Heterodyne Technology for future SOFIA Instruments

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Heterodyne Spectroscopy with SOFIA

Important tool to study physical properties over a wide range of sources:

- Detailed studies of localized sources
  - multi-line studies
  - line detection experiments
  - absorption lines
    → spectral mapping: few pixels, many frequencies

- Mapping of strong lines in extended sources
  - gas kinematics
  - 3D structure
    → spatial mapping: many pixels, few frequencies

Canonical lines of interest:
- [NII]: 1461 GHz (205 μm)
- [CII]: 1900 GHz (158 μm)
- [OI]: 2060 GHz (145 μm)
- [OI]: 4745 GHz (63 μm)
Spectral Mapping: current Status

• Mixer bandwidth is limited
  - many mixers needed for full spectral coverage
  - optical pre-separation of bands may be complex

Example 4GREAT: two dichroic mirrors ($D_{13}$, $D_{24}$) and one wiregrid polarizer (WG) to separate 4 bands

Durán+ 2020, submitted
Spectral Mapping: possible new approaches

- Grating or grism as “predisperser”
  - disperse signal to $N$ individual mixer bands
  - allows observing $N$ lines simultaneously
  - may achieve continuous spectral coverage (however not instantaneous!) with a manageable number of conventional mixer channels
  - requires dedicated local oscillator source for each band
  - opto-mechanically challenging
  - S/N will vary strongly between bands
Spectral Mapping: possible new approaches

- **Dedicated spectral mapper (RF filter bank)**
  - frequency comb LO feeds array of mixers spectrally spaced by their IF bandwidth
  - instantaneous continuous frequency coverage
  - requires mixers with large IF bandwidth (not HEB)

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Groppi+ 2019
Mixer Technology

• **SIS (superconductor-isolator-superconductor) tunnel junctions**: work horse at $f < 1$ THz
  - limited RF frequency, but large IF bandwidth

• **HEB (hot electron bolometer)**: work horse at $f > 1$ THz
  - unlimited RF frequency, but limited IF bandwidth

• **Photomixing detectors** (room temperature!)

• **Graphene bolometers**

Wang+ 2019

Lara-Avila+ 2019
Spatial Mapping: pixels, pixels, pixels!

Limitations to array size:

- **Telescope:**
  - Field of view
  - Instrument mass (600 kg; upGREAT weighs 595 kg)

- **Aircraft:**
  - Electrical power

- **Operating efficiency**
  - Tuning overhead

- **Technology, complexity, money, ...**
  - Optimistic price tag: 25,000 US-$ / pixel
Field of View

- SOFIA's FOV is 8 arcmin $\varnothing$, 50 arcmin$^2$
- Beam FWHM is $\sim0.1$ arcsec $\times \lambda / \mu$m
- Minimum beam spacing in heterodyne system is $\sim2 \times$ FWHM

$\rightarrow$ each beam occupies $\geq0.04$ arcsec$^2 \times (\lambda / \mu$m$)^2$

$\rightarrow$ SOFIA's focal plane accommodates

$\leq 4.5 \times 10^6 / (\lambda / \mu$m$)^2$ heterodyne pixels

- Canonical lines of interest:
  - [NII]: 107 pixels
  - [CII]: 180 pixels
  - [OI$_{145}$]: 214 pixels
  - [OI$_{63}$]: 1133 pixels
  - dual polarization: take any TWO of the above
Pixel-# @1.9 THz

up to 163 pixels possible

technical reasons (LO-distribution, manufacturing) may limit to 100 or even 64 pixels
Size comparison: N159

3.25 h GREAT observing time
~15 sec / point

Okada et al. 2014
Size comparison: N159

3.25 h GREAT observing time
~15 sec / point
64 pixel array requires ~25 pointings for Nyquist sampling
⇒ 6 min plus overhead (typically ~15 min)

Okada et al. 2014
Heterodyne Array Components

- high per pixel cost, weight and complexity → need to be efficient!
- optics (mostly) and cryogenics same as for single pixel
- IF-processing/backends: every component needs to be multiplied!
- mixers and LO coupling: highest concentration of critical components and no space available...
Mixer Focal Plane: sizes and reimaging

- Pixel size in telescope focal plane $\sim 50\lambda$
  - 8.3 mm @ 1.9 THz
  - 3.3 mm @ 4.7 THz

- "natural" optical pixel size $\leq 6\lambda$
  - 1.0 mm @ 1.9 THz
  - 0.4 mm @ 4.7 THz

- "natural" mechanical pixel size: $\sim 10$ mm (IF-connector)

- Reimaging required (pixels individually, whole array)

- Possible approaches:
  - open structure mixers: very tight tolerances!
  - waveguide mixers: difficult machining
Focal Plane Unit

- **individual mixer approach** (upGREAT) not attractive for large array
- **multi-mixer blocks** (e.g. SuperCam, CHAI)
- **fully integrated focal plane?**
Focal Plane Unit

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Local Oscillators

- Each mixer requires a local oscillator signal to mix with the sky signal
- Substantial amount of local oscillator power is needed
- Sources of choice:
  - $\leq 2$THz: multiplied microwave sources
  - $\geq 2$THz: quantum cascade lasers
- The LO power needs to be distributed to the individual mixers
LO Distribution I: Fourier Grating

- Reflective phase grating as LO multiplexer

- elegant and simple
- good efficiency (~90%)
- power balancing is challenging

upGREAT's 7-beam Fourier grating
Risacher+ 2018

81-beam Fourier grating
Gan+ 2019
LO distribution II: Multi-pixel Multiplier Chain

1.9 THz

Goldsmith 2014

Siles+ 2017

x8 Active Frequency Multiplier (AMC)

GaN Power Amplifier (PA)

210-230 GHz Triplers

630-690 GHz Triplers

1.89-2.06 THz Triplers

16-Pixel Integrated Horns

L 18 cm x W 12 cm x H 10 cm
Spectrometer Backend

- **Digital Fourier transform spectrometers:**
  - FPGA based
  - CMOS SoC

- **Bandwidth limitation**
  (250 km/s @ 63 μm)

- Traditionally mounted on telescope structure (CWR)
  → size & weight limit
  - make more compact and lighter
  - separate sampling (on telescope) and processing (in PI rack)
  - RF over fiber?

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*Zhang+ 2019*

*4-channel FFTS board*

*Klein+ 2019*

*CMOS SoC spectrometer*

*4-channel FFTS board*
Conclusion

- ~100 pixel array (possibly dual polarization) is challenging but feasible
- main areas of development:
  - mixer, feedhorn, optics
  - local oscillator
  - backends
  - system aspects: electronics, power consumption, tuning

Thank you