There's (more than) Music in the Air:

Low-Cost, Hands-On Teaching of Software Defined Radio (SDR)

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Legal Note

There's (More Than) Music in the Air: Low-Cost, Hands-On Teaching of Software Defined Radio

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Parts of the LabVIEW code can be downloaded from: **www.georg-eggers.de/labview4lectures**

Abstract

There's (More Than) Music in the Air: Low-Cost, Hands-On Teaching of Software Defined Radio

Professor Georg Eggers, Munich University of applied Sciences

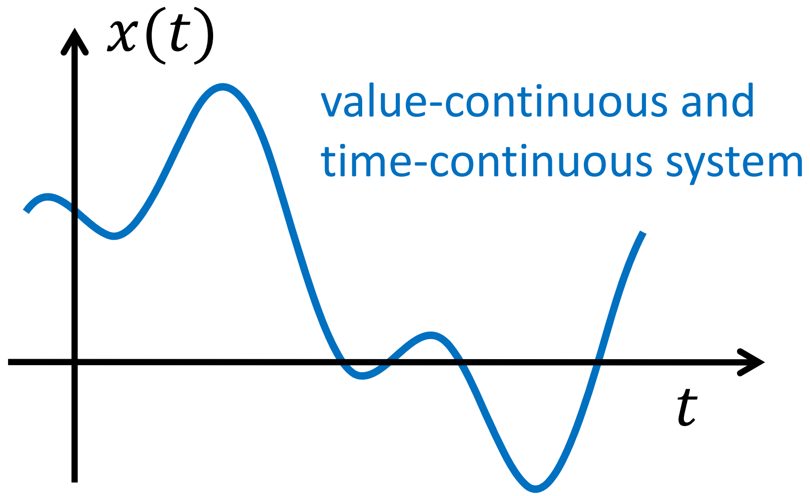
Due to its flexibility in modulation and demodulation of RF signals, software defined radio (SDR) has become a key issue in many fields of wireless data transmission. It should therefore be included in up-to-date lectures on signal processing but the substantial prices of commercial programmable SDR-hardware make it difficult to provide hands-on experiences with SDR to many students. However, recent hardware developments promise to make real-live SDR available at very low cost (between $10-$200 USD).

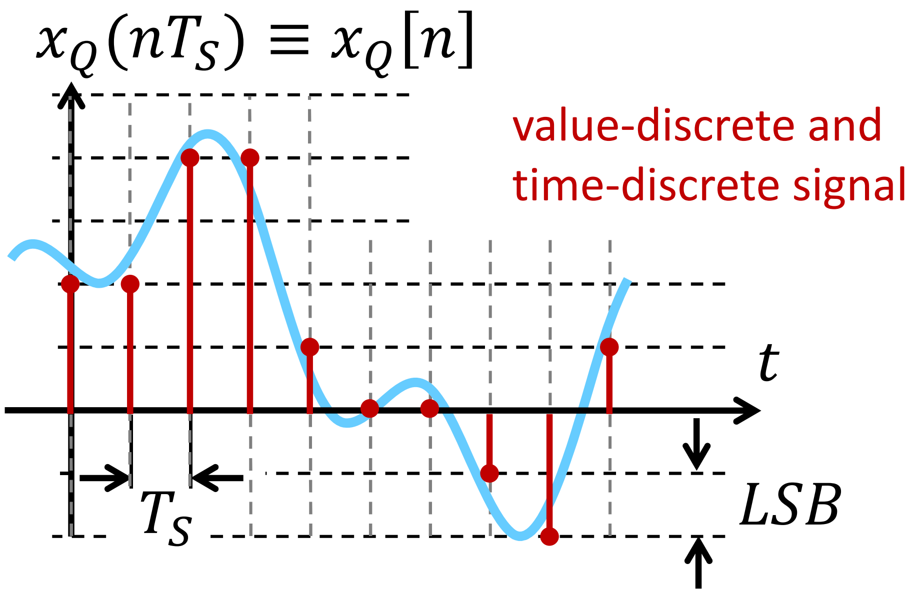
This talk will introduce the SDR basics and show up the possibilities to integrate low-cost SDR hardware into the LabVIEW environment for teaching purposes. It will then discuss the potential and the limits of such hardware by means of different wireless communication standards. This shall include live demonstrations (as far as the conference room's shielding situation allows …).

Presentation material and LabVIEW software examples will subsequently be made available from:
http://www.georg-eggers.de/labview4lectures

Contents

Continuous and Discrete Signals





Time discretization:

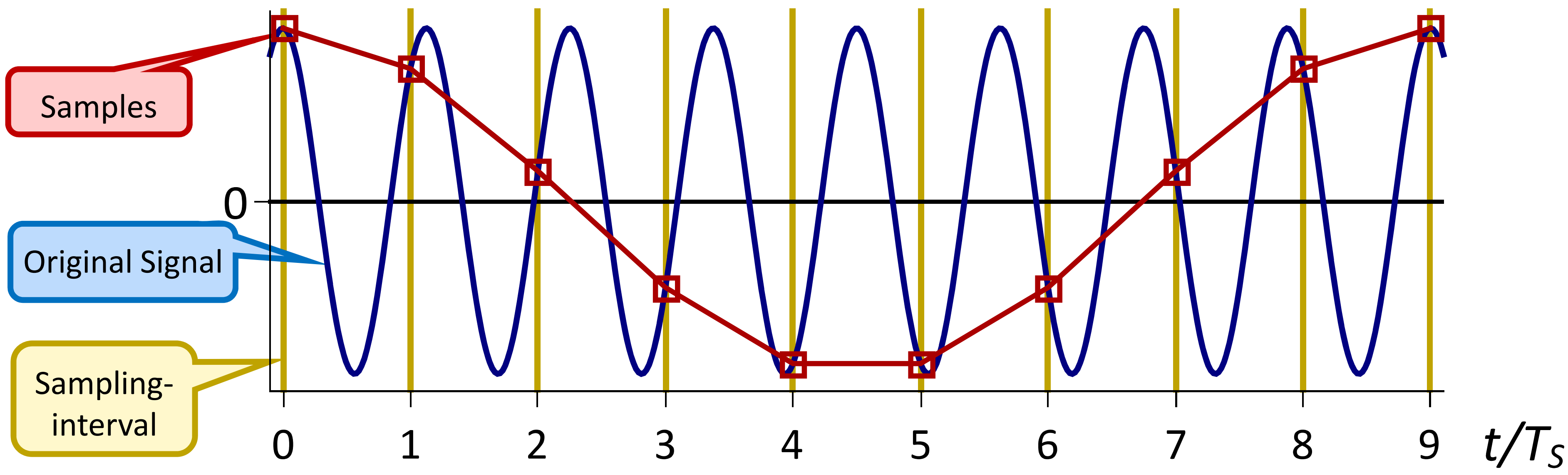
T_S: Sampling interval

$\frac{1}{T_S} = f_S$: Sampling frequency

Value discretization:

LSB: least significant bit

The Deadly Sin of Time-Discrete Signal processing



- **Never ever** violate the Nyquist criterion $f_{\text{Sig,max}} < \frac{1}{2} f_S$ … or be doomed!
- My favorite FM station broadcasts at 100 MHz – will I need a 200-MHz-ADC?

Some Math Magic … Signal Mixing

- Never ever violate the Nyquist criterion $f_{\text{Sig,max}} < \frac{1}{2} f_S$ … or be doomed!
- My favorite FM station broadcast at 100 MHz
  – will I need a 200-MHz-ADC?
- No, because $\cos x \cdot \cos y = \frac{1}{2}[\cos(x-y) + \cos(x+y)]$?!
- Just let be $x = 2\pi f_{Sig} t, y = 2\pi f_{Mix} t$,

$$\cos(2\pi f_{Sig} t) \cdot \cos(2\pi f_{Mix} t) = \frac{1}{2}\left(\cos[2\pi(f_{Sig} - f_{Mix})t] + \cos[2\pi(f_{Sig} + f_{Mix})t]\right)$$

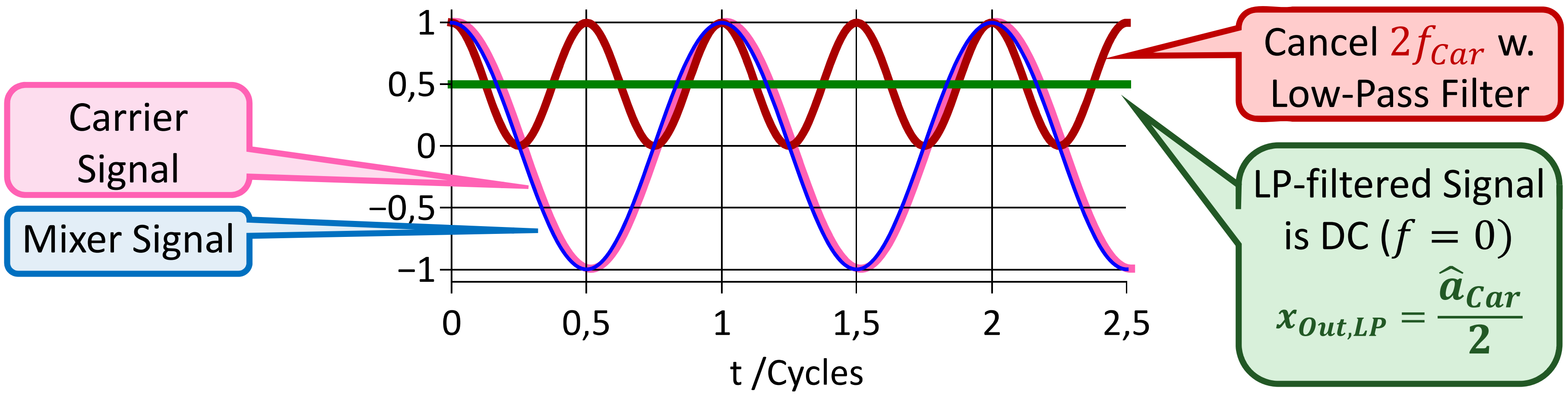
Cancel this with Low-Pass Filter

- Signal multiplication and low-pass filtering results in frequency shift
  → Move high signal frequencies into Nyquist conforming range

Math Magic: The Homodyne Receiver

- Homodyne: Make f_{Mix} equal to your radio carrier frequency f_{Car}

$$\hat{a}_{Car}\cos(2\pi f_{Car}t)\cdot\cos(2\pi f_{Mix}t)=\frac{\hat{a}_{Car}}{2}(\cos[2\pi(0)t]+\cos[2\pi(2f_{Car})t])$$

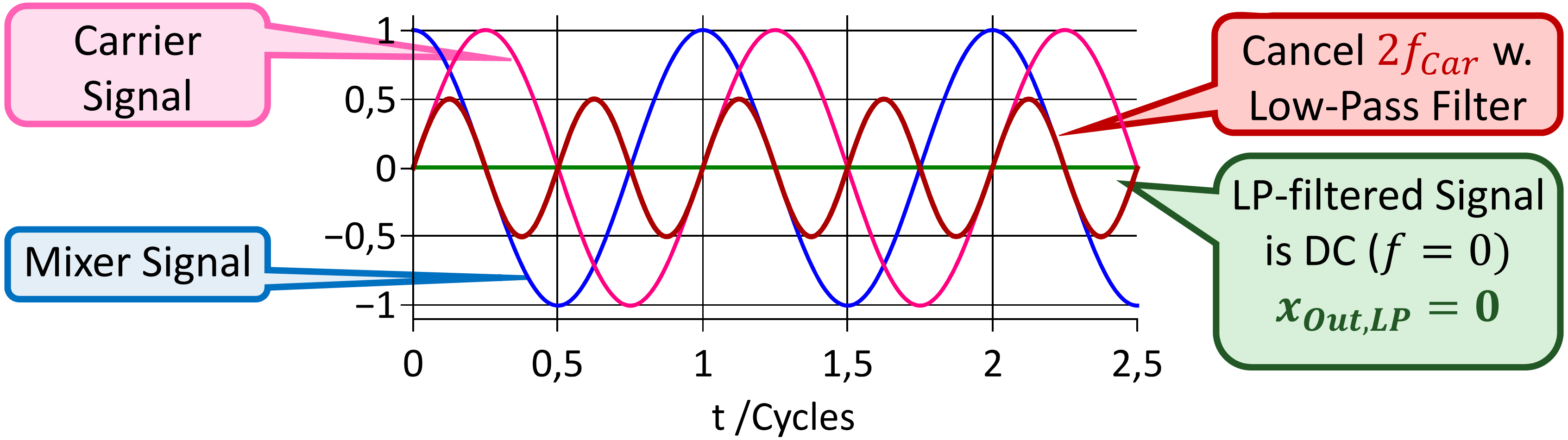


Looks easy, but …

Math Magic: The Homodyne Receiver

- What happens, if modulation and carrier are 90° out of phase?

$$\hat{a}_{Car} \sin(2\pi f_{Car} t) \cdot \cos(2\pi f_{Mix} t) = \frac{1}{2}(\sin[2\pi(0)t] + \sin[2\pi(2f_{Car})t])$$

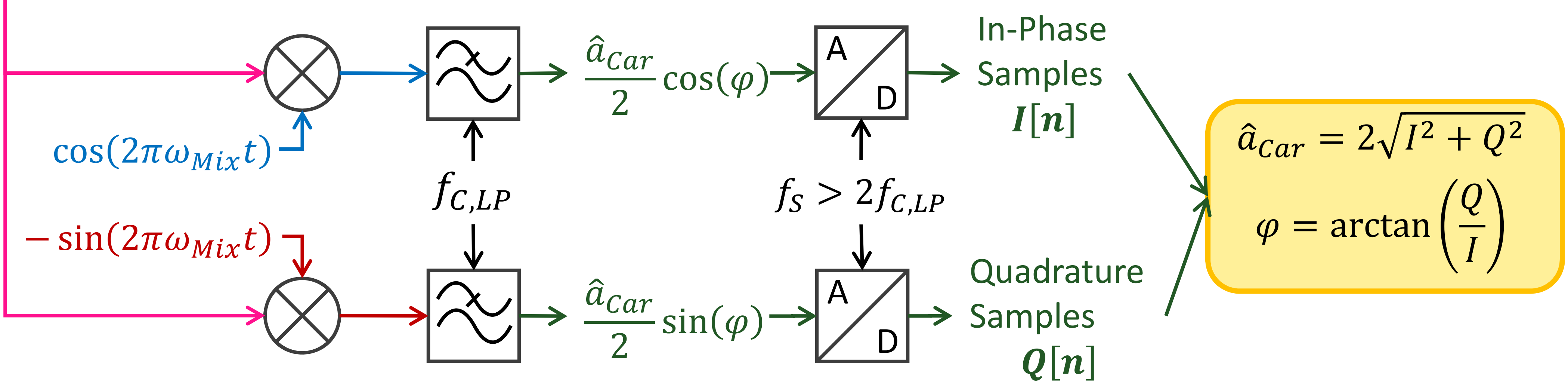


So what?

Math Magic: The Homodyne Receiver

- Describe Carrier Signal as sum of cosine and sine signal

$$x_{Car}(t) = \hat{a}_{Car}\cos(2\pi f_{Car}t + \varphi) = \hat{a}_{Car}[\cos\varphi\cos(2\pi f_{Car}t) - \sin\varphi\sin(2\pi f_{Car}t)]$$



… et voila: Radio Signals without HF!

NI-USRP: Professional SDR Equipment

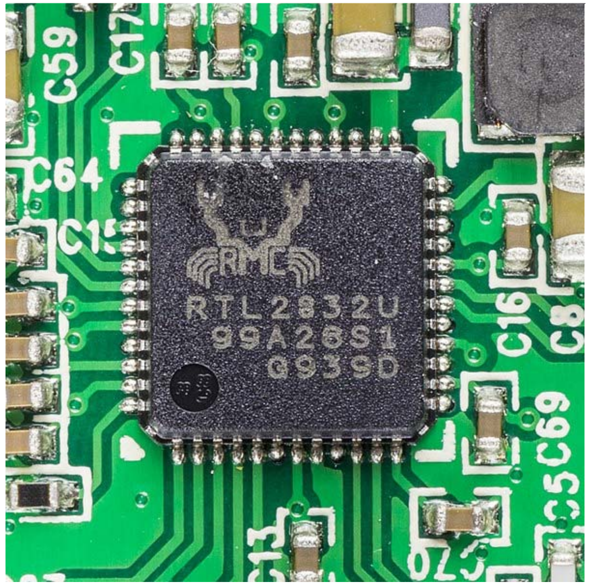
Image: ni.com,
PRODUCT FLYER USRP Software Defined Radios

- f_{Car}: 10 MHz .. 6 GHz
- $f_{Sig,max}$: up to 120 MHz
- Receive (RX) and Transmit (TX)
- FPGA for signal processing
- USB3, Ethernet, MXIe
- NI-USRP Driver integrates into LabVIEW
- Price: 1 k€ .. f_{Sig}

… difficult to afford for teaching

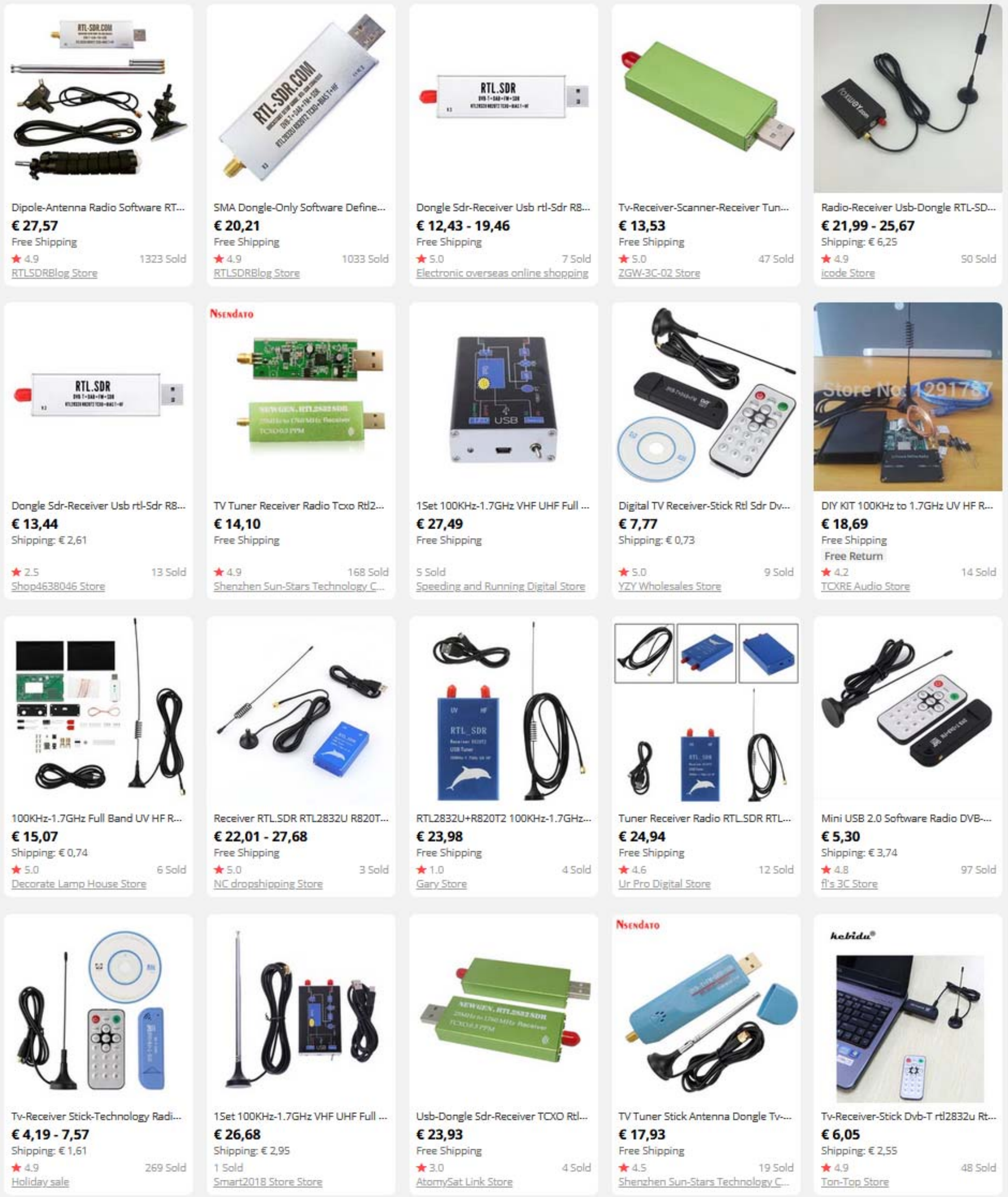
RTL-SDR: Next to No-Cost

- Based on Realtec RTL2832U
- Intended Use: DVB/DAB receivers
- 8-bit ADCs for I/Q-Sampling @ 3.2 MS/s
- USB2-Interface
- Datasheet subject to NDA
- Enthusiast Eric Fry at osmocom.org discovered possibility of raw I/Q-data transfer
- Paired with a tuner/mixer chip, most commonly
  - Elonics E4000
  - Rafael Micro R820T
- No transmission capabilities



RTL-SDR: Next to No-Cost

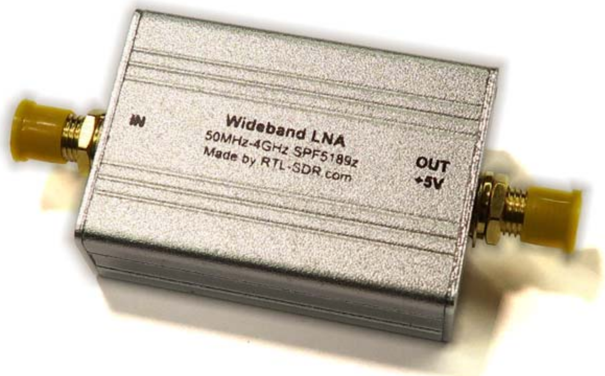
- Numerous versions available from (Chinese) online-shops
- Unmodified DVB/DAB receivers start at ca. US$ 5,-
- Units optimized for SDR programming start at ca. US$ 15,-



Aliexpress.com

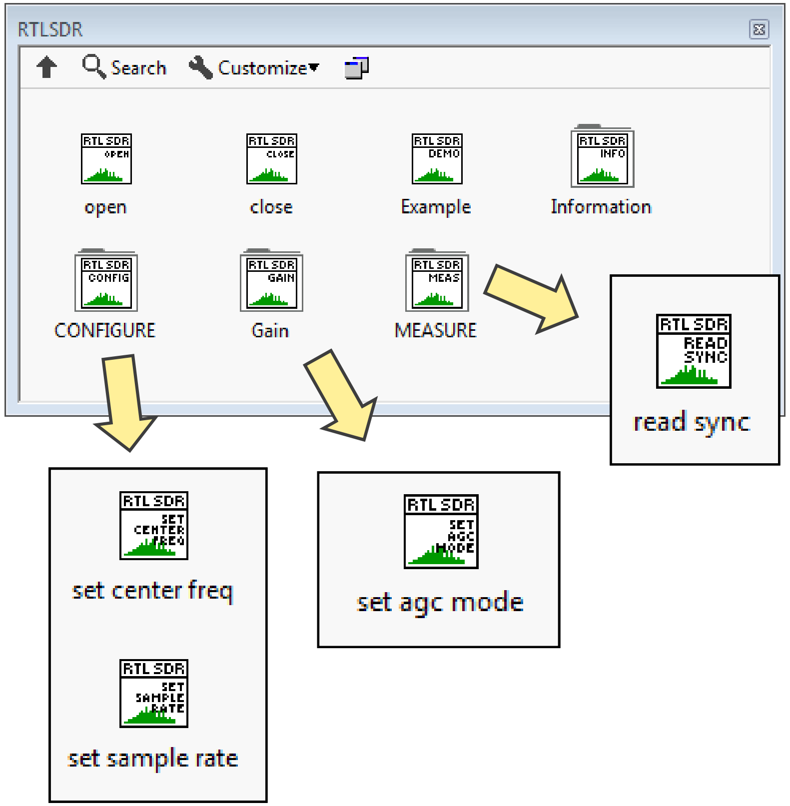
RTL-SDR.COM-Dongle

- RTL2832U Controller
  - $f_{S,max} \approx$ 2,5 MHz @ 8 bit I/Q
- Rafael Micro R820T2 tuner chip
  - $f_{Car} = 24\,..\,1766$ MHz
- Ca. € 26,- including antenna set
- Setup instructions on rtl-sdr.com
- RF-Input bias voltage for antenna preamplifier, which is available as an add-on
- Metal housing acts as heat spreader



RTL-SDR: Integration with LabVIEW

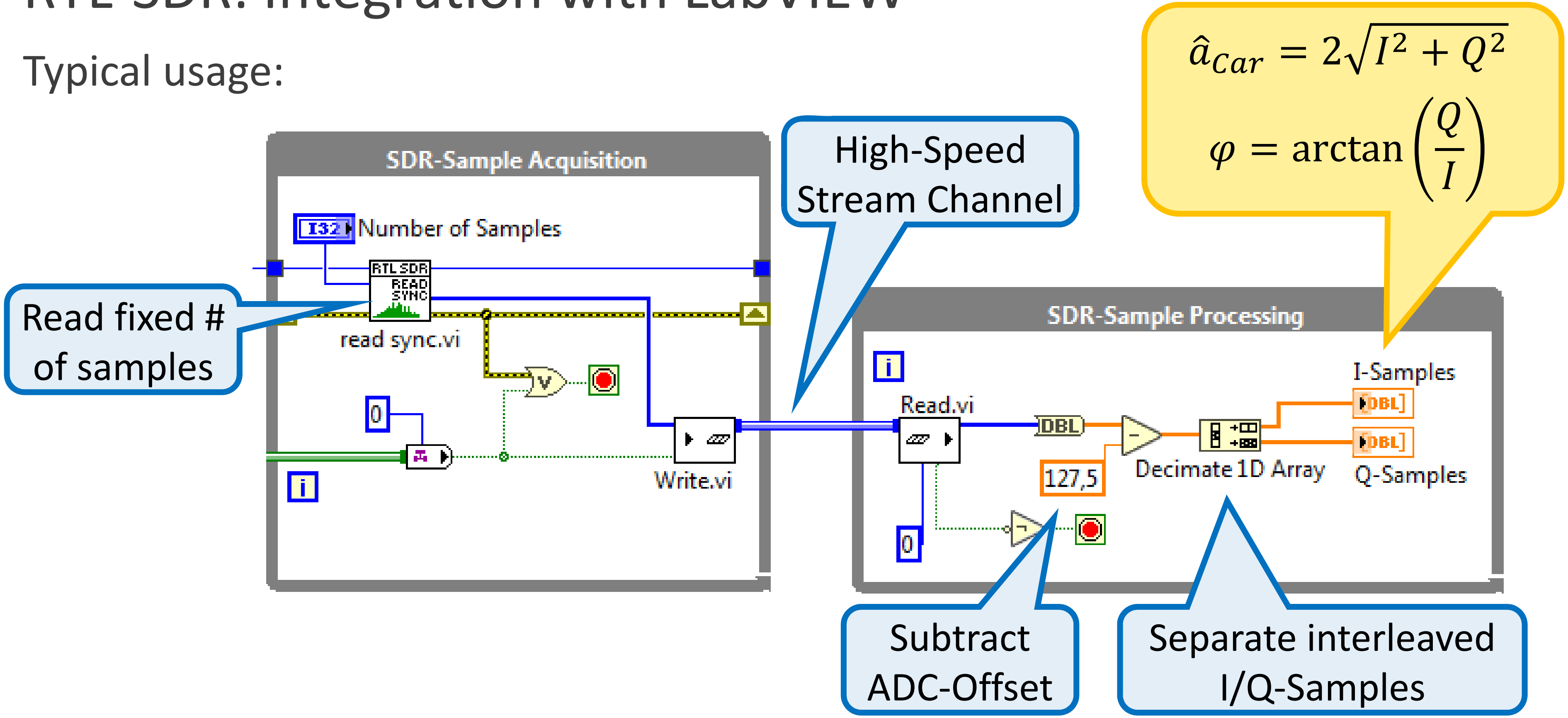
- NI-Forum user **Albert Lederer** (Albert.lederer) prepared a **vipm-package "RTL SDR"** based on rtlsdr.dll by S. Markgraf and D. Stolnikov
- Installable from VI Package Manager (VIPM)
- Usage is similar to sound-card programming
- Supplies 8-Bit unsigned interleaved I/Q-Data



- See NI Forum Link for Details: https://forums.ni.com/t5/Example-Program-Drafts/Using-RTL-SDR-with-Labview-Chapter-1-Labview-on-Windows/ta-p/3538774

RTL-SDR: Integration with LabVIEW

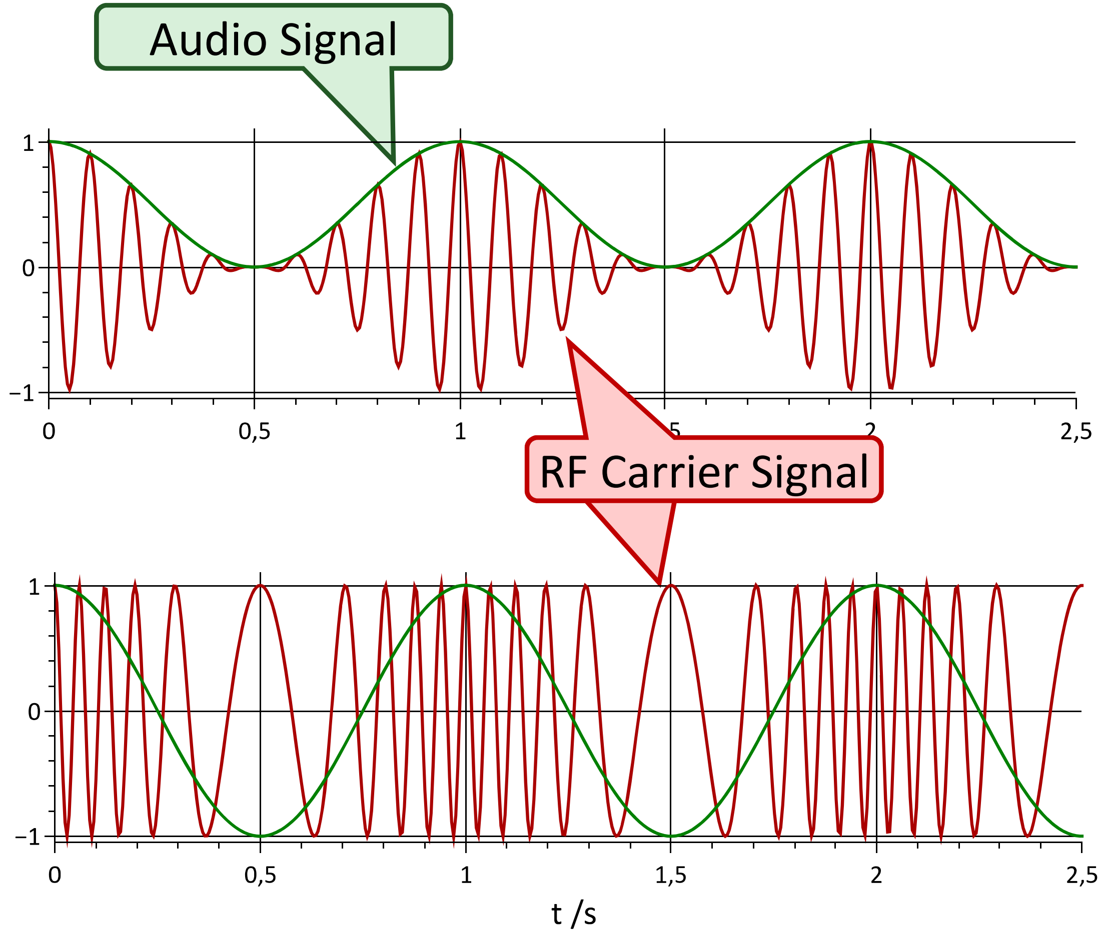
Typical usage:



3a: Example:

RF Signal Modulation

- Amplitude Modulation (AM):
  - (Audio) signal is envelope of carrier signal amplitude
  - Carrier signal amplitude is
    $$\hat{a}_{Car} = 2\sqrt{I^2 + Q^2}$$
- Frequency Modulation (FM):
  - (Audio) signal is difference between actual and nominal carrier signal frequency
  - Carrier signal phase is
    $\varphi = \arctan\left(\frac{Q}{I}\right)$ …?



FM Demodulation: Link between phase and frequency

- Frequency of Carrier Signal is modulated by audio signal $x_{Aud}(t)$

$$f_{RF}(t) = f_{Car} + c\, x_{Aud}(t)$$

$$x_{Car}(t) = \hat{a}_{Car} \cos\left[2\pi \int_0^t f_{Car} + c\, x_{Aud}(\tau)\, d\tau\right] = \hat{a}_{Car} \cos\left[2\pi f_{Car} t + \underbrace{2\pi c \int_0^t x_{Aud}(\tau) d\tau}_{\varphi_{Car}(t)}\right]$$

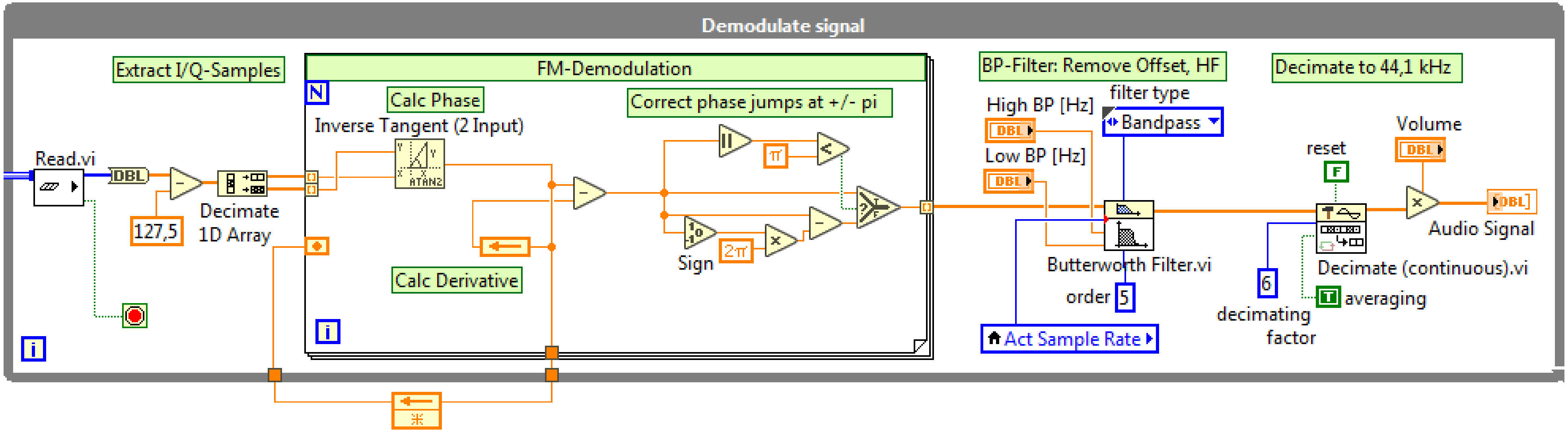
$$\varphi = \arctan\left(\frac{Q}{I}\right) = 2\pi c \int_0^t x_{Aud}(\tau) d\tau \rightarrow \frac{d\varphi(t)}{dt} \propto x_{Aud}(t)$$

- FM audio signal is derivative of radio signal phase

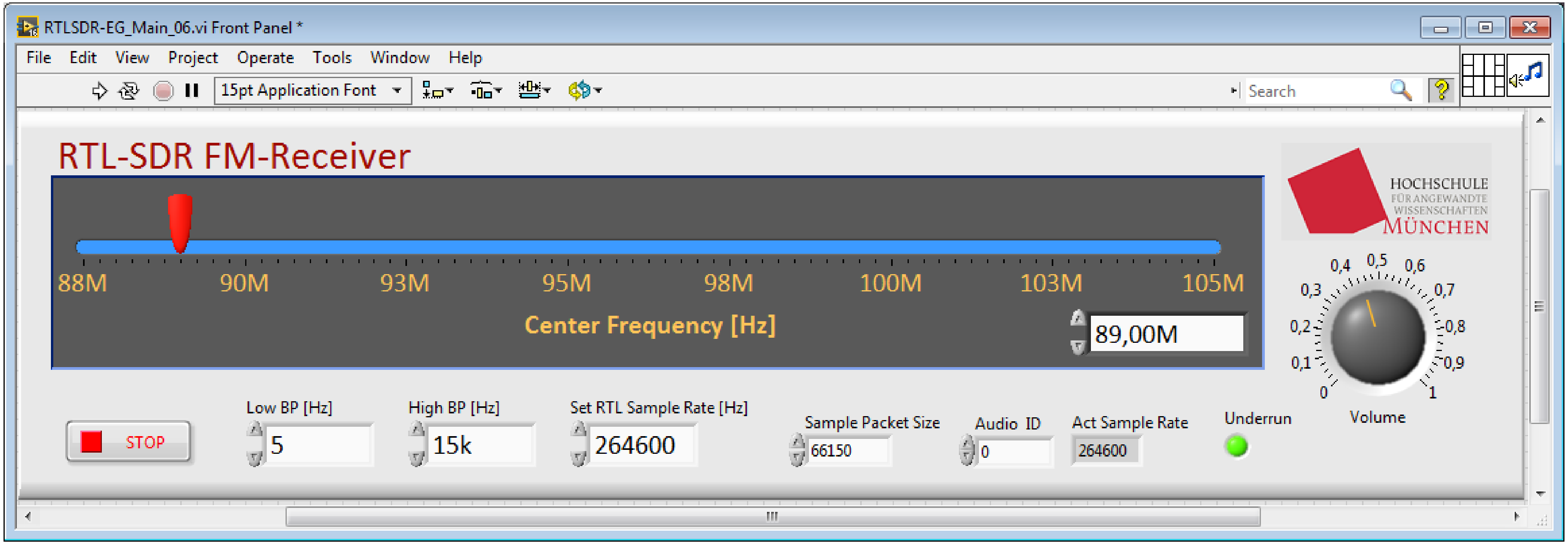
FM Demodulation: LabVIEW implementation on RTL-SDR

$$\frac{d\varphi}{dt} = \frac{d}{dt}\arctan\left(\frac{Q}{I}\right) \propto x_{Aud}(t)$$

- FM audio signal is derivative of radio signal phase
- Time discrete signal: $\frac{dx_{Aud}[n]}{dt} = \frac{x_{Aud}[n]-x_{Aud}[n-1]}{T_S}$



FM Demodulation: LabVIEW implementation on RTL-SDR

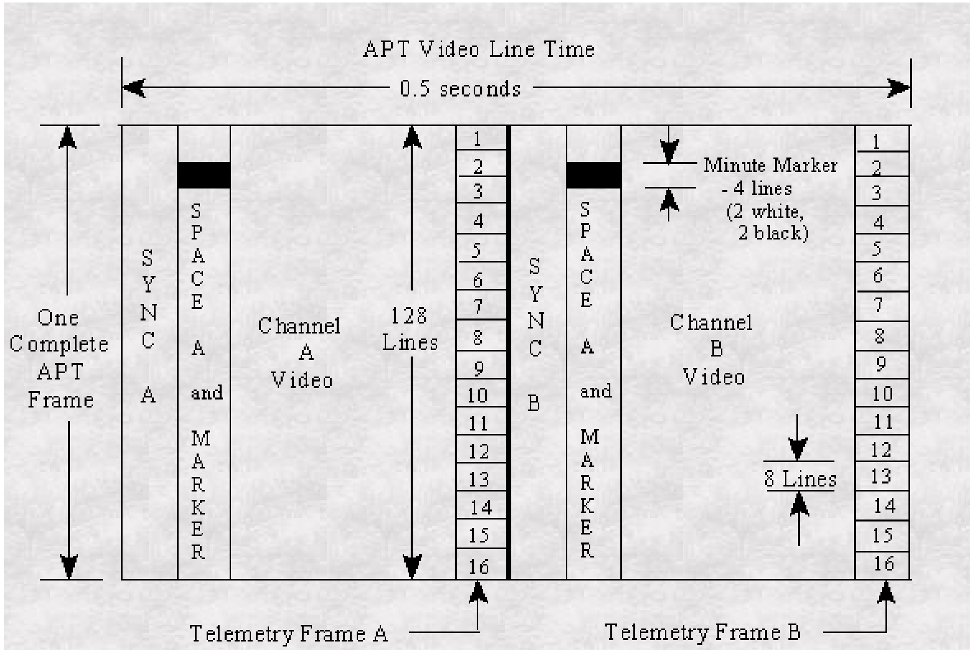


- VI available from **www.georg-eggers.de/labview4lectures**
- Based on Alfred Lederer's vipm-package sample code

3b: Example:

FM+AM Demodulation: NOAA Satelite Images

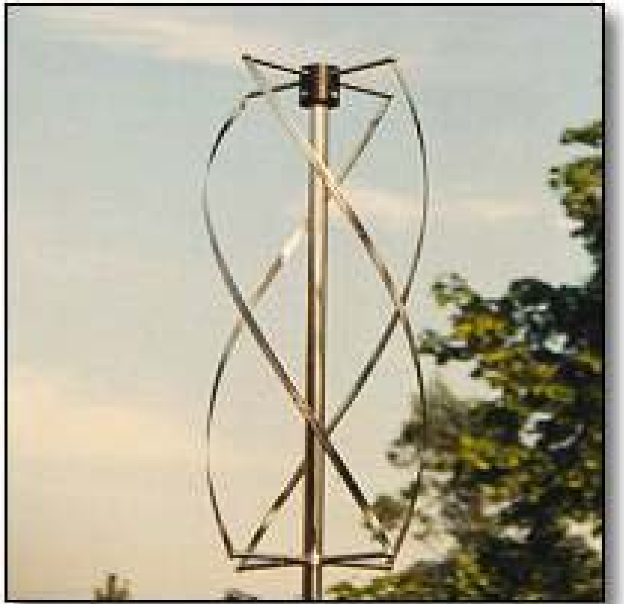
- National Oceanic and Atmospheric Administration (NOAA) runs series of weather satellites with automatic picture transmission (APT) feature:
  - RF signal at $f_{Car} \approx 138 \text{ MHz}$
  - FM-demodulation results in audible signal with $f_{aud} = 2{,}4 \text{ kHz}$, can be recorded as *.wav audio file
  - Image data amplitude modulated to audible signal
  - Line wise transmission 0,5s/line
  - Sync signal at start of every line
  - IR and VIS image and telemetry data



3b: Example:

AM Demodulation: NOAA Satellite Images

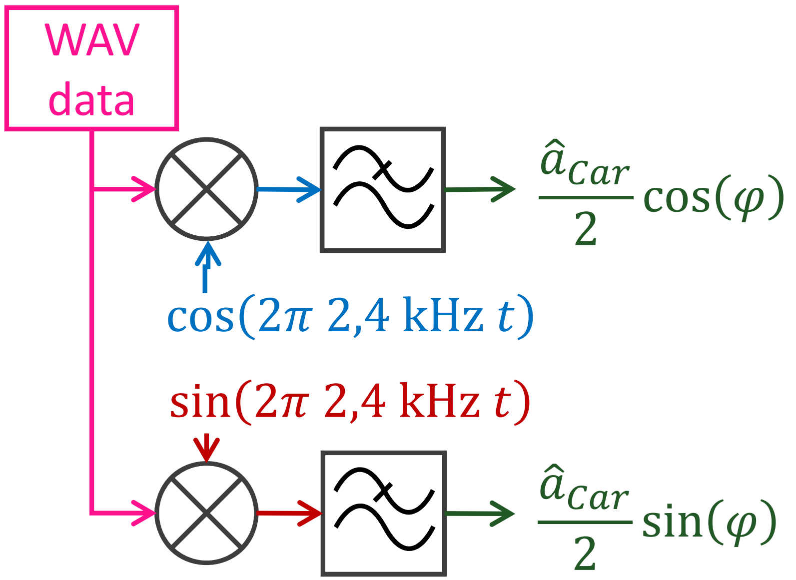
- Reception is possible, but difficult with RTL-SDR equipment:
  - Low RF power requires dedicated antenna
  - Wide field of view required as satellite passes from horizon to horizon
  - Passing times have to be determined (e.g. using Gpredict: http://gpredict.oz9aec.net/)
- Audio files of receptions available for download, e.g.
  - http://www.fredvandenbosch.nl/satellites_WAV.html (Files from this website were used for this presentation)
  - https://network.satnogs.org/
  - http://hans.mayer.tv/html/noaa18.html

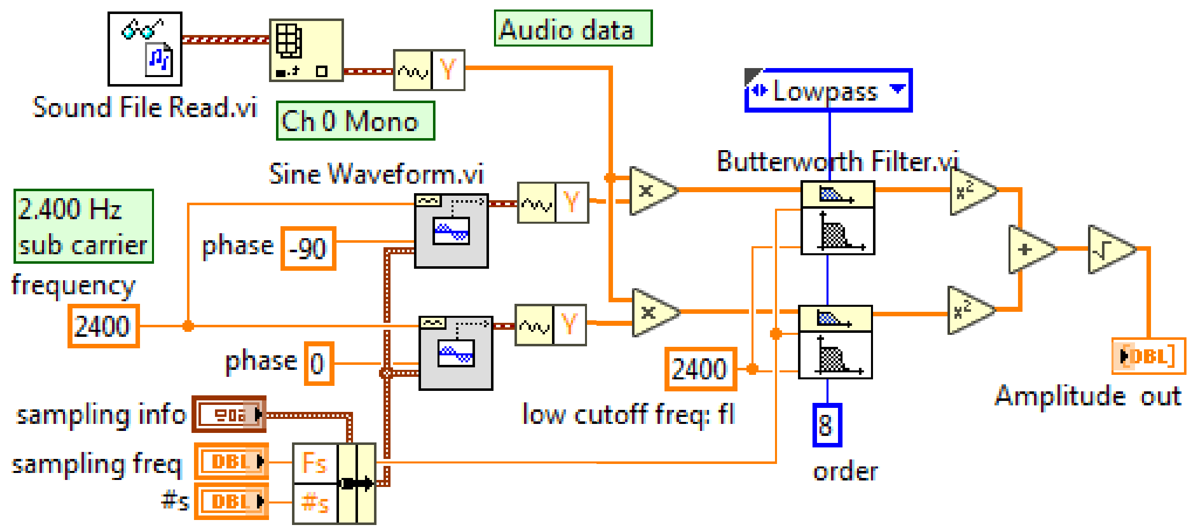


National Oceanic and Atmospheric Administration (3)

AM Demodulation: NOAA Satellite Images

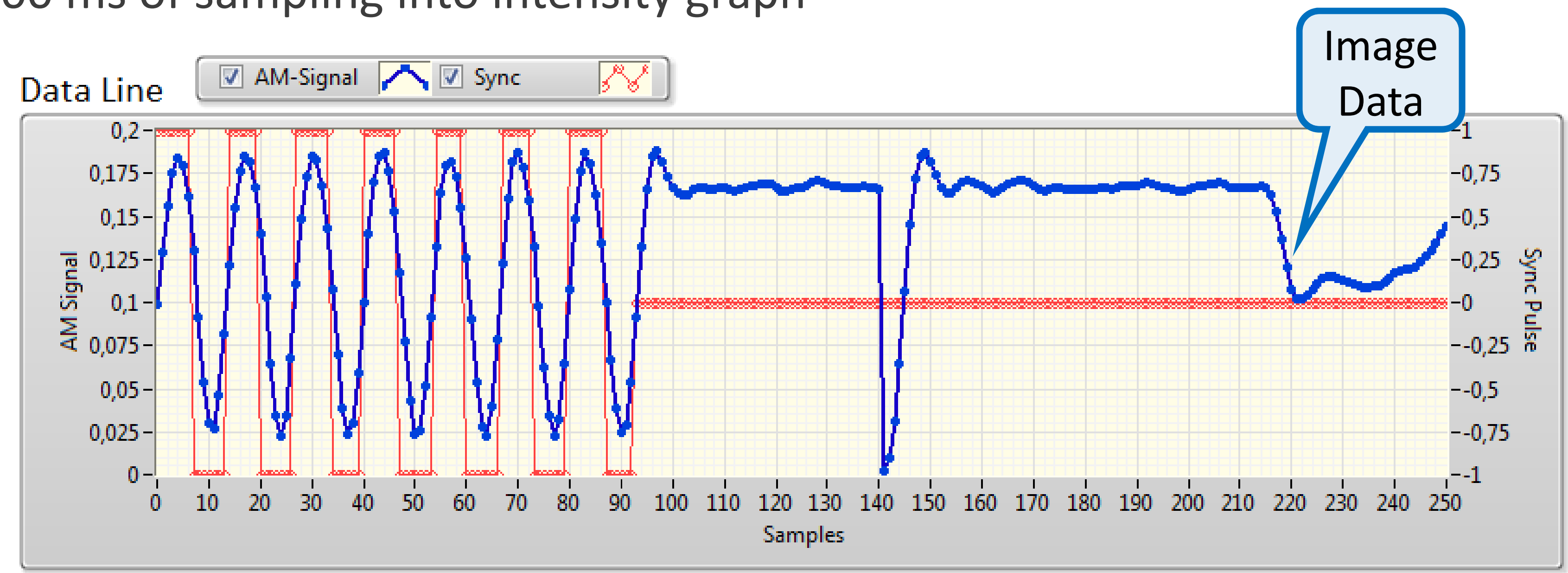
- LabVIEW sample decodes wav audio file
  - Implementation of AM demodulation





AM Demodulation: NOAA Satellite Images

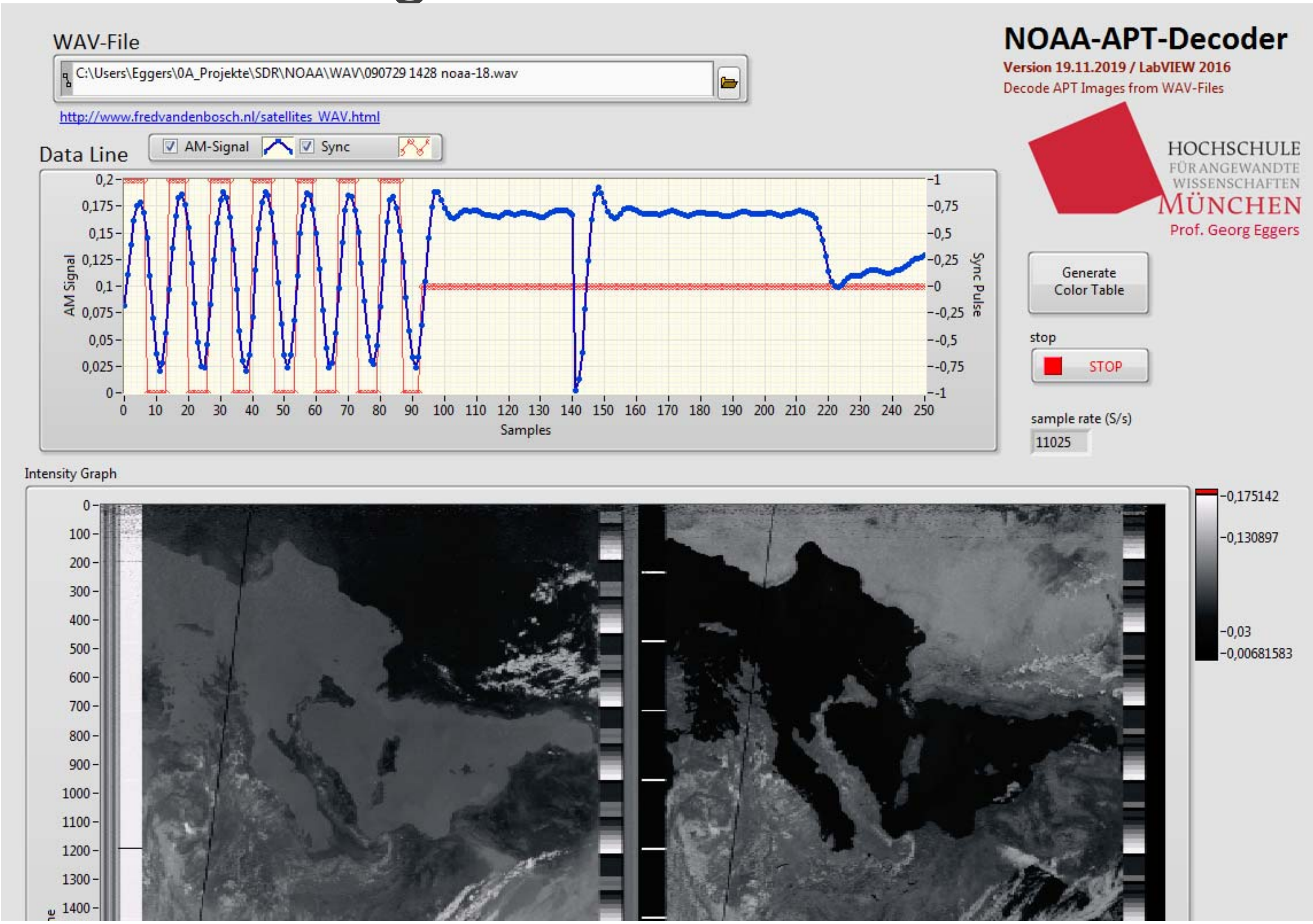
- Search for sync signal at beginning of each line: 7 cycles rect @ 832 Hz
  - Generate sync signal as waveform
  - Cross correlation search
- Put 500 ms of sampling into intensity graph



3b: Example:

AM Demodulation: NOAA Satellite Images

- Display image data as 2-d array in intensity graph
- Displayed image recorded by Fred van den Bosch, http://www.fredvandenbosch.nl/



- VI available from **www.georg-eggers.de/labview4lectures**

3c: Example:

Automatic dependent surveillance—broadcast (ADS–B)

- Commercial aircrafts periodically transmit position data determined by satellite navigation
  - Carrier Frequency $f_{Car} = 1090\ \mathrm{MHz}$
  - Binary Amplitude Modulation with $0{,}5\ \mu\mathrm{s}$ bit length
- Reception possible for RTL-SDR with Rafael Micro R820T2 tuner chip
  - $\frac{\lambda}{4}$-Size Antenna is easy to build
  - I/Q-Sampling at $f_s = 2\ \mathrm{MHz}$ means one sample per bit

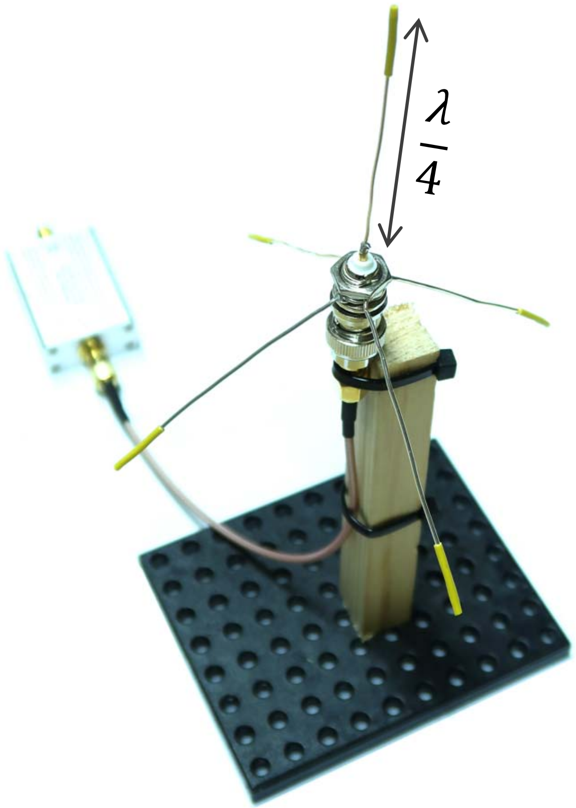
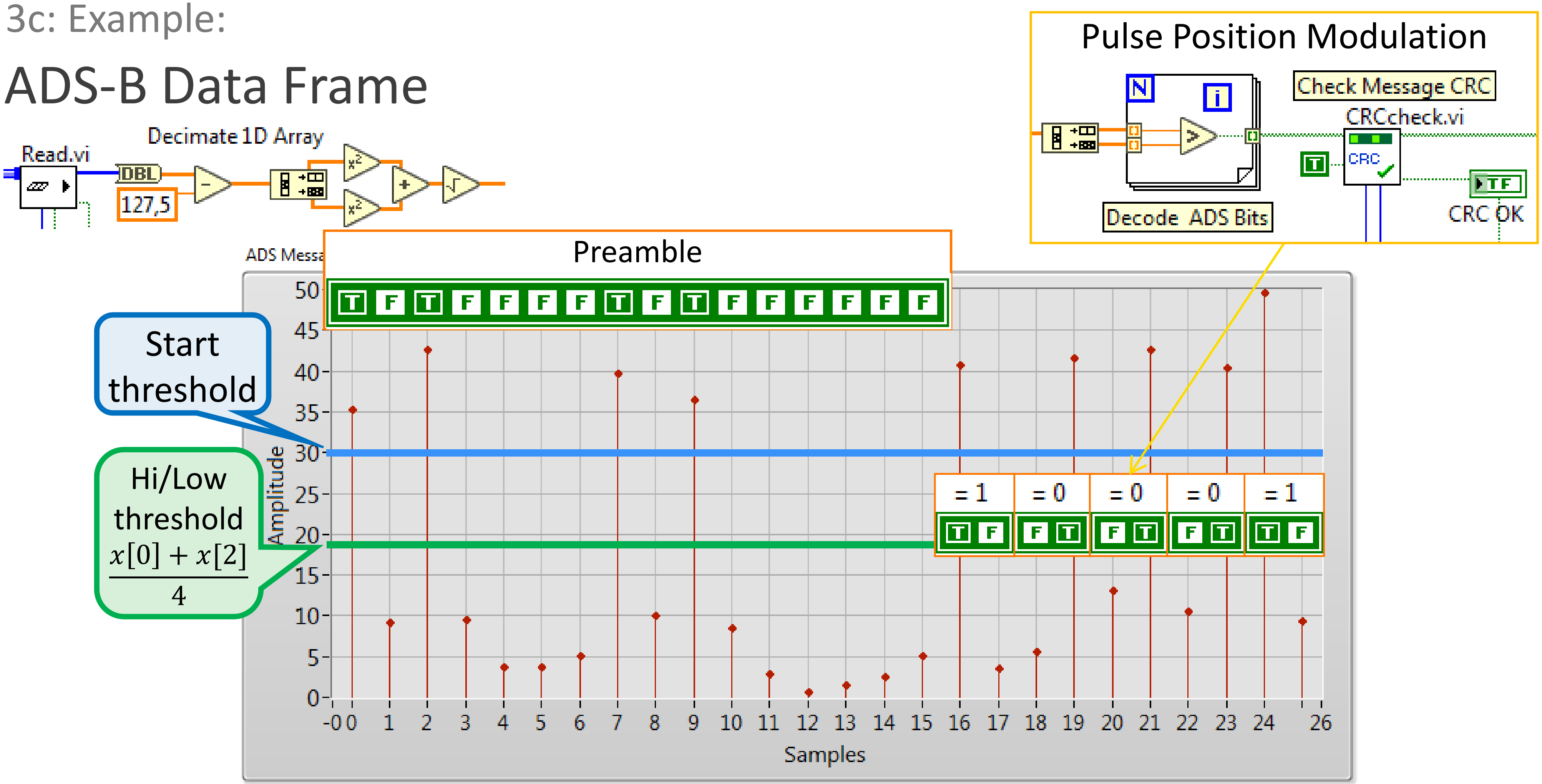


Image: www.faa.gov

3c: Example:

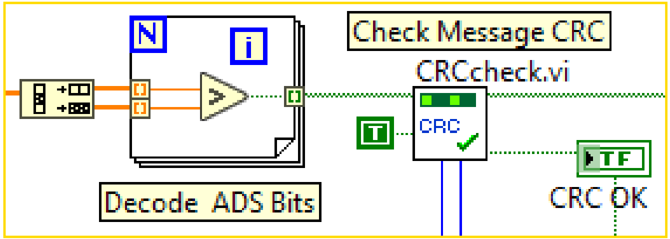
ADS-B Data Frame

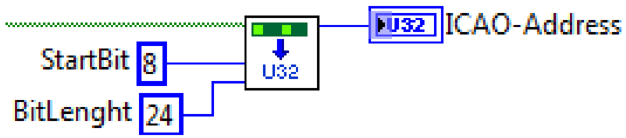


3c: Example:

Automatic dependent surveillance—broadcast (ADS–B)

- 224 Samples with pulse-position modulation transformed into 112 bits (10→1; 01→0)
- 112 Bit ADS-B Message always contains the aircraft's ICAO ID number (Bit 8..31)
- Message contains either
  - Aircraft identification
  - Surface position
  - Airborne position and altitude
  - Airborne velocities
  - Aircraft status
- Received packages can be checked with air monitoring website, e.g. flightradar24.com

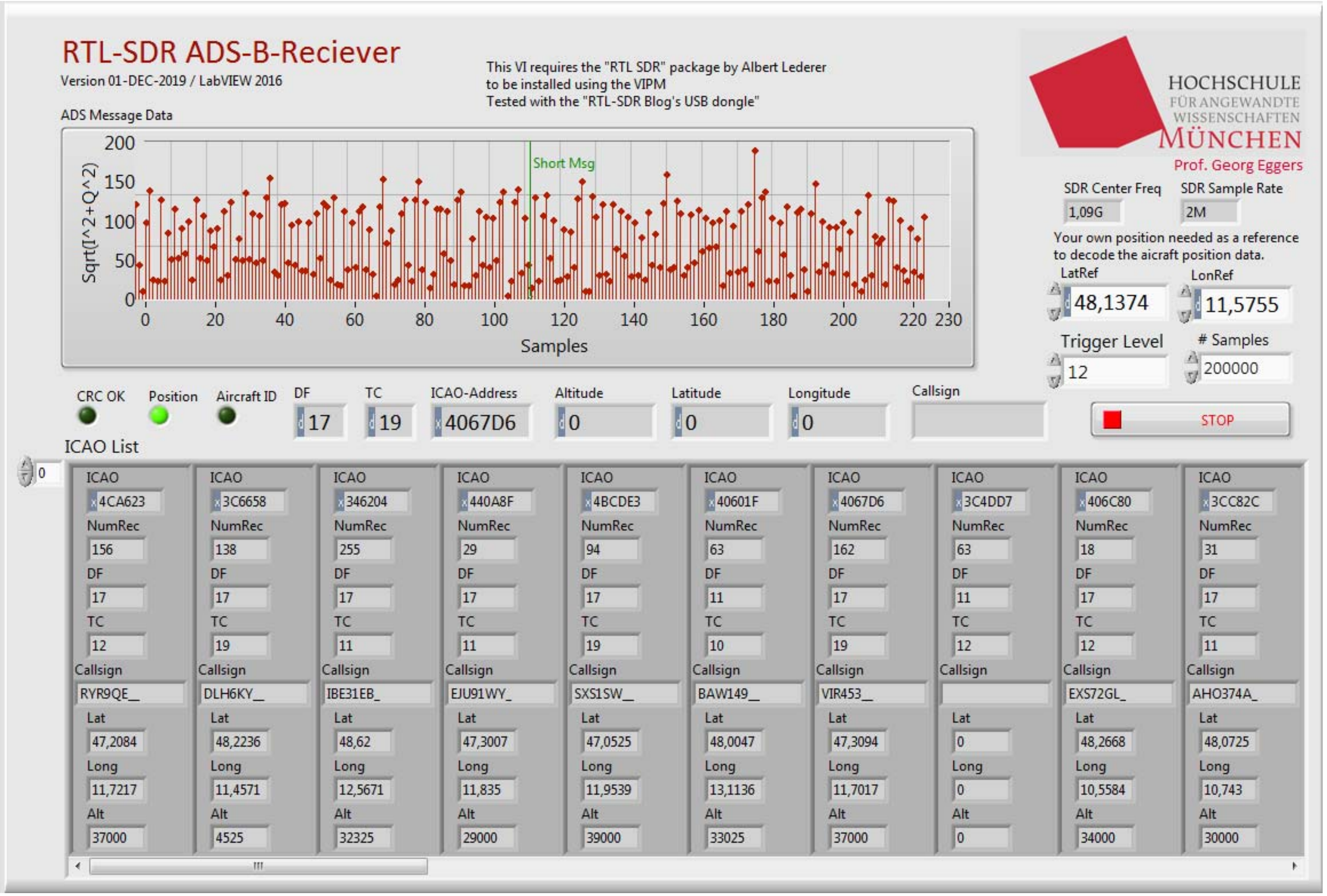




3c: Example:

Automatic dependent surveillance—broadcast (ADS–B)

- Aicraft data can be verified with flight monitoring websites, e.g. “flightradar24.com”
- Callsign decoding has been fixed after conference



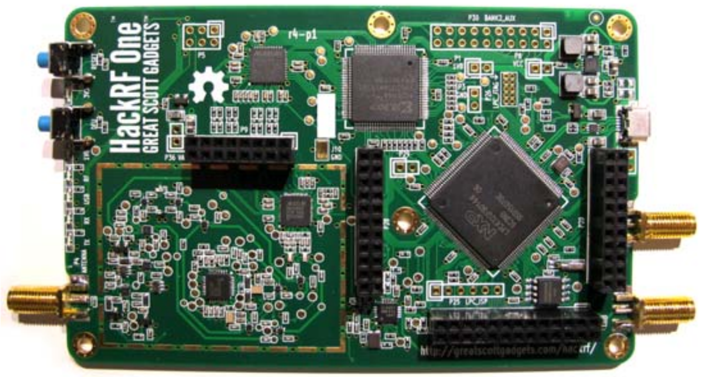
ICAO	NumRec	DF	TC	Callsign	Lat	Long	Alt
4CA623	156	17	12	RYR9QE_	47,2084	11,7217	37000
3C6658	138	17	19	DLH6KY_	48,2236	11,4571	4525
346204	255	17	11	IBE31EB_	48,62	12,5671	32325
440A8F	29	17	11	EJU91WY_	47,3007	11,835	29000
4BCDE3	94	17	19	SXS1SW_	47,0525	11,9539	39000
40601F	63	11	10	BAW149_	48,0047	13,1136	33025
4067D6	162	17	19	VIR453_	47,3094	11,7017	37000
3C4DD7	63	11	12		0	0	0
406C80	18	17	12	EXS72GL_	48,2668	10,5584	34000
3CC82C	31	17	11	AHO374A_	48,0725	10,743	30000

- VI available from **www.georg-eggers.de/labview4lectures**

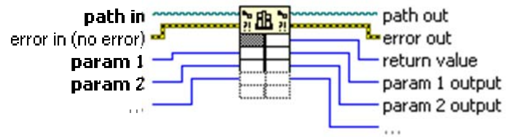
NATIONAL INSTRUMENTS

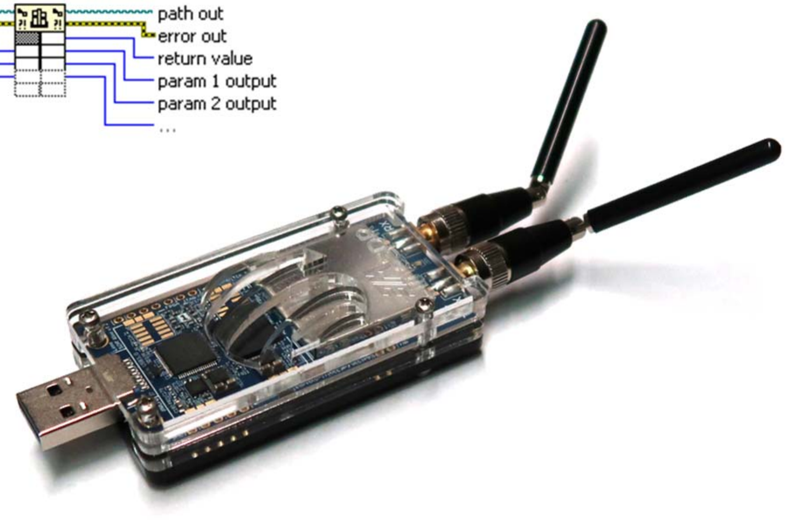
HOCHSCHULE FÜR ANGEWANDTE WISSENSCHAFTEN MÜNCHEN
Georg Eggers, FK06

Open Source SDR-Hardware with Tx-Capabilities



- HackRF One
  - 1 MHz to 6 GHz operating frequency, half-duplex transceiver
  - 20 MS/s 8-bit quadrature samples (8-bit I and 8-bit Q)
- LimeSDR mini
  - 10 MHz to 3,5 GHz operating frequency, full-duplex transceiver
  - 30,72 MS/s 12-bit quadrature samples
- Both work fine with SDR# & GNU Radio, but …
- No LabVIEW drivers available
  - DLLs available as open source
  - Programming of Call Library Function Nodes with „Import shared library“ failed due to extensive use of pointers, streams and structs
  - OPENUSRP-Project tries to integrate LimeSDR into NI-USRP by faking identity of an Ettus USRP B210





Conclusions

- SDR allows hands-on training of HF demodulation techniques
  - HF signals become accessible by frequency shifting through signal mixing
  - Mathematical mechanisms are fairly understandable
  - Analog and digital broadcast data can be explored
  - Both FM and AM demodulation can be performed easily within LabVIEW
- RTL-SDR
  - offers access to real radio data at incredibly low cost
  - can easily be accessed in LabVIEW thanks to Alfred Lederer‘s driver package
- There‘s lots and lots of radio signals to explore …

➔SDR is a great topic to include in signal processing courses

Try it yourself: www.georg-eggers.de/labview4lectures

References

(1) **RTL-SDR Blog**
https://www.rtl-sdr.com/

(2) Albert Lederer: **Using RTL-SDR with Labview**
https://forums.ni.com/t5/Example-Program-Drafts/Using-RTL-SDR-with-Labview-Chapter-1-Labview-on-Windows/ta-p/3538774

(3) National Oceanic and Atmospheric Administration:
User's Guide for Building and Operating Environmental Satellite Receiving Stations
https://noaasis.noaa.gov/NOAASIS/pubs/Users_Guide-Building_Receive_Stations_March_2009.pdf

(4) Fred van den Bosch: **NOAA satellite WAV-files**
http://www.fredvandenbosch.nl/satellites_WAV.html

(5) NI Forum User "IdE": **ADS-B Decoding with LabVIEW USRP**
https://forums.ni.com/t5/Software-Defined-Radio/ADS-B-Decoder-Airplane-Tracker/ta-p/3500055?profile.language=en

(6) Junzi Zun: **The 1090MHz Riddle: An open-access book about decoding Mode-S and ADS-B data**
https://mode-s.org/decode/index.html

(7) Salvatore Sanfilippo: **Dump1090 open source project:**
https://github.com/antirez/dump1090

Thank You

- Albert Lederer, Steve Markgraf and Dimitri Stolnikov :
  - Making RTL-SDR available to LabVIEW users
- Nancy Dib, M.Eng.
  - Hosting this session
  - Not asking for the presentation slides in advance …
- The Munich University of applied Sciences‘ students of mechatronics
  - For enduring all these experiments in their lectures

- The audience of the talk
  - For not escaping into the buffet zone

FULL FORCE AHEAD

NIDays 2019