Medical diagnostic systems

(Orvosbiológiai képalkotó rendszerek)

B-mode imaging components

(B-mód képalkotás összetevői)

Miklós Gyöngy

The origins: pulse-echo ranging [Szabo 2004, pp. 1-12]

Sonar: SOund NAvigation and Ranging

– Titanic disaster (1912)

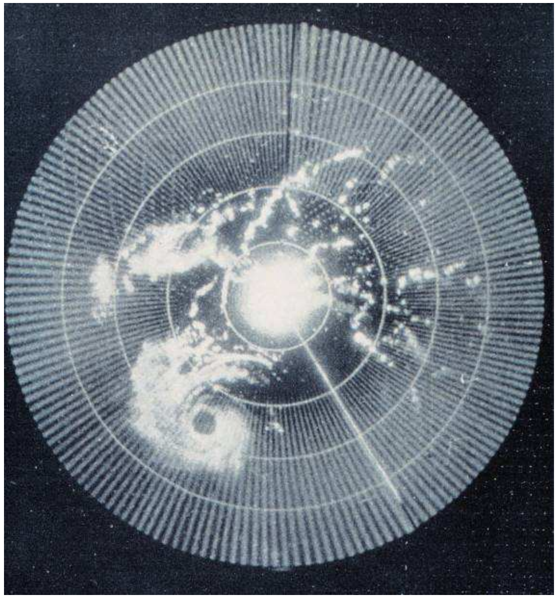
– Anti-submarine warfare (1916-)

Radar: RAdio Detection and Ranging

– Tesla (1917)

- Early experiments in medical ultrasound came from equipment and experience in above two fields

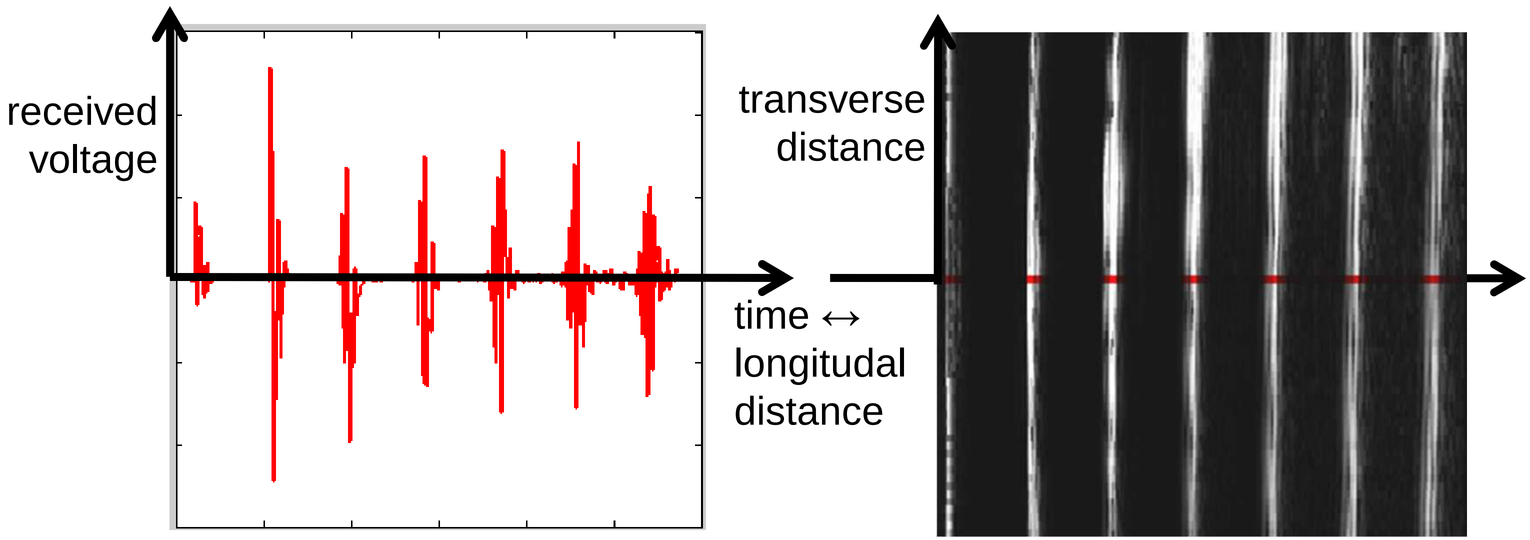
- Ranging (distance measurement based on time of arrival information) relies on relatively constant speed of sound



“Hurricane Abby approaching the coast of British Honduras” NOAA Photo Library, http://www.photolib.noaa.gov/htmls/wea01219.htm

The origins: using an oscilloscope

- Echo returning from transmission observed on oscilloscope
- Amplitude-mode (A-mode): traditional oscilloscope display
- Brightness-mode (B-mode): display envelope of each A-line on top of each other



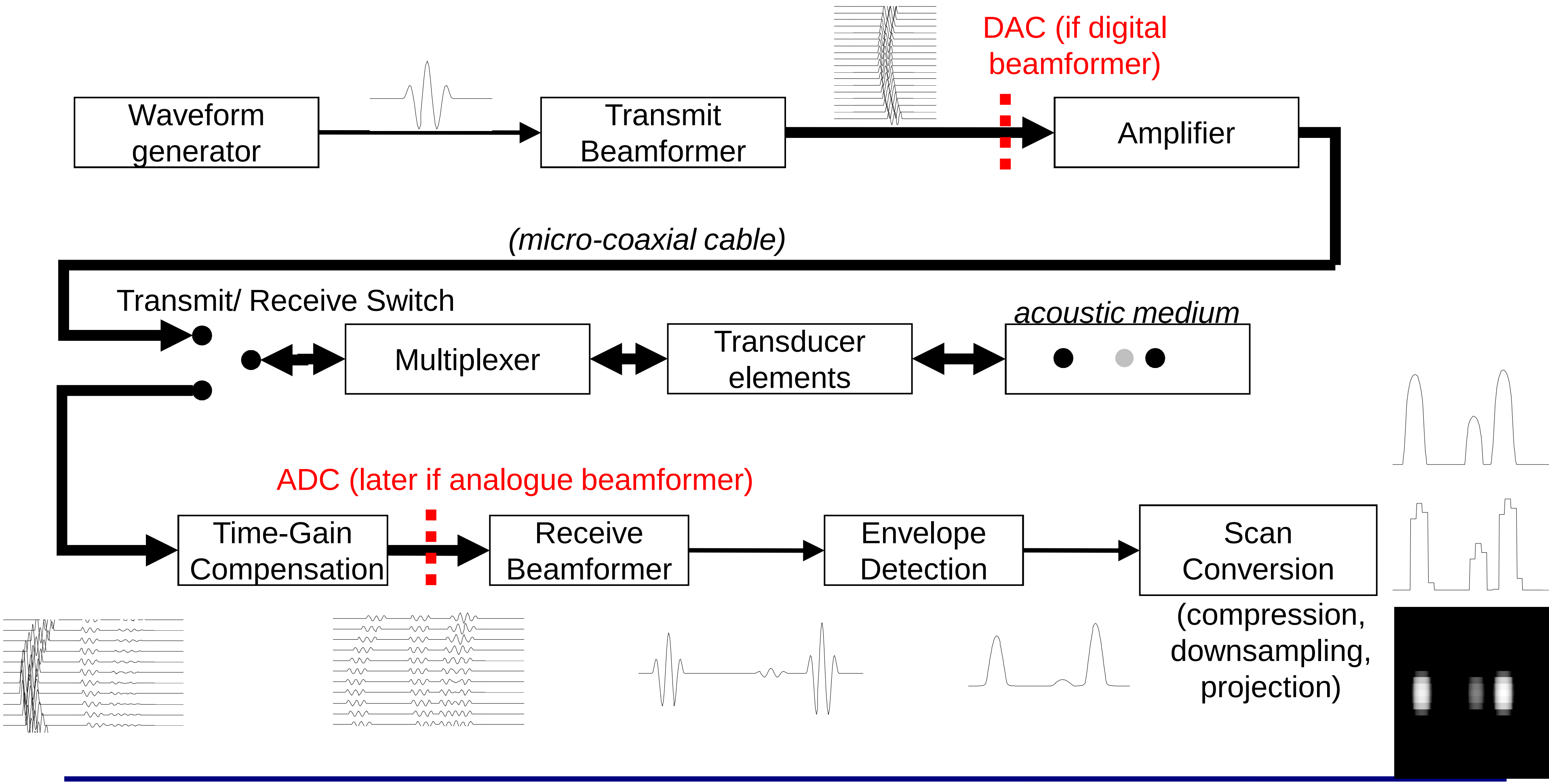
Multiple reflections from a boundary. Left: A-line. Right: B-mode image

The role of technology [Szabo 2004, pp. 16-20]

Advances in transducers
- piezoelectricity (Curie brothers, 1880)
- mass, reproducible manufacture
- miniaturization (e.g. MEMS)

Advances in electronics
- application-specific integrated circuit (ASIC)
- digital signal processors (DSP)
- very large scale integration (VLSI)
- move towards digitization (beamforming, TGC)
- reduced cost of digital storage

Pulse-echo pathway (A-line)



User control/access

Transmission

- Typical commercial system:
  - choose imaging depth (determines focus)
  - choose frequency (determines waveform)
- Research system: arbitrary transmission

Reception

- Typical commercial system:
  - access to bitmap screen grab
  - access to post-beamformed RF data (maybe!)
- Research system: pre-beamformed channel RF

panel of imaging parameters on the z.one ultrasound system (ZONARE Medical Systems)

Needs for user control/access

Clinician:

- basic parameters (resolution, depth)

Researcher of registration/segmentation

- ideally post-beamformed (BF) data

Researcher of new imaging modalities:

- some research possible with BF data (e.g. estimation of acoustic parameters)
- ideally, total control over imaging parameters
- calibration of transmitted and received signal for quantitative studies

panel of imaging parameters on a z.one ultrasound system (ZONARE Medical Systems)

Ultrasound systems for research use

Name	Commerical (C)/ Purpose-built (P)	Channel data (C)/ Post-beamformed (P)	Other options
Antares (Siemens)	C	P	
DiPhAS (IBMT,Fraunhofer)			
LeCoeur (OPEN)	C	C	arbitrary transmission
RASMUS (DTU)	P	C	arbitrary transmission
SonixTouch (Ultrasonix)	C	C	imaging parameters
SONOS 500 URP (Agilent + U. Virginia)	C/P	C	
SITAU FP (Dasel)	C	C	programmable width transmission
t3000 (Terason)	C	P	arbitrary apodization, focal depth
ULA-OP (U. Florence)	P	C	arbitrary transmission
z.one ZONARE	C	C	(on request) arbitrary transmission

[Tortoli *et al.* 2009; Wilson *et al.* 2006]

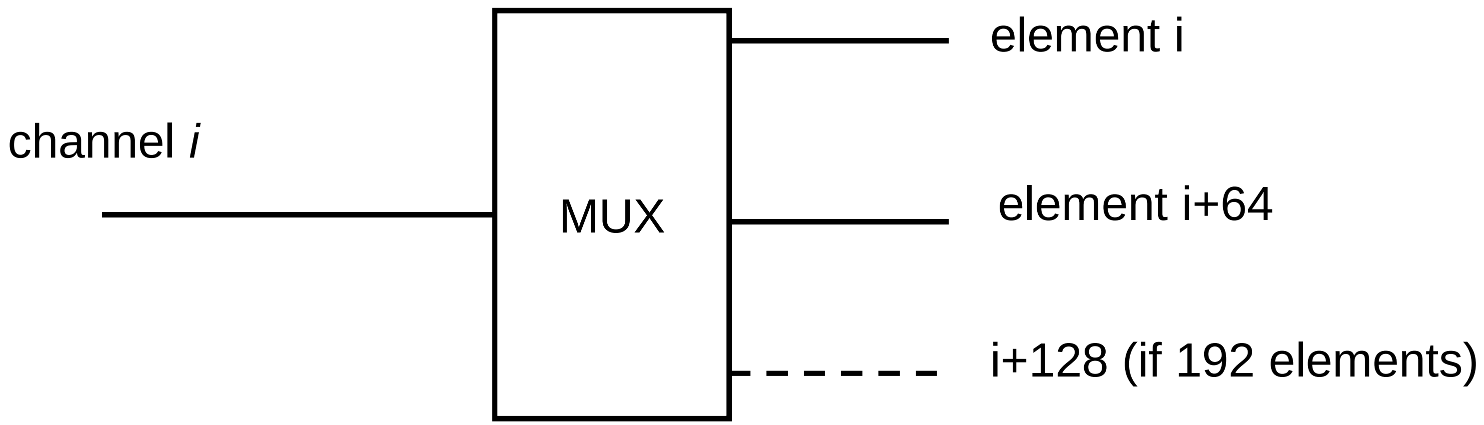
Transmit/Receive switch

- Implementations:
  - diode
  - transmission line (frequency selective)
- Transmission: ~10 V; Reception: ~mV

  → Some leakage will always occur
- Receive circuitry needs to be resistant to saturation blinding (especially from matching layer)

Multiplexing

- Reduction of complexity
- Maintain fixed subaperture during linear scan

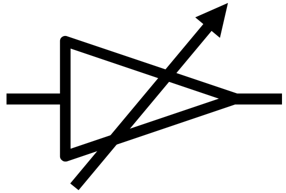


- Shifting of subaperture during linear scan:

  (1,2,...64), (65,2,...,64), (65,66,3,...,64), etc.

Time-gain compensation (TGC) [Brunner 2002]

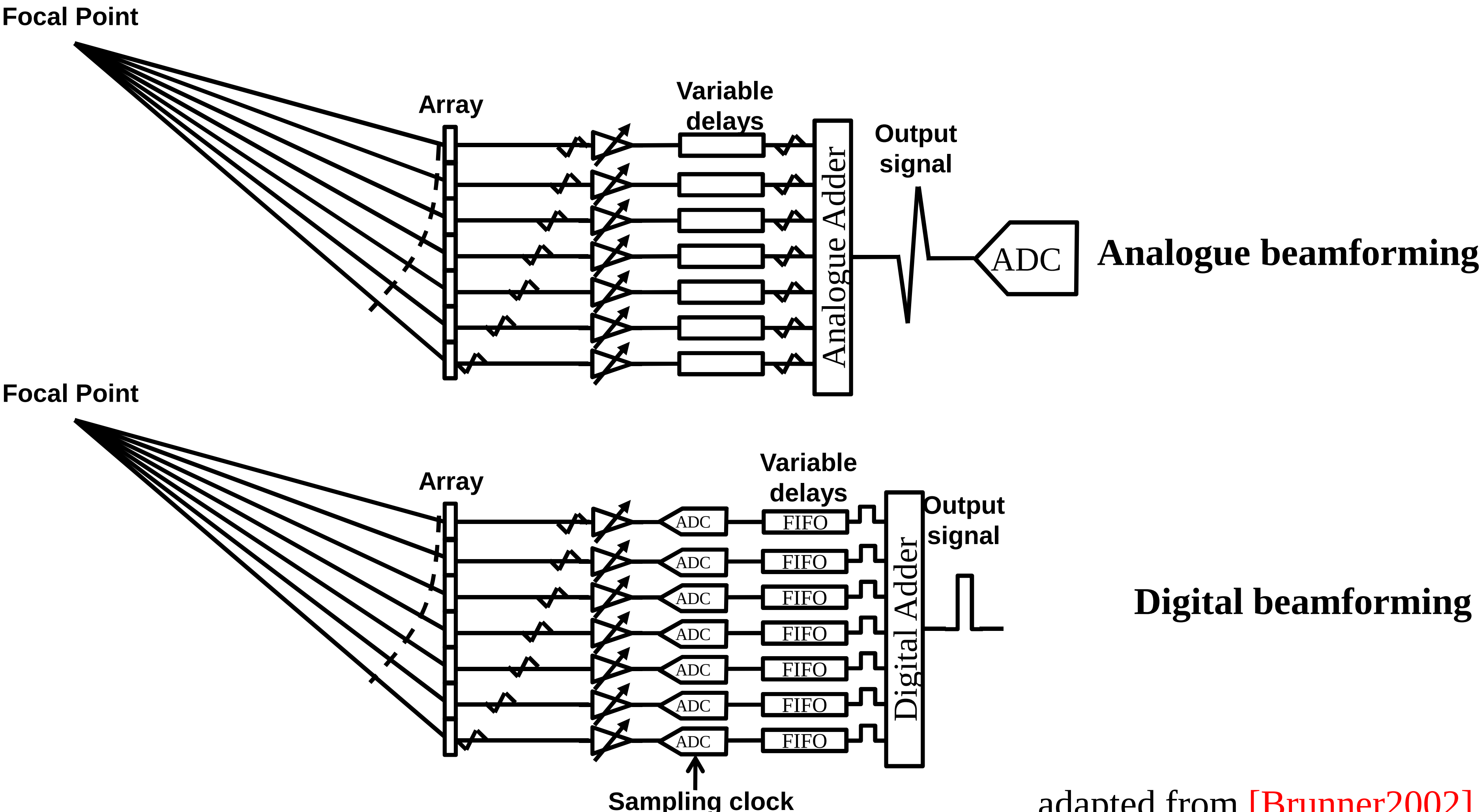
- Diffraction loss relatively unimportant. Consider, in the worst case, spherically diverging Tx/Rx beams. Identical scatterer at 5 cm, 10 cm, causes -12 dB signal difference.
- Tissue attenuation ~1dB/MHz/cm. 5 MHz signal, 10 cm penetration depth, causes -100 dB loss.
- Linear-in-decibel variable-gain amplifiers (VGA) needed to for time-gain compensation (TGC)



Frequency-shift compensation [Szabo 2004, pp. 86-88]

- Tissue causes frequency-dependent attenuation
- Frequency peak of a Gaussian-modulated pulse shifts with distance (~1 MHz for 5 cm imaging depth, 50% fractional bandwidth)
- Depth-dependent compensation needed (but where in the signal processing pathway is it most appropriate?)

Medical diagnostic systems – B-mode imaging



adapted from [Brunner2002]

Analogue beamforming

– Difficult to match channels across delay lines

– Many delay taps needed or phase shifting

+ Only one ADC needed – can make it high-spec

Digital beamforming

– High cost of in-sync, fast (vs) high-resolution ADCs

– Large bit depth and sampling rate incur large storage and computational costs

+ Easier to program/configure

+ Novel implementations (e.g. several receive beams)

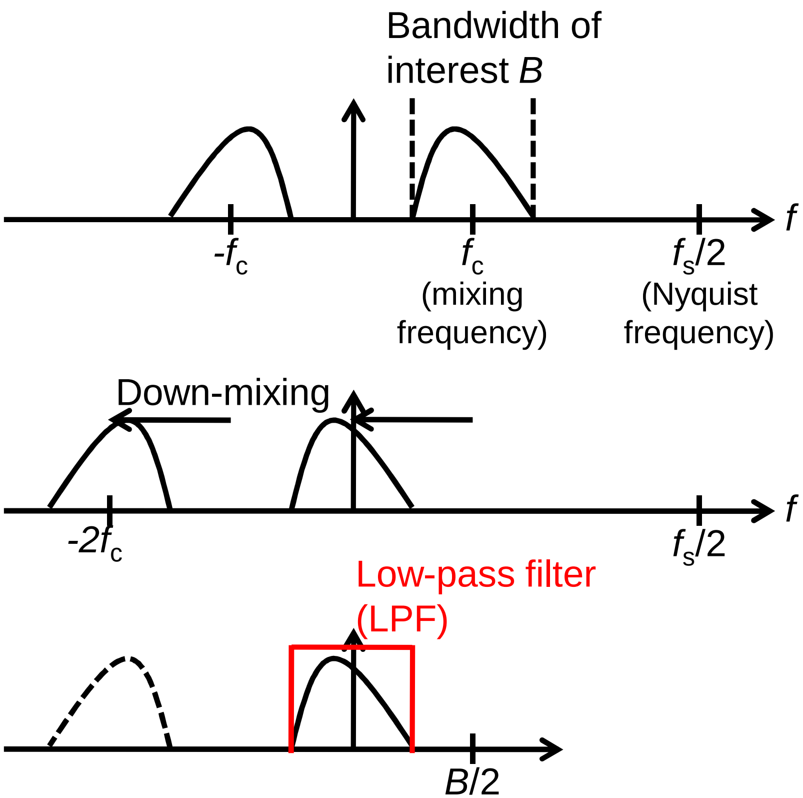
[Brunner 2002]

ADC considerations

- Fast MHz applications, *flash ADC* is used (comparator for every signal level)
- Oversampling: sample at a higher rate, take average of values. E.g. 10 bits at 100 MHz can generate 12-bit data at 25 MHz
- Sigma-delta processing: “pulse density modulation” – local density of 1s represents value (used both for ADC and DAC)
- IQ (in-phase/quadrature) modulation/demodulation

IQ demodulation

1. Mix bandwidth of interest down to baseband
2. Apply LFP
3. Sample at reduced sample rate (less storage cost)



IQ demodulation adapted from [Kirkhorn 1999]

RF signal recovery

1. Upsample to original sample rate (interpolation)
2. Remodulate by mixing frequency f_c

IQ (*in-phase/quadrature*) data: interpretation

$$x_{IQ} = \text{LPF}\{\exp(-\omega_c t)\, x_{RF}\} =$$
$$\text{LPF}\{\cos(\omega_c t)\, x_{RF} - j\sin(\omega_c t)\, x_{RF}\} = x_I + jx_Q$$

- Express RF signal as sum of slowly varying signal $i(t)$ modulating *in-phase* cosine oscillation and slowly varying $q(t)$ modulating *quadrature* sinusoid

  $x_{RF} = i(t)\cos(\omega_c t) + q(t)\sin(\omega_c t)$ where $i(t)$, $q(t)$ are slowly varying
- IQ signal is then

  $x_{IQ} = 0.5\ \text{LPF}\{i(t)(1+\cos(2\omega_c t)-j\sin(2\omega_c t)) + \text{q(t)}(\sin(2\omega_c t)-j-j\cos(2\omega_c t))\}$

  $= 0.5\ i(t)\ -0.5\ jq(t)$
- Low-pass filter removes $\pm 2f_c$
- $\text{Re}\{x_{IQ}\}$ contains in-phase signal
- $\text{Im}\{x_{IQ}\}$ contains quadrature signal
- $|x_{IQ}|$ gives envelope

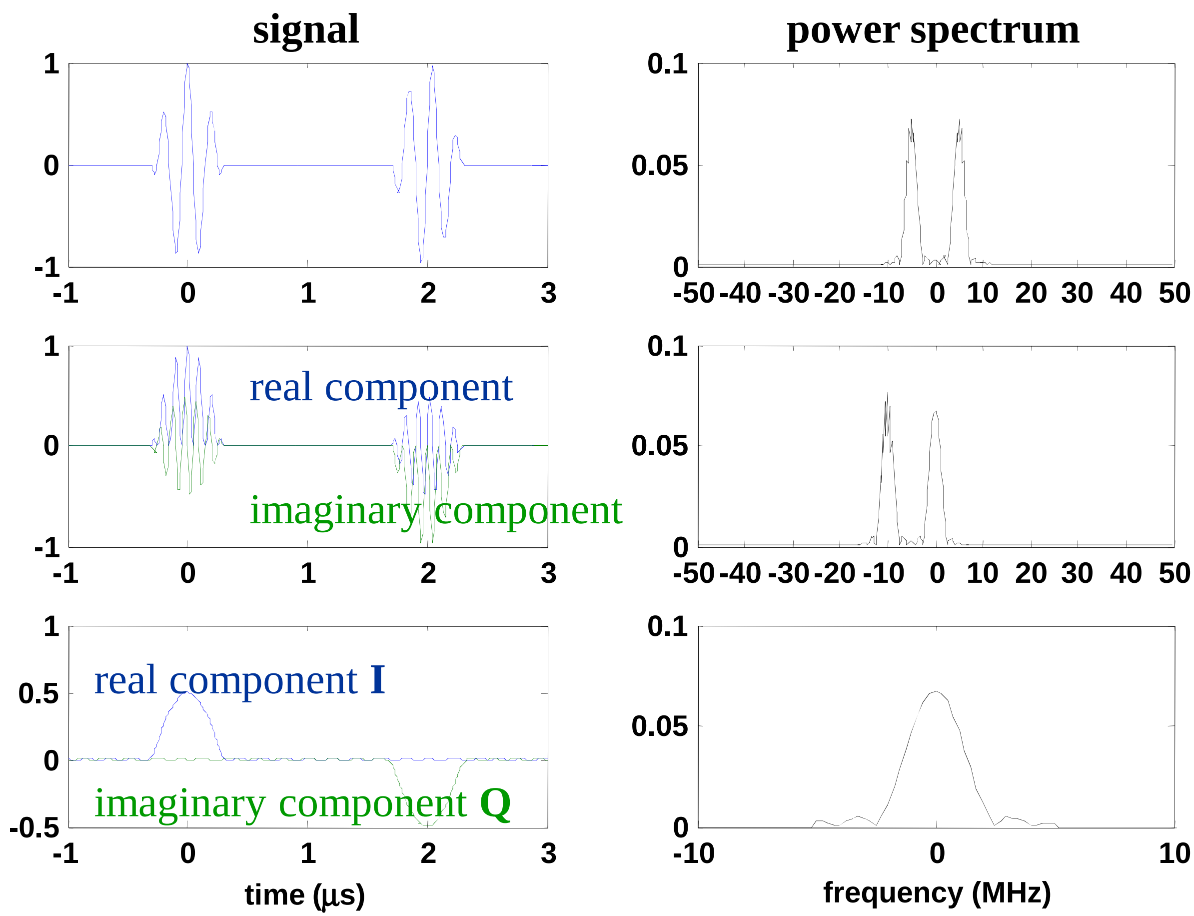
IQ example: cosinusoid (in-phase) around *t*=0 µs, sinusoid (quadrature) around *t*=2 µs (both 3 cycles at 5 MHz)

RF signal

demodulated signal

IQ signal (after LPF)

Note how IQ signal can be sampled at much lower rate!



Envelope detection

- Take magnitude of x_{IQ}

  OR

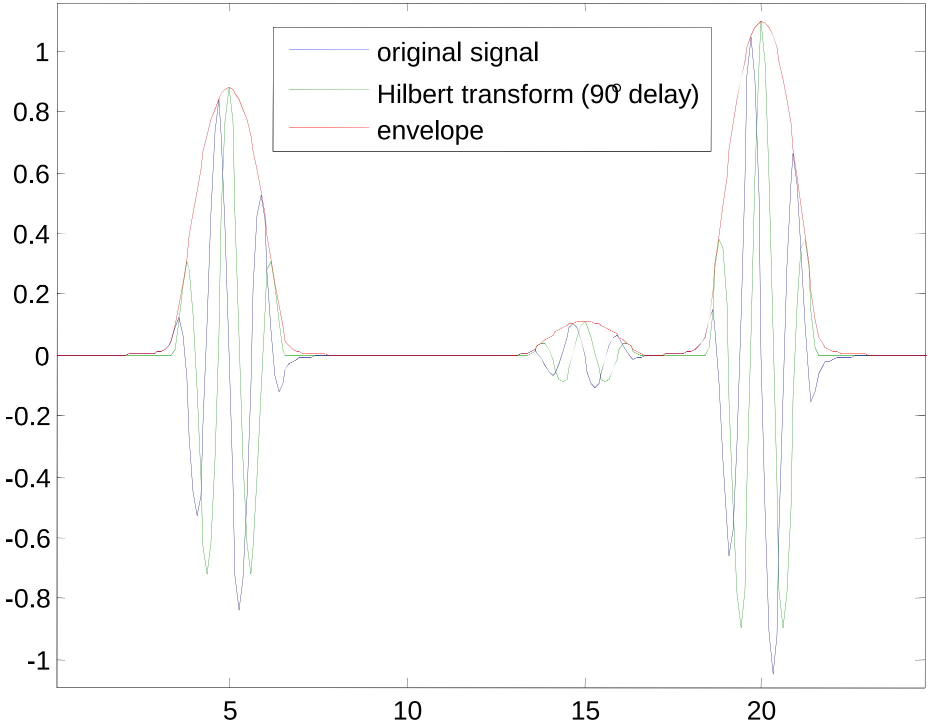
- Hilbert transform $H\{.\}$ of reconstructed x_{RF} : 90º phase shift
- Analytic function of r(t):

  $$x_{RF}(t) + j \times H\{x_{RF}(t)\}$$

- In Matlab: abs(hilbert(r(t)))

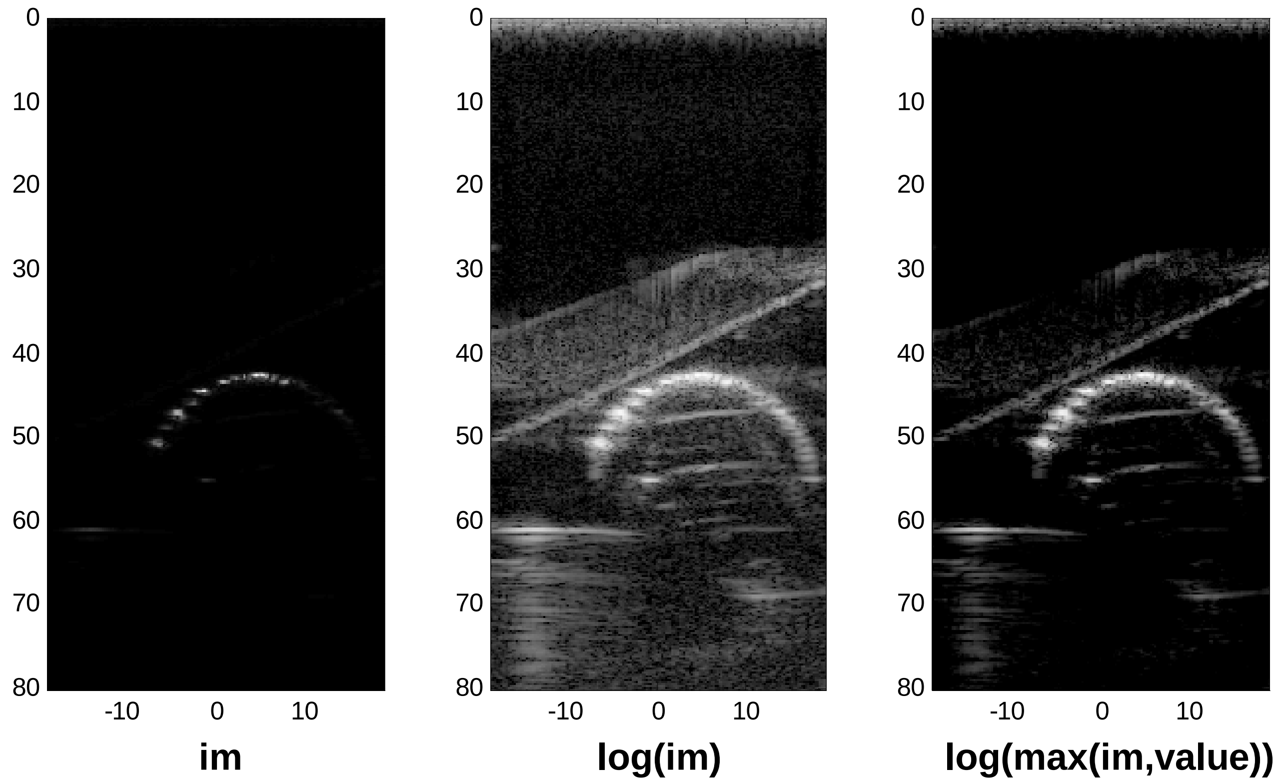
  (hilbert(.) actually generates analytic function!)

- In your own time: consider similarities between IQ and Hilbert transforms



Scan conversion

- Log compression for perception of large (~60 dB) dynamic range
- Threshold to reject noise



References

[Brunner 2002] Ultrasound system considerations and their impact on front-end components

[Kirkhorn 1999] Introduction to IQ-demodulation of RF data. http://folk.ntnu.no/htorp/Undervisning/TTK10/IQdemodulation.pdf

[Szabo 2004] Diagnostic ultrasound imaging: Inside out

[Tortoli *et al.* 2009] ULA-OP: an advanced open platform for ultrasound research

[Wilson *et al.* 2006] The Ultrasonix 500RP: a commercial ultrasound research interface