Инфракрасный ВОЛоконный Гетеродинный Анализатор

IVOLGA

High resolution heterodyne spectroscopy for studies of planetary atmospheres

A.V.Rodin, A,Yu. Klimchuk, A.I.Nadezhdinsky, O.V.Benderov
and IVOLGA team

МФТИ Московский физико-технический институт

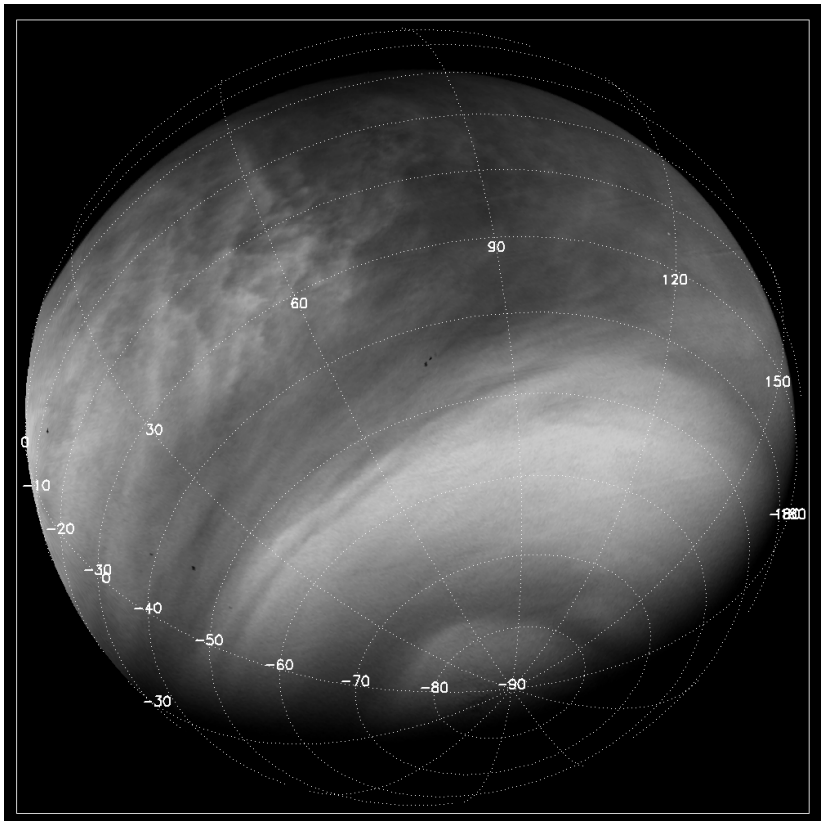
ИОФ РАН

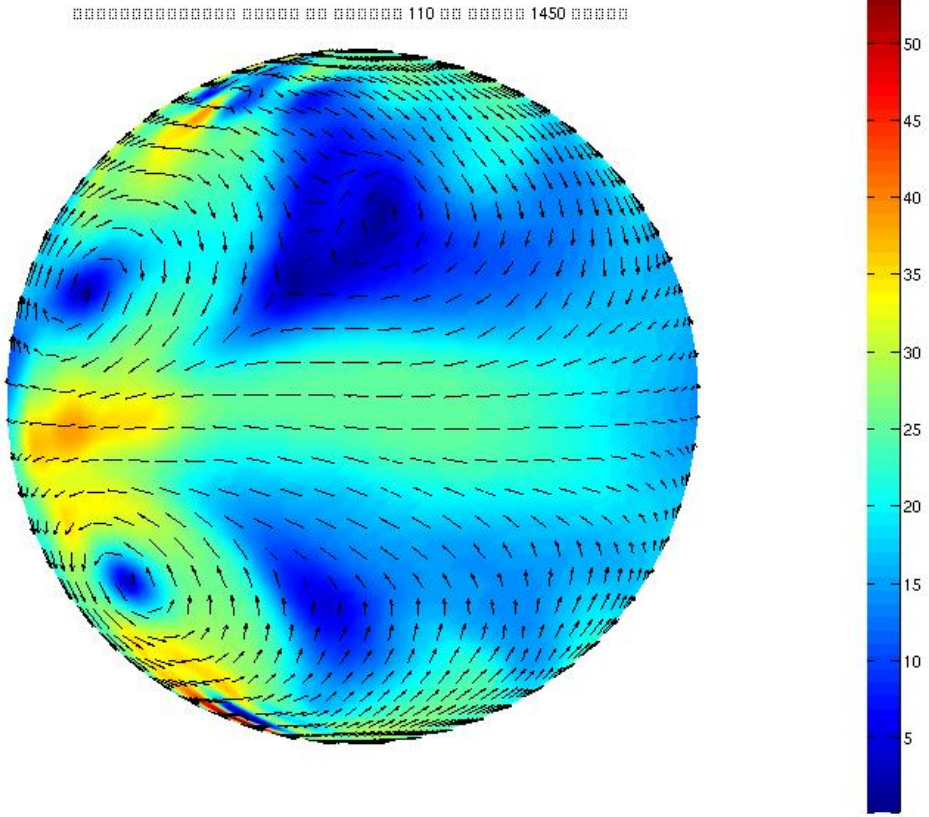
ИКИ

Why ultra-high resolution?

- Trace gas analysis
- Isotopic ratios
- Vertical profiling of pressure & temperature
- Doppler wind measurements

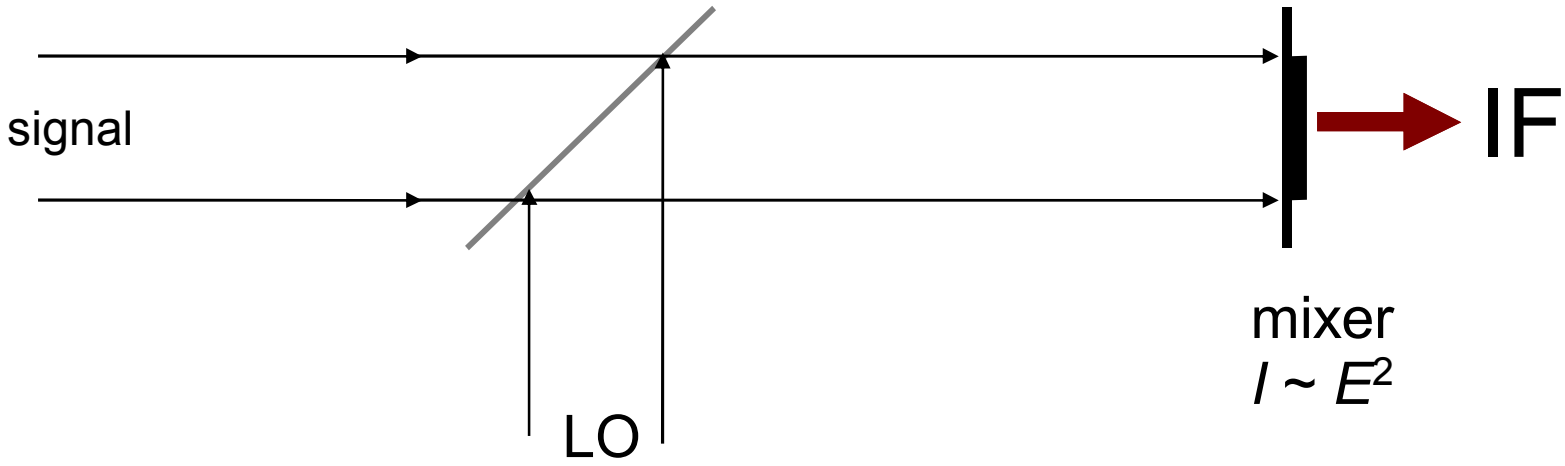
Etc...etc...etc...





Why heterodyne?

- Signal level decreases with channel bandwidth
- Noise level is invariant
- Heterodyning is the only method to provide acceptable S/N at ultra-high resolution



First paper on the optical heterodyning, 1956

1956 г. Июль *Т. LIX, вып. 3*

УСПЕХИ ФИЗИЧЕСКИХ НАУК

ГЕТЕРОДИНИРОВАНИЕ СВЕТА

С. И. Боровицкий и Г. С. Горелик

Недавно появилась статья Форрестера, Гудмундсена и Джонсона [1] с описанием опытов, в которых им удалось получить одно из явлений, которые могут быть описаны как интерференция двух некогерентных световых излучений. Американским исследователям удалось осуществить с помощью специально разработанного для этой цели фотоэлектрического преобразователя гетеродинирование, или, как они выражаются, смешение (mixing) двух оптических спектральных линий, разностная частота которых принадлежит к области сверхвысоких радиочастот.

Problems

- shot noise

- LO stability

- low angular aperture

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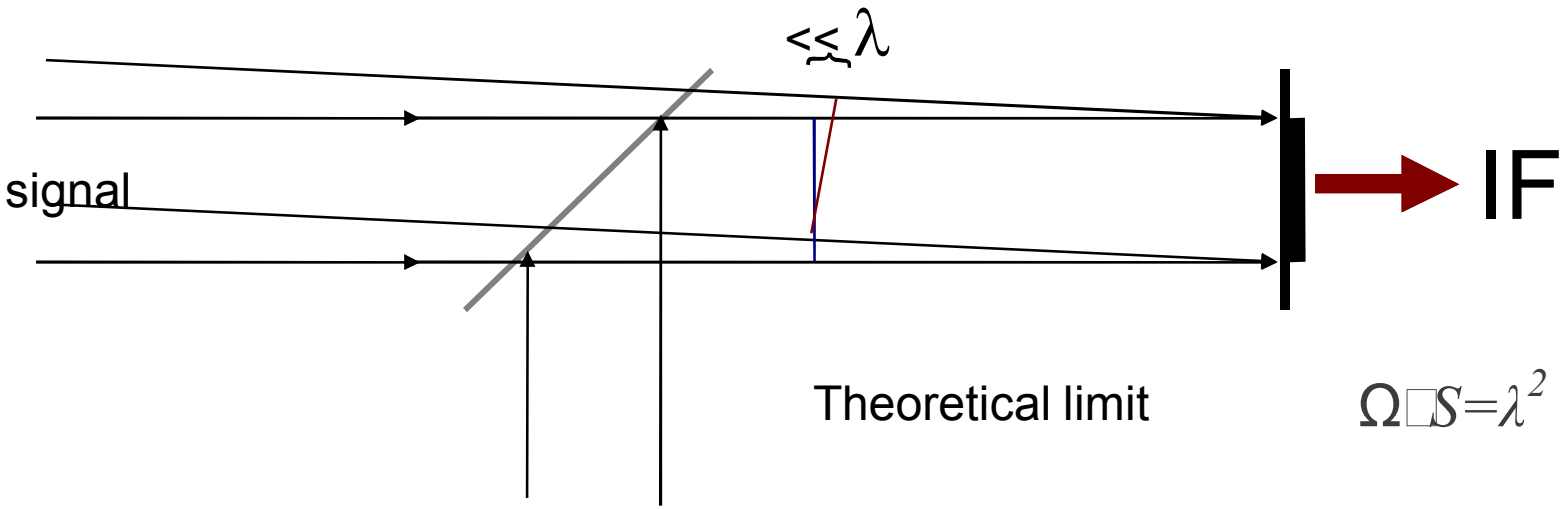
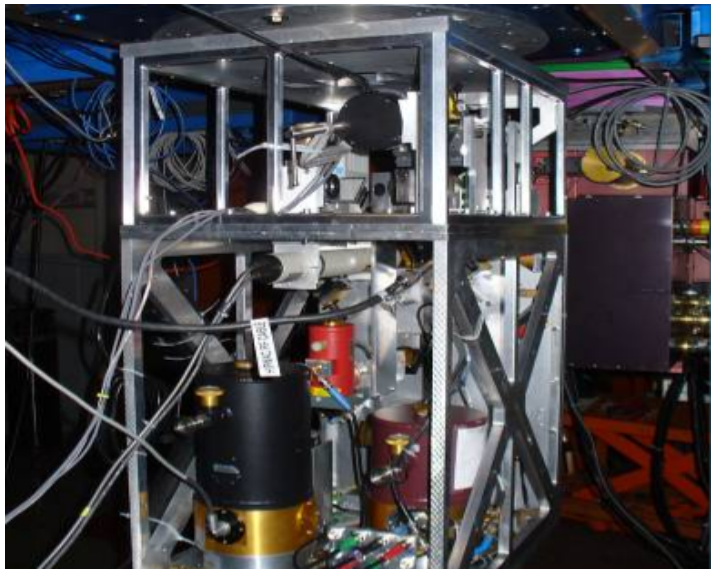
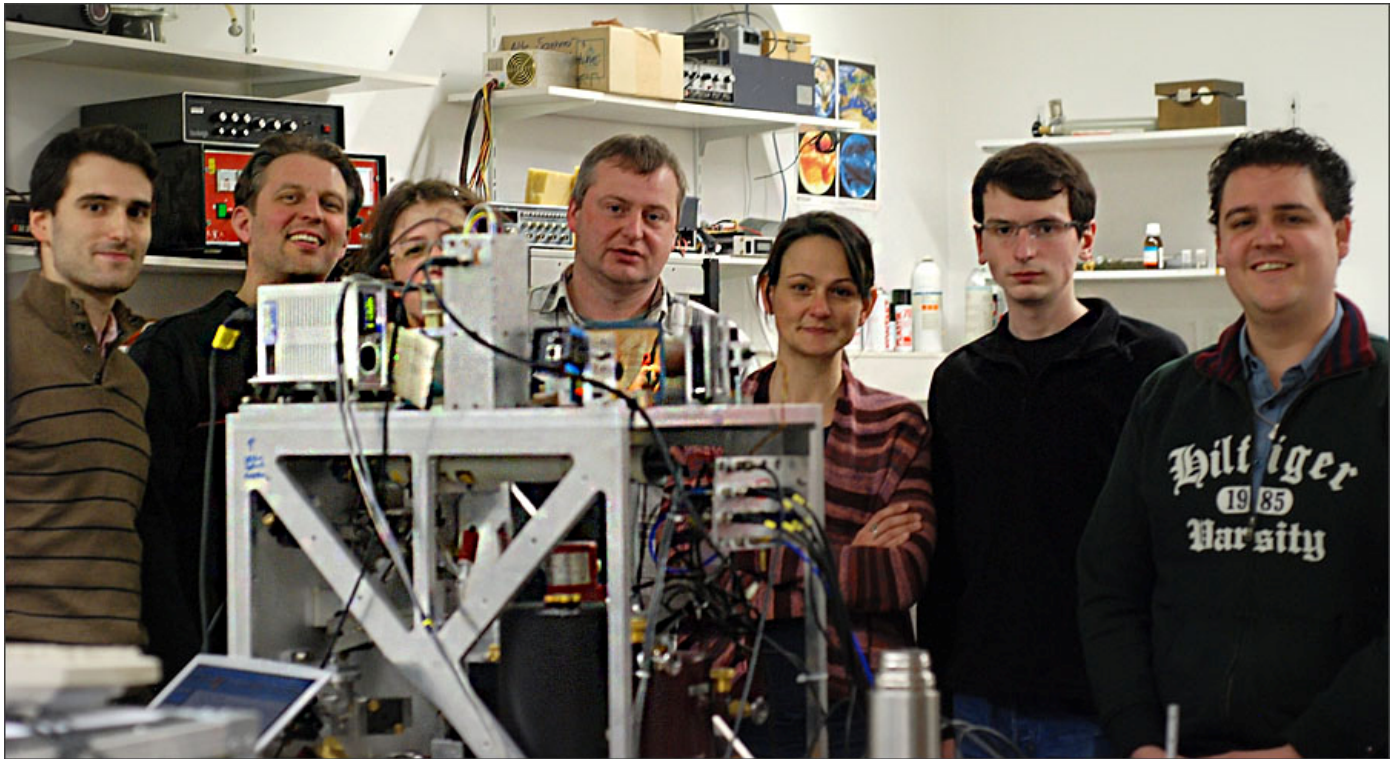


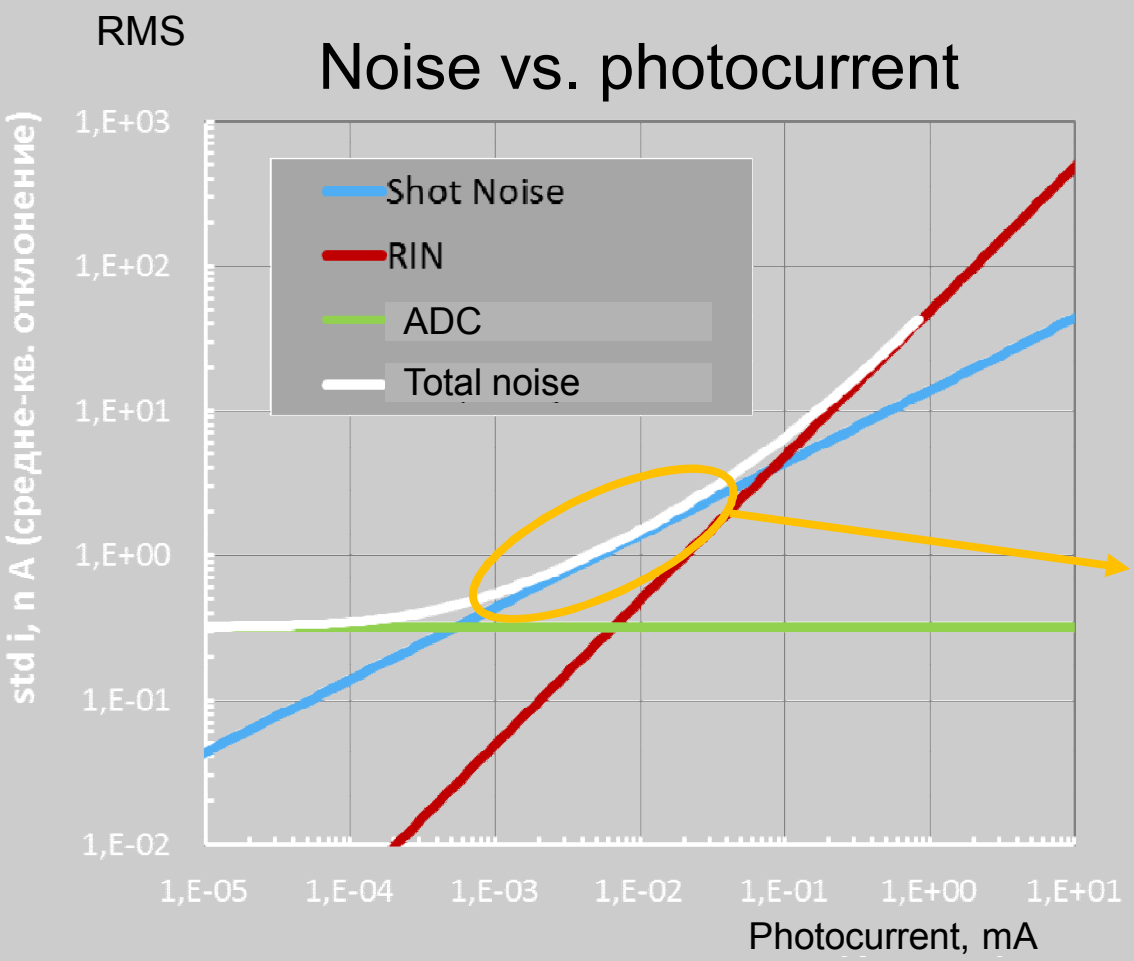
One of few examples: THIS



9-12 μm
QCL laser as LO
open diplexer
MCT mixer
1 GHz acousto-optical IF analyzer



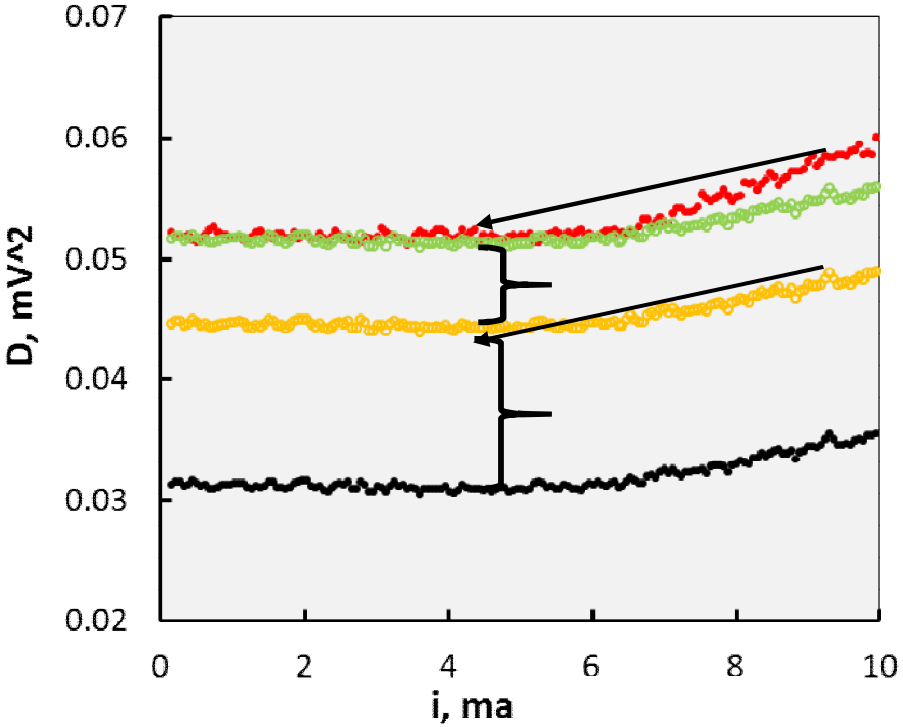
New concept: TDLS as LO, no IF fiber coupler as a diplexer



There is an optimal area where shot noise dominates
Corresponding LO power ~ 2-20 μW

Homodyne noise:

First detection of beating between nearby components of the broadband signal [Forreter *1961*]



- Experiment, LO
- Experiment, LO+signal
- Model, homodyne noise
- Model, shot noise

Homodyne noise contribution $D_{HOM} = i^2 \frac{BR^2}{2\Delta w}$

Shot noise contribution $D_{SN} = ieBR^2$

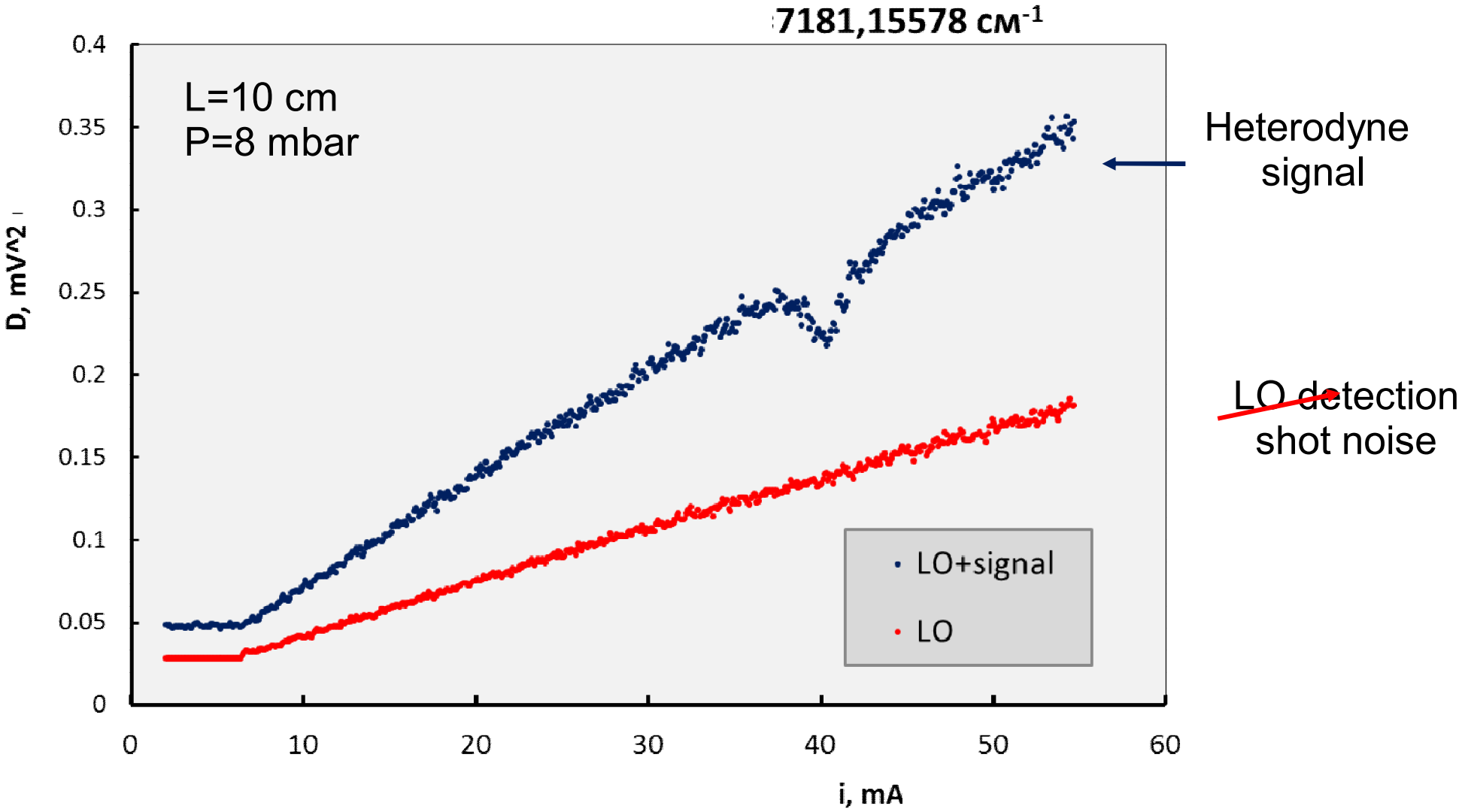
Δw - broadband spectrum FWHM

$$\frac{D_{HOM}}{D_{SN}} \sim \frac{e}{G}$$

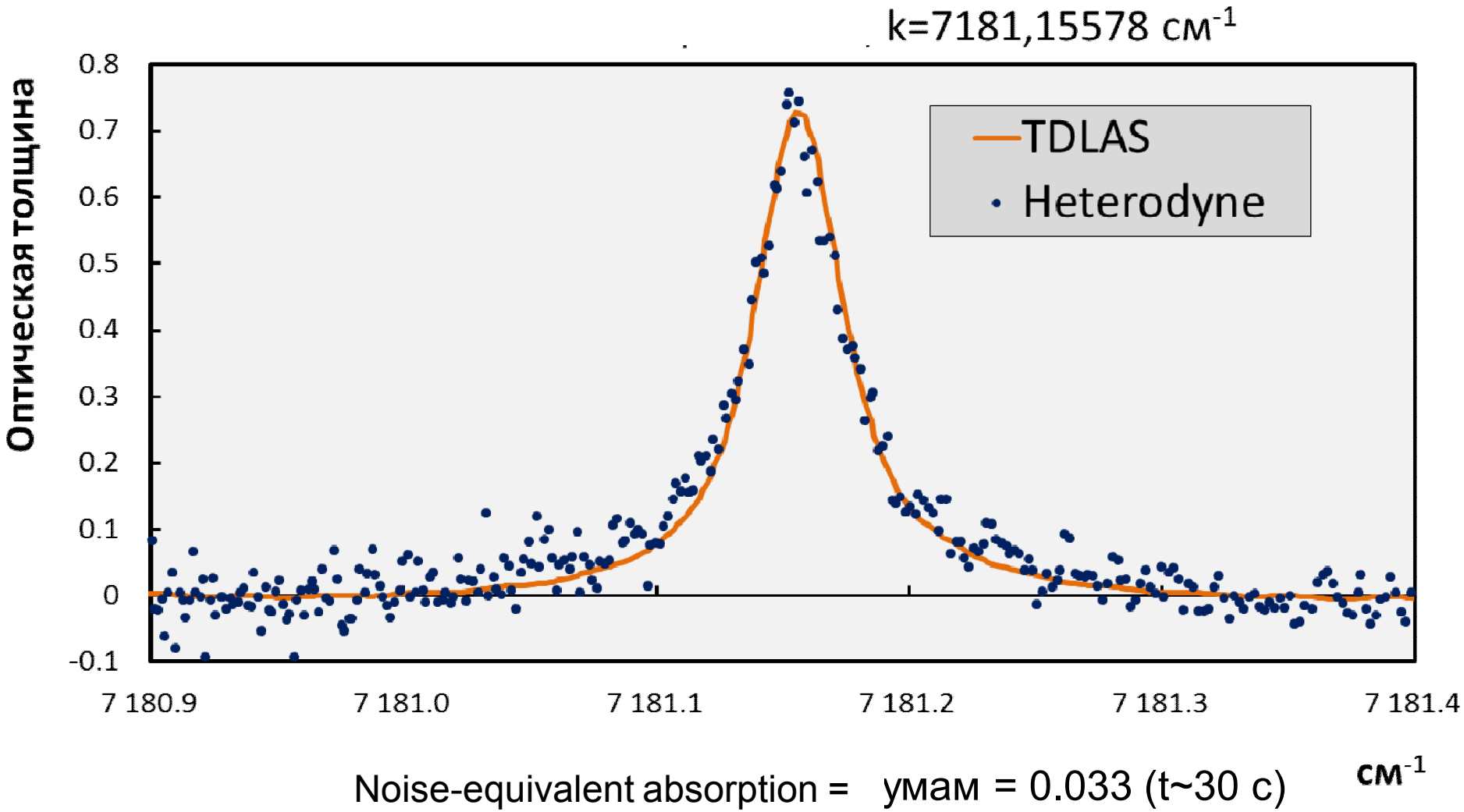
G – radiation spectral density

One needs to account for homodyne noise while doing high resolution spectroscopy!

Laboratory measurement of H_2O absorption line

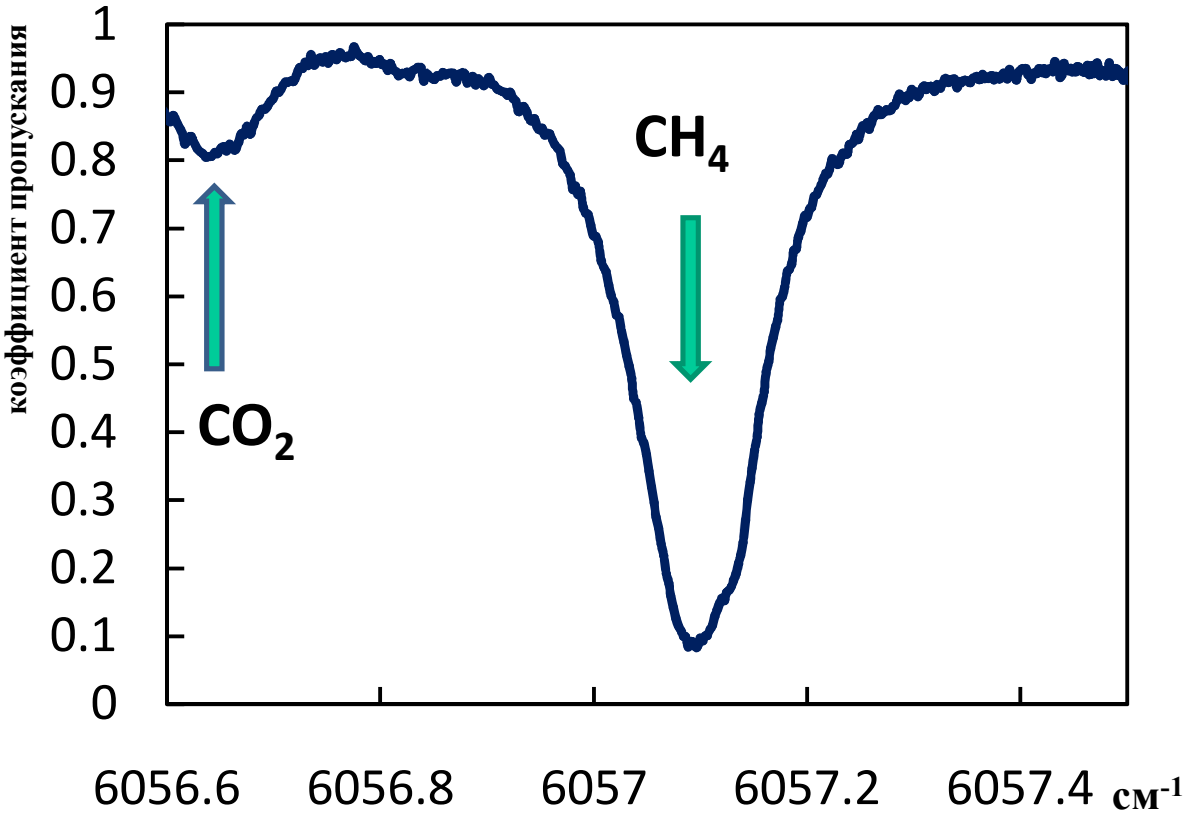


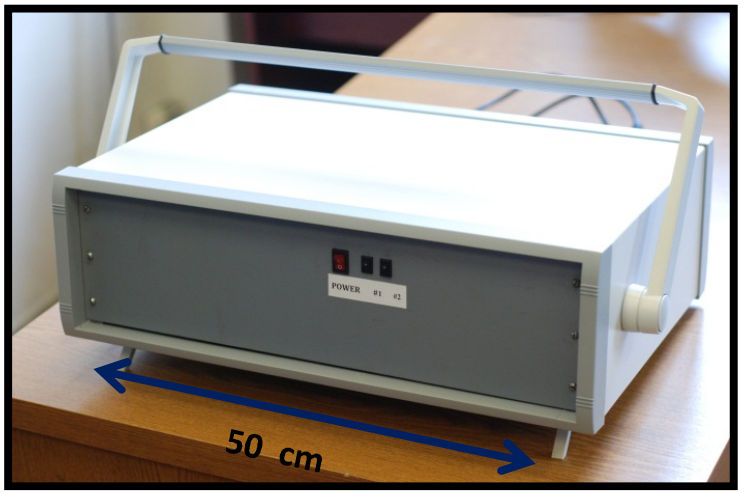
Heterodyne vs. TDLAS



Noise-equivalent absorption = умам = 0.033 (t~30 c)

NIR transmission of the Earth atmosphere: for the first time with ultra-high resolution!



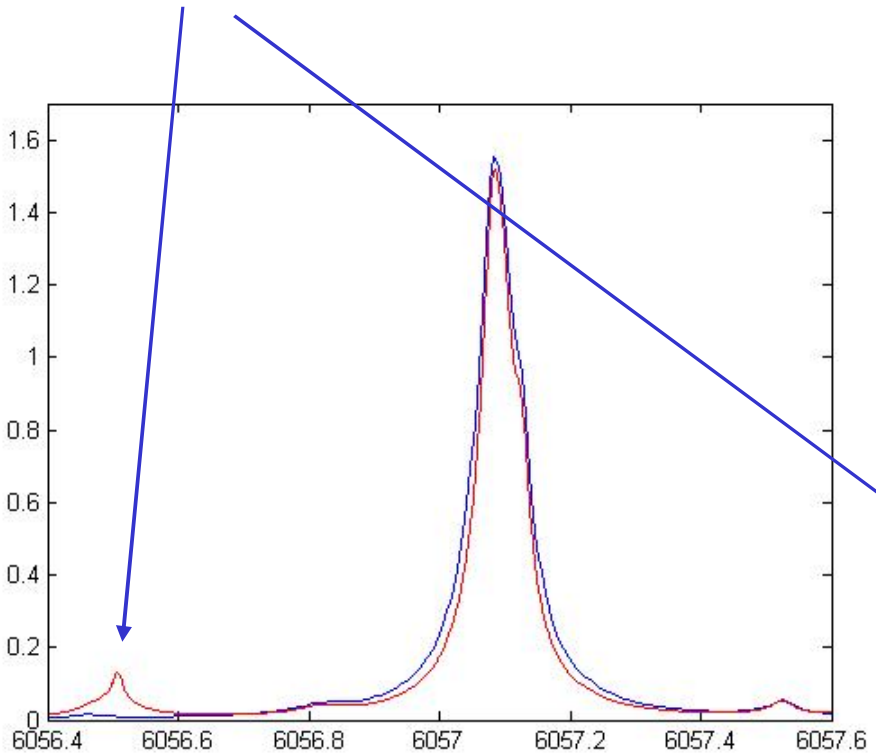


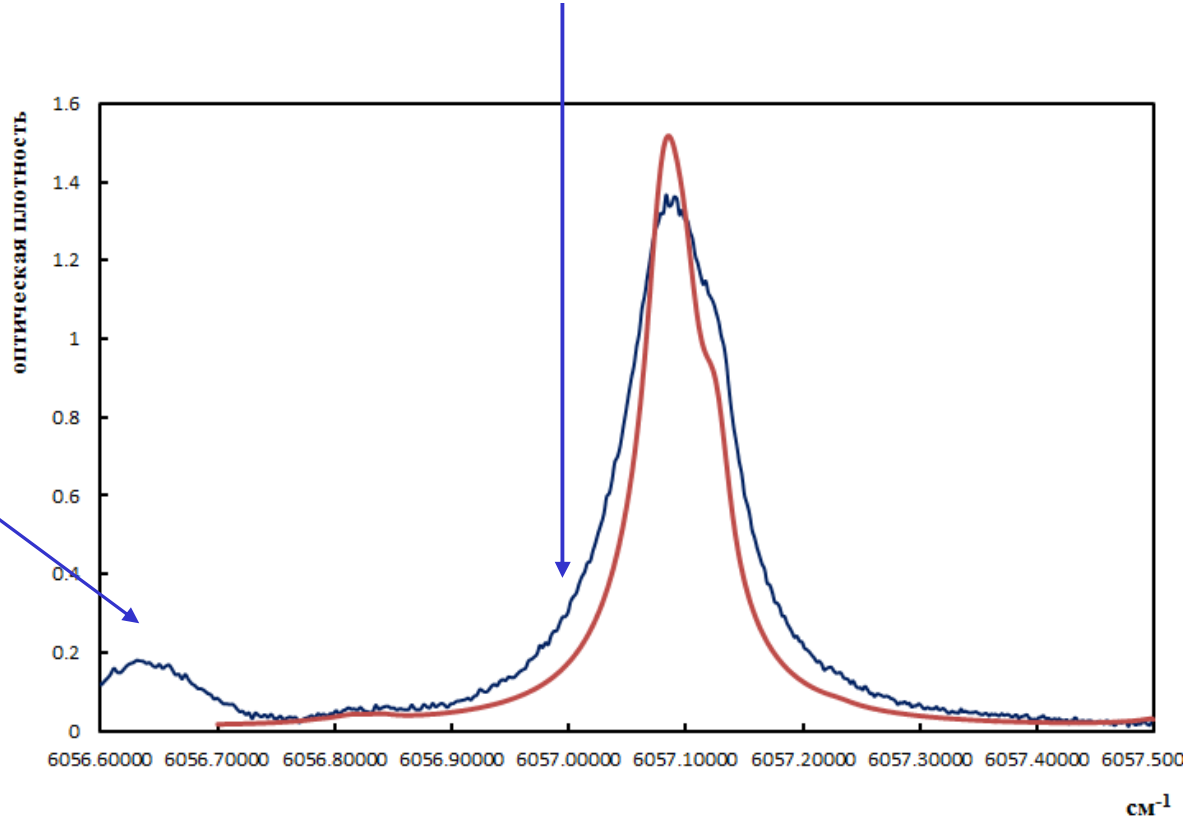
Exposure – 10 min.
S/N ratio ~300
CH4/CO2 retrievals error ~10^{-3}
Spectral resolution ~10^{8}
Mass ~ 3 kg

Transmission of the Earth atmosphere: experiment vs. synthetic spectra

Line profile reflects shallow distribution of CO_2

Incorrect broadening parameterization?
Or just shallow distribution?





LBLRTM

our calculations

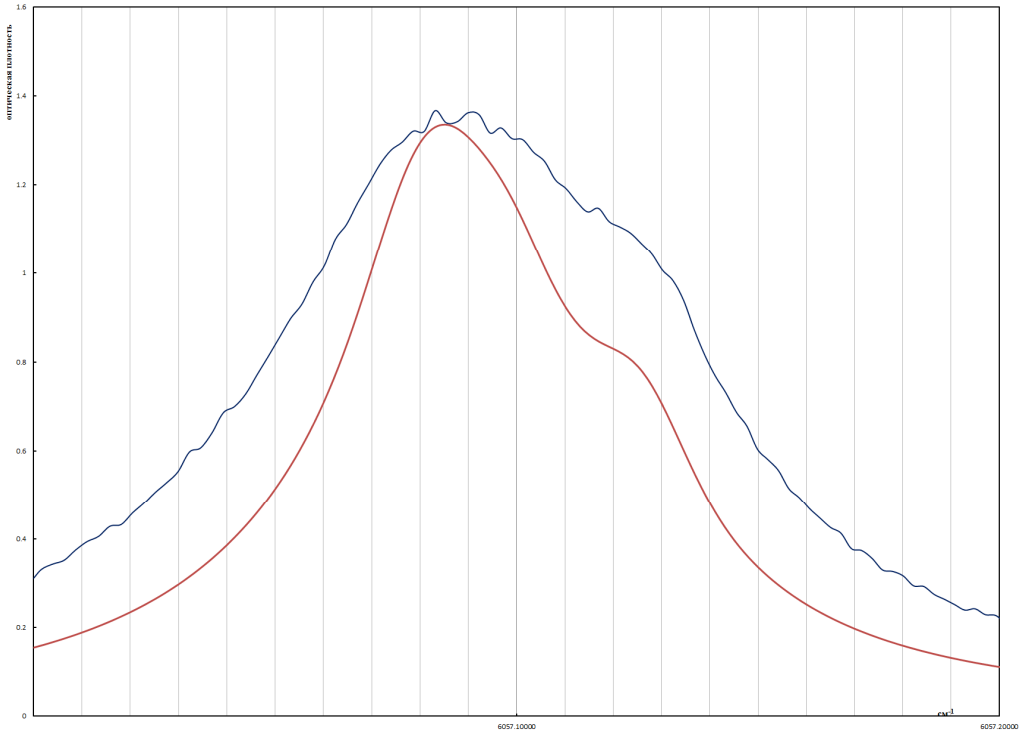
our calculations

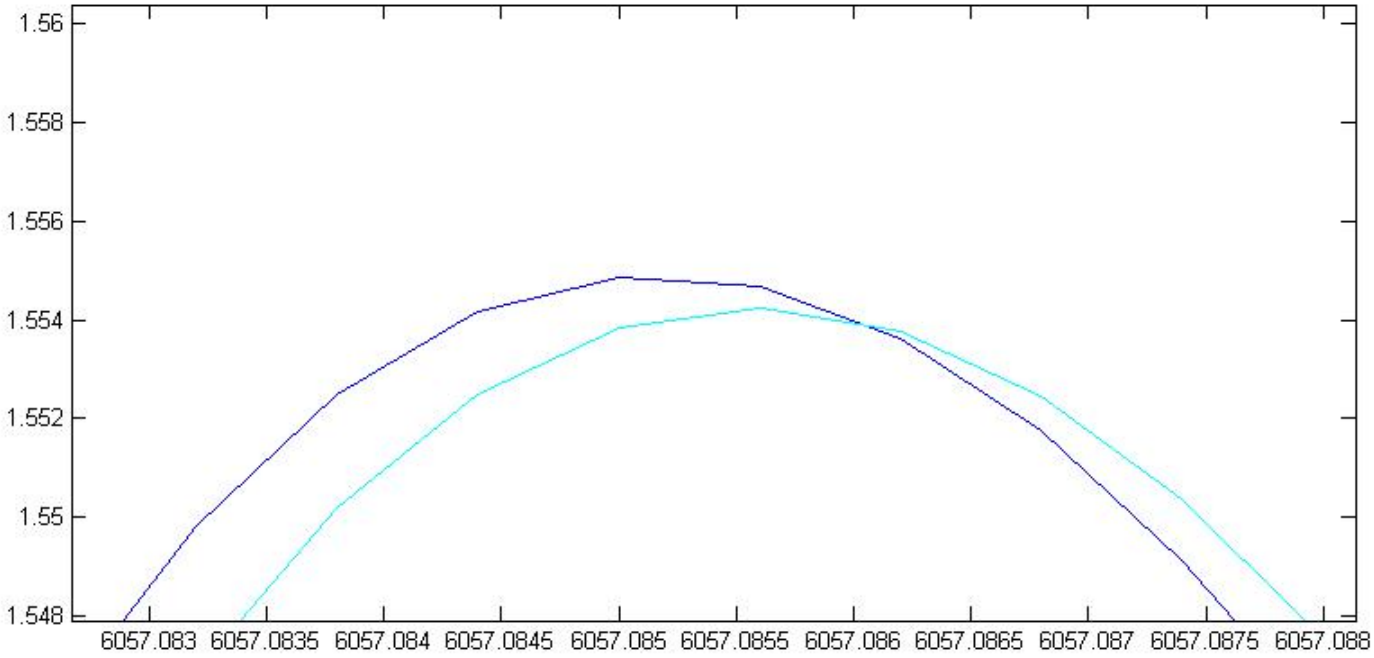
experiment

Search for Doppler wind markers

our calculations

experiment



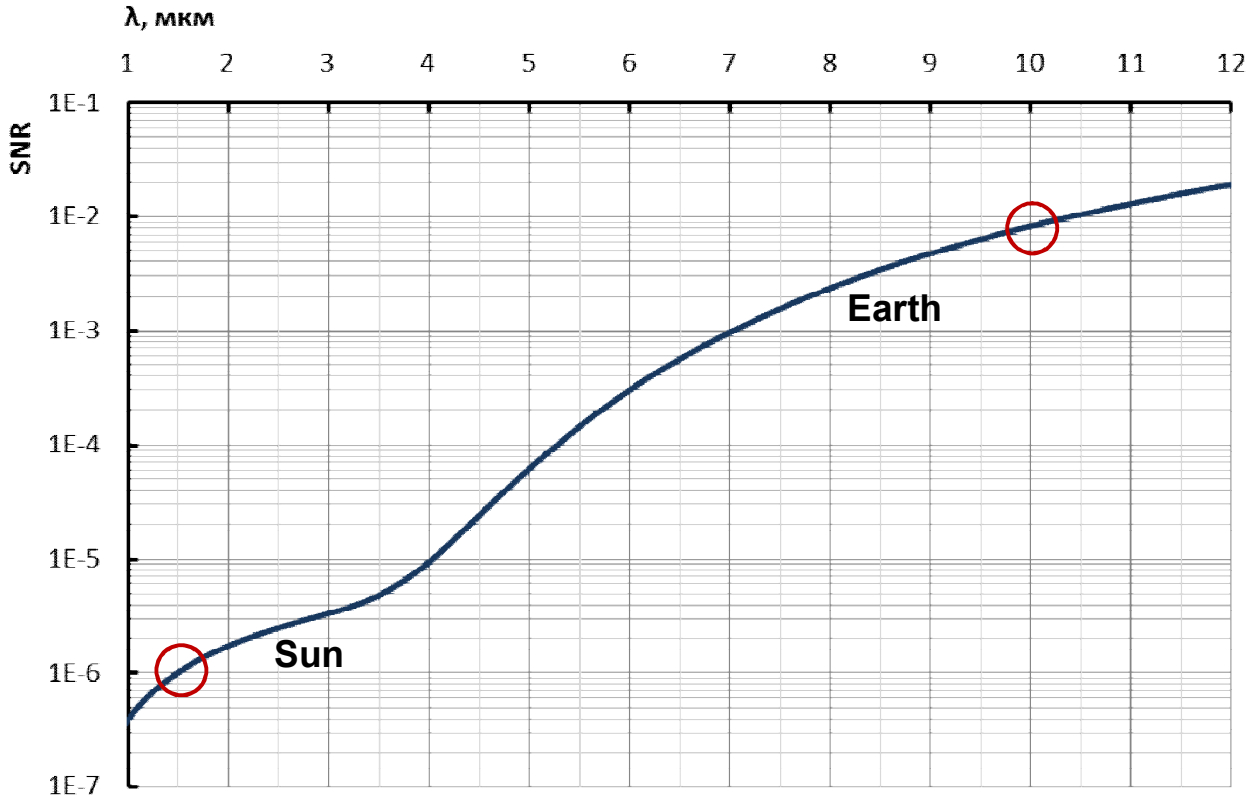


no wind

80 m/s
in the stratosphere

Why near infrared is bad for heterodyning

S/N ratio for nadir observations:



Black body: $$I(\lambda) = \frac{2hc}{\lambda^3 exp\frac{hc}{\lambda kT} - 1}$$

Signal:
$$S(\lambda) = {}^{1}/_{2}\, I(\lambda)\lambda^2 = \frac{hc}{\lambda exp\frac{hc}{\lambda kT} - 1}$$

Noise: $$N(\lambda) = h\frac{c}{\lambda}$$

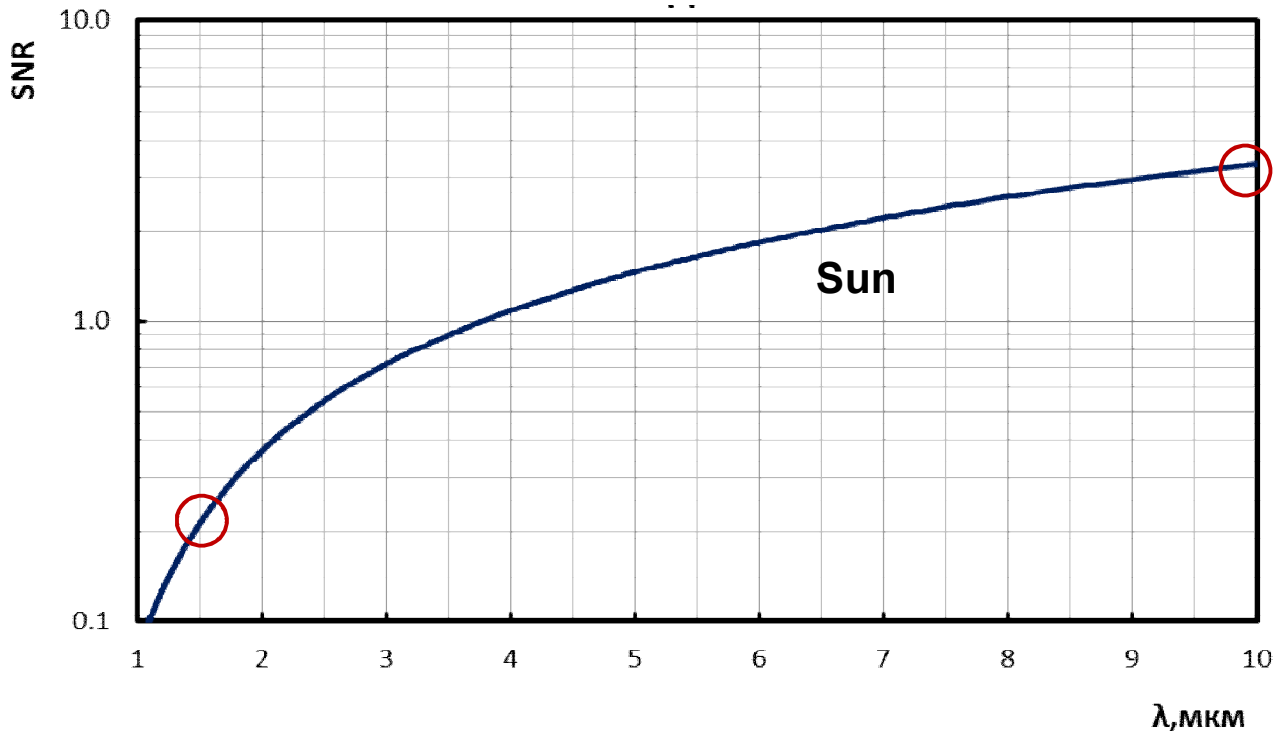
S/N: $$SNR = \frac{1}{exp\frac{hc}{\lambda kT} - 1}$$

$$\frac{SNR_{10\mu}}{SNR_{1,5\mu}} \sim 6700$$

Only mid-infrared is suitable for astronomical observations

Or not so bad?

S/N ratio for solar occultations



$$\frac{SNR_{10\mu}}{SNR_{1,5\mu}} \sim 15$$

NIR is suitable for in situ or in-orbit solar occultations due to simplicity of the instrument

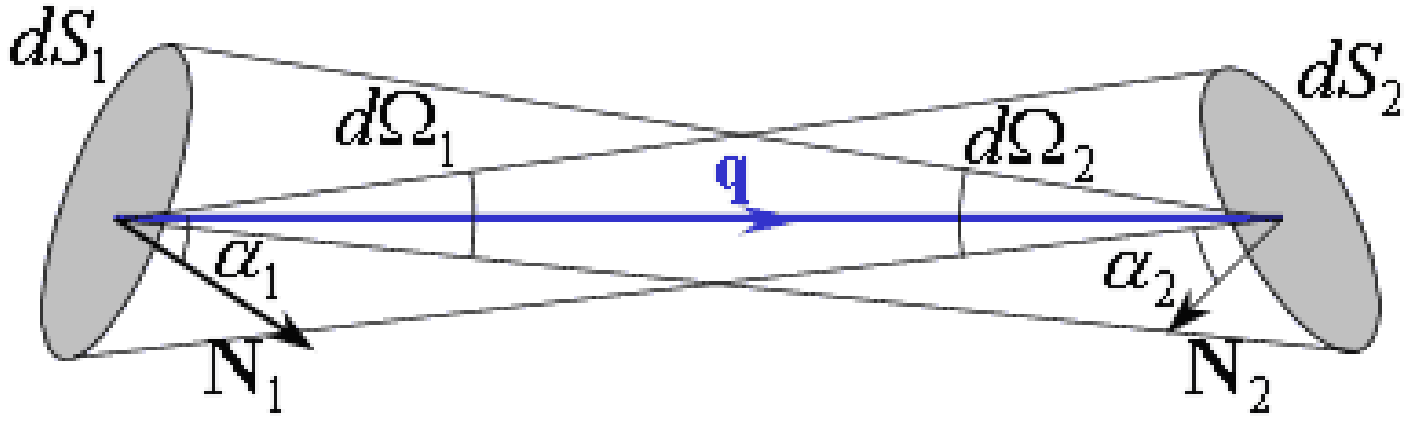
Future developments

(i) Aperture-efficient entrance optics

(ii) MIR replacement for fibers

(ii) Detectors with ultimate performance

FOV allowed by heterodyne systems do not match observation goals:



$$\Omega_1 S_1 = \Omega_2 S_2$$

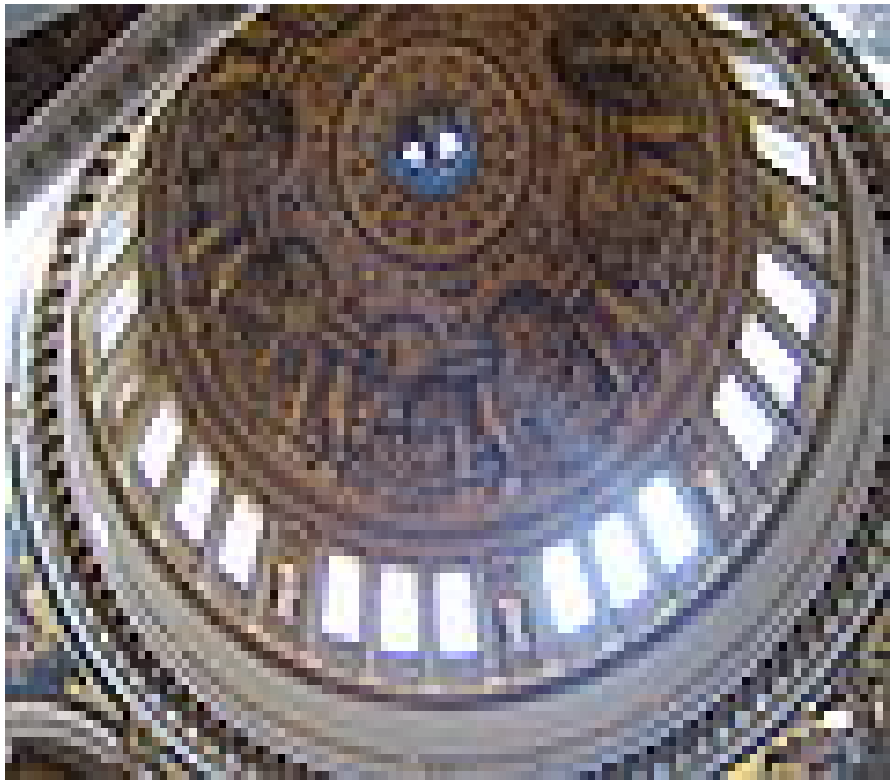
- SPICAV: d=30 mm, field of view 1 °
- IRTF: d=3 m, field of view 118”

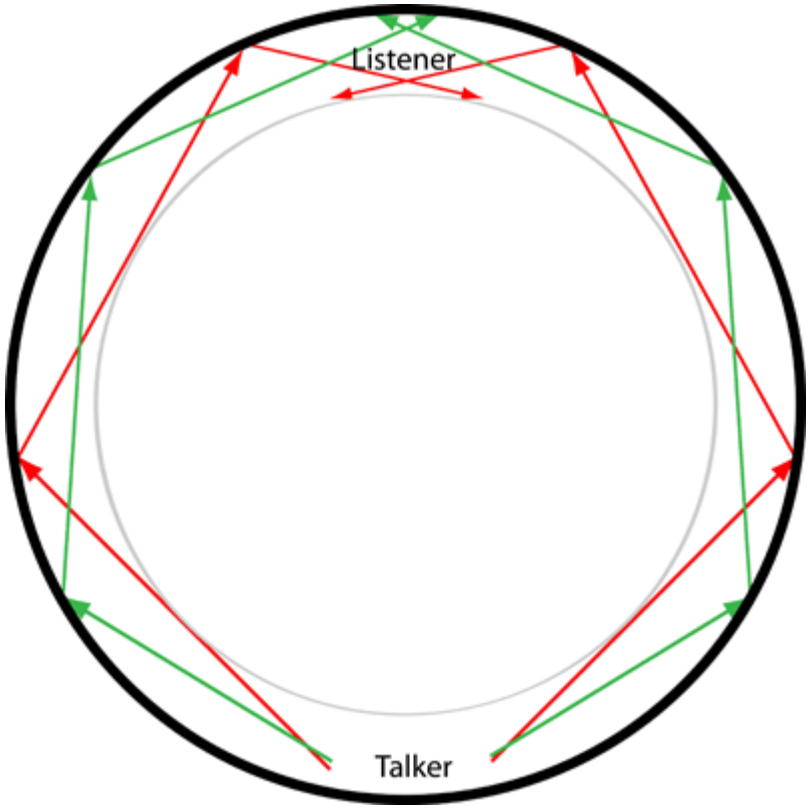
Due to small aperture of single mode optical fiber ($\Omega * S \sim 10^{-7}$ $sm^2 * ster$) => available signal is too weak

However single mode fiber implements theoretical limit for heterodyning $\Omega * S \approx \lambda^2$

Can we overcome it?

Whispering gallery mode





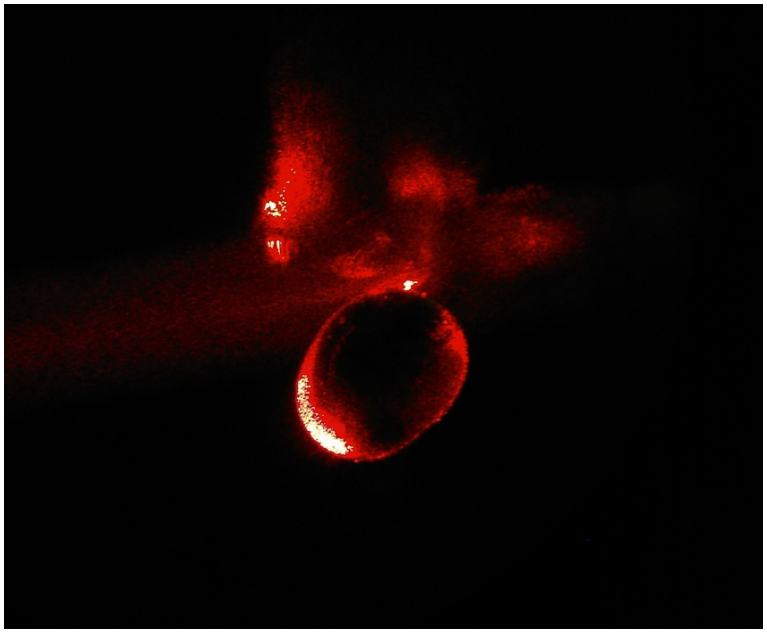
Nature 108, 42-42 (08 September **1921**) | doi:10.1038/108042a0

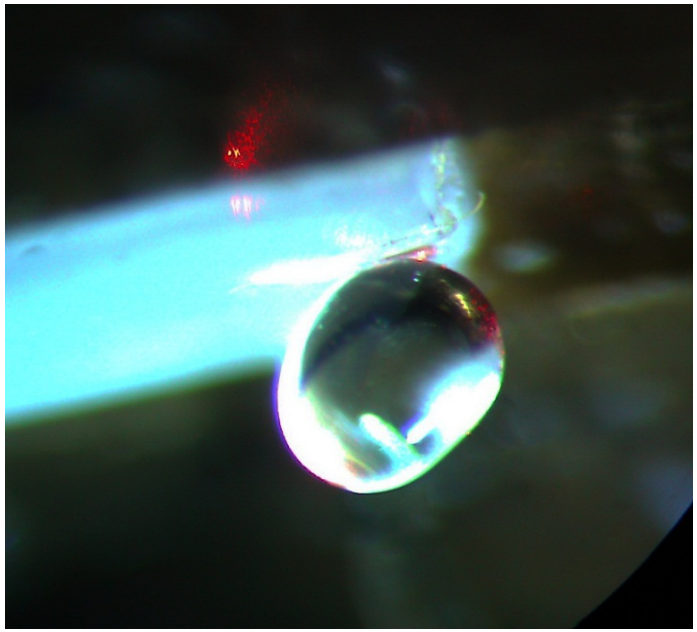
Whispering-Gallery Phenomena at St. Paul's Cathedral

C. V. RAMAN & G. A. SUTHERLAND

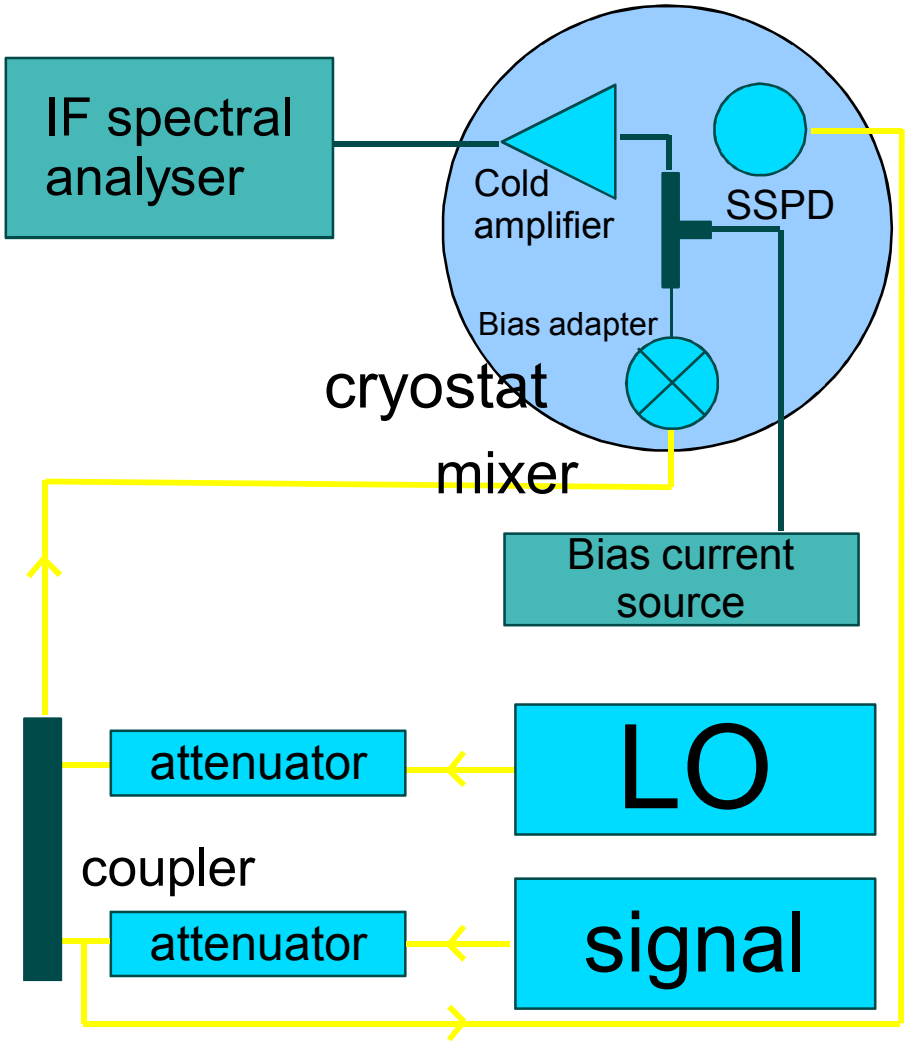
“Whispering-gallery mode” resonators

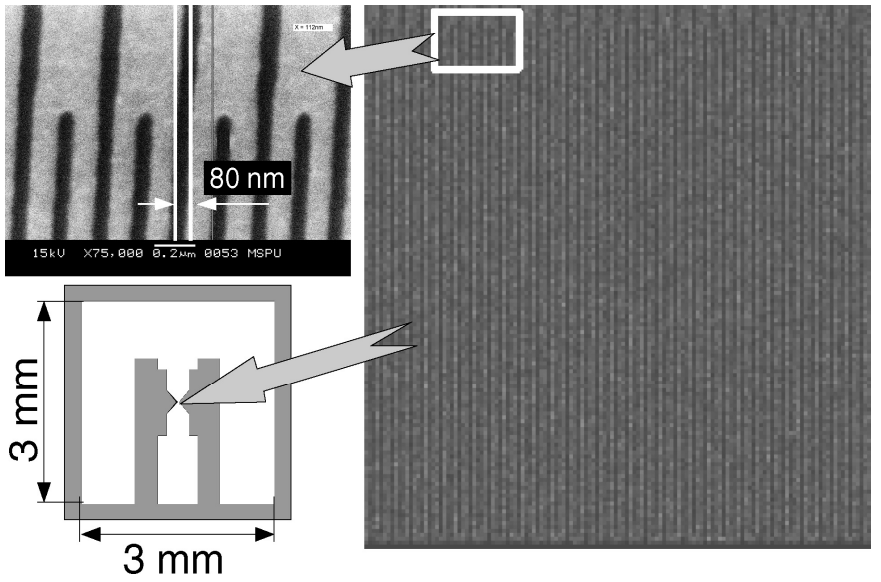
- **Resonators** – microspheres, discs , tori
- Extremely high Q-factor (10^6 - 10^9)
- Exited WGMs emit from the equator
- For resonators with integrable shapes the emission is isotropic

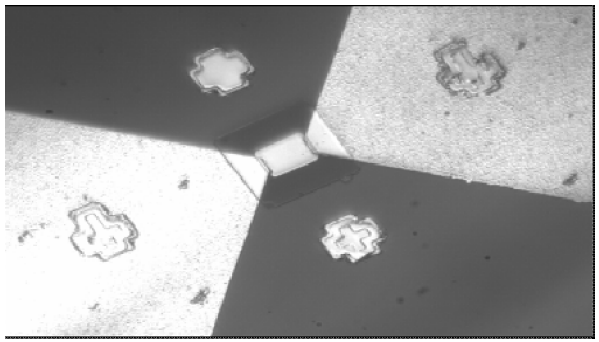




Hot electron bolometer as an IR mixer

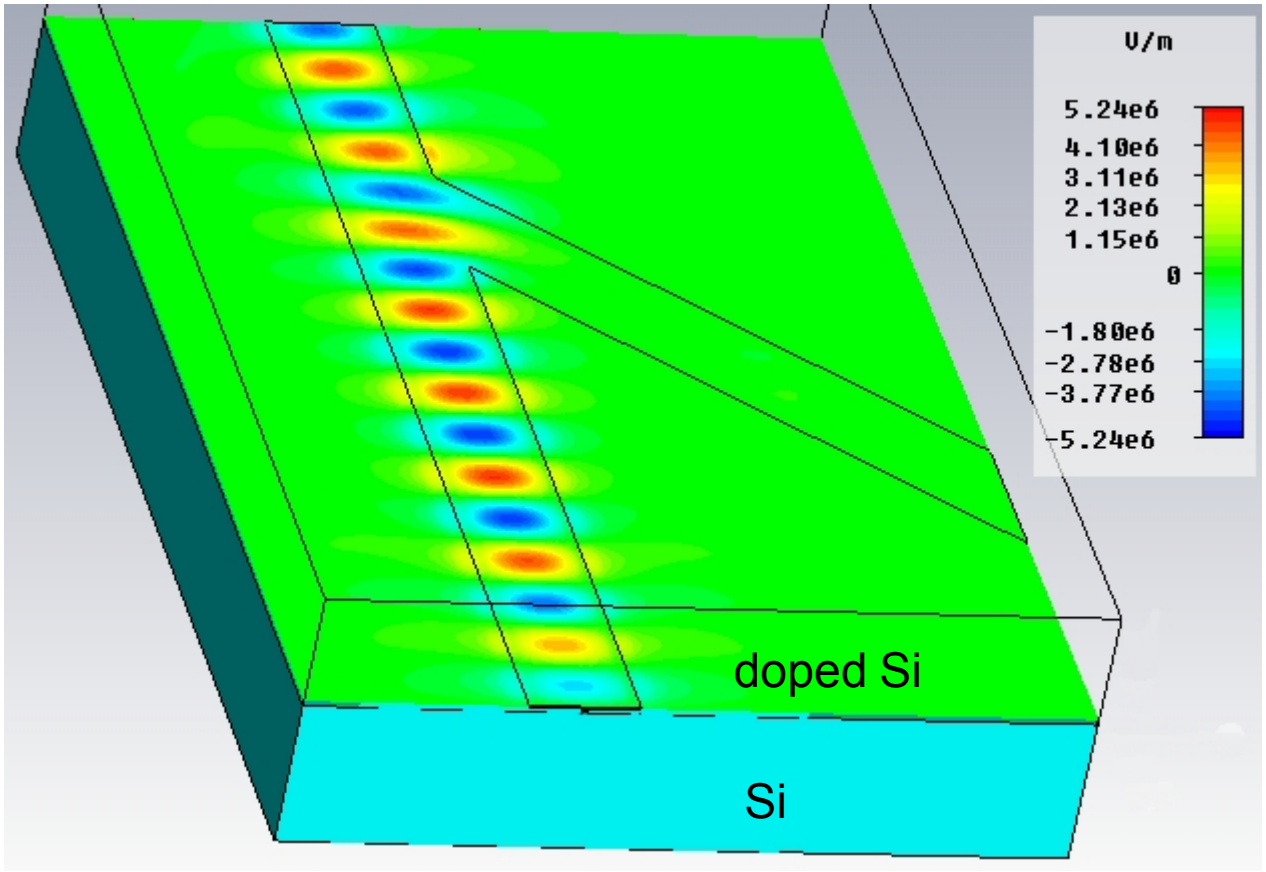






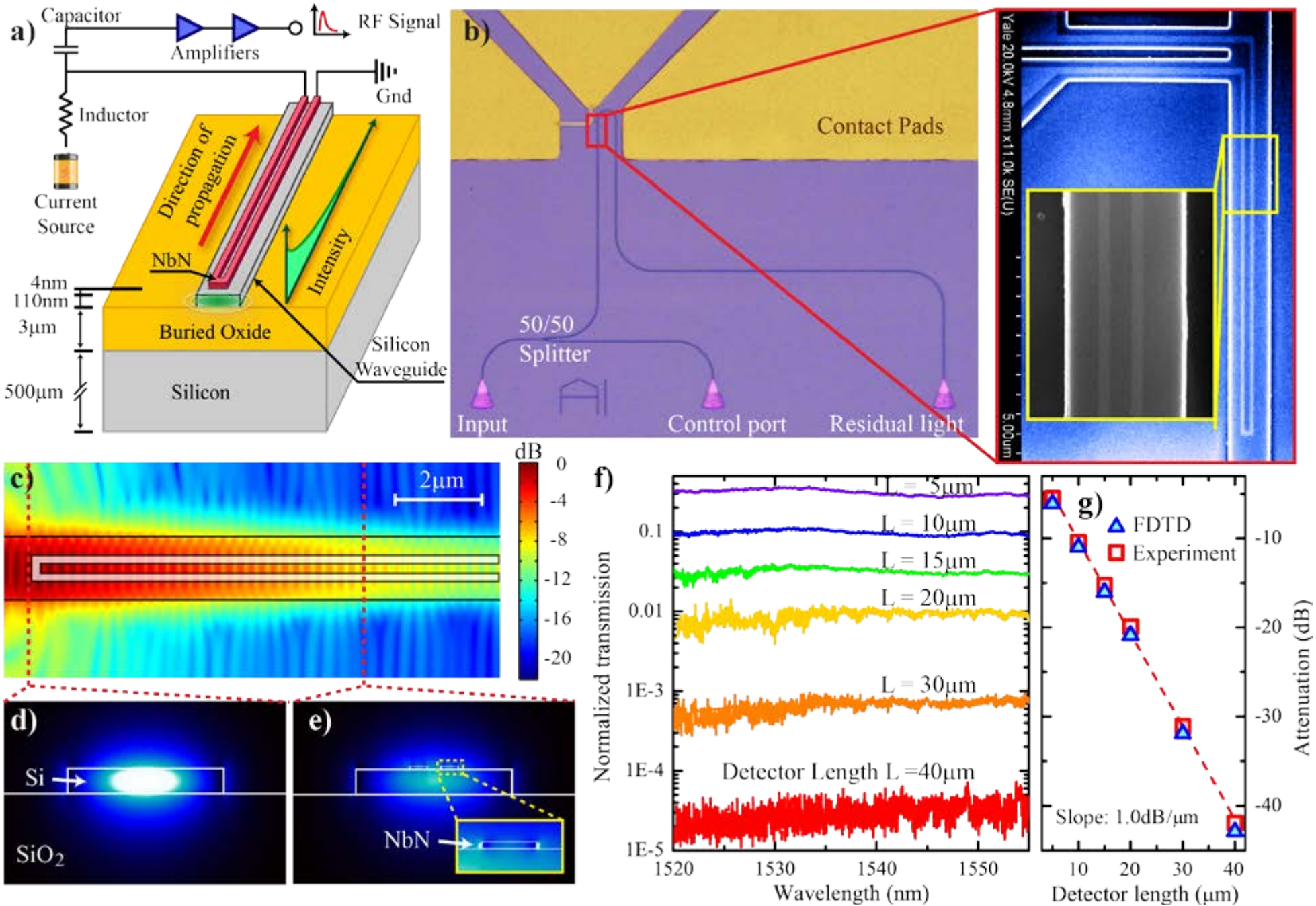
IF range 0.1 – 5 GHz

Possible design for asymmetric single mode coupler



HEB-based SSPD detector integrated with on-chip waveguide system

(Pernice *et al.*, 2012)



Summary

A simple, compact high resolution heterodyne spectrometer based on tunable DFB laser and single mode optical fiber has been elaborated. The instrument may be used for atmospheric studies using Sun observations both from the orbit and planet's surface

Astronomical observations require moving to mid infrared using integrated waveguide optics and QCL lasers as LO

Near field photonic solutions may significantly improve the instrument performance and make it fit for spacecraft applications

Thank you!