# DSP-Based GFSK Demodulator for AAU Ground Station Group 627

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## Agenda



Modulation Scheme

Spacelink Format

Blackfin Architecture

Program Flow

System Block Division

Sampler

Channel Filter

Packet Detection

Mid-Frequency Estimation

Time Synchronization

Symbol Decision

Acceptance Test

Conclusion

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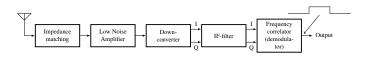
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### Motivation



- ► Make something needed
- ► Satlab Improve receiver for ground station



- ► Better reception
- ▶ More Flexible
- Soft-bit decision

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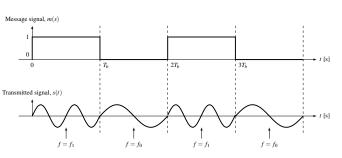
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### Modulation Scheme - FSK





► FSK - Frequency Shift Keying

$$s(t) = \sqrt{\frac{2E_b}{T_b}} \cos\left[2\pi f_c t + \phi(t)\right] \tag{1}$$

$$\phi(t) = \phi(0) \pm h\pi t/T_b \tag{2}$$

$$\Delta f = |f_1 - f_0| = \frac{h}{T_b} = \frac{1}{\frac{1}{9600}} = 9600 \text{ Hz}$$
 (3)

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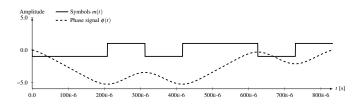
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### Modulation Scheme – GFSK





$$lacktriangledown$$
  $\phi(t)=\phi(0)+rac{h\pi}{T_b}\int_0^{T_b}m_{
m NRZ}(t)dt$ 

► Basis for demodulating by phase

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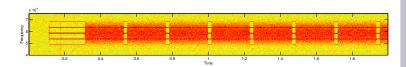
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### Spacelink Format



Training	Sync Word	FSM	Length	CSP Header	Data	HMAC
240 B	6 B	1 B	2B	4 B	23/84 B	2B
	Preamble				— FEC Data —	

► Recording from AAUSAT III



- ► Signal generator
- ► Short package =  $8 \cdot (24B + 6B + 1B + 128B) = 1272$  Symbols

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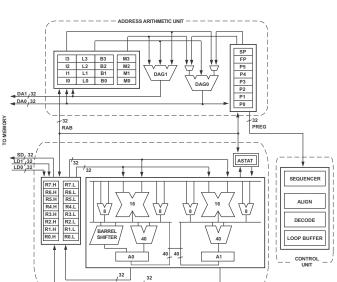
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### Blackfin Architecture





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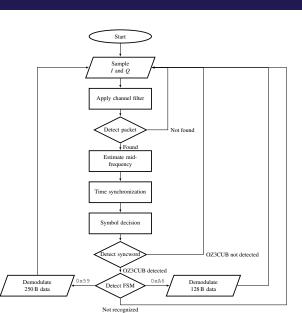
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## Division Into Sub Modules - Program Flow





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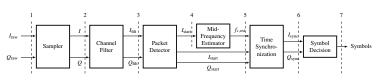
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### System Block Division



The modules which defines the defines the demodulator.



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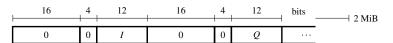
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### Sampler Sorting Data Input



### Sorting the input data.



```
uint32_t *buf32 = (uint32_t *)buffer;
fract16 *buf16I;
fract16 *buf16Q;

while (n < SAMBLOCK/2) {
   buf16I[i] = (fract16)((buf32[n] << 4)&0xFFFF); n++;
   buf16Q[i] = (fract16)((buf32[n] << 4)&0xFFFF); n++;
   i++;
}</pre>
```

► Implementation appropriate inside the channel filter.

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#### Sampler

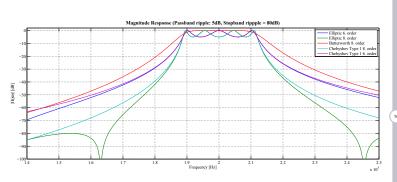
Channel Filter
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- ▶ Bandwidth is defined from Doppler range.
- ► Frequency characteristic is chosen from existing filter
- Group Delay of Butterworth is constant.

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▶ 4th order LP  $\rightarrow$  8th order BP.

$$H(s) = \frac{1}{s^4 + 2.61s^3 + 3.41s^2 + 2.61s + 1} \bigg|_{s = \frac{s^2 + \Omega_0^2}{8s}}$$

$$H(z) = \frac{B^4 S^4}{aS^8 + bS^7 + cS^6 + dS^5 + eS^4 + fS^3 + gS^2 + hS + i} \bigg|_{S = \frac{2}{T_S} \cdot \frac{z - 1}{z + 1}}$$

$$\begin{array}{l} {\rm a} \, = 1 \\ {\rm b} \, = 2.61B \\ {\rm c} \, = 3.41B^2 + 4\Omega_0^2 \\ {\rm d} \, = 2.61B(B^2 + 3\Omega_0^2) \\ {\rm e} \, = B^4 + 6.82B^2\Omega_0^2 + 6\Omega_0^4 \\ {\rm f} \, = 2.61B(B^2 + 3\Omega_0^2)\Omega_0^2 \\ {\rm g} \, = 3.41B^2\Omega_0^4 + 4\Omega_0^6 \\ {\rm h} \, = 2.61B\Omega_0^6 \\ {\rm i} \, = \Omega_0^8 \end{array}$$

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Implementation



$$H(z) = 67.263E-6 \cdot \frac{1-4z^{-2}+6z^{-4}-4z^{-6}+z^{-8}}{1+0.65z^{-1}+3.65z^{-2}+1.73z^{-3}+4.89z^{-4}+1.52z^{-5}+2.84z^{-6}+0.44z^{-7}+0.60z^{-8}}$$

 2nd order cascades by pairing poles closest to unit circle with the closest zero.

$$H(z) = k \cdot \frac{(z - z_1)(z - z_2)}{(z - p_n)(z - p_n^*)} = k \cdot \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{a_0 + a_1 z^{-1} + a_2 z^{-2}}$$

▶ Discrete Time Domain

$$y(n) = b_0 x(n) + b_1 x(n-1) + b_2 x(n-2) - a_1 y(n-1) - a_2 y(n-2)$$

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Packet Detection
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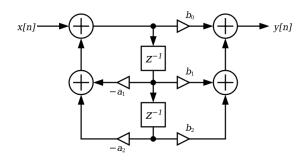
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Cascade Form



### Direct Form II



$$w(n) = x(n) - a_1 w(n-1) - a_2 w(n-2)$$
  
$$y(n) = b_0 w(n) + b_1 w(n-1) + b_2 w(n-2)$$

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Implementation



```
void biquad_df2(fract16 *input, fract16 *output, fract16 *coeff, uint32 N) {
      fract16 xn=0:
      fract16 v1=0; fract16 v2=0; fract16 v3=0; fract16 v4=0;
      fract16 w1n=0; fract16 w1n1=0; fract16 w1n2 = 0;
      fract16 w2n=0: fract16 w2n1=0: fract16 w2n2 = 0:
      fract16 w3n=0; fract16 w3n1=0; fract16 w3n2 = 0;
      fract16 w4n=0; fract16 w4n1=0; fract16 w4n2 = 0;
       int i:
10
       for (i = 0; i < N; i++) {
11
           xn = input[i];
           w1n = ((xn << 15) - coeff[3]*w1n1 - coeff[4]*w1n2)
14
                                                                      >> 15:
           v1 = (coeff[0]*w1n + coeff[1]*w1n1 + coeff[2]*w1n2)
                                                                      >> 15;
16
           w2n = ((v1 << 15) - coeff[9]*w2n1 - coeff[5]*w2n2)
                                                                      >> 15;
           v2 = (coeff[6]*w2n + coeff[7]*w2n1 + coeff[8]*w2n2)
18
                                                                      >> 15;
19
20
           w3n = ((v2 << 15) - coeff[13]*w3n1 - coeff[14]*w3n2)
                                                                      >> 15:
21
           v3 = (coeff[10]*w3n + coeff[11]*w3n1 + coeff[12]*w3n2) >> 15:
22
23
           w4n = ((v3 << 15) - coeff[19]*w4n1 - coeff[15]*w4n2)
                                                                      >> 15:
24
           v4 = (coeff[16]*w4n + coeff[17]*w4n1 + coeff[18]*w4n2) >> 15:
25
26
           output[i] = y4;
27
28
           w4n2 = w4n1:
29
           w4n1 = w4n:
           w3n2 = w3n1:
30
31
           w3n1 = w3n:
32
           w2n2 = w2n1;
33
           w2n1 = w2n;
34
           w1n2 = w1n1;
35
           w1n1 = w1n;
```

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### ► C-Code

Implementation

```
w1n = ((xn<<15) - coeff[3]*w1n1 - coeff[4]*w1n2) >> 15;
y1 = (coeff[0]*w1n + coeff[1]*w1n1 + coeff[2]*w1n2) >> 15;
```

### Assembly

```
A1 = R0.L * R1.L, A0 = R0.L * R1.H || R3 = [P0+4];

R0.H = (A1 -= R2.L * R7.L), A0 -= R2.H * R7.L || R4 = [P0+8];

A1 = R0.L * R3.L, R2.L = (A0 -= R0.H * R3.H);

R2.H = (A1 -= R0.H * R4.L) || R1 = [P0+12];

M0 = R2;
```

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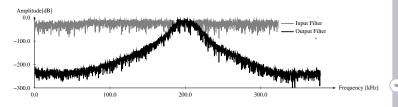
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Conclusion

Test on Blackfin DSP



### DSP test with Q15 frequency sweep and C-filter



- Frequency Characteristic as specified.
- ► Theoretical cycle usage of 1.8% (Optimal)

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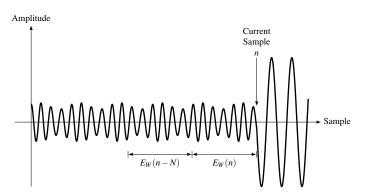
**Double Sliding Window Design** 



$$E_w(n) = \frac{1}{N} \sum_{i=n-N+1}^{n} x_i^2$$

$$Ratio(n) = \frac{E_w(n)}{E_w(n-N)}$$

$$Ratio(n) = \frac{E_w(n)}{E_w(n-N)}$$



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Modulation Scheme

System Block Division

Channel Filter

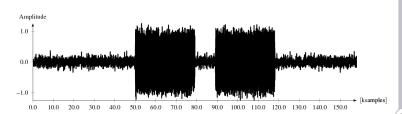
#### Packet Detection

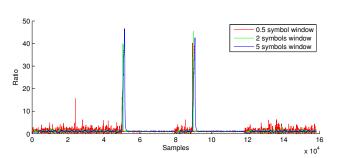
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Test of Window Size at 5 dB SNR







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Acceptance Test

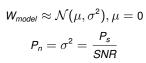
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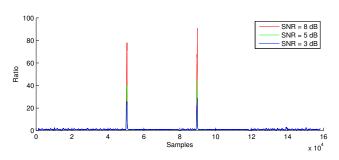
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Test of SNR Influence with Window Size of 2 Symbols







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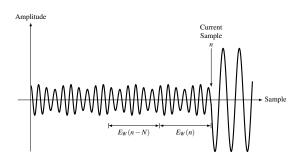
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Implementation



$$E_w(n) = E_w(n) - \frac{x_{n-N}^2}{N} + \frac{x_n^2}{N}$$



- Window size power of two.
- Store old windows as a constant vector
- ▶ 2 mult, 1 sub, 1 add, 1 division

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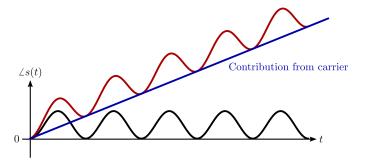
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### Mid-Frequency Estimation

Purpose



- ► Specify contribution from carrier



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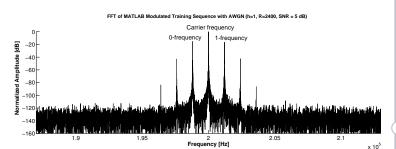
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## Mid-Frequency Estimation

**Properties** 





- Performing an 8192-point FFT on the DSP
- 8192 samples are approximately 13 bytes of training sequence
  - $f_s = 758\,272\,\text{Hz}, R = 9600, \text{SPS} \approx 79$

N [samples]	f <sub>res</sub> [Hz]	FFT cycles [kcycles]	max cycles [kcycles]	FFT usage [%]
8192	92.6	213	142.433	0.150

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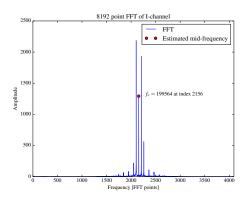
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## Mid-Frequency Estimation

Test Results



### Tested with signal generator.



- Actual mid-frequency
  - ▶ 199 567 Hz
- Estimated mid-frequency
  - ▶ 199 564 Hz

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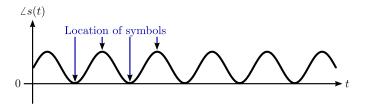
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Conclusion

# Time Synchronization Purpose



► Timing is needed to decide the value of each symbol



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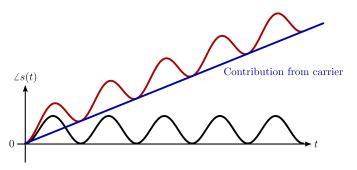
Symbol Decision

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Frequency translation



- ▶ The downconverted phase-signal is used for time synchronization
- ► The phase-signal is computed
- ► The slope added by the carrier and Doppler shift is subtracted



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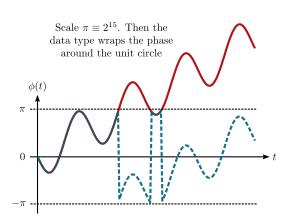
Acceptance Test

Conclusion



Wrapping





- lacktriangle Wrapping:  $arg\_fr16(phi) \in [-\pi,\pi)$ ,  $fract16 \in [-2^{15},2^{15})$ .
- Scale  $\pi \equiv 2^{15}$  wraps around unit circle.

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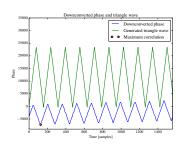
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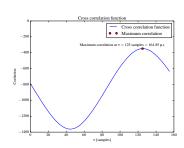
Cross-Correlation



Cross-correlation of downconverted phase-signal, y<sub>2</sub>, and pre-computed triangle wave, y<sub>1</sub>

$$\psi_{y_1y_2}[\tau] = \frac{1}{N} \sum_{n=0}^{N-2T_b-1} y_1[n] y_2[n+\tau], \quad \tau \in [0, \ 2T_b]$$





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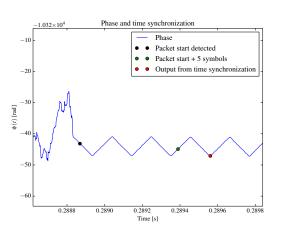
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Test Results





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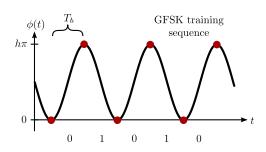
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 $\mathsf{Phase} \to \mathsf{Symbols}$ 





- ► Positive/negative phase change ⇔ 1/0 symbol.
- $T_b = f_s/R = 758272/9600 = 78.987 \text{ samples/s}.$
- From measurement:  $T_b = 78.63 \text{ samples/s}$ .
- Fractional number of samples:

 $T_b = [78788078788078788078788078788078788078] \sim 78.63$ 

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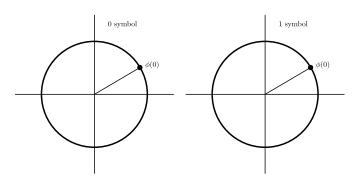
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Wrapping Phase → Symbols





Wrapped phase at the beginning of a symbol.

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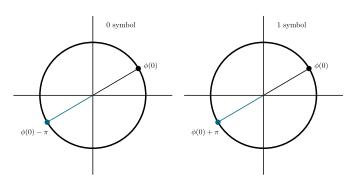
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Wrapping Phase o Symbols





Next symbol (for h = 1):  $\phi(0) + \pi = \phi(0) - \pi$ .

► The same for 0- and 1-symbol.

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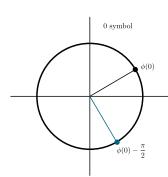
#### 30 Symbol Decision

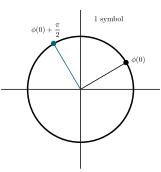
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Conclusion

Wrapping Phase o Symbols







Half way to next symbol: Here is a difference!

$$\hat{m}_n = \begin{cases} 1 & \text{if} \quad \hat{\phi}_{n+0.5} - \hat{\phi}_n > 0 \\ 0 & \text{if} \quad \hat{\phi}_{n+0.5} - \hat{\phi}_n < 0 \\ \text{undefined} & \text{otherwise} \end{cases}$$

Sync word: Symbol-wise comparison.

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Test Results



### Tested with signal generator.

### Drifting

- ▶ Little drifting with  $T_b \equiv 79 \text{ samples/s}$ .
- Correct demodulation of small packet.

### With Slope

- $f_{c,err} \approx 4000 \, \text{Hz}$ .
- Correct demodulation of small packet.

### Finding Sync Word and FSM

▶ Sync word = 0Z4CUB, FSM = 0xA6 (small packet).

#### GFSK Demodulator Group 627

Modulation Scheme

System Block Division

Channel Filter

Mid-Frequency Estimation

Symbol Decision

Real-Time Summary



### Cycle Count

Total number of clock cycles available: 142 433 491.

Module	Cycles Used	DSP Usage
Sampler	109 263 467	77%
Channel Filter	295 467 922	207%
Packet Detector	26 435 831	19%
Mid-Frequency Estimator	14 322 454	10%
Time Synchronization	26 638 224	19%
Symbol Decision	4 587 500	3%
Total	476 715 398	335%

- ▶ C filter  $\rightarrow$  Assembly: 86 913 124 clock cycles  $\sim$  61 %.
- Downsample complex signal.
- Move data when it is processed.

#### GFSK Demodulator Group 627

Modulation Scheme

Spacelink Forma

Blackfin Architecture

Program Flow

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cket Detection

Mid-Frequency Estimation Time Synchronization

Symbol Decision

Acceptance Test



Conclusion



### Signals

Strong, medium, weak.

### Criteria

- Correct sync word and FSM.
- Cannot check symbol-by-symbol.

### Results

Strong Found sync word and FSM.

Medium Found sync word and FSM.

Weak Wrong sync word – found later in buffer.

#### GFSK Demodulator Group 627

Modulation Scheme

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Program F

System Block Division

Channel Filter

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Mid-Frequency Estimation

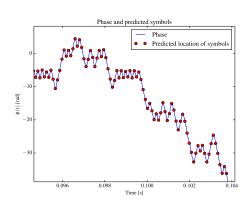
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Symbol Decision



Conclusion





### GFSK Demodulator Group 627

Modulation Scheme

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Blackfin Architecture

Program Flow

System Block Division

Channel Filter
Packet Detection

Mid-Frequency Estimation Time Synchronization

Symbol Decision

33 Acceptance Test

Conclusion

Demonstration

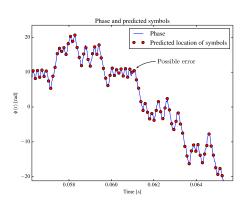
Medium signal.

- ▶ Sampled *I* and Q + estimated  $f_c$  → Phase.
- ▶ Time synchronized + variable  $T_b$  → Predicted location of symbols.
- ▶ No drifting correct sync word and FSM.



35





- Weak signal.
- ▶ Sampled *I* and Q + estimated  $f_c$  → Phase.
- ▶ Time synchronized + variable  $T_b$  → Predicted location of symbols.
- ► No drifting wrong sync word.

### GFSK Demodulator Group 627

Modulation Scheme

Spacelink Format

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Packet Detection

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Time Synchronization

Symbol Decision

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Conclusion

Demonstration

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### Conclusion



- Detect packet from signal generator.
- Correctly demodulate recording from AAUSAT3.
- Prepared for real-time optimization.

#### GFSK Demodulator Group 627

Modulation Scheme

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Blackfin Architecture

Program Flow

System Block Division

Channel Filter

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Packet Detection

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Symbol Decision

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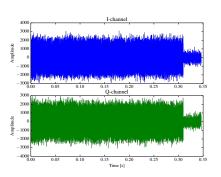
Dept. of Electronic Systems Aalborg University

### Demonstration



### What is Shown?

- ► Medium signal strength.
- Demodulation on DSP.
- ► Amplitude, spectrogram, FFT (training).
- ► Interactive phase + decisions.



#### GFSK Demodulator Group 627

Modulation Scheme

Spacelink Forma

Blackfin Architecture

Program F

System Block Division

Channel Filter

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Mid-Frequency Estimation

Symbol Decision

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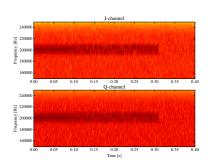


### Demonstration



### What is Shown?

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#### GFSK Demodulator Group 627

Modulation Scheme

Spacelink For

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Program

System Block Division

Channel Filter

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Mid-Frequency Estimation

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Symbol Decision

Conclusion

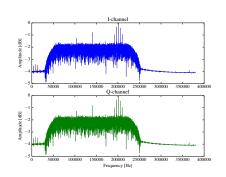


### Demonstration



### What is Shown?

- ► Medium signal strength.
- Demodulation on DSP.
- ► Amplitude, spectrogram, FFT (training).
- ► Interactive phase + decisions.



#### GFSK Demodulator Group 627

Modulation Scheme

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Blackfin Architecture

Program

System Block Division

Sampler

Channel Filter

Packet Detection

Mid-Frequency Estimation

Time Synchronizano

Symbol Decision



