

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

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

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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



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

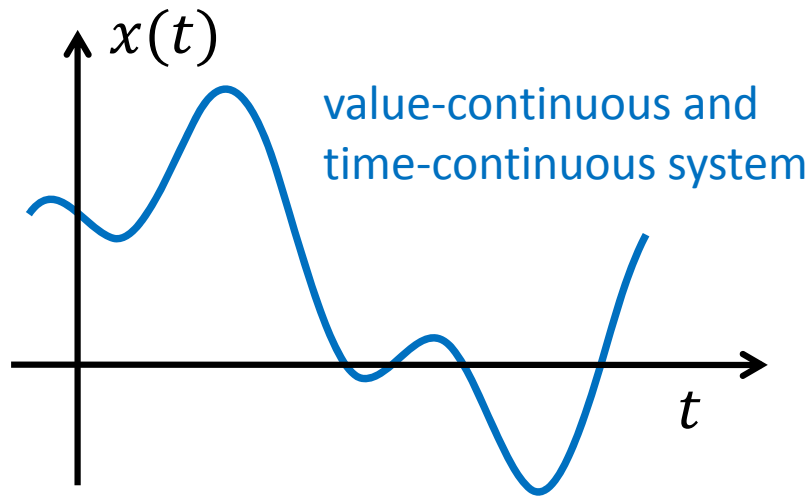


Contents

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 - b. NOAA Weather Satellite Images
 - c. Receiving ADS-B Plane Broadcasts
4. Conclusions, Outlook

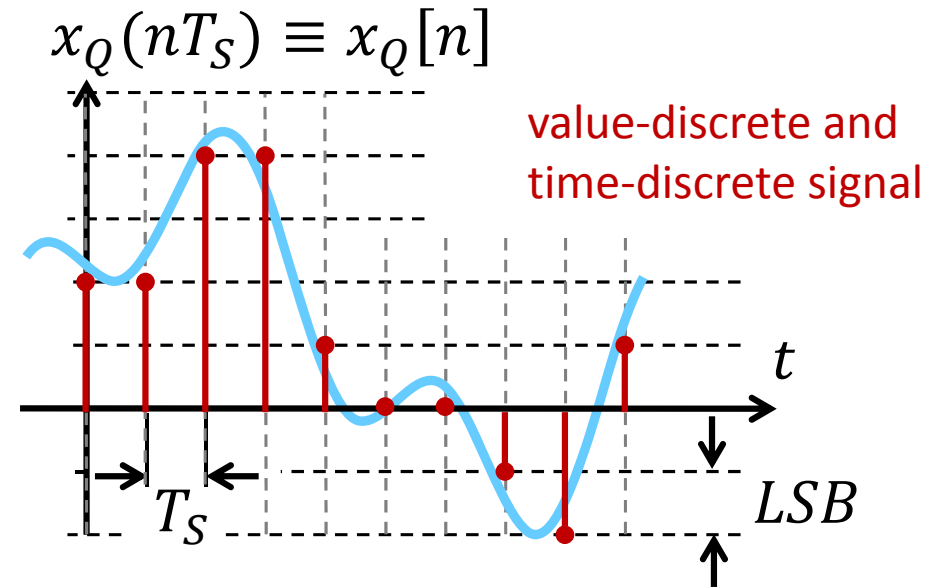
1.a: Integrating SDR into courses in signal processing

Continuous and Discrete Signals



Time discretization:

T_S : Sampling interval
 $\frac{1}{T_S} = f_s$: Sampling frequency

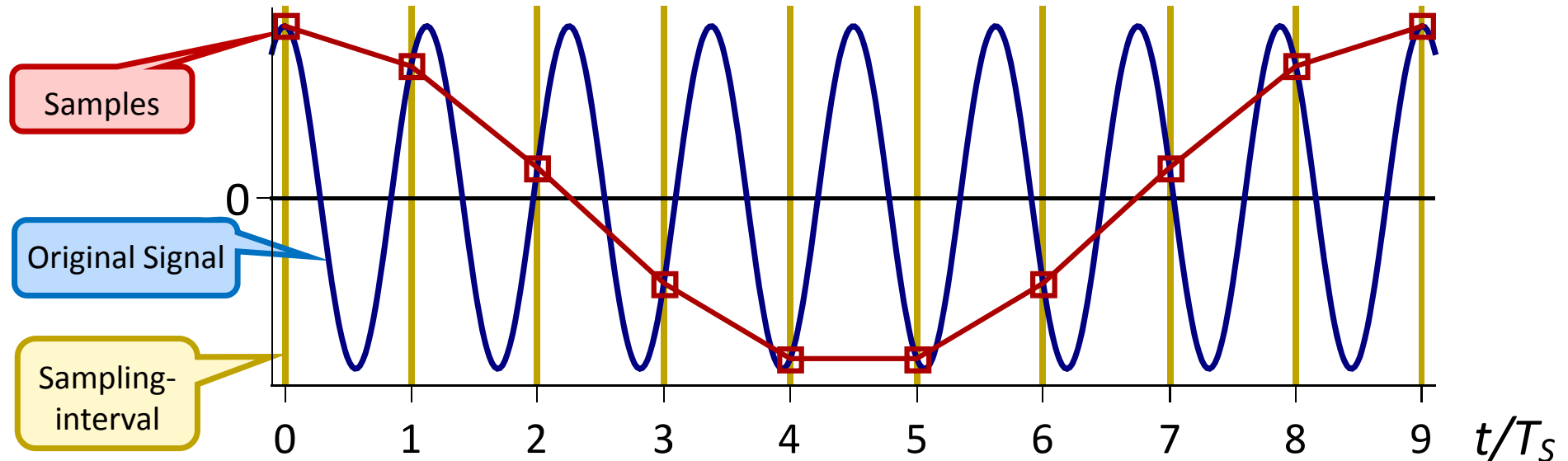


Value discretization:

LSB : least significant bit

1a: Integrating SDR into courses in signal processing

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?

1b: Integrating SDR into courses in signal processing

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 $x = 2\pi f_{\text{sig}}t$, $y = 2\pi f_{\text{mix}}t$,

$$\cos(2\pi f_{\text{sig}}t) \cdot \cos(2\pi f_{\text{mix}}t) = \frac{1}{2} (\cos[2\pi(f_{\text{sig}} - f_{\text{mix}})t] + \cos[2\pi(f_{\text{sig}} + f_{\text{mix}})t])$$

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



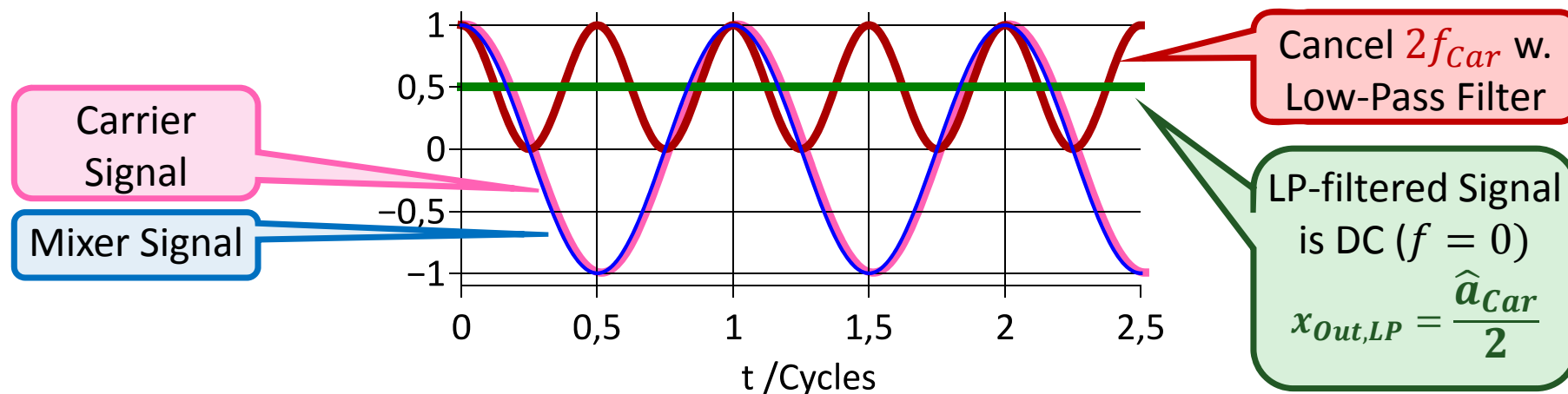
Cancel this with
Low-Pass Filter

1b: Integrating SDR into courses in signal processing

Math Magic: The Homodyne Receiver

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

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



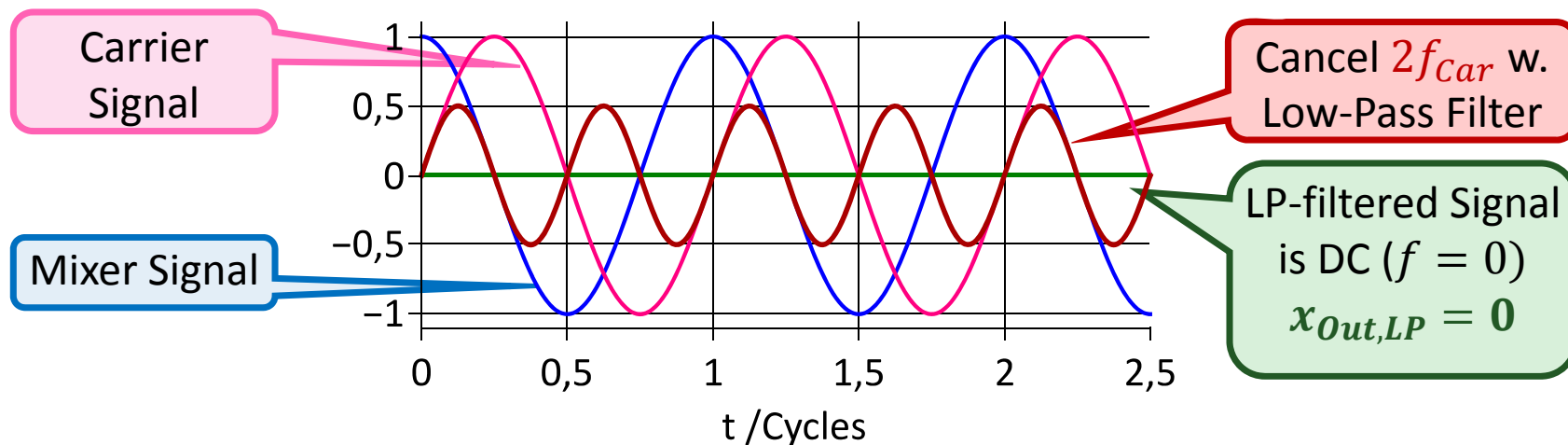
Looks easy, but ...

1b: Integrating SDR into courses in signal processing

Math Magic: The Homodyne Receiver

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

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

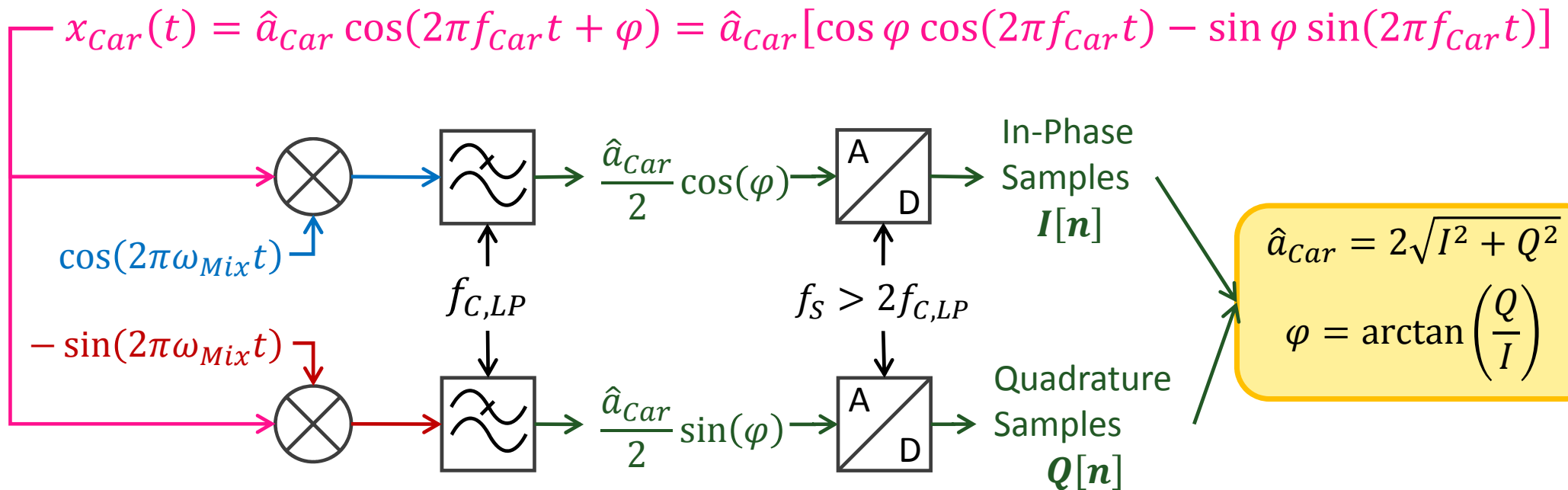


So what?

1b: Integrating SDR into courses in signal processing

Math Magic: The Homodyne Receiver

- Describe Carrier Signal as sum of cosine and sine signal



... et voila: Radio Signals without HF!

2a: SDR Hardware

NI-USRP: Professional SDR Equipment



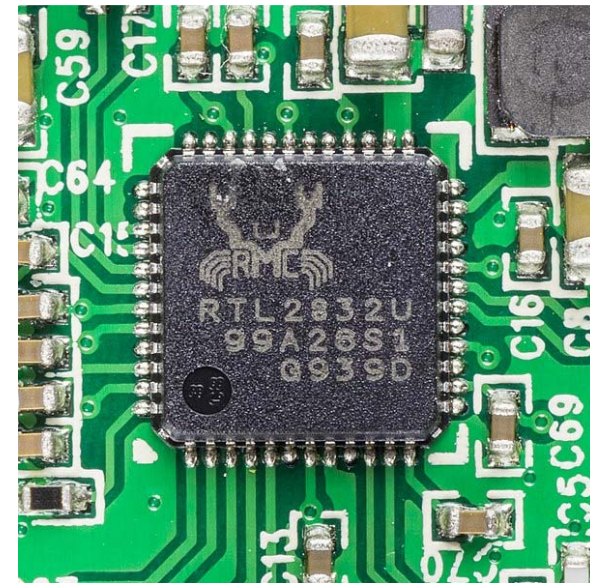
- f_{car} : 10 MHz .. 6 GHz
- $f_{sig,max}$: up to 120 MHz
- Receive (RX) and Transmit (TX)
- FPGA for signal processing

- USB3, Ethernet, MXIe
- NI-USRP Driver integrates into LabVIEW
- **Price: 1 k€ .. f_{sig}**
- **... difficult to afford for teaching**

2b: SDR Hardware

RTL-SDR: Next to No-Cost





















- Based on Realtek 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



2b: SDR Hardware

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,-

 <p>Dipole-Antenna Radio Software RT... € 27,57 Free Shipping ★ 4.9 1323 Sold RTLSDRBlog Store</p>	 <p>SMA Dongle-Only Software Define... € 20,21 Free Shipping ★ 4.9 1033 Sold RTLSDRBlog Store</p>	 <p>Dongle Sdr-Receiver Usb rtl-sdr RB... € 12,43 - 19,46 Free Shipping ★ 5.0 75 Sold Electronic overseas online shopping</p>	 <p>Tv-Receiver-Scanner-Receiver Tun... € 13,53 Free Shipping ★ 5.0 47 Sold ZGW-3C-02 Store</p>	 <p>Radio-Receiver Usb-Dongle RTL-SD... € 21,99 - 25,67 Shipping: € 6,25 ★ 4.9 50 Sold icode Store</p>
 <p>Dongle Sdr-Receiver Usb rtl-sdr RB... € 13,44 Shipping: € 2,61 ★ 2.5 13 Sold Shop4638046 Store</p>	 <p>TV Tuner Receiver Radio Txco Rt2... € 14,10 Free Shipping ★ 4.9 168 Sold Shenzhen Sun-Stars Technology C...</p>	 <p>1Set 100kHz-1.7GHz VHF UHF Full ... € 27,49 Free Shipping 5 Sold Speeding and Running Digital Store</p>	 <p>Digital TV Receiver-Stick Rtl Sdr Dv... € 7,77 Shipping: € 0,73 ★ 5.0 9 Sold YZY Wholesales Store</p>	 <p>DIY KIT 100kHz to 1.7GHz UV HF R... € 18,69 Free Shipping Free Return ★ 4.2 14 Sold TCXRE Audio Store</p>
 <p>100kHz-1.7GHz Full Band UV HF R... € 15,07 Shipping: € 0,74 ★ 5.0 6 Sold Decorate Lamp House Store</p>	 <p>Receiver RTL-SDR RTL2832U R820T... € 22,01 - 27,68 Free Shipping ★ 5.0 3 Sold NC dropshipping Store</p>	 <p>RTL2832U+R820T2 100kHz-1.7GHz... € 23,98 Free Shipping ★ 1.0 4 Sold Gary Store</p>	 <p>Tuner Receiver Radio RTL-SDR RTL... € 24,94 Free Shipping ★ 4.6 12 Sold Ur Pro Digital Store</p>	 <p>Mini USB 2.0 Software Radio DVB... € 5,30 Shipping: € 3,74 ★ 4.8 97 Sold f's 3C Store</p>
 <p>Tv-Receiver Stick-Technology Radi... € 4,19 - 7,57 Shipping: € 1,61 ★ 4.9 269 Sold Holiday sale</p>	 <p>1Set 100kHz-1.7GHz VHF UHF Full ... € 26,68 Shipping: € 2,95 1 Sold Smart2018 Store Store</p>	 <p>Usb-Dongle Sdr-Receiver TCXO Rtl... € 23,93 Free Shipping ★ 3.0 4 Sold Atom/Sat-Link Store</p>	 <p>TV Tuner Stick Antenna Dongle Tv... € 17,93 Free Shipping ★ 4.5 19 Sold Shenzhen Sun-Stars Technology C...</p>	 <p>Tv-Receiver-Stick Dvb-T rtl2832u Rt... € 6,05 Shipping: € 2,55 ★ 4.9 48 Sold Ton-Top Store</p>

2b: SDR Hardware

RTL-SDR.COM-Dongle

- RTL2832U Controller
 - $f_{S,max} \approx 2,5 \text{ MHz @ 8 bit I/Q}$
- Rafael Micro R820T2 tuner chip
 - $f_{car} = 24 .. 1766 \text{ MHz}$
- 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



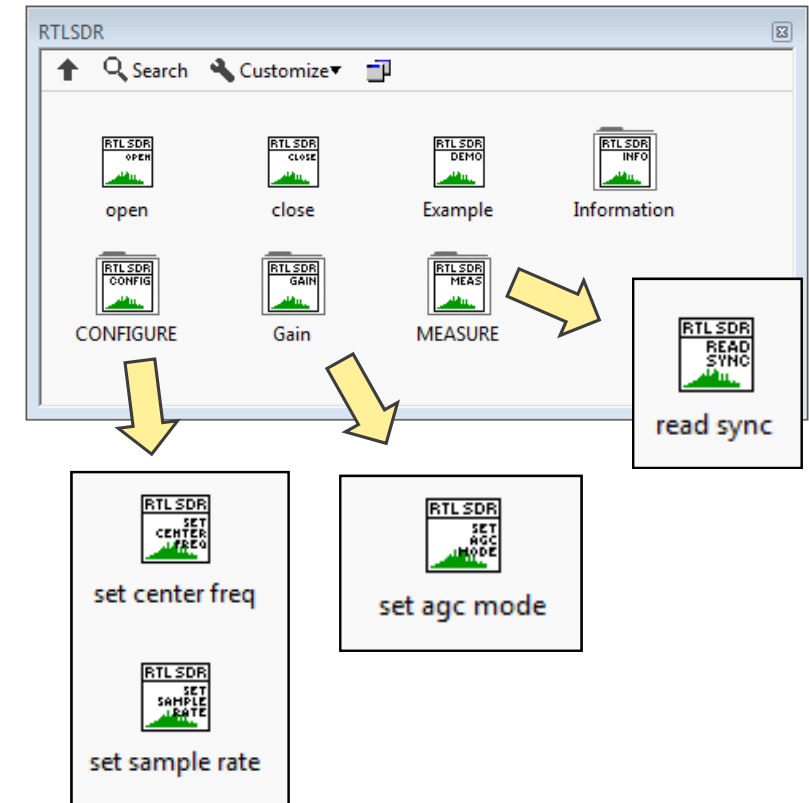
2b: SDR Hardware

RTL-SDR: Integration with LabVIEW

- NI-Forum user **Albert Lederer** (Albert.lederer) prepared a **vipm-package “RTL SDR”** based on rtl_sdr.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:

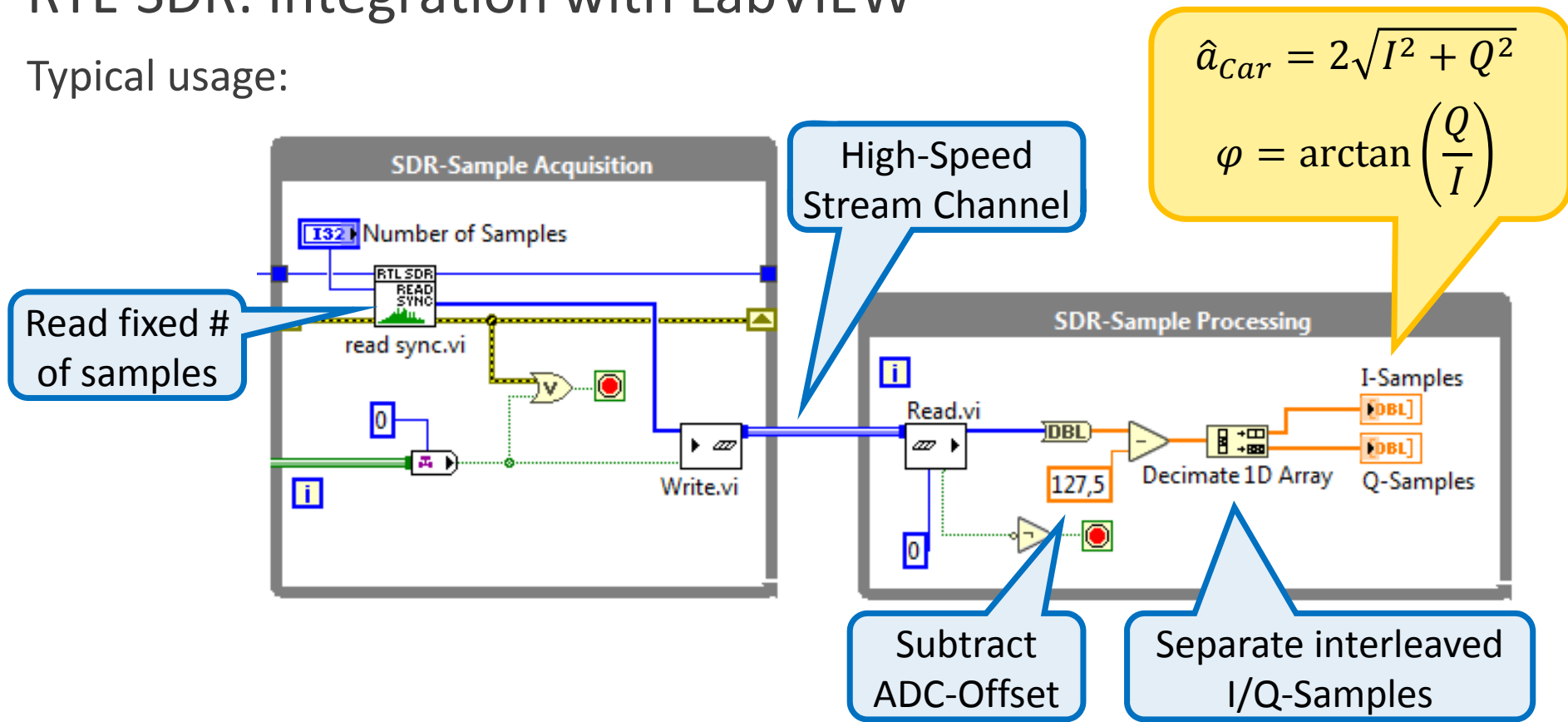
<https://forums.ni.com/t5/Example-Program-Drafts/Using-RTL-SDR-with-Labview-Chapter-1-Labview-on-Windows/ta-p/3538774>



2b: SDR Hardware

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

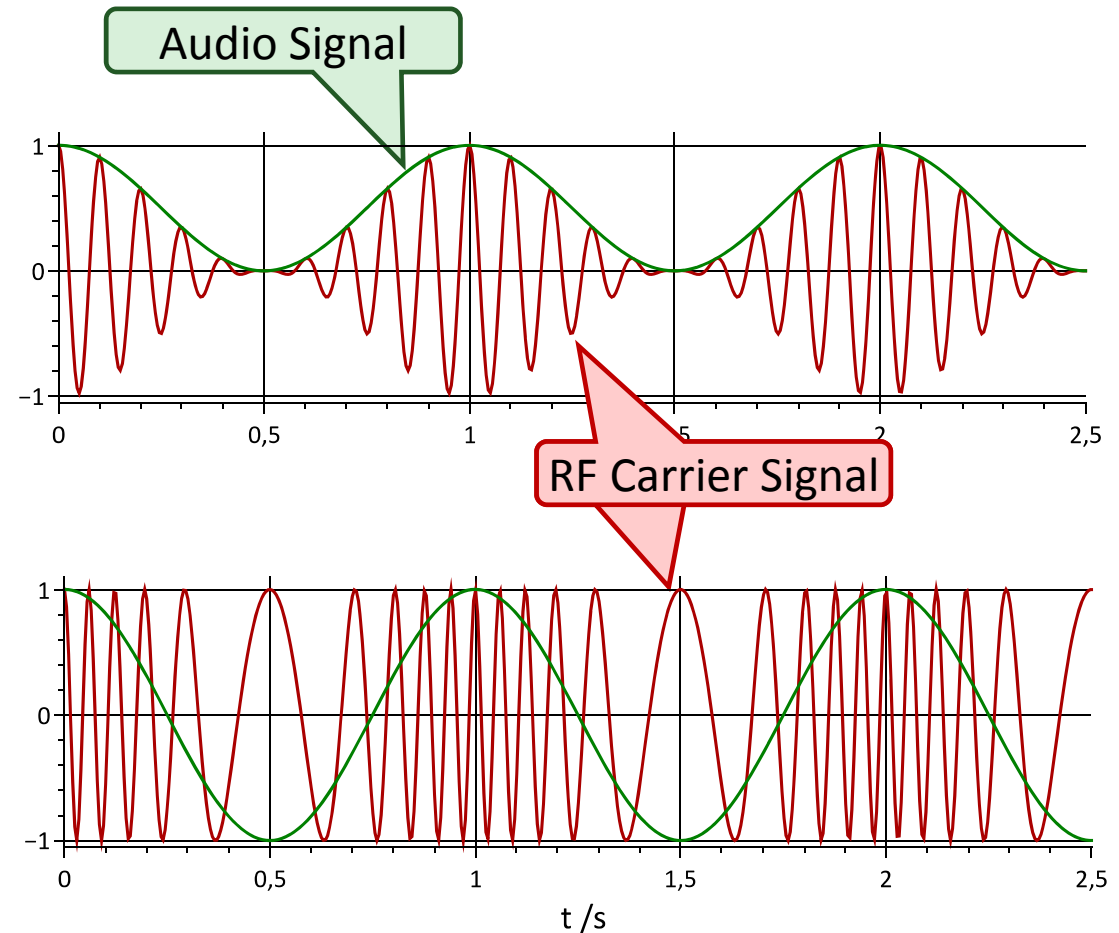
$$\hat{a}_{car} = 2\sqrt{I^2 + Q^2}$$

- Frequency Modulation (FM):

- (Audio) signal is difference between actual and nominal carrier signal frequency

- Carrier signal phase is

$$\varphi = \arctan\left(\frac{Q}{I}\right) \dots?$$



3a: Example:

FM Demodulation: Link between phase and frequency

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

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

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

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

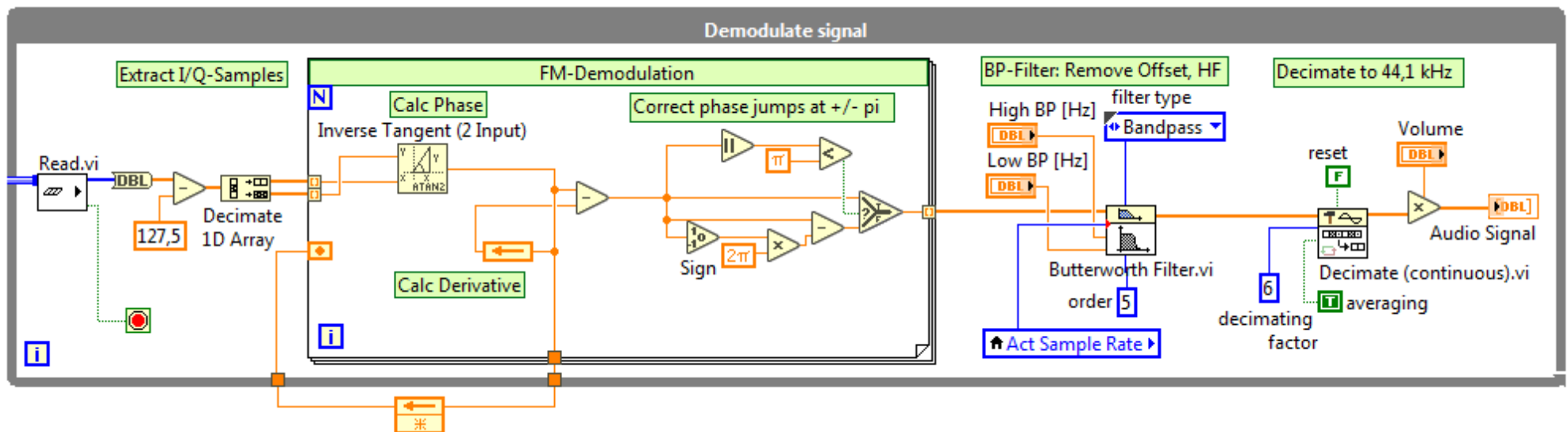
- FM audio signal is derivative of radio signal phase

3a: Example:

FM Demodulation: LabVIEW implementation on RTL-SDR

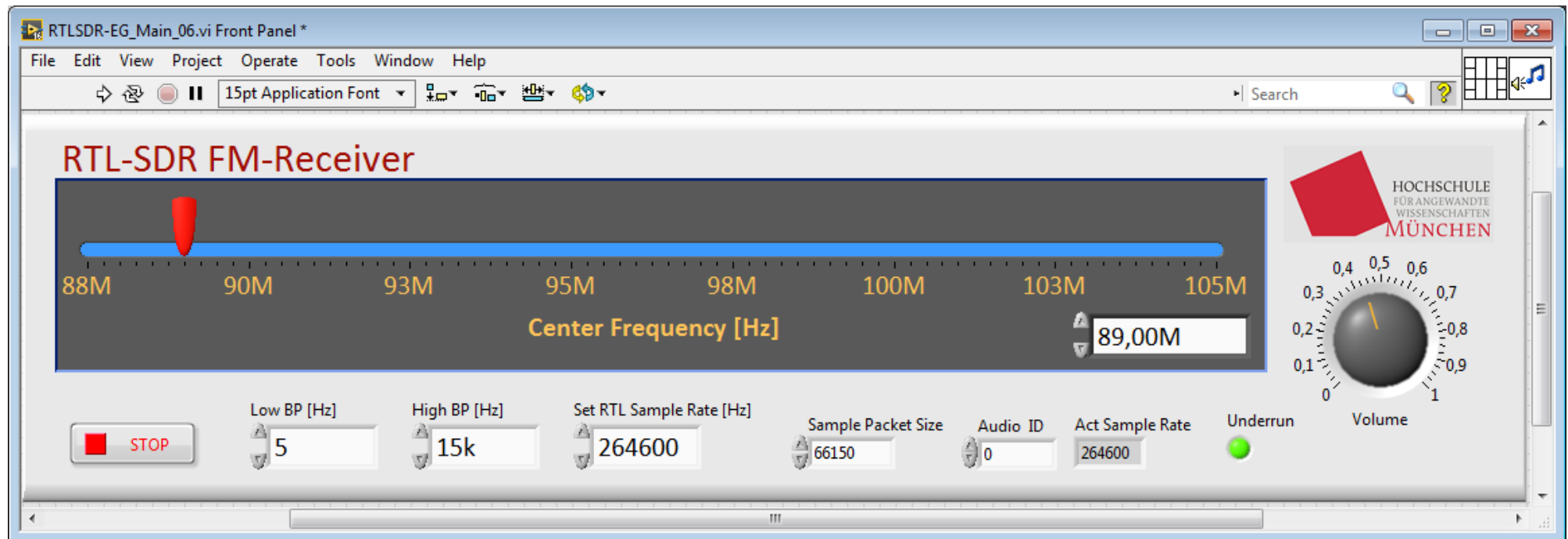
$$\frac{d\phi}{dt} = \frac{d}{dt} \arctan\left(\frac{Q}{I}\right) \propto x_{Aud}(t)$$

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



3a: Example:

FM Demodulation: LabVIEW implementation on RTL-SDR

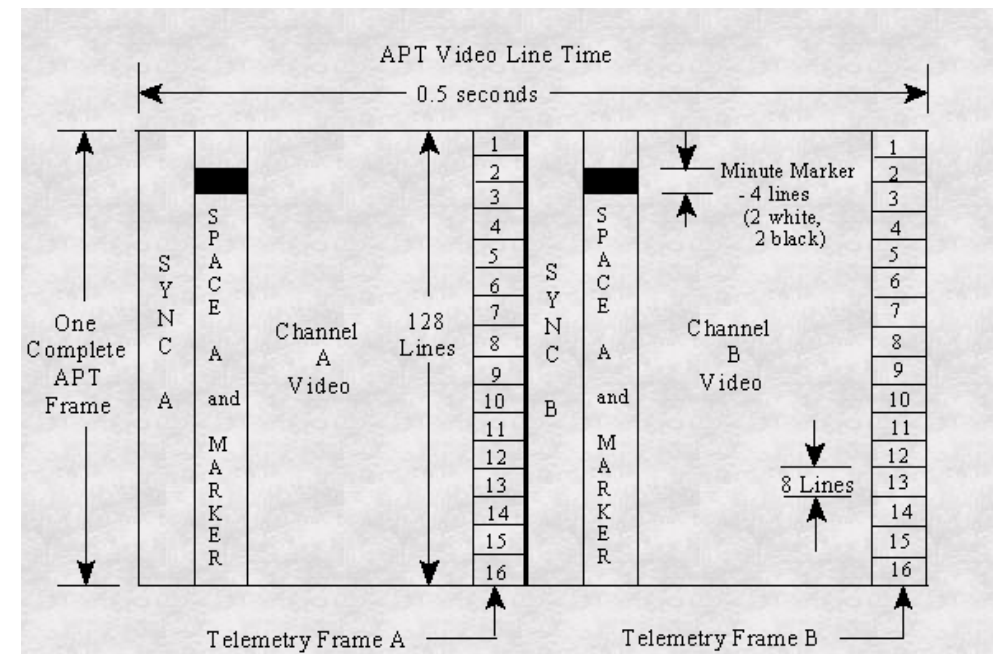


- VI available from www.georg-eggert.de/labview4lectures
- Based on Alfred Lederer's vipm-package sample code

3b: Example:

FM+AM Demodulation: NOAA Satellite Images

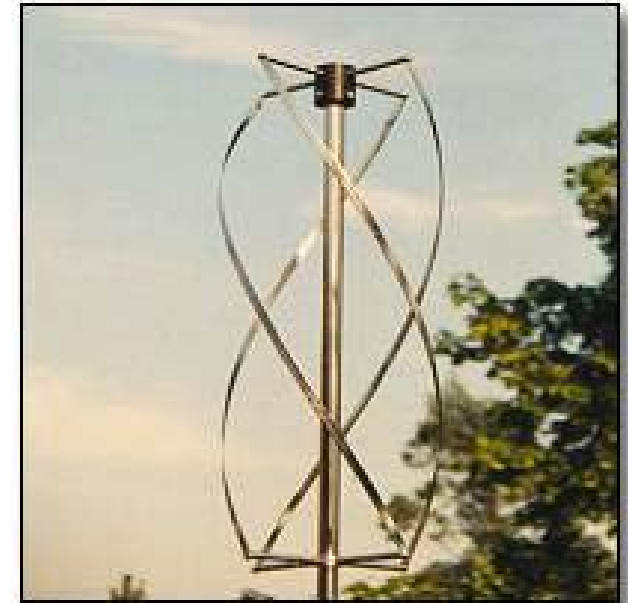
- National Oceanic and Atmospheric Administration (NOAA) runs series of weather satellites with automatic picture transmission (APT) feature:
 - RF signal at $f_{Car} \approx 138$ MHz
 - FM-demodulation results in audible signal with $f_{aud} = 2,4$ kHz, can be recorded as *.wav audio file
 - Image data 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

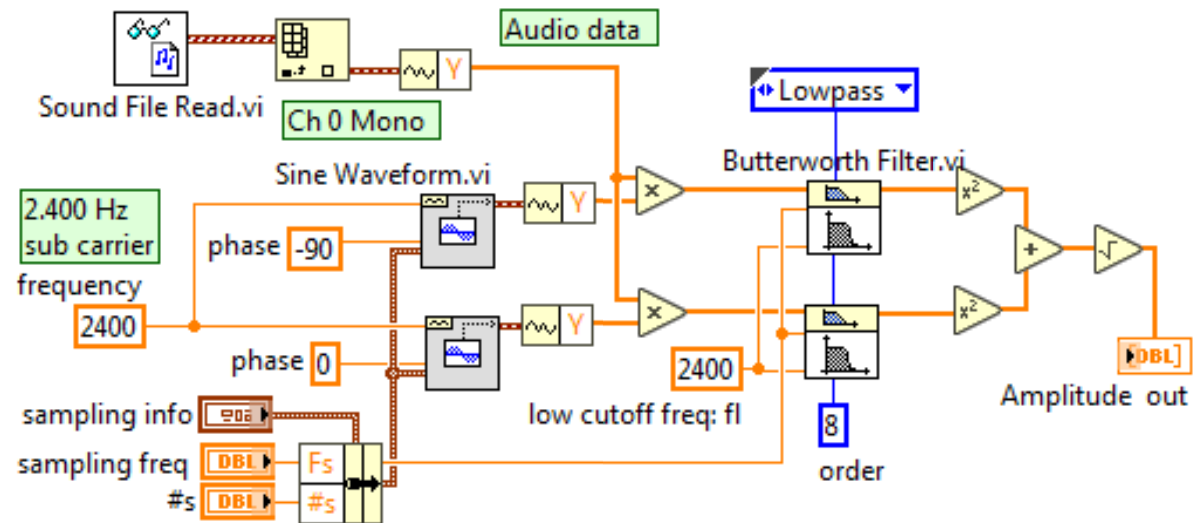
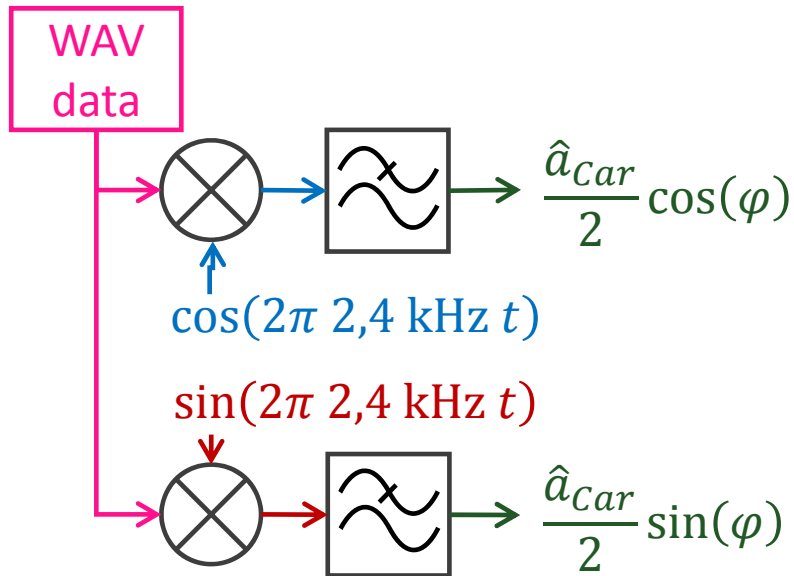
- Reception is possible, but difficult with RTL-SDR equipment:
 - Low RF power requires dedicated antenna
 - Wide field of view required as satellite passes from horizon to horizon
 - Passing times have to be determined (e.g. using Gpredict: <http://gpredict.oz9aec.net/>)
- Audio files of receptions 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>



3b: Example:

AM Demodulation: NOAA Satellite Images

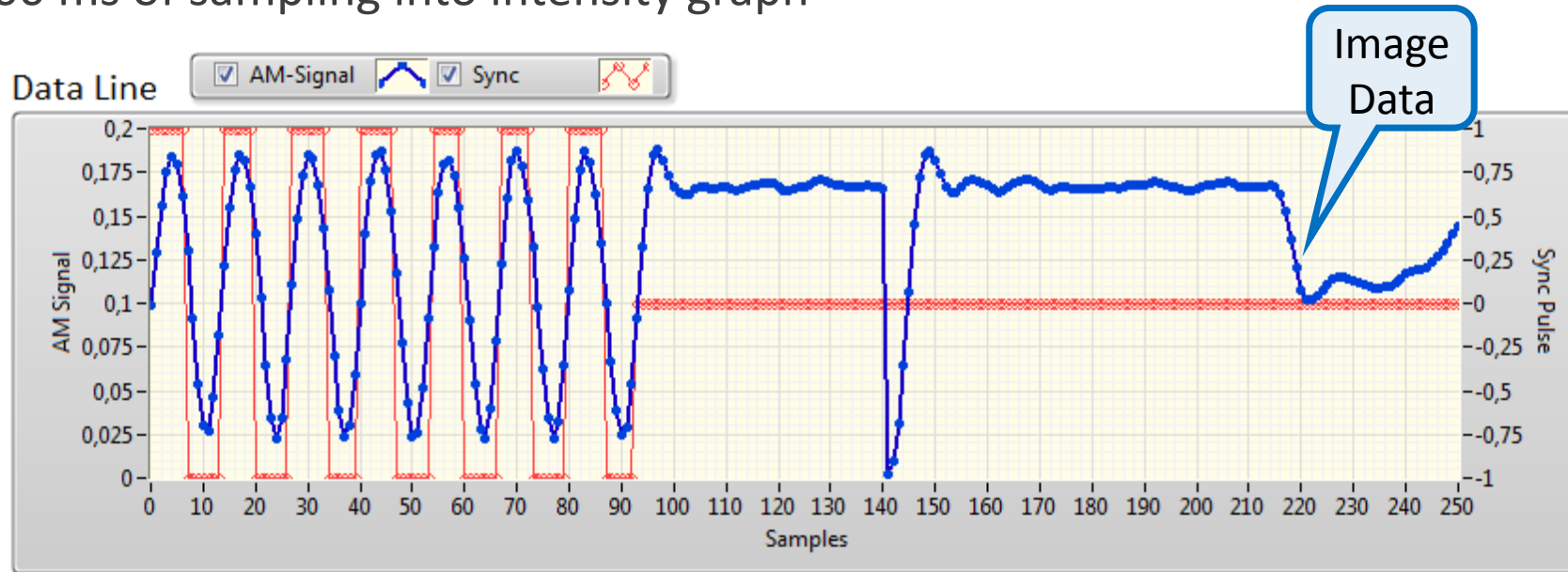
- LabVIEW sample decodes wav audio file
 - Implementation of AM demodulation



3b: Example:

AM Demodulation: NOAA Satellite Images

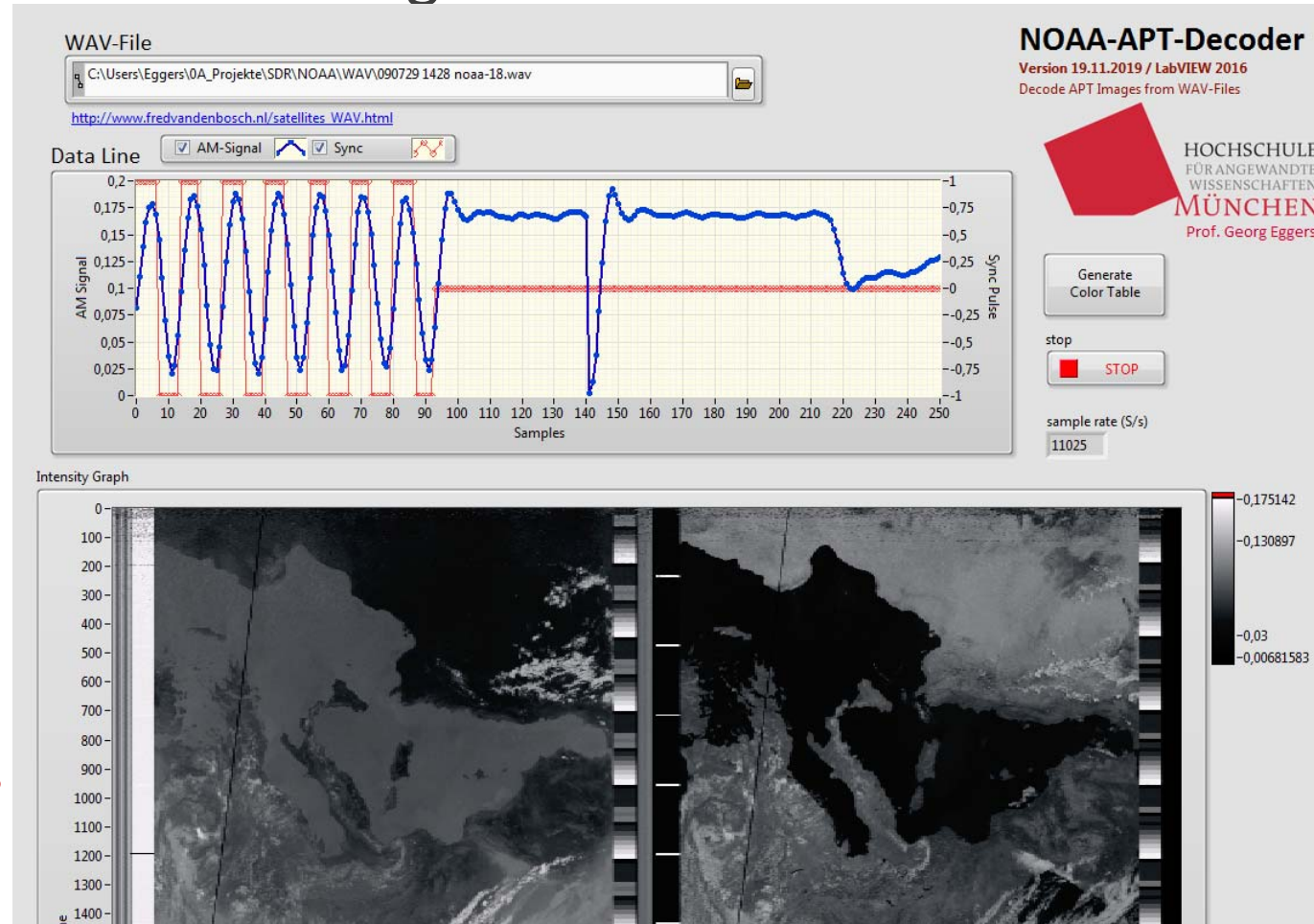
- Search for sync signal at beginning of each line: 7 cycles rect @ 832 Hz
 - Generate sync signal as waveform
 - Cross correlation search
- Put 500 ms of sampling into intensity graph



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-eggert.de/labview4lectures



3c: Example:

Automatic dependent surveillance—broadcast (ADS-B)

- Commercial aircrafts periodically transmit position data determined by satellite navigation
 - Carrier Frequency $f_{Car} = 1090$ MHz
 - Binary Amplitude Modulation with $0,5 \mu\text{s}$ 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 $f_s = 2$ MHz means one sample per bit

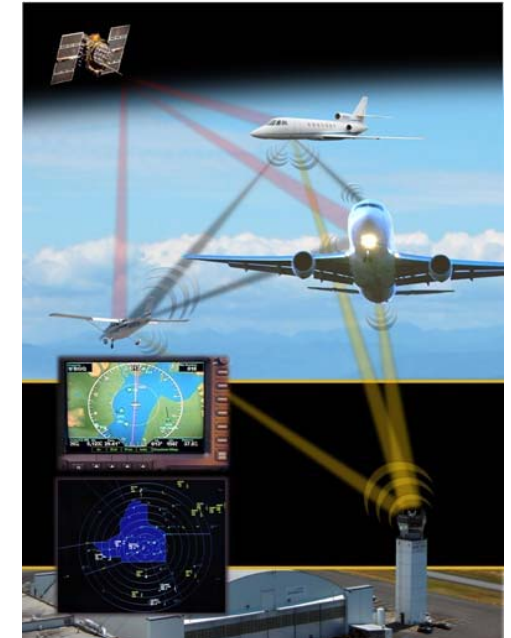
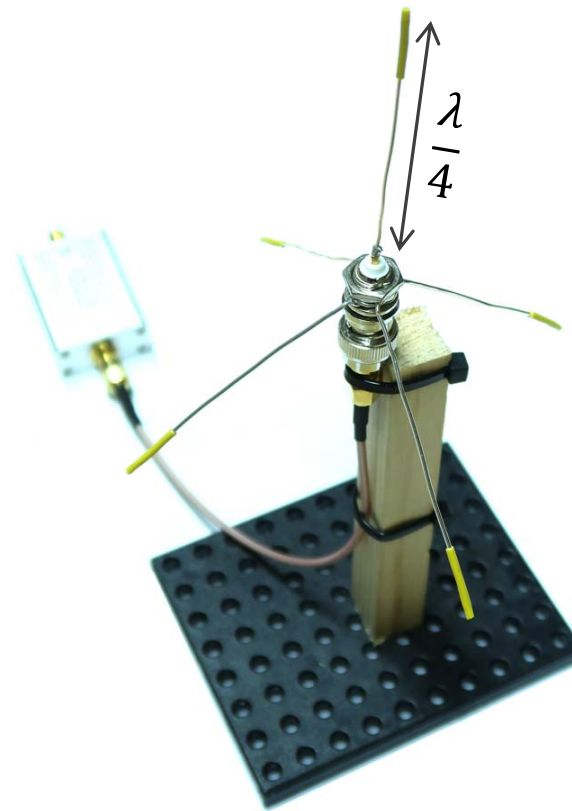
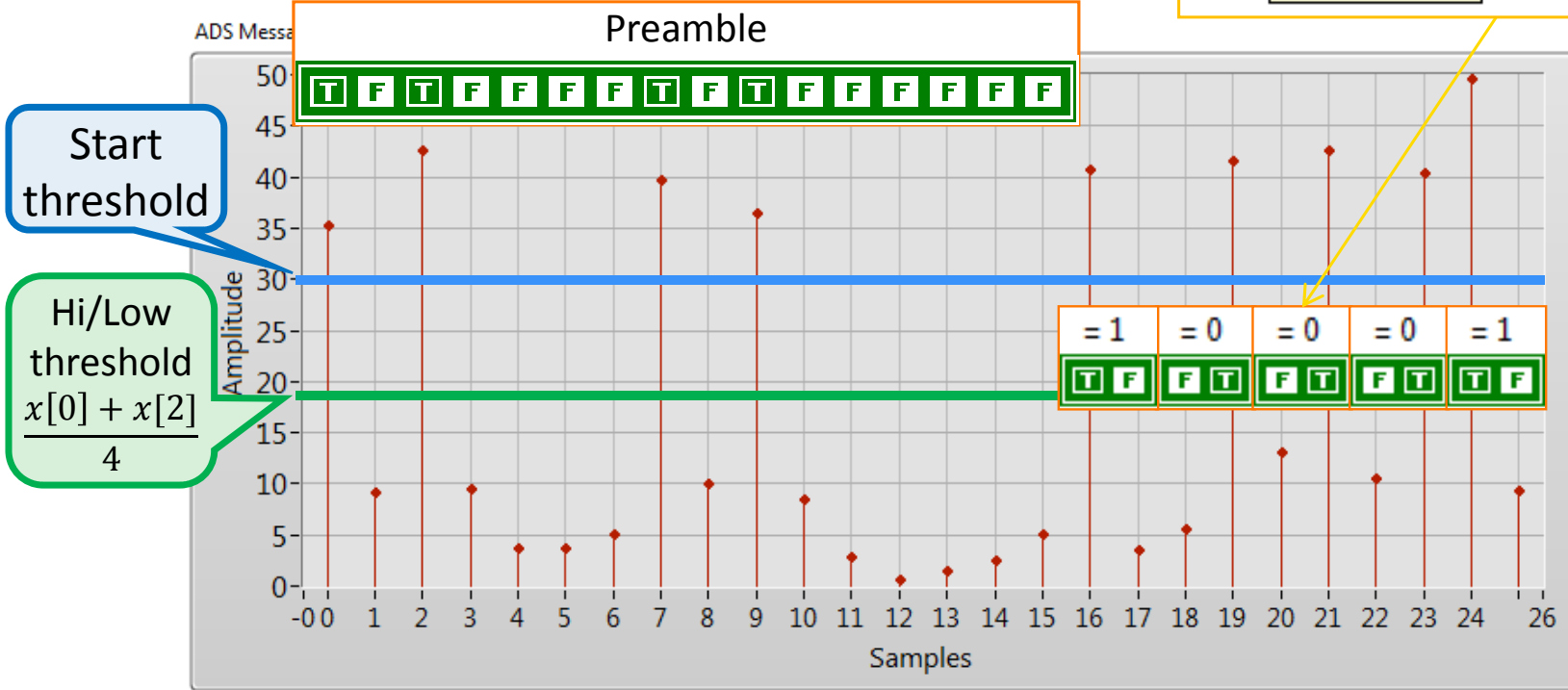
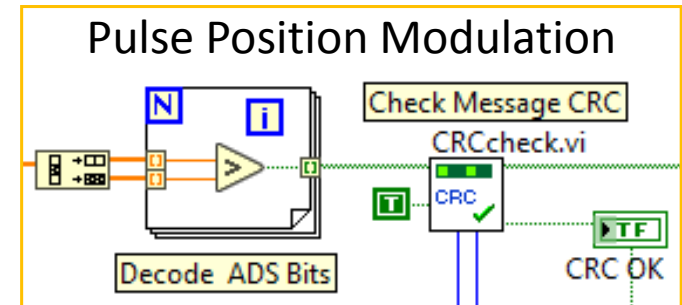
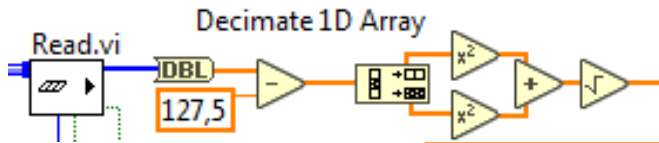


Image: www.faa.gov

3c: Example:

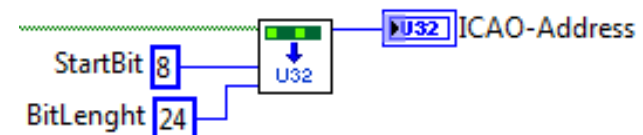
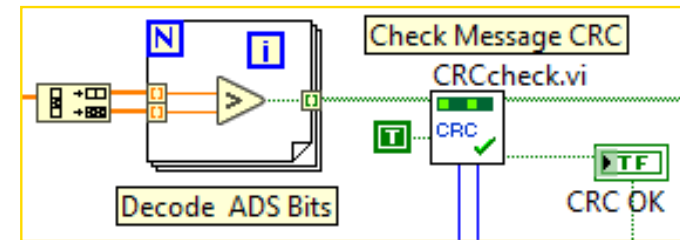
ADS-B Data Frame



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)

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

RTL-SDR ADS-B-Receiver
Version 01-DEC-2019 / LabVIEW 2016

This VI requires the "RTL SDR" package by Albert Lederer to be installed using the VIPM
Tested with the "RTL-SDR Blog's USB dongle"

SDR Center Freq: 1,09G | SDR Sample Rate: 2M

Your own position needed as a reference to decode the aircraft position data.
LatRef: 48,1374 | LonRef: 11,5755

Trigger Level: 12 | # Samples: 200000

STOP

CRC OK	Position	Aircraft ID	DF	TC	ICAO-Address	Altitude	Latitude	Longitude	Callsign
<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	17	19	4067D6	0	0	0	

ICAO List

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

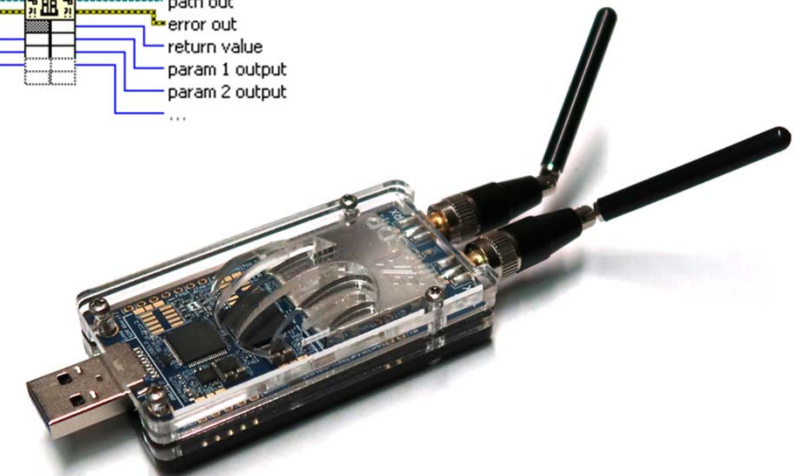
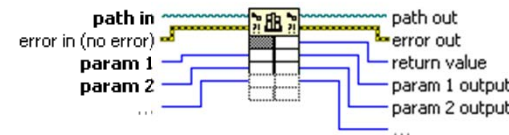
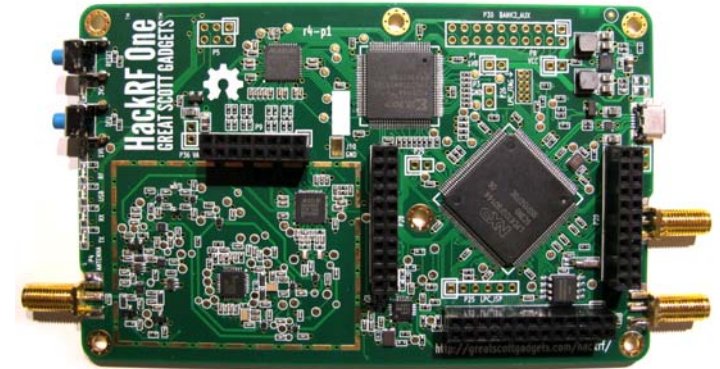
▪ VI available from

www.georg-eggert.de/labview4lectures

Outlook

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



Closing

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-eggert.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>

Closing

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

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