
0.000036227r,  0.000016260r, -0.000007287r, -0.000029980r, -0.000047609r, -0.000057017r,
-0.000056698r, -0.000047061r, -0.000030318r, -0.000009998r,  0.000009774r,  0.000025125r,
0.000033191r,  0.000032681r,  0.000024093r,  0.000009582r, -0.000007511r, -0.000023351r,
-0.000034388r, -0.000038062r, -0.000033291r, -0.000020656r, -0.000002250r,  0.000018764r,
0.000038797r,  0.000054536r,  0.000063573r,  0.000064829r,  0.000058697r,  0.000046902r,
0.000032091r,  0.000017271r,  0.000005199r, -0.000002150r, -0.000003927r, -0.000000513r,
0.000006630r,  0.000015310r,  0.000023099r,  0.000027833r,  0.000028040r,  0.000023206r,
0.000013835r,  0.000001293r, -0.000012493r, -0.000025448r, -0.000035754r, -0.000042176r,
-0.000044256r, -0.000042331r, -0.000037396r, -0.000030846r, -0.000024158r, -0.000018587r,
-0.000014940r, -0.000013460r, -0.000013842r, -0.000015367r, -0.000017104r, -0.000018148r,
-0.000017816r, -0.000015789r, -0.000012143r, -0.000007302r, -0.000001908r,  0.000003340r,
0.000007847r,  0.000011241r,  0.000013421r,  0.000014541r,  0.000014929r,  0.000014967r,
0.000014977r,  0.000015128r,  0.000015396r,  0.000015586r,  0.000015403r,  0.000014552r,
0.000012852r,  0.000010307r,  0.000007138r,  0.000003758r,  0.000000683r, -0.000001579r,
-0.000002658r, -0.000002414r, -0.000000992r,  0.000001197r,  0.000003557r,  0.000005433r,
0.000006260r,  0.000005699r,  0.000003723r,  0.000000643r, -0.000002948r, -0.000006294r,
-0.000008634r, -0.000009372r, -0.000008217r, -0.000005257r, -0.000000962r,  0.000003900r,
```

```
    0.000008412r,  0.000011687r,  0.000013056r,  0.000012202r,  0.000009229r,  0.000004652r,
    -0.000000710r, -0.000005891r, -0.000009977r, -0.000012281r, -0.000012486r, -0.000010699r,
    -0.000007429r, -0.000003476r,  0.000000236r,  0.000002847r,  0.000003741r,  0.000002667r,
    -0.000000212r, -0.000004353r, -0.000008946r, -0.000013079r, -0.000015918r, -0.000016875r,
    -0.000015720r, -0.000012614r, -0.000008078r, -0.000002878r,  0.000002128r,  0.000006158r,
    0.000008654r,  0.000009381r,  0.000008454r,  0.000006305r,  0.000003575r,  0.000000980r,
    -0.000000836r, -0.000001430r, -0.000000640r,  0.000001396r,  0.000004279r,  0.000007437r,
    0.000010249r,  0.000012171r,  0.000012834r,  0.000012118r,  0.000010153r,  0.000007293r,
    0.000004027r,  0.000000882r, -0.000001677r, -0.000003335r, -0.000003974r, -0.000003678r,
    -0.000002702r, -0.000001405r, -0.000000169r,  0.000000677r,  0.000000921r,  0.000000501r,
    -0.000000495r, -0.000001860r, -0.000003317r, -0.000004586r, -0.000005432r, -0.000005719r,
    -0.000005421r, -0.000004619r, -0.000003481r, -0.000002215r, -0.000001025r, -0.000000078r,
    0.000000530r,  0.000000782r,  0.000000727r,  0.000000469r,  0.000000131r, -0.000000173r,
    -0.000000360r, -0.000000389r, -0.000000268r, -0.000000042r,  0.000000225r,  0.000000464r,
    0.000000624r,  0.000000678r,  0.000000627r,  0.000000499r,  0.000000333r,  0.000000174r,
    0.000000054r, -0.000000010r, -0.000000021r,  0.000000003r,  0.000000034r,  0.000000047r,
    0.000000025r, -0.000000034r, -0.000000115r, -0.000000194r, -0.000000240r, -0.000000225r,
    -0.000000137r,  0.000000025r,  0.000000240r,  0.000000475r,  0.000000691r,  0.000000849r,
    0.000000922r,  0.000000898r,  0.000000786r,  0.000000610r,  0.000000406r,  0.000000213r,
    0.000000065r, -0.000000017r, -0.000000026r,  0.000000027r,  0.000000119r,  0.000000218r,
    0.000000294r,  0.000000324r,  0.000000296r,  0.000000212r,  0.000000086r, -0.000000060r,
    -0.000000199r, -0.000000309r, -0.000000375r, -0.000000390r, -0.000000360r, -0.000000296r,
    -0.000000215r, -0.000000134r, -0.000000067r, -0.000000021r,  0.000000000r,  0.000000002r,
    -0.000000009r, -0.000000025r, -0.000000037r, -0.000000042r, -0.000000040r, -0.000000031r,
    -0.000000019r, -0.000000009r, -0.000000001r,  0.000000002r,  0.000000002r,  0.000000001r,
    -0.000000000r
```

1.6 Exercises 6

Listing 8: *ex6-sinegen.asm* - A dual channel sine wave generator using a look-up table of coefficients.

```
/*
Program sinegen is a simple dual channel sine wave generator, which uses a look-up table for the coefficients.
In the example below, it produces frequencies of 6 kHz and 12 kHz.

Author: Patrick Gaydecki (modified by Haseeb Malik, Jakub Mandula, Tarig Mustafa, Kevin Golan)
Date  : 02.10.2017 (modified 5/3/19)
*/

.section L1_data_a;  // Linker places 12 kHz LUT starting at 0x11800000
.BYTE4/r32 lut1[]=0.0r,0.999r,0.0r,-0.999r;                    //Hard coded 12 kHz values from LUT
.section L1_data_b;  // Linker places 6 kHz LUT starting at 0x11900000
.BYTE4/r32 lut2[]=0.0r,0.7071r,0.999r,0.7071r,0.0r,-0.7071r,-0.999r,-0.7071r; //Hard coded 6 kHz values from LUT

.section program;
.global _main;
.align 4;
# include <defBF706.h>

_main:
call codec_configure;
call sport_configure;

P0=length(lut1)*4;              //Initializing a circular buffer to hold LUT for 12 kHz
I0=0x11800000;B0=I0;L0=P0;          //Populating buffer 1 with LUT data for 12 kHz
P0=length(lut2)*4;              //Initializing another circular buffer to hold LUT for 6 kHz
I1=0x11900000;B1=I1;L1=P0;          //Populating buffer 2 with LUT data for 6 kHz

get_audio:
wait_left:
// Wait for left data then dummy read
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_left;
R0=[REG_SPORT0_RXPRI_B];

R0=[I0++];                  //Writing value from LUT for 12 kHz to left output and then moving to next value
R0=R0>>8;                 //Bit-shifting to accomodate 24 Bit DAC in codec

[REG_SPORT0_TXPRI_A]=R0;
wait_right:
// Wait for right data then dummy read
R0=[REG_SPORT0_CTL_B];
CC=BITTST(R0, 31);
if !CC jump wait_right;
R0=[REG_SPORT0_RXPRI_B];

R0=[I1++];                  //Writing value from LUT for 6 kHz to right output, then moving to next value
R0=R0>>8;                 //Bit-shifting to accomodate 24 bit DAC in codec

[REG_SPORT0_TXPRI_A]=R0;
jump get_audio;
._main.end:

// Function codec_configure initialises the ADAU1761 codec. Refer to the control register
// descriptions, page 51 onwards of the ADAU1761 data sheet.
codec_configure:
[--SP] = RETS;                            // Push stack (only for nested calls)
R1=0x01(X); R0=0x4000(X); call TWI_write; // Enable master clock, disable PLL
R1=0x7f(X); R0=0x40f9(X); call TWI_write; // Enable all clocks
R1=0x03(X); R0=0x40fa(X); call TWI_write; // Enable all clocks
R1=0x01(X); R0=0x4015(X); call TWI_write; // Set serial port master mode
R1=0x13(X); R0=0x4019(X); call TWI_write; // Set ADC to on, both channels
R1=0x21(X); R0=0x401c(X); call TWI_write; // Enable left channel mixer
R1=0x41(X); R0=0x401e(X); call TWI_write; // Enable right channel mixer
R1=0x03(X); R0=0x4029(X); call TWI_write; // Turn on power, both channels
R1=0x03(X); R0=0x402a(X); call TWI_write; // Set both DACs on
```

```
R1=0x01(X); R0=0x40f2(X); call TWI_write; // DAC gets L, R input from serial port
R1=0x01(X); R0=0x40f3(X); call TWI_write; // ADC sends L, R input to serial port
R1=0x0b(X); R0=0x400a(X); call TWI_write; // Set left line-in gain to 0 dB
R1=0x0b(X); R0=0x400c(X); call TWI_write; // Set right line-in gain to 0 dB
R1=0xe7(X); R0=0x4023(X); call TWI_write; // Set left headphone volume to 0 dB
R1=0xe7(X); R0=0x4024(X); call TWI_write; // Set right headphone volume to 0 dB
R1=0x00(X); R0=0x4017(X); call TWI_write; // Set codec default sample rate, 48 kHz
NOP;
RETS = [SP++];                            // Pop stack (only for nested calls)
RTS;
codec_configure.end:

// Function sport_configure initialises the SPORT0. Refer to pages 26-59, 26-67,
// 26-75 and 26-76 of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
sport_configure:
R0=0x3F0(X); [REG_PORTC_FER]=R0;          // Set up Port C in peripheral mode
R0=0x3F0(X); [REG_PORTC_FER_SET]=R0;      // Set up Port C in peripheral mode
R0=0x2001973; [REG_SPORT0_CTL_A]=R0;      // Set up SPORT0 (A) as TX to codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_A]=R0;      // 64 bits per frame, clock divisor of 1
R0=0x1973(X); [REG_SPORT0_CTL_B]=R0;      // Set up SPORT0 (B) as RX from codec, 24 bits
R0=0x0400001; [REG_SPORT0_DIV_B]=R0;      // 64 bits per frame, clock divisor of 1
RTS;
sport_configure.end:

// Function TWI_write is a simple driver for the TWI. Refer to page 24-15 onwards
// of the ADSP-BF70x Blackfin+ Processor Hardware Reference manual.
TWI_write:
R3=R0 <<0x8; R0=R0 >>>0x8; R2=R3|R0;      // Reverse low order and high order bytes
R0=0x3232(X); [REG_TWI0_CLKDIV]=R0;       // Set duty cycle
R0=0x008c(X); [REG_TWI0_CTL]=R0;          // Set prescale and enable TWI
R0=0x0038(X); [REG_TWI0_MSTRADDR]=R0;     // Address of codec
[REG_TWI0_TXDATA16]=R2;                   // Address of register to set, LSB then MSB
R0=0x00c1(X); [REG_TWI0_MSTRCTL]=R0;      // Command to send three bytes and enable tx
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
[REG_TWI0_TXDATA8]=R1;                    // Data to write
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x050; [REG_TWI0_ISTAT]=R0;            // Clear TXERV interrupt
[--SP] = RETS; call delay; RETS = [SP++]; // Delay
R0=0x010; [REG_TWI0_ISTAT]=R0;            // Clear MCOMP interrupt
rts;
TWI_write.end:

// Function delay introduces a delay to allow TWI communication
delay:
P0=0x8000;
loop LC0=P0;
NOP; NOP; NOP;
loop_end;
RTS;
delay.end:
```

2 Hardware Design

2.1 Introduction

This report presents a design for a standalone real-time stereo audio system that is capable of processing both speech and music. The selected components were chosen in order to provide high-quality audio while maintaining reasonable costs. Additional requirements include adequate debugging capabilities, and a memory to store the result of and accommodate a high-resolution FIR filtering process.

2.2 Specifications

The ADC and DAC resolution was chosen to be 16 bits as any higher resolution is considered imperceptible for a typical human ear [4]. This results in a SQNR of 96 dB - as per equation 1, which is more than the SNR of most CODECs. In order to maximize the available dynamic range, the minimal SNR of the CODEC was set to be at least 90dB.

$$SQNR = 20\log_{10}(2^N) \tag{1}$$

A sampling frequency of 48 kHz is today's industry standard for studio-quality music [5] and would also accommodate the Compact Disk standard of 16-bit Audio at a sampling frequency of 44.1 kHz. The minimal specifications for the DSP processor and the CODEC are summarized in tables 1 and 2 respectively.

Sampling Frequency	48kHz
Bitrate (per channel)	16bit
Minimum number of filter taps	2048 (stereo)
Minimum number of MMACs	200MMAC
Peripherals	SPI, TWI, UART, PLL, GPIO, SPORT

Table 1: DSP system minimal specifications requirements

Number of channels	2 ADCs and 2 DACs (stereo)
Sampling Frequency	48kHz
Bitrate (per channel)	16bit
Minimum SNR	90dB (stereo)
Peripherals	TWI, SPI or SPORT

Table 2: CODEC minimal specifications requirements

2.3 DPS Processor

For the signal processing, the DSP has to perform at least one full convolution per sample. At a sampling frequency of 48 kHz and a minimum number of 2048 taps per channel, this demands

at least 200 MMACs. Thus the minimum specifications for the desired processor are listed in the Table 1.

Based on these minimal requirements, the group has selected the Blackfin ADSP-BF592 DSP chip. At a price of only approximately £4, it features two 16-bit MACs operating at up to 400 MHz [1] . This would theoretically allow single channel, real-time filtering, using up to 8192 filter taps per sample.

Alternately, this surplus in computational power can be used for other processes. The chip possesses all necessary hardware communication peripherals in a DSP system. This includes the SPORT and TWI for sending and receiving data from the codec, SPI for stand-alone ROM booting, and UART and JTAG for communicating with the debugger.

2.4 Codec

The requirements for the codec is to provide ADC and DAC facilities at 16-bit resolution. However, a codec with a 24-bit resolution was found to be more economical. The main parameters considered were the dynamic range and the Signal-to-Noise ratio (SNR). Other feature requirements for the codec were a stereo-audio interface and SPI capabilities.

As a result, the ADAU1961 24-bit stereo audio codec with integrated PLL was chosen. At a price of £2.5 [3], it has an SNR of 98 dB and communicates using both SPI and TWI [2]. These are essential for communicating with the flash ROM and receiving control signals from the DSP chip respectively.

2.5 Memory

The processor implements a modified Harvard architecture combined with a 2 level hierarchical memory structure [1]. This allows for high-speed processing of multiple datasets using pipelining. For the particular application of filtering, allowing the data and instructions to be accessed simultaneously.

The first memory level is implemented in a modified Harvard architecture. One region is allocated for instructions, and another 2 independent regions can be used to store vector data (such as real and imaginary vectors). The second level is intended to be a slower form of memory and thus is implemented in the Von Neumann architecture. This second level is intended to store data for non-speed-critical operations. Additional to the two levels, memory is to be reserved for the memory mapped control registers of peripherals.

Further to such a layered RAM structure, it is necessary for the Bootloader to be stored in non-volatile memory (flash ROM – via SPI Master). Doing so enables program instructions/firmware to be stored permanently within the system such that the device can operate as standalone from the point of power-on. Further to physically storing program instructions and firmware within the device, in order to accommodate rapid debugging, UART boot mode is to be supported.

2.6 Interface with Codec

Communication with the Codec is established through 2 peripherals: TWI and SPORT.

TWI is compatible with I2C, a standard protocol, and used for occasional control communications with Codec. TWI is bi-directional and runs at a lower frequency than the other peripheral connection: SPORT. A possible use-case for the TWI is the sharing of information regarding volume. The DSP System would query for volume levels by sending a protocoled message to the Codec, and the Codec would then reply with the volume data (contained in peripheral registers) after having received the information.

The SPORT implements the SPI framework for communication with the Codec. SPORT is used for passing digitized serial audio data that is going to be processed from the Codec into the DSP. After the DSP system has completed its processing of the audio signal, the resulting signal is fed back to the codec.

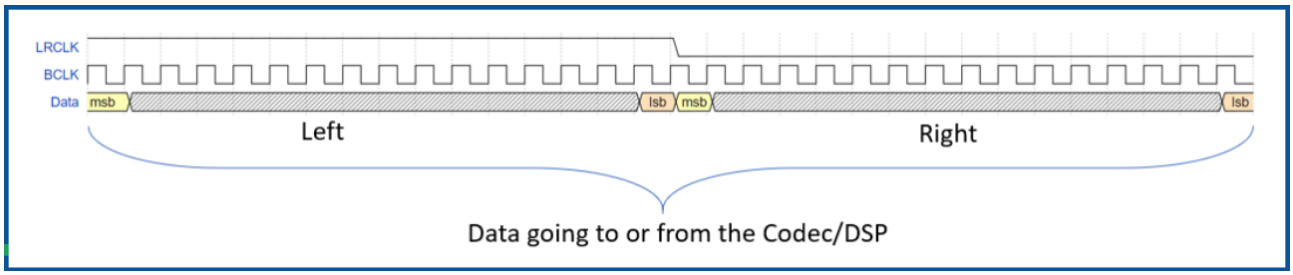

Figure 1: Timing diagram for Codec/DPS communication.

2.7 GPIO

GPIO pins can be configured by the user at run-time through their respective control registers. The logic levels of the pins can be programmed to be edge-sensitive or level-sensitive. In some ways, the number of GPIO pins the system possesses reflects the flexibility of the system at hand.

- Defining the I/O configuration of a given pin.
- Managing control and status of a given signal/pin.
- Configuring GPIO interrupts.

2.8 UART for interfacing with debugger

The UART ports in the DSP system's processor are used to interface the system with external hosts or interfaces for debugging, data transfer and communications. In addition to this, the UART can be used to boot-load the processor after launching or resetting it. This application, however, is dependent upon the boot mode pins' configuration.

2.9 SPI and Flash memory

The serial peripheral interface (SPI) provides the interface to the Flash memory for accessing the bootloader when operating in a standalone environment. SPI provides a mechanism to interface a high-speed system with external peripherals that run at lower clock speeds. Flash memory is non-volatile and electrically erasable. In the context of this DSP system, it would be used to store the operating system. Upon reset or system launch, the OS would then be read from the processor's code memory before execution - making it standalone.

2.10 PLL

Different parts of the DSP run at different clock rates. To deal with the difference in clock speeds in the system, a PLL can be used to localize the high-frequency operations of the processor. Different parts of the system inevitably run at a lower clock speed than the main processor. This is because if they would accommodate the clock speed of the main processor, resulting EM interference and noise would damage performance. Therefore, a PLL is required to maintain the clock speeds that minimize interference in the system's different parts.

The SPORT implementation can be described by the figure above. The transmission of the data and its synchronization is driven by two clock signals: The Left-Right Clock (LRCLK) and the Bit Clock (BCLK). When the LRCLK transitions from logic 1 to logic 0 (or the opposite), a new stream of data from a channel is signaled to the DSP. The DSP will then read the data from the channels at a rate in-sync with the BCLK. In the system at hand, each channel is defined over 16 bits. The allocation of the SPORT follows Time Division Multiplexing as more than one channel is used in the system.

2.11 Real-Time DSP System

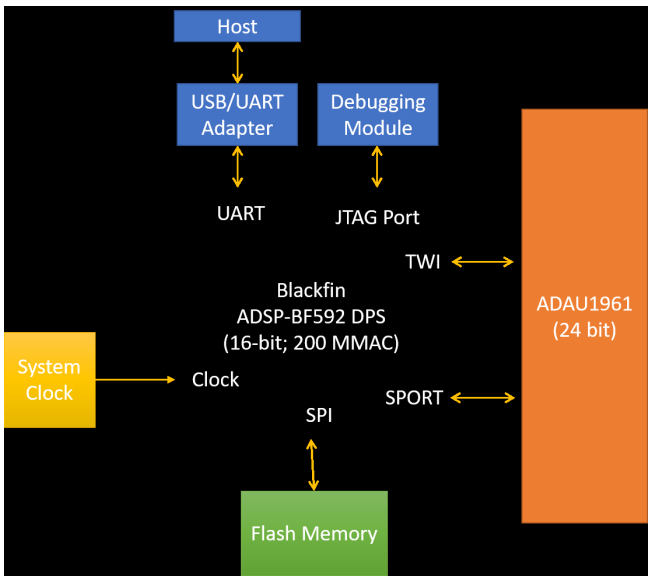

Figure 2: Real-time DPS Design Block diagram.

2.12 Conclusion

This report examined the various design constraints and considerations involved when designing a Digital Signal Processing system. The report first began with an outline of the main requirements a DSP system needs to meet to match industry standards. Based on these definitions, a processor model was proposed and its main characteristics were described. The following is a summary of the chosen parameters for the proposed system.

- ADSP-BF592 DSP device, operating at 200MMAC (16 bit)
- External clocking system
- UART interface for boot mode and serial connection to computer
- Serial flash memory to hold the operating system, connected to the SPI
- ADAU1961 24-bit stereo codec, connected to TWI (control) and SPORT (audio data)
- JTAG debugging interface

References

[1] Analog Devices. *Datasheet: Blackfin Embedded Processor ADSP-BF592*. July 2013. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/ADSP-BF592.pdf (visited on 03/31/2019).

[2] Analog Devices. *Datasheet: Stereo, Low Power, 96 kHz, 24-Bit Audio Codec with Integrated PLL ADAU1961*. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/ADAU1961.pdf.

[3] Digi-Key Electronics. *ADAU1961WBCPZ-RL-ND*. URL: https://www.digikey.com/product-detail/en/analog-devices-inc/ADAU1961WBCPZ-RL/ADAU1961WBCPZ-RL-ND/2606643 (visited on 03/31/2019).

[4] Helen M. Jackson, Michael D. Capp, and J. Robert Stuart. "The Audibility of Typical Digital Audio Filters in a High-Fidelity Playback System". In: (Oct. 2014). URL: http://www.aes.org/e-lib/browse.cfm?elib=17497.

[5] Audio Engineering Society. "AES recommended practice for professional digital audio Preferred sampling frequencies for applications employing pulse-code modulation". 2018. URL: http://www.aes.org/tmpFiles/aessc/20190331/aes05-2018-i.pdf.

Link to code repository: https://github.com/mandulaj/2019DSPLabCode