Flicker noise of high-speed p-i-n photodiodes

E. Rubiola[#%], E. Salik[@%], N. Yu[%], L. Maleki[%]

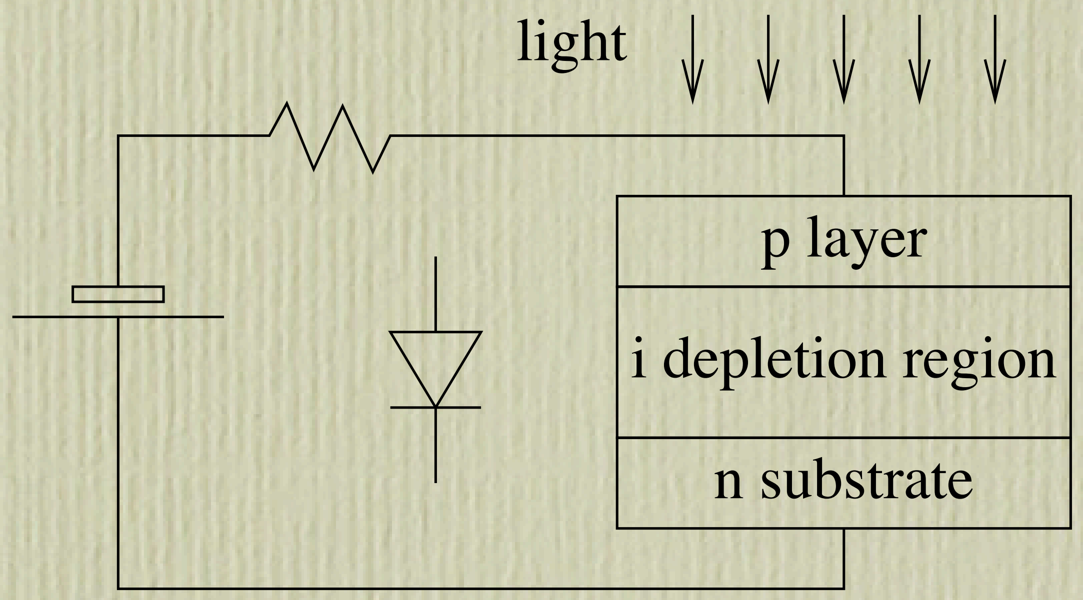
FEMTO-ST Institute, Besançon, France
% JPL/CALTECH, Pasadena, CA, USA
@ Dept. of Physics, California State Polytechnic University, Pomona, CA, USA

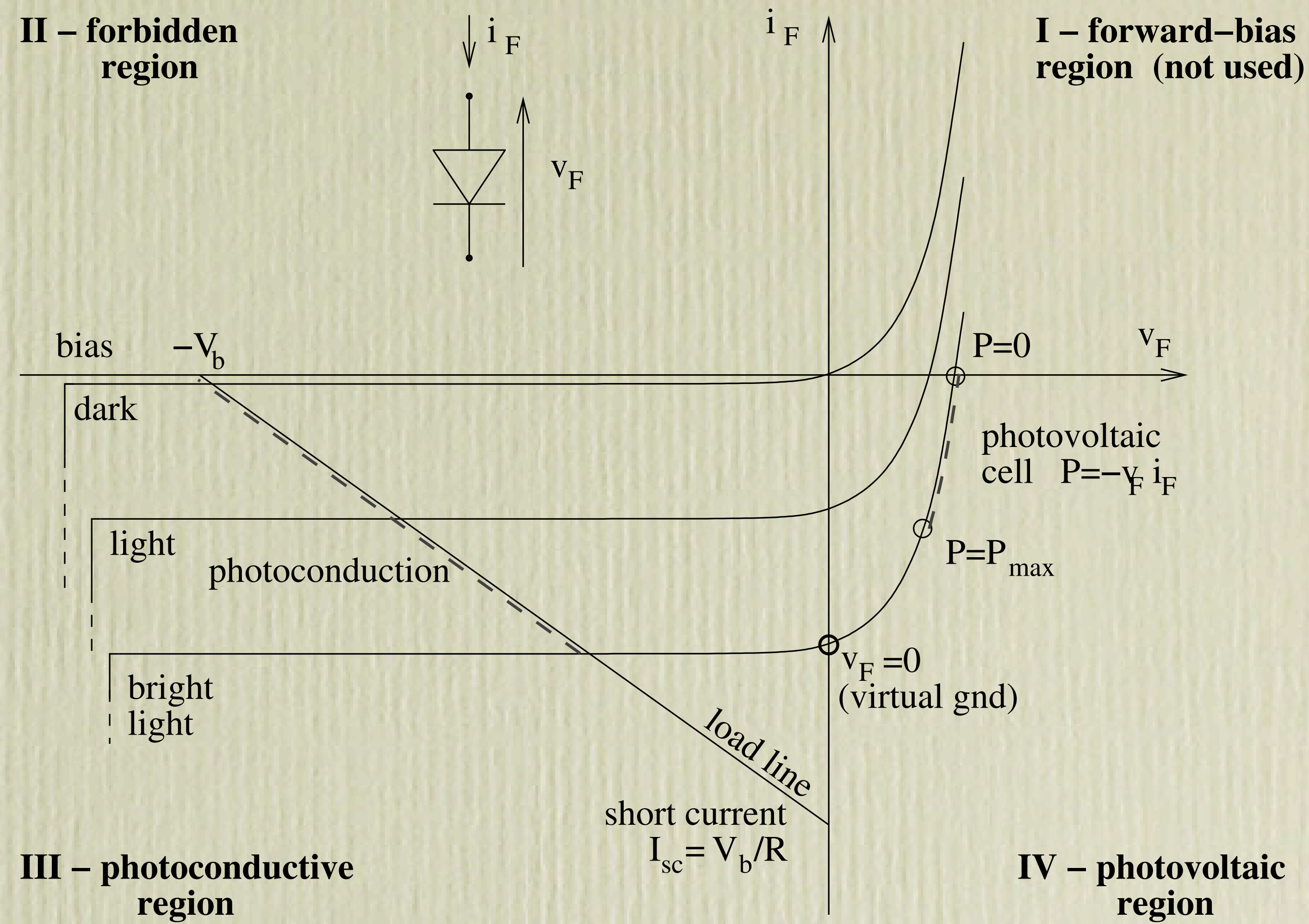
Outline

- introduction
- method
- background noise
- results

Work carried out at the JPL/CALTECH
under NASA contract, with support from ARL and AOSP/DARPA

p-i-n InGaAs photodiode





$$i_F = I_s \left[\exp \frac{v_F}{kT/q} - 1 \right] - i_P$$

$$kT/q \simeq 25.6 \text{ mV at } 300 \text{ K}$$

$$i_P = \eta \Phi = \eta \frac{P}{h\nu} \quad \text{photocurrent}$$

$$= \rho P \qquad \rho = \text{responsivity}$$

photoconductive region => lowest C => high speed

Signal and noise

microwave-modulated IR $P_\lambda(t) = \overline{P}_\lambda \left[1 + m \cos 2\pi\nu_0 t\right]$

microwave photocurrent with AM and PM noise $i_{\text{ac}}(t) = \rho \overline{P}_\lambda m \left[1 + \alpha(t)\right] \cos\left[\omega_0 t + \phi(t)\right]$

white noise $S_i = 2q\bar{\imath}$

Virtually no information on AM/PM flicker is available

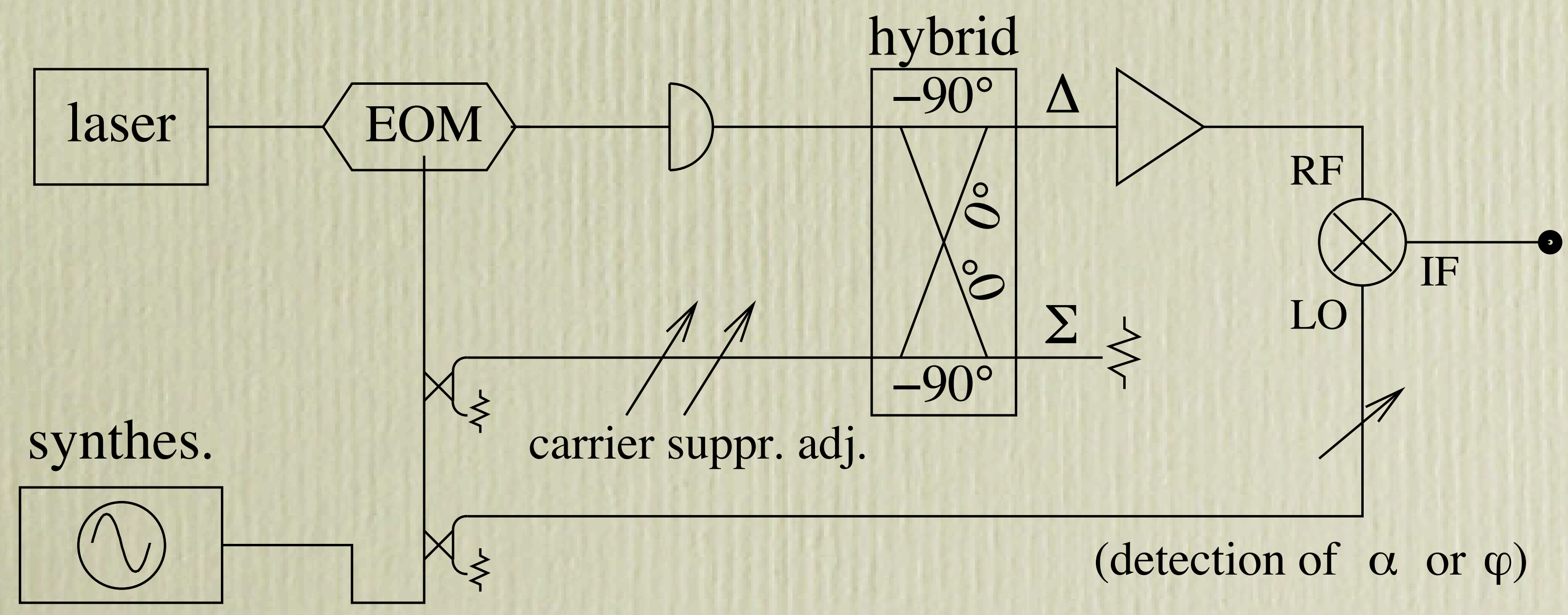
Motivations

- frequency distribution systems
  deep space network, VLBI, inter-lab link
- laser metrology
- photonic oscillators (Leeson effect)
  (E. Rubiola, The Leeson effect, arXiv:physics/0502143)

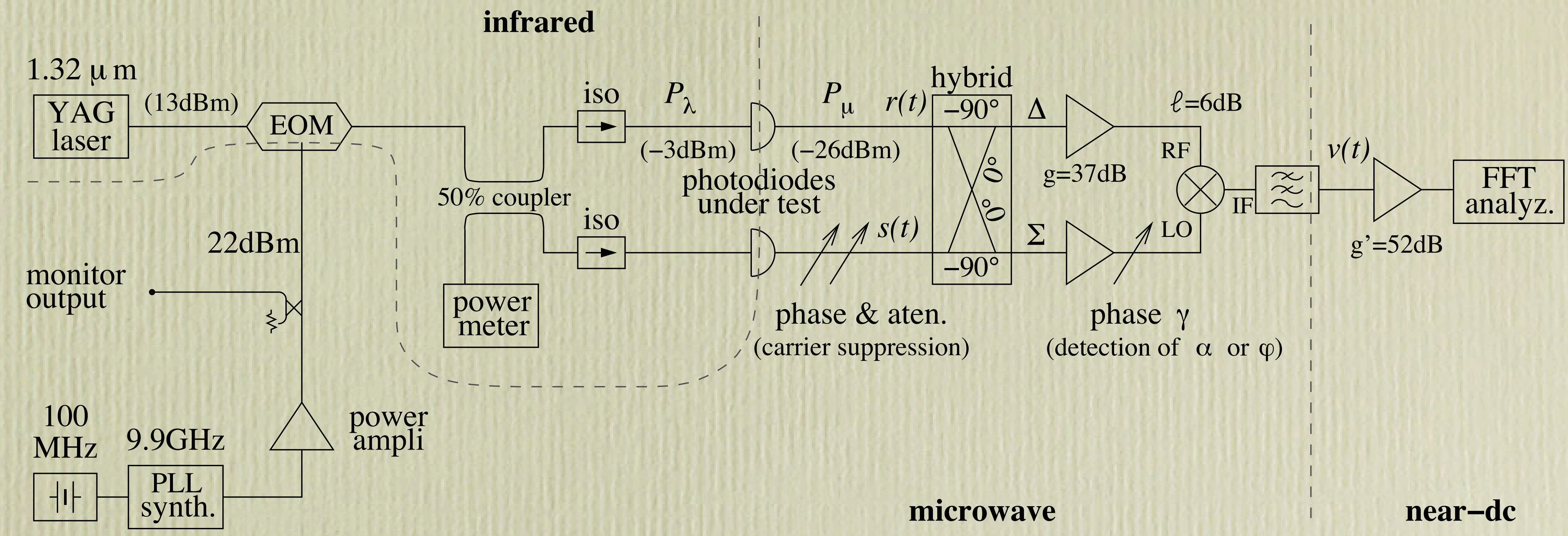
Experimental method (1)

- the photodiode output is insufficient to saturate a mixer
- a preliminary survey suggests that the photodiode phase flickering is lower than that of a microwave amplifier

  (typical amplifier flicker -105 dBrad^2/Hz at 1 Hz)
- we choose some photodiodes similar to one another, with a max speed of 12-15 GHz
  (Discovery Semiconductors, Fermionics, Lasertron)
- a single-photodiode interferometric (bridge) scheme can't work because the equilibrium condition is difficult



Experimental method (2)



- **bridge (interferometric) scheme**
  # low phase noise, limited by the noise figure of the Δ amplifier
  # carrier rejection in Δ => the Δ amplifier does not flicker
  # rejection of the source noise
  Rev. Sci. Instr. **73** 6 p. 2445 (2002), and arXiv:physics/0503015
- the noise of the Σ amplifier is not detected
  Electron. Lett. **39** 19 p. 1389 (2003)

Background noise (1)

- well understood:
  - phase-to-voltage gain [V/rad]

$$k_d = \sqrt{\frac{g P_\mu R_0}{\ell}} - \begin{bmatrix}\text{dissip.}\\ \text{loss}\end{bmatrix}$$

  - thermal noise

$$S_{\phi\, t} = \frac{2FkT_0}{P_\mu} + \begin{bmatrix}\text{dissip.}\\ \text{loss}\end{bmatrix}$$
$$= \frac{2FkT_0}{R_0 \rho^2 \overline{P}_\lambda^2 m^2} + \begin{bmatrix}\text{dissip.}\\ \text{loss}\end{bmatrix}$$

  - shot noise

$$S_{\phi\, s} = \frac{4q}{\rho m^2 \overline{P}_\lambda}$$

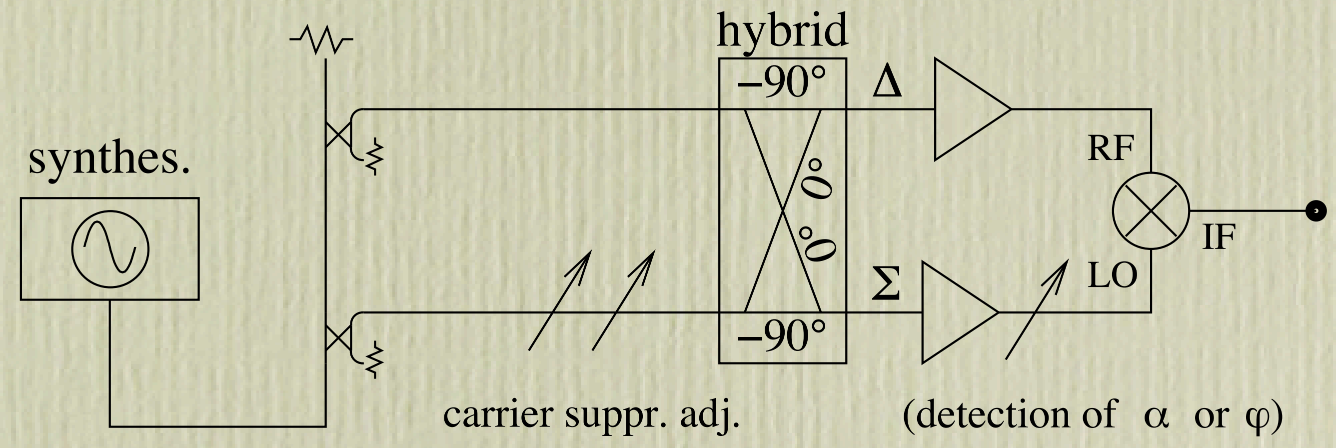
g	power gain (Δ ampli)
P_μ	microw. pow.
R_0	charact. resist. (50 Ω)
ℓ	ssb mixer loss
F	noise figure (Δ ampli)
kT_0	thermal energy ($4{\times}10^{-21}$ J)
q	electron charge ($1.6{\times}10^{-19}$ C)
ρ	responsivity [A/W]
m	modulation index
P_λ	optical power

- experimentally determined or up-bounded:
  - contamination from AM noise (RIN)

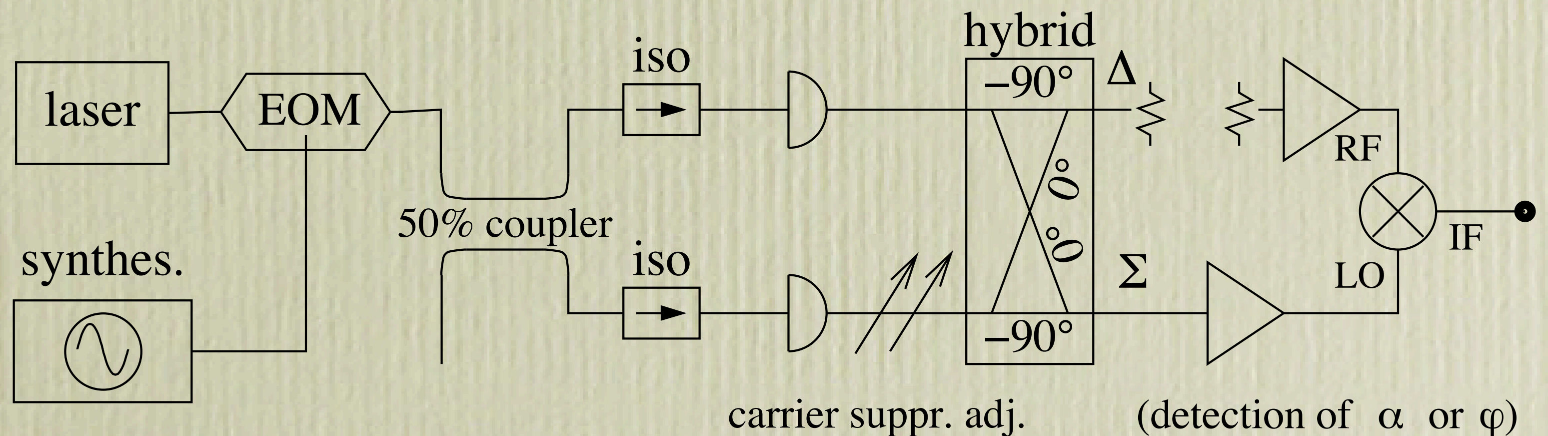
Background noise (2)

low optical power => thermal noise >> shot noise

1. replace the detectors with microwave signals



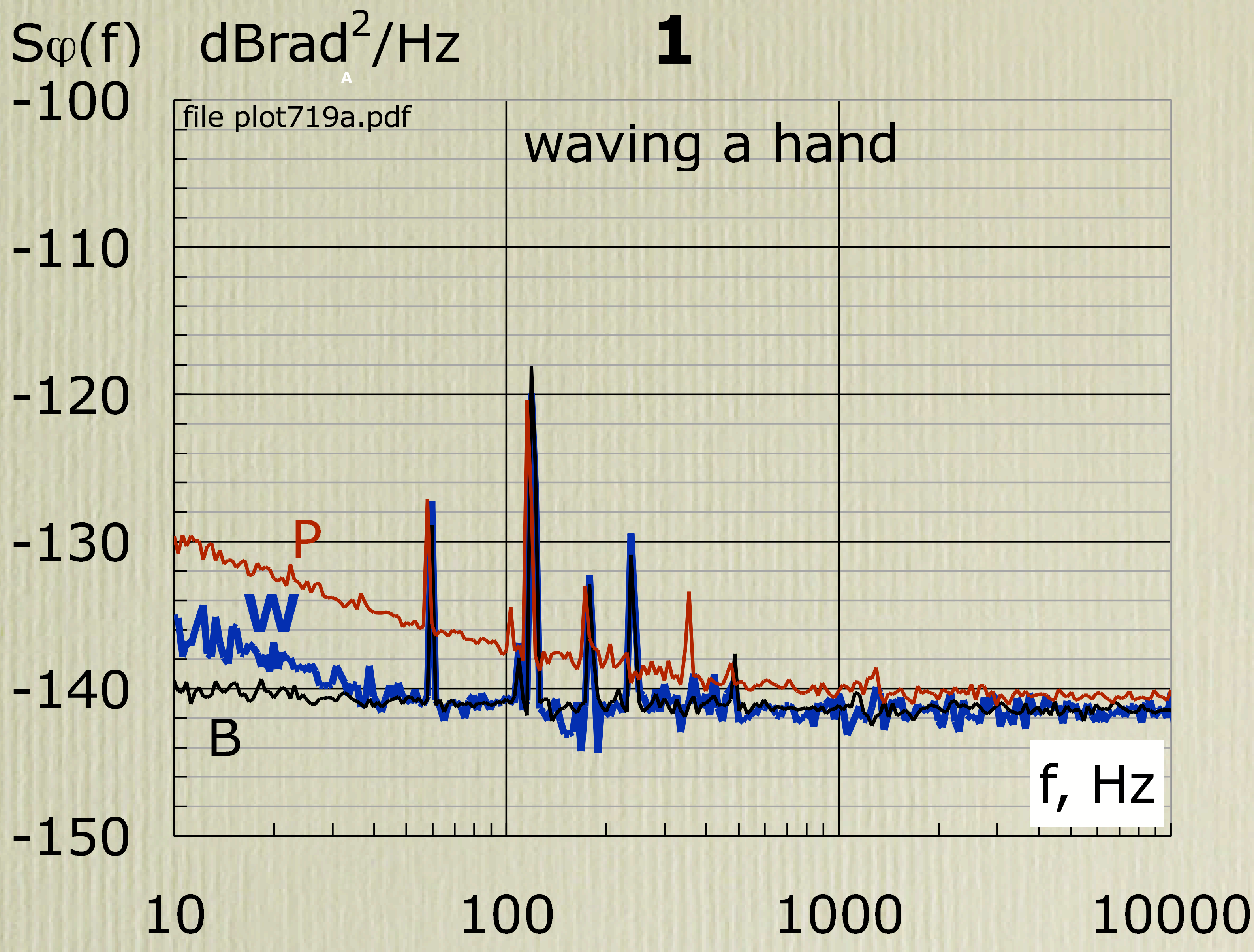
2. terminate the input of the delta amplifier



... and take the worst case

Technical difficulties (1): crosstalk

- high EOM driving power (22 dBm)
- low photodiode output power (-26 dBm)
- finite isolation (100-120 dB?)
- even small fluctuations of the environment induce noise as a consequence of the fluctuating crosstalk
- work nighttime, when nobody is around



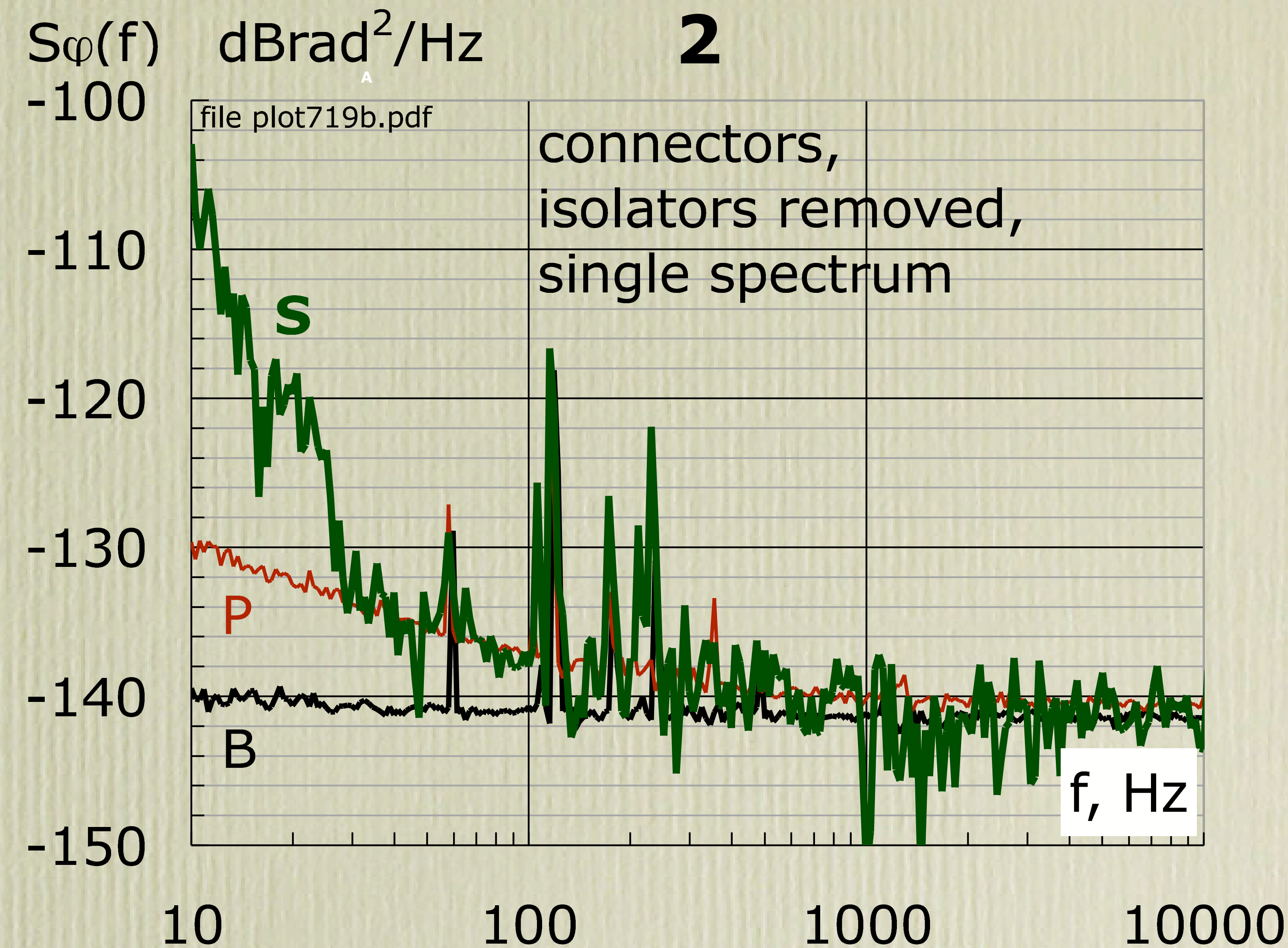
W: waving a hand 0.2 m/s, 3 m far from the system

B: background noise

P: photodiode noise

Technical difficulties (2): reflections

- back reflection causes the spectrum to be polluted
- flares appear at random in some spectra, as shown
- unexplained physical mechanism



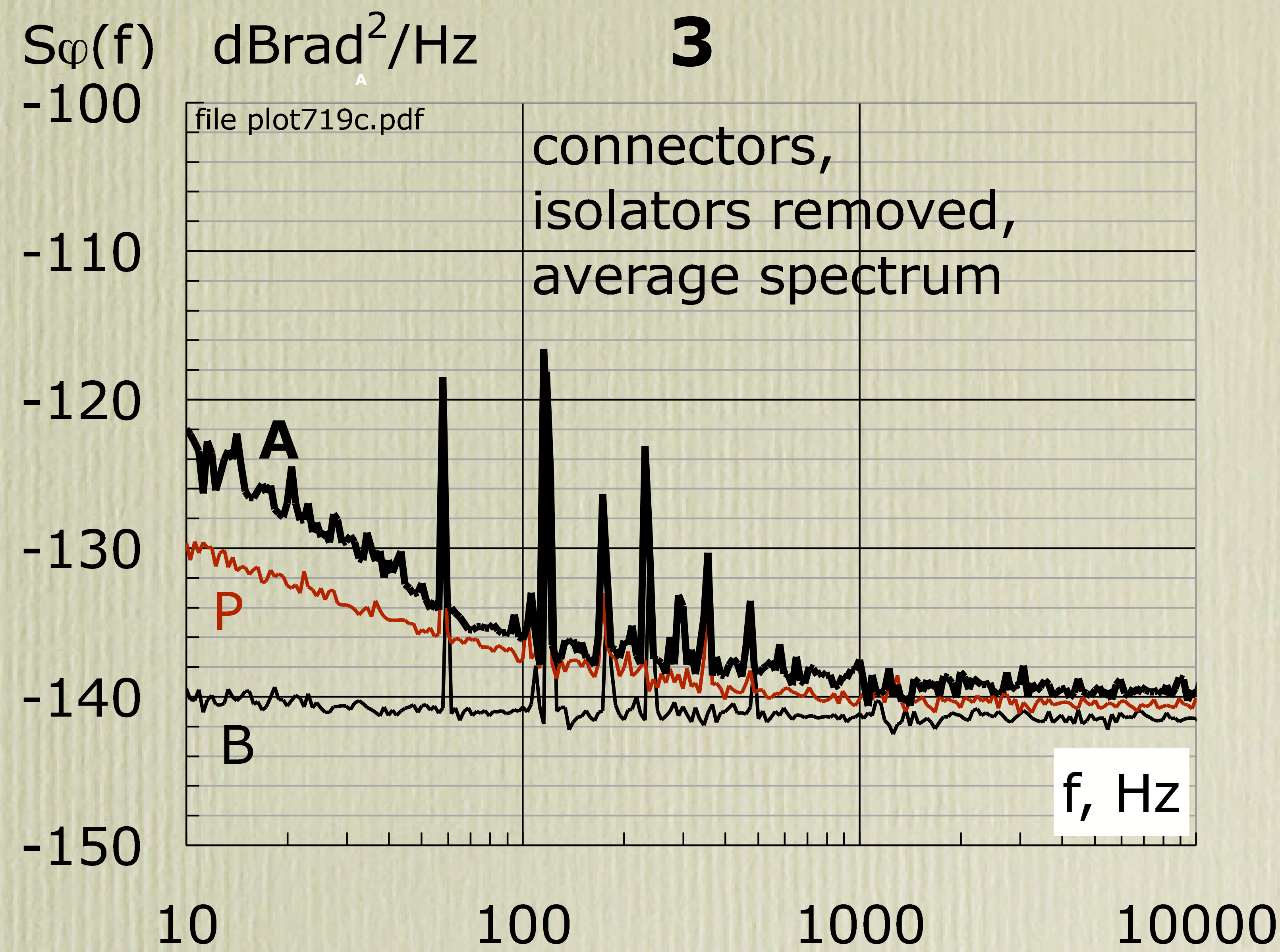
S: example of single spectrum, with optical connectors and no isolators

B: background noise

P: photodiode noise

Technical difficulties (3): reflections

- back reflections causes spectra to be polluted at random
- the average spectrum is smooth
- wrong slope
- it is difficult to identify and to discard polluted spectra



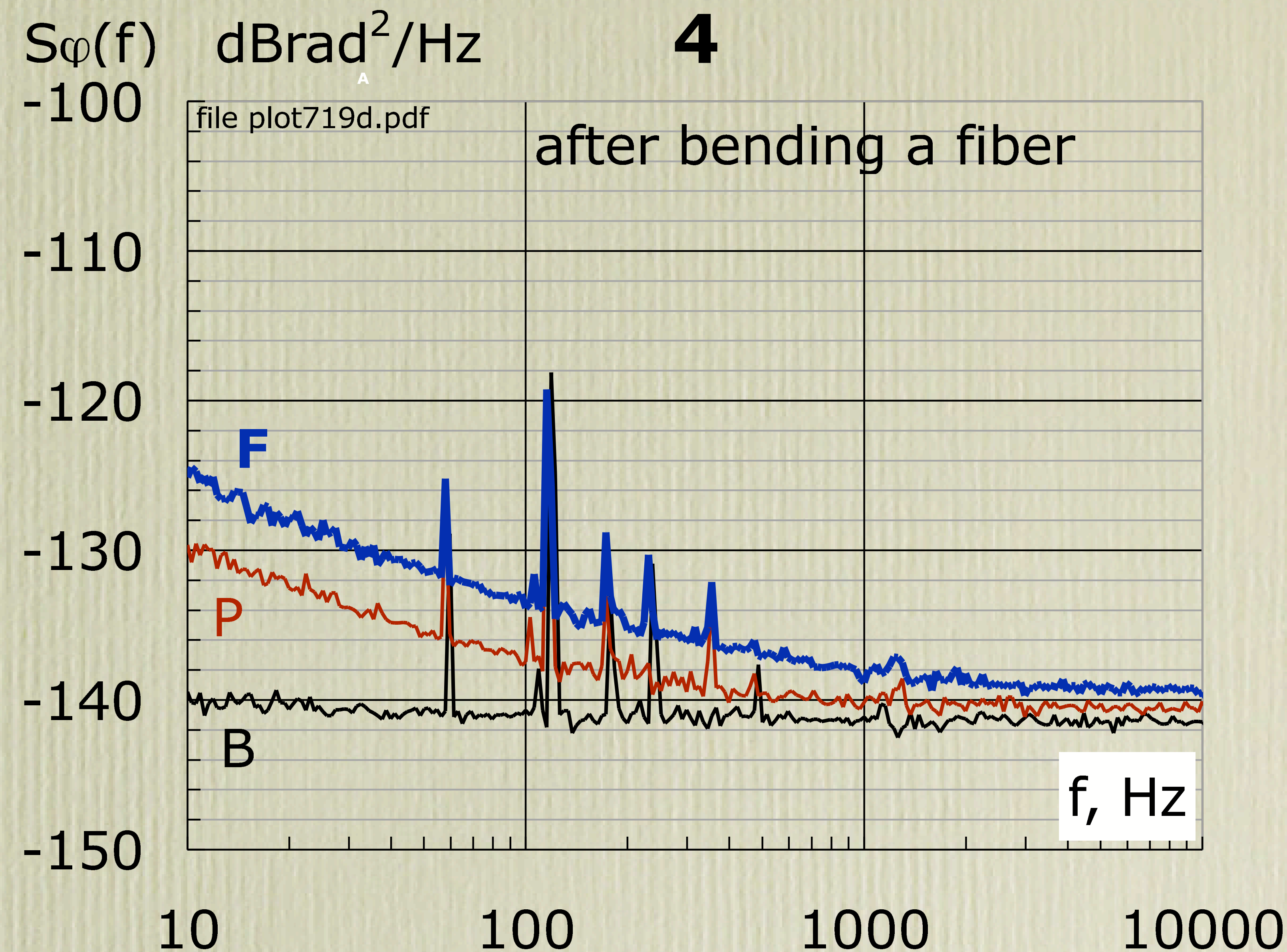
A: average spectrum, with optical connectors and no isolators

B: background noise

P: photodiode noise

Technical difficulties (4): fibers

- the path of the optical fibers affects the internal stresses, and in turn the reflections
- unpredictable effect on noise, which is *not* the photodiode noise
- trimming the system takes patience

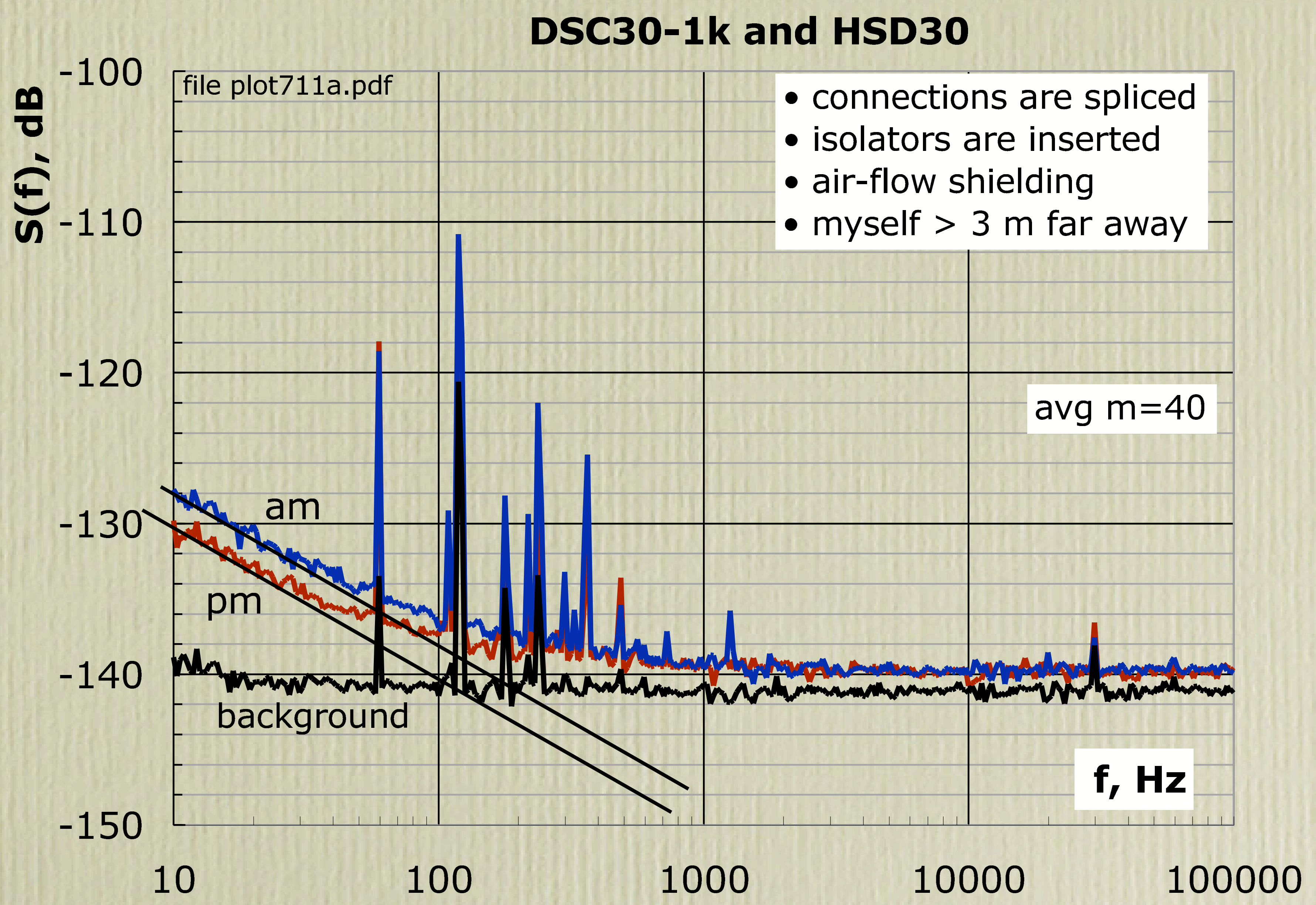


F: after bending a fiber, 1/f noise can increase unpredictably

B: background noise

P: photodiode noise

Example of photodiode noise



... after patient adjustement

Some results

all the pair of two different photodiodes are compared

photodiode	$S_\alpha(1\,\mathrm{Hz})$		$S_\varphi(1\,\mathrm{Hz})$	
	estimate	uncertainty	estimate	uncertainty
HSD30	-122.7	-7.1 $+3.4$	-127.6	-8.6 $+3.6$
DSC30-1K	-119.8	-3.1 $+2.4$	-120.8	-1.8 $+1.7$
QDMH3	-114.3	-1.5 $+1.4$	-120.2	-1.7 $+1.6$
unit	dB/Hz	dB	dBrad^2/Hz	dB

estimated uncertainty

0.5 dB	random, affects the differences (amplified by the three-corner method)
1 dB	systematic, affects all values in the same way (non amplified by the three-corner method)

Conclusions

- the photodetectors we measured are similar in AM and PM 1/f noise
- the 1/f noise is about -120 dB[rad^2]/Hz
- other effects are easily mistaken for the photodetector 1/f noise
- environment and packaging deserve attention in order to take the full benefit from the low noise of the junction

www.arxiv.org, read the document arXiv:physics/0503022v1