INVESTIGATING THE USRP: I/Q IMBALANCE

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Purpose of the work

- Design methodologies
  - buy hardware → plug it in → something does not work
  - buy hardware → test it (and replace if needed) → plug it in → something does not work, but at least the hardware is ok
- Fast and simple test routines …
  - …are advantageous for development purposes
  - …needed in production testing "*every second is worth a million*"
- Contributions in this work:
  - Test procedure for receiver IQ imbalance
  - Measurement of KTH USRPs (# 4)
  - New insights in seven-parameter sinewave fit (baseband model, L-phenomena)

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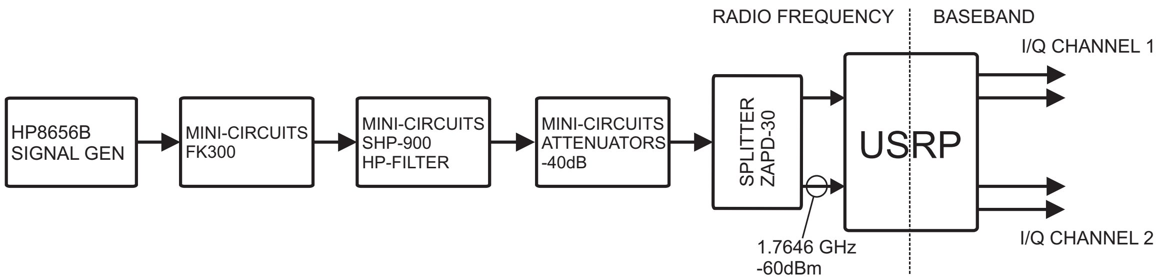
1.7 GHz TONE EXCITATION - BASEBAND OUTPUT



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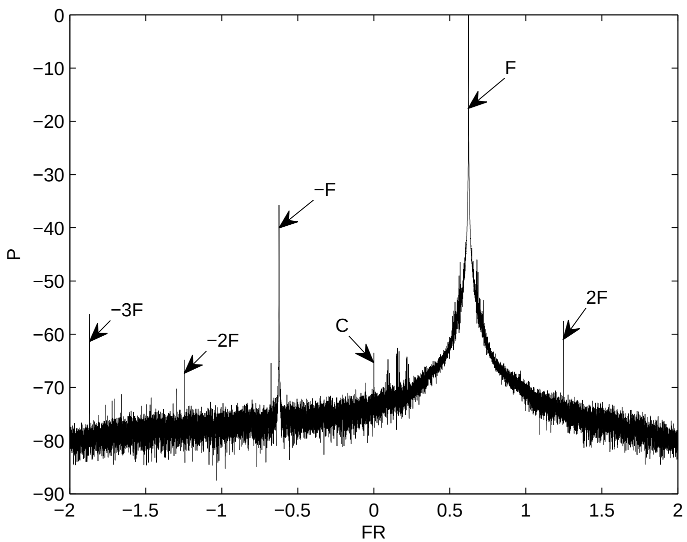
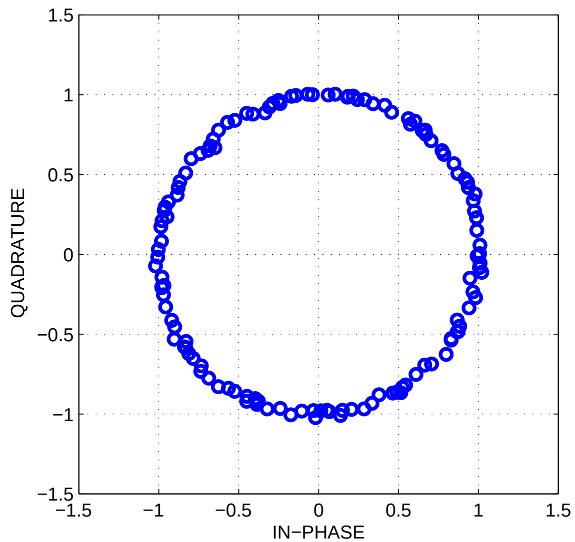




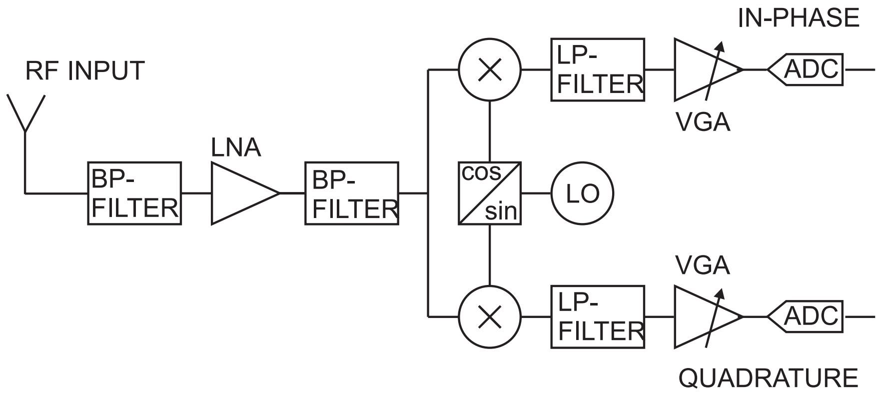
PERFECT I/Q DEMODULATOR

- Baseband representation of the **RF input** $\sin(2\pi F_{\mathbf{RF}}\, t)$

$$z_n = x_n + j\, y_n = \cos(\omega_o\, n) + j\, \sin(\omega_o\, n) = e^{j\omega_o n} \quad (1)$$

(relatively an arbitrary scaling, absolute time, or initial phase)

- angular frequency $\omega_o = 2\pi F / F_{\mathrm{S}} = 0.6/4 = 0.15$
  - $F = F_{\mathrm{RF}} - F_{\mathrm{LO}} = 1764.6 - 1764.0 = 0.6$ MHz
  - F_{S}, F_{RF} and F_{LO} are not required for the proposed test method
  - $\Delta\, F_{\mathrm{LO}}$ 10-20 kHz for the USRP



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Practical I/Q demodulator

- in-phase representation of the RF stimuli

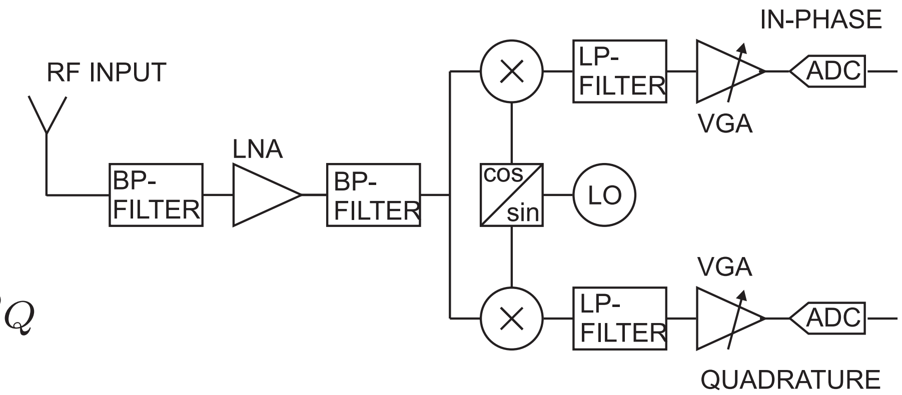
$$x_n = g_I \sin\left(\omega_o n + \phi_I + \frac{\pi}{2}\right) + c_I + v_n^I \tag{2}$$

- quadrature

$$y_n = g_Q \sin\left(\omega_o n + \phi_Q\right) + c_Q + v_n^Q . \tag{3}$$

- g_I, g_Q are gains; ϕ_I, ϕ_Q initial phases; c_I, c_Q DC offsets; v_n^I and v_n^Q are noise terms

- Parameters of interest
  - *gain imbalance* $G = \dfrac{g_I}{g_Q}$
  - *quadrature skew* $Q = \phi_I - \phi_Q$
  - *LO leakage* $L = 2\dfrac{c_I^2 + c_Q^2}{g_I^2 + g_Q^2}$



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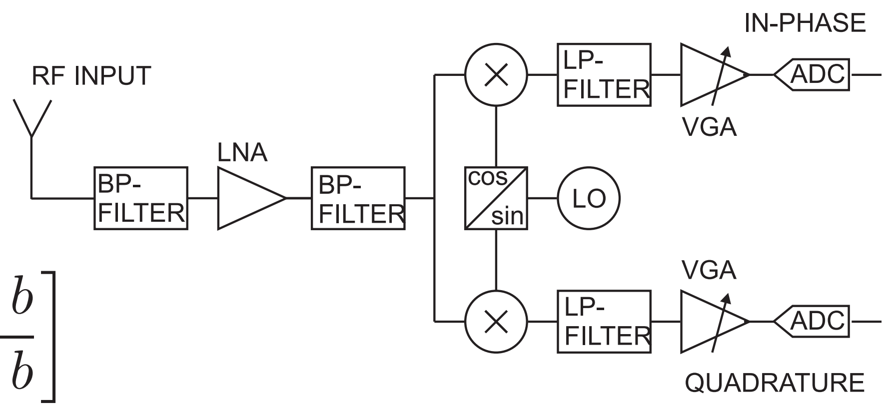
REFORMULATION OF PROBLEM

Baseband data $z_n = x_n + j\, y_n$ can be written as

$$z_n = a\, e^{i\omega n} + b^*\, e^{-i\omega n} + c + v_n. \tag{4}$$

- a, b c are complex-valued constants
- v_n complex-valued zero mean noise
- Parameters of interest
  - *gain imbalance* $G = \dfrac{|a+b|}{|a-b|}$
  - *quadrature skew* $Q = \angle \left[\dfrac{a+b}{a-b} \right]$
  - *LO leakage* $L = \dfrac{|c|^2}{|a|^2 + |b|^2}$
- Based on $\{z_n\}_1^N$ find estimates $\widehat{a}$, $\widehat{b}$, $\widehat{c}$ and $\widehat{\omega}$ (7 parameters)



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NON-LINEAR LEAST-SQUARES ESTIMATION

- 1. $\widehat{\omega}$ found by a one-dimensional search (Periodogram-type of cost function)
  2. $\widehat{a}$, $\widehat{b}$ $\widehat{c}$ linear least-squares based on $\widehat{\omega}$
  3. $\widehat{G}$, $\widehat{Q}$ and $\widehat{L}$ from $\widehat{a}$, $\widehat{b}$ $\widehat{c}$
- Comments
  - "Slight" modification of a classical spectral estimation problem
  - "Gaussian noise", but "no need" for maximum likelihood, because the practical performance is "independent" on the noise variances in I and Q channels.
  - NLS equals MLE when the channels have same noise power.
  - NLS solves the same problem as seven-parameter fit (P.M. Ramos), but in a different way
  - Asymptotic Cramér-Rao bounds available for the estimates.

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Theorem 1: Consider any unbiased estimator producing the estimates $\widehat{G}$, $\widehat{Q}$, and $\widehat{L}$ based on the receiver output $\mathbf{z}$. *If*

- *noise is Gaussian*
- *number of samples large*

then the asymptotic variances are bounded from below by:

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$$\sigma_G^2 = \frac{1+G^2}{N\,\mathrm{SNR}_Q} \tag{5}$$

$$\sigma_Q^2 = \frac{1+G^2}{N\,\mathrm{SNR}_I} \tag{6}$$

$$\sigma_L^2 = \frac{2L(1+L)}{N\,\mathrm{SNR}} \tag{7}$$

where SNR *denotes the average SNR, that is* $\mathrm{SNR} = (\mathrm{SNR}_I + \mathrm{SNR}_Q)/2$. ■

Matlab: Non-linear least-squares

```
function []=iqmain(y);
y=y/sqrt(cov(y)); N = length(y); T =(1:N)';
%Frequency estimate - requires IQparest.m and myfun2.m
west = IQparest(y,4);
%LS-fit of linear parameters
zhat = exp(i*west*T);
Zhat = [zhat conj(zhat) ones(N,1)];
hateta = Zhat\y;
%Extract a, b, c
hata = hateta(1);
hatb = conj(hateta(2));
hatc = hateta(end);
%% Calculate quantities of interest
G = abs(hata+hatb)/abs(hata-hatb);
Q = angle((hata+hatb)/(hata-hatb));
L = abs(hatc)^2/(abs(hata)^2 + abs(hatb)^2);
```

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MATLAB: EXAMPLE OF RESULTS

```
>> iqmain(z)
---
data sequence length N: 50000
gain imbalance G:  -0.1319 dB
quadrature skew Q: -1.8305 deg
LO leakage: -27.134 dB
>>
```

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- Results presented in dB and deegrees
- Elapsed time (Intel U2500@1.20GHz - old laptop)
  - $N = 1024$: `Elapsed time is 0.023951 seconds`
  - $N = 50000$: `Elapsed time is 0.579940 seconds`

Datasheet values for AD8347 at 1.905 GHz

The FLEXRF family of daughter-boards, which are widely used with the USRP platform, is designed around the AD8347 direct conversion quadrature demodulator.

	Typ (Min/Max)	
G_{dB}	$+0.3$	dB
Q_o	± 1 (± 3)	degree
L_{dBm}	-60	dBm (at RFIP)
L_{dBm}	-42	dBm (At IMXO/QMXO)

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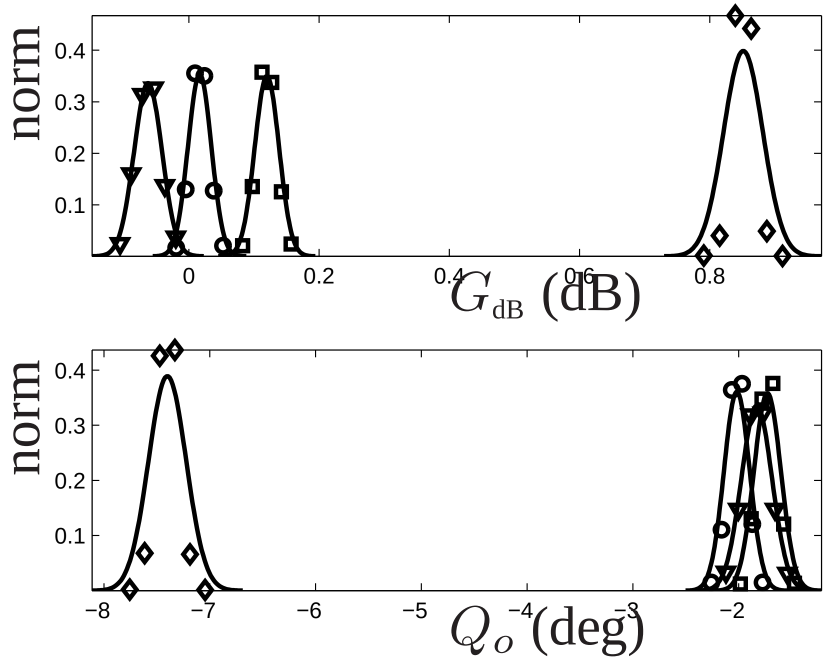
- (Practitioner) Collect large number of data and run, but . . .
- . . . (Rapid testing) is it sufficient with a handful of periods?

GAIN IMBALANCE AND QUADRATURE SKEW



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USRP results based on non-overlapping segments ($N = 64$). USRP #1: Channel 1 (○), Channel 2 (□), USRP #2: Channel 1 (◇), Channel 2 (▽).

- G and Q can be estimated from short sample records (here $N = 64$)
- 1 out of 4 receives with outlier performance

LO LEAKAGE

- Datashet: $L_{\text{dBm}} = -60$ dBm (at AD8347 RFIP)
- RFIP: $P_{\text{RFIP}} = P_{\text{RF}} + 13$ dBm (MGA-82563) $\Rightarrow L_{\text{dBm}} = -60 + 13 + L_{\text{dB}}$
- $L_{\text{dBm}} < -100$ dBm at RFIP for all USRPs (enabled compensation)
- $L_{\text{dBm}} - 66$ dBm to -90 dBm (disabled compensation)
  - Effective USRP-internal DC compensation

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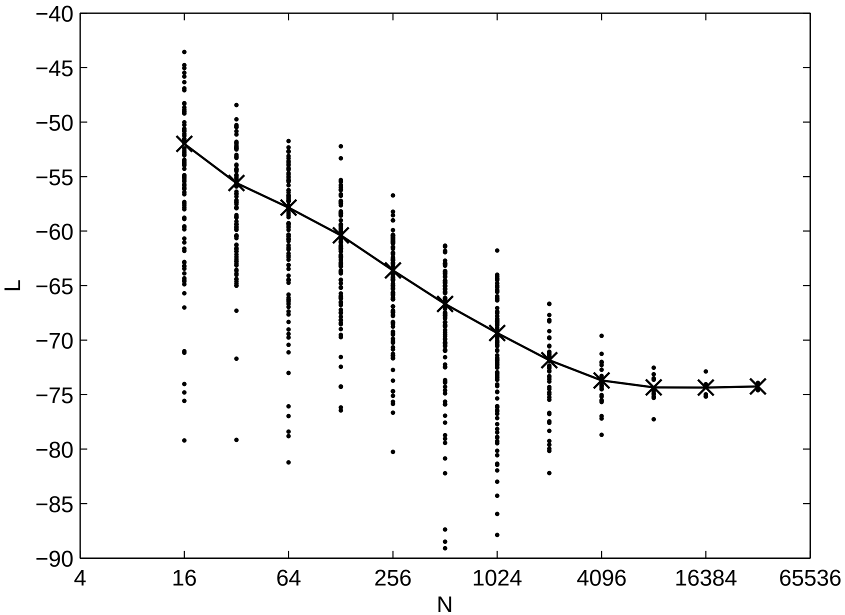

CONCLUSIONS

- Tone test for IQ imbalance
  - Low-complexity and (almost statistically) efficient
  - Same LS-problem solved as by seven-parameter fit (P.M. Ramos)
- KTH USRPs
  - 3 out 4 USRPs have performance according to the data-sheet
  - Outlier performance isolated to one FLEXRF1800
  - Efficient LO leakage compensation (enabled as default)
- Estimator properties
  - $N = 64$ sufficient for G (± 0.1 dB) and Q (± 0.5 deg)
  - $N = 64 \Rightarrow L$ spread 40 dB and bias 15 dB!
  - $N = 16$k needed for L within a couple of dBs

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