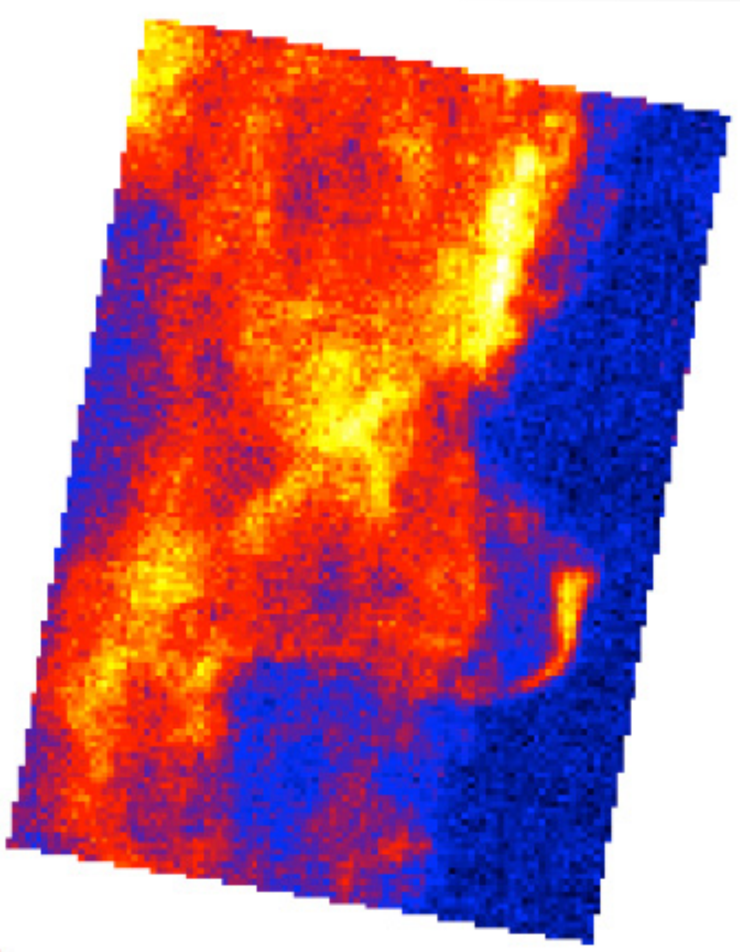
High Resolution Spectroscopy with GREAT



Horsehead Nebula in C^+ using upGREAT

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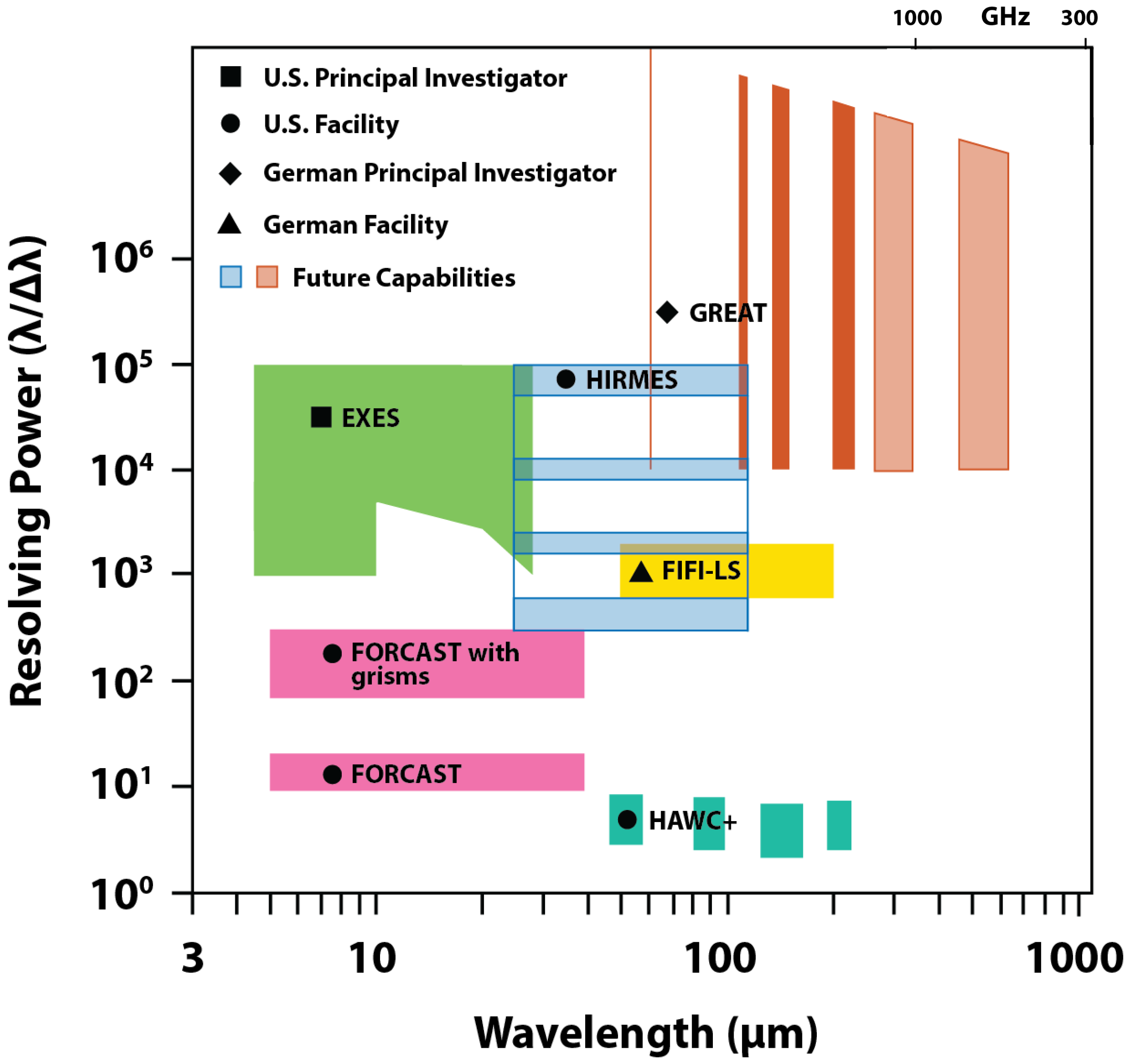
Outline

- Main concepts
- Science Examples
- Bands and configurations
- Preparing an observation
  - Exposure time
  - Atmosphere and Frequency tuning
  - Observing templates and Modes
  - Choosing the off position
- Maps
- GREAT vs HIFI and FIFI-LS

German REceiver for Astronomy at TeraHertz Frequencies

GREAT covers the far-IR to sub-mm wavelength range at high resolution.



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GREAT in a nutshell

PI: Rolf Güsten
Max Plank Institute for Radioastronomy, Bonn

- Heterodyne dual-receiver system
- R = 10-50 10^6, i.e. < 0.1 km/s
- Instantaneous usable band width: ~ 2GHz, but 0.9 for [OI] line
- Angular resolution: 6-50'' (14.1'' @ C^+)
- Simultaneous observations of lines in different detector bands

GREAT is a Principal Investigator Science Instrument (PSI).

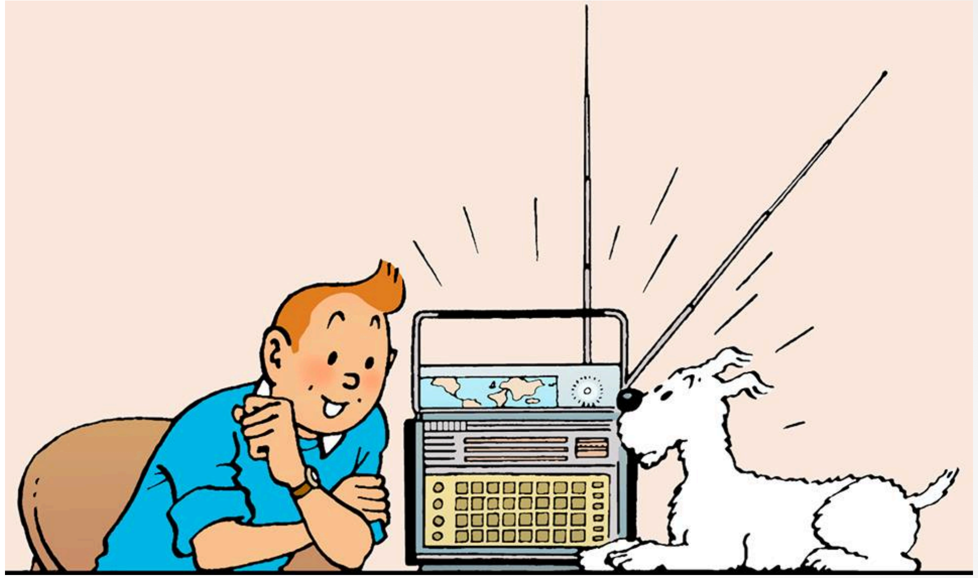
This means that:

- Guest Observers will receive calibrated data from the GREAT team
- The GREAT PI may designate up to 3 co-authors to your program

Heterodyne concept

The **GREAT** instrument lowers the input signal by mixing it with a local signal. This allows the amplification and detection of the signal.

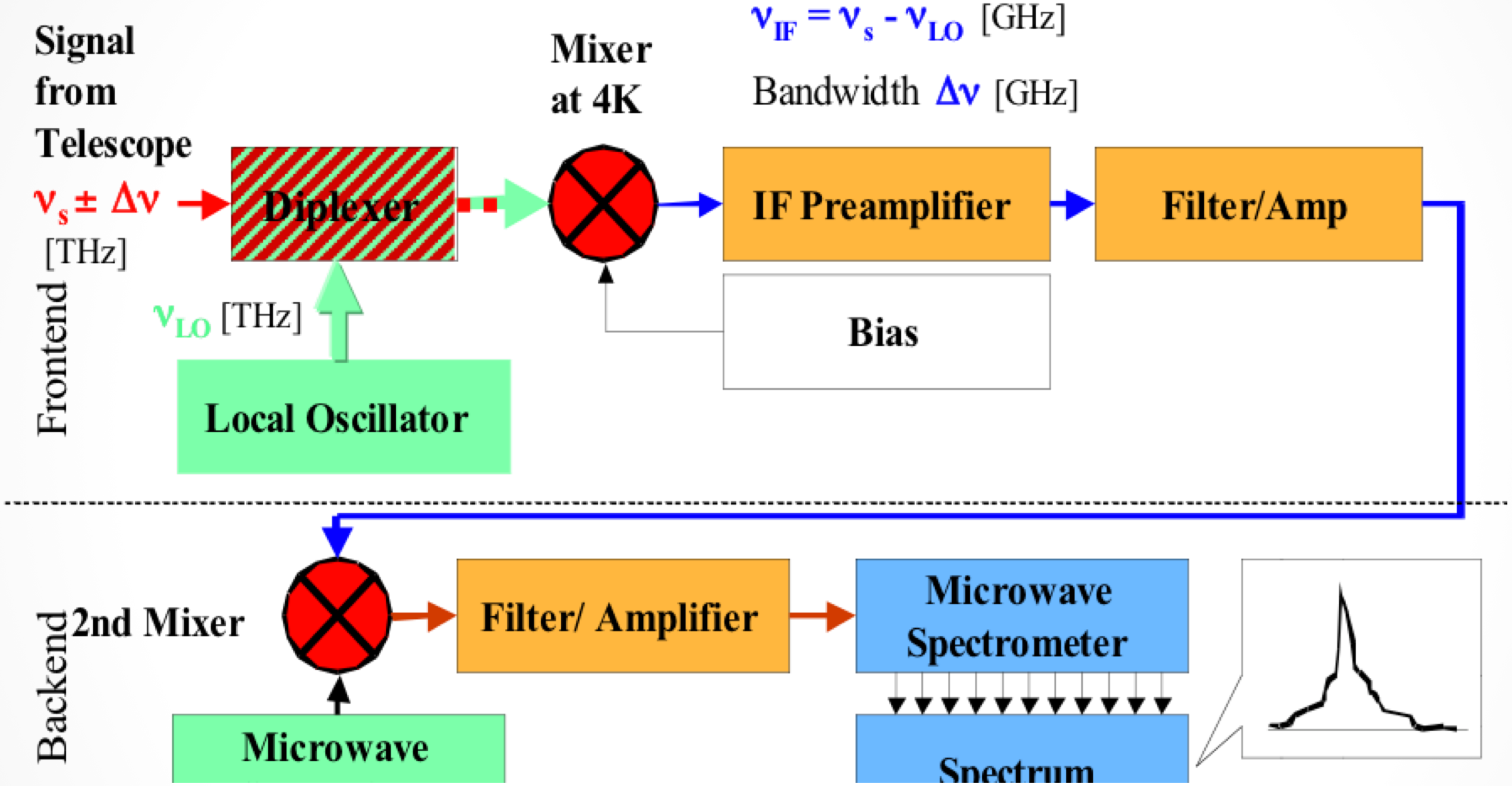
The sky signal (***RF***) is combined with that of a synthetic source (the ***Local Oscillator – LO***) tuned to a nearby frequency, in a non-linear electronic device (the ***mixer***).



This results in *beats*, i.e. pulses at a much lower frequency (the ***Intermediate Frequency – IF***), which have the same amplitude and phase of the original signal (*coherent detection*).

The process is called *down-conversion*, and it is used in many domestic devices such as radio, TV, etc.

A GREAT receiver channel



The second mixer is needed to match the operational frequencies of the first mixer to that of the microwave spectrometer.

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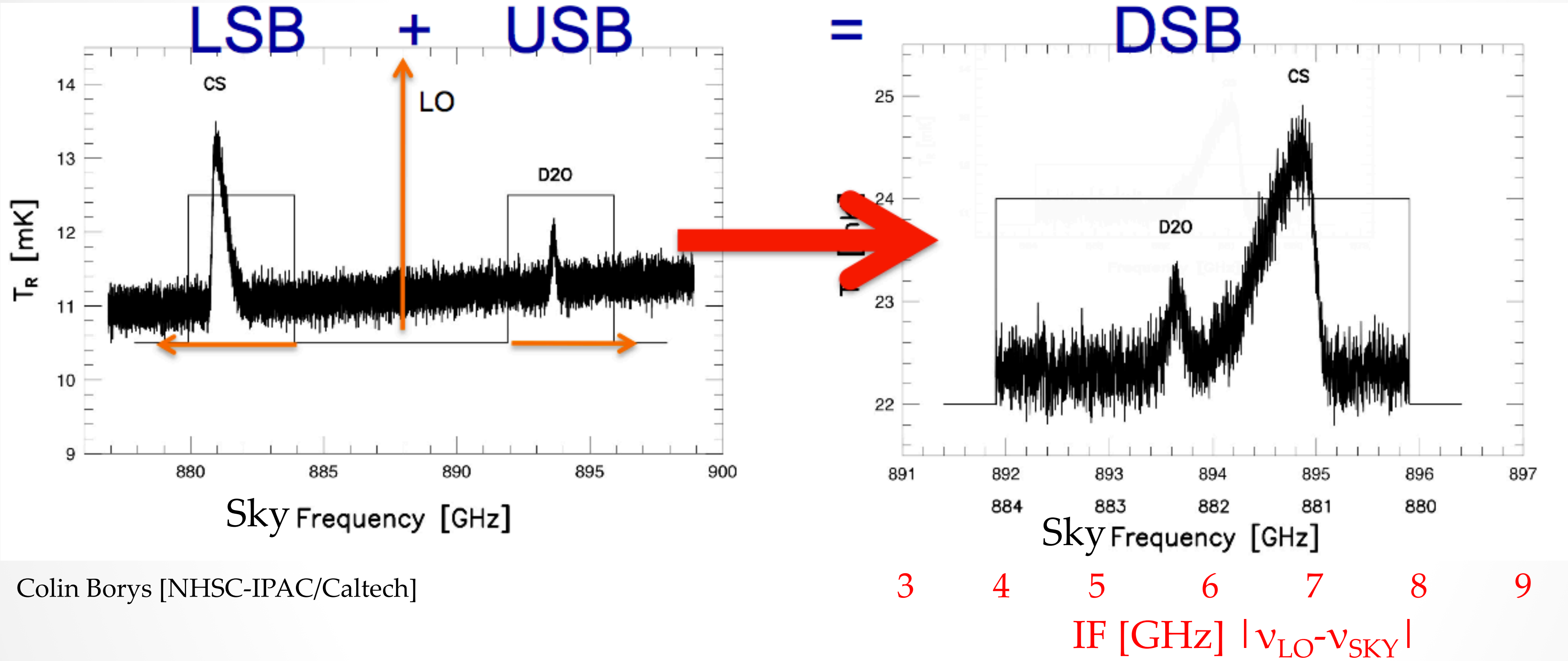
Dual Sideband Receiver



Colin Borys [NHSC-IPAC/Caltech]

When the local oscillator signal is mixed with the sky signal, the difference $|\nu_{LO}-\nu_{SKY}|$ (IF, Intermediate Frequency) is detected. The resulting signal is the combination of two bands symmetric to the LO frequency which is used to tune the observation.

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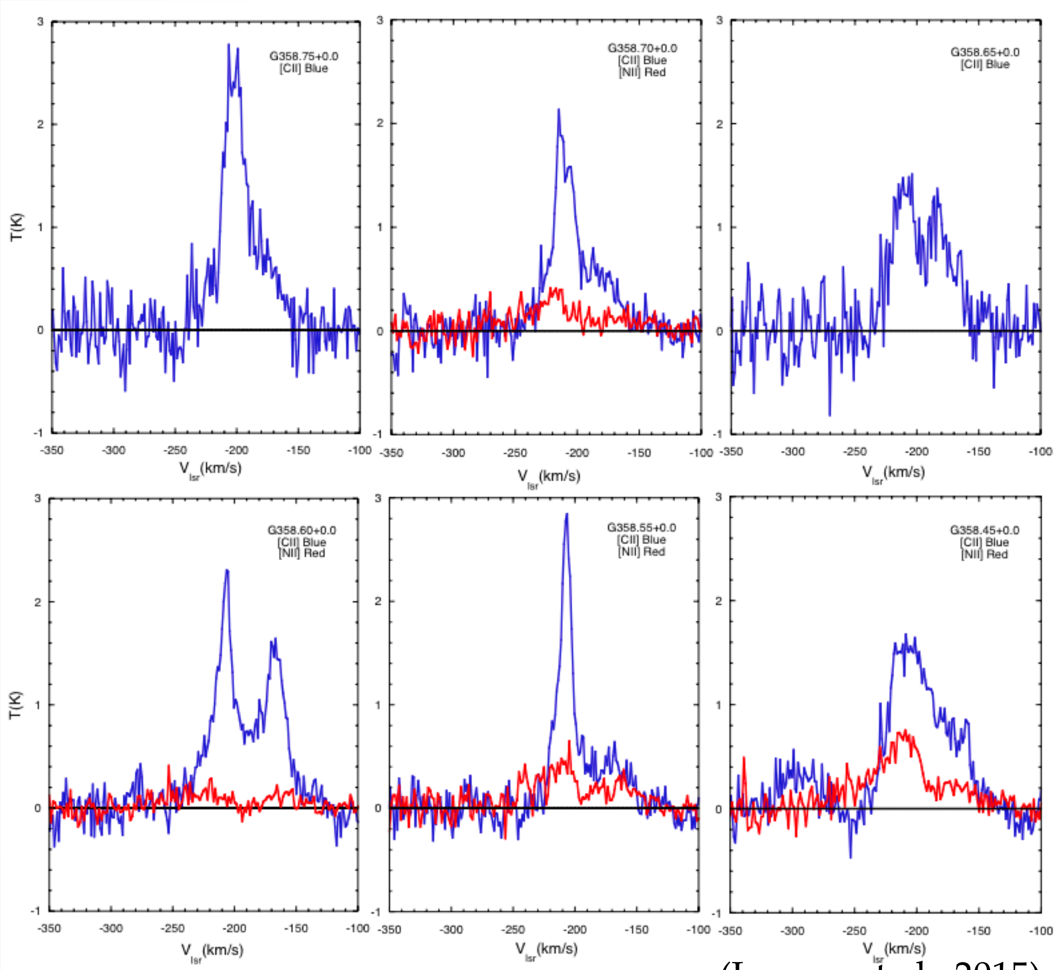
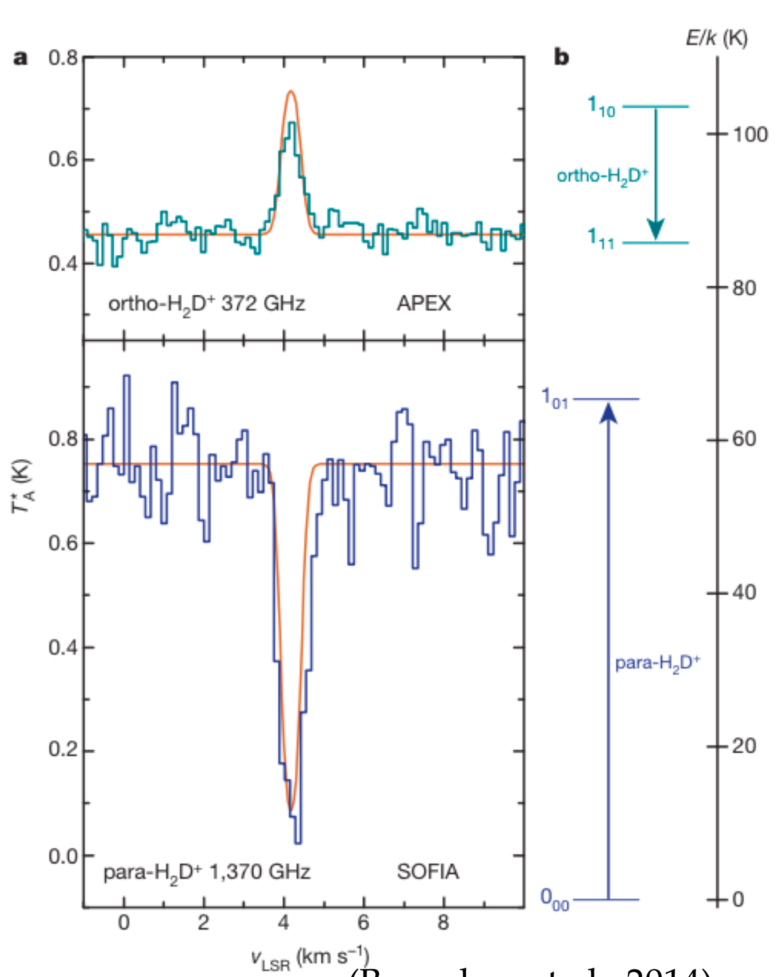
Science examples: lines



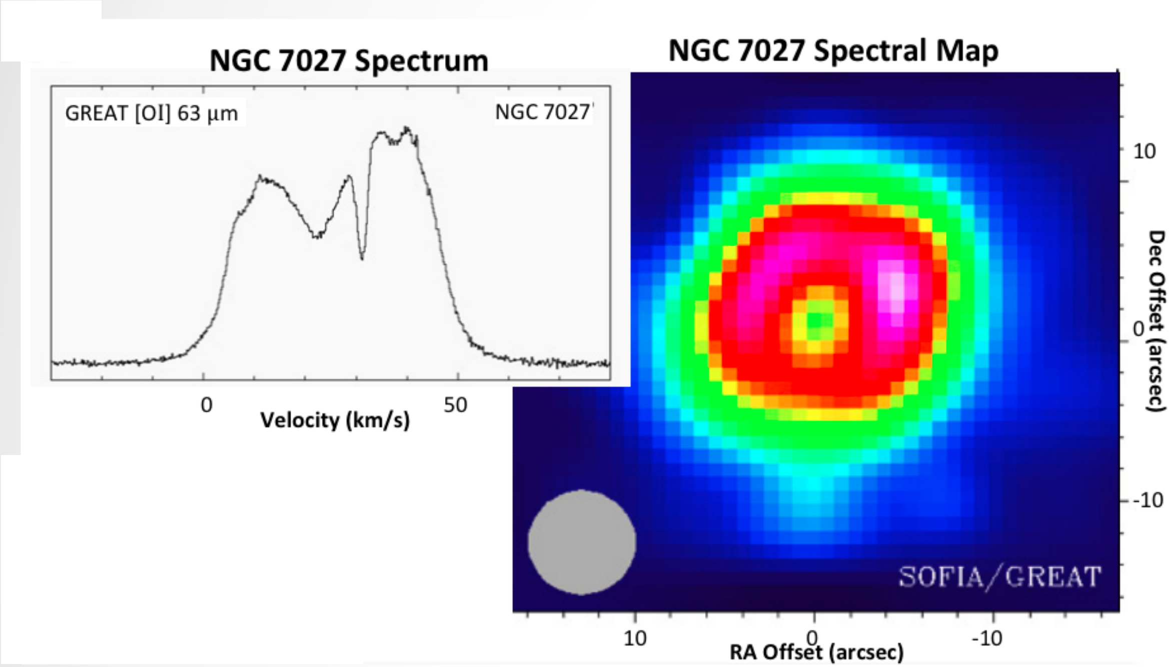
(Langer et al., 2015)

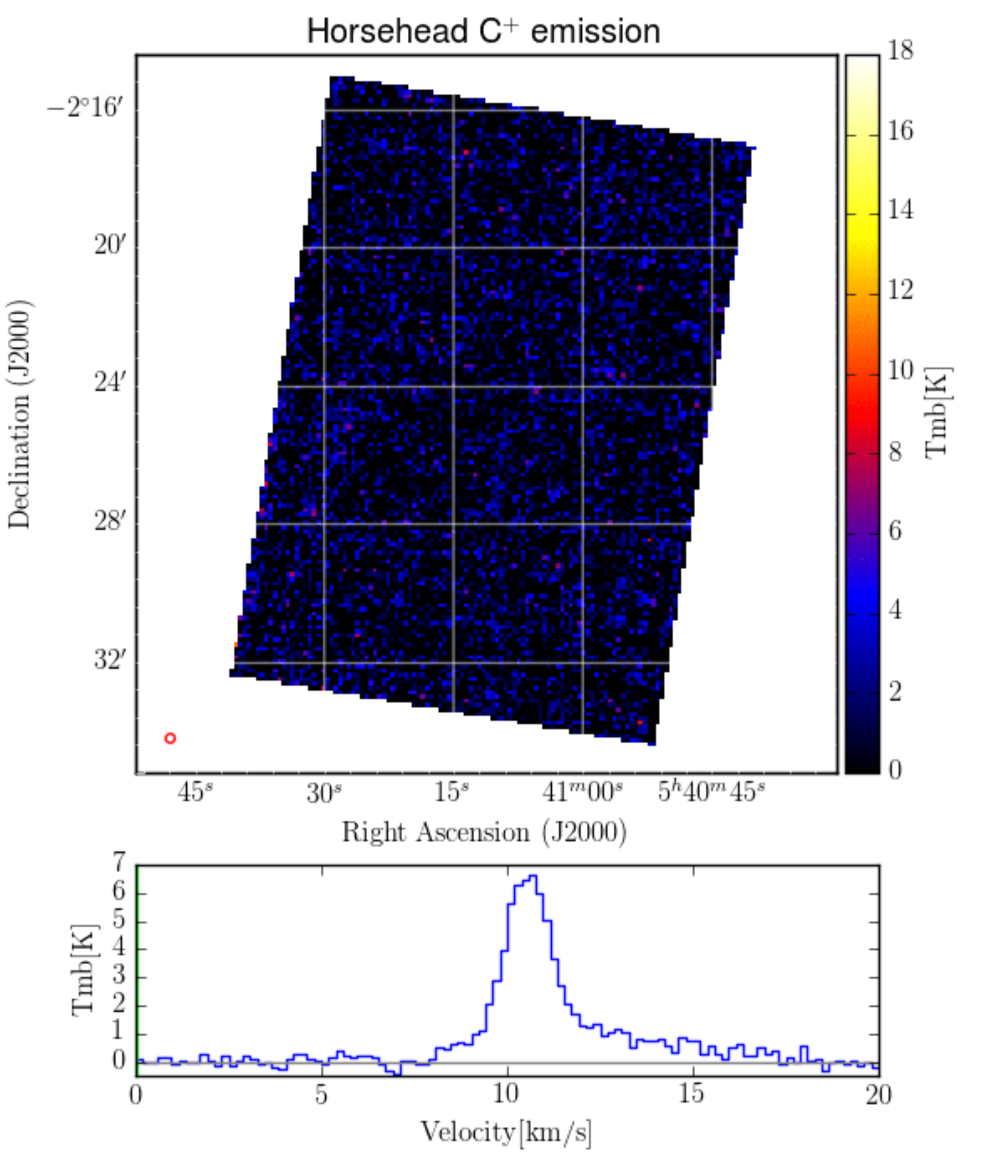


(Bruenken et al., 2014)

High resolution FIR/SMM wave spectroscopy:
faint (and bright) broad emission lines, faint absorption lines.

Science Examples: maps





Maps of bright emission lines

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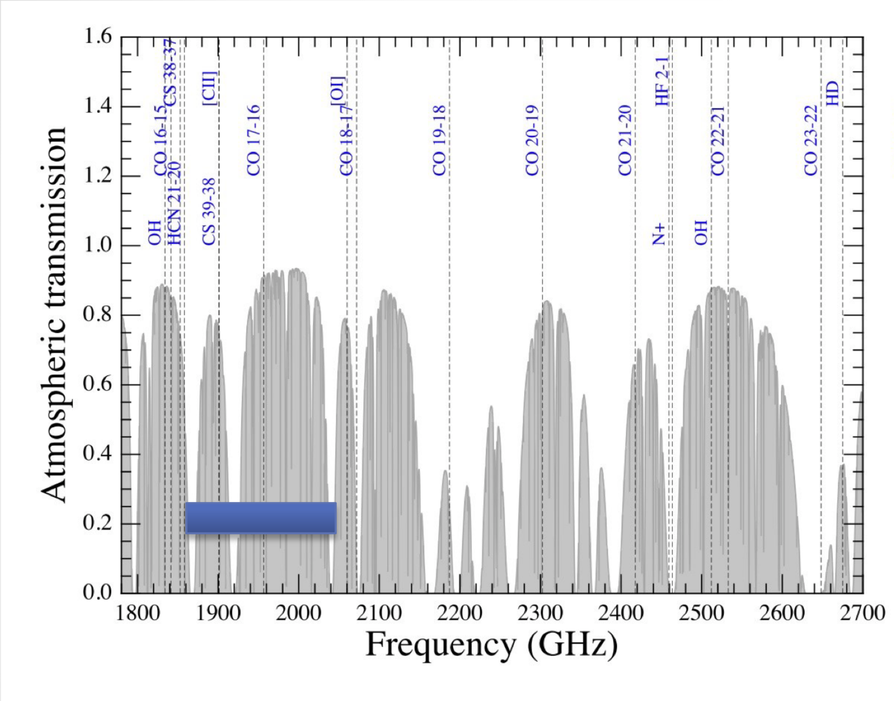
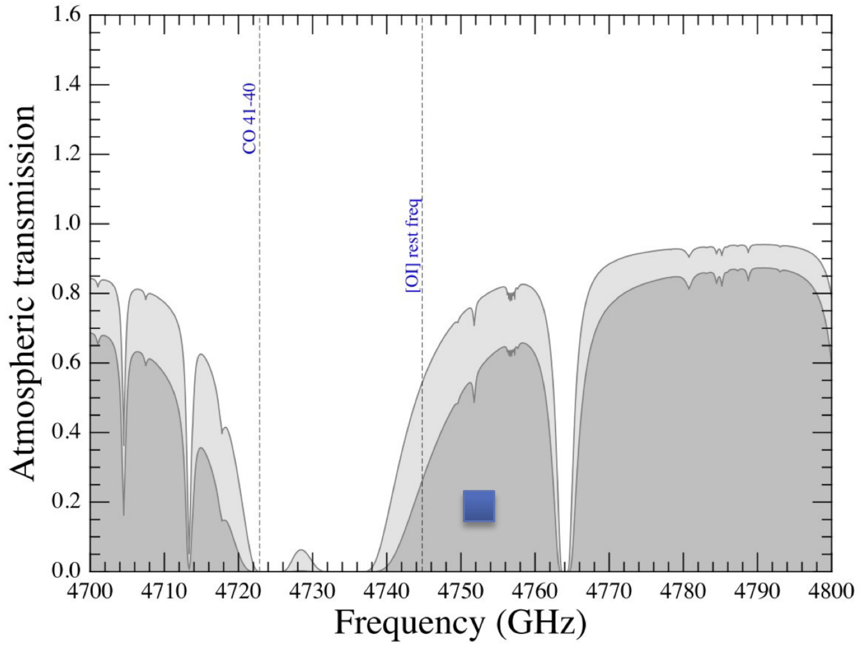
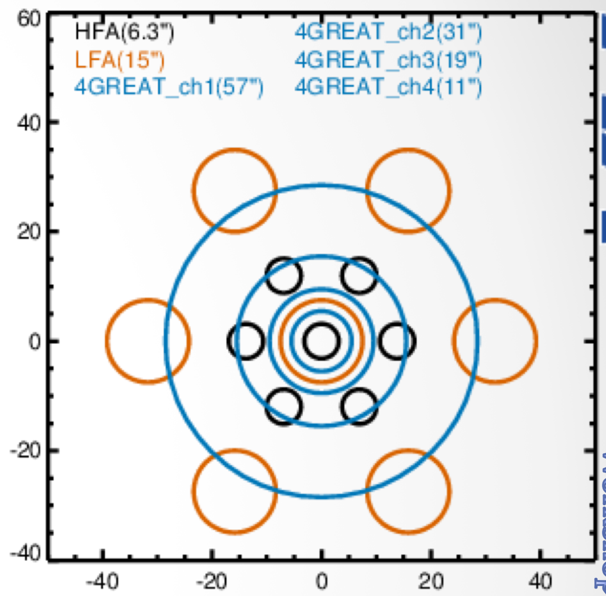
Bands (upGREAT)



LFA (L2)



HFA



Low Frequency Array: 1830-2006 GHz

- 14 pixels (7 pixels , 2 polarizations)
- Optimized for [CII] observations
- High and low ends only covered in one polarization (7 pixels)
- Beam ~ 15 arcsec

High Frequency Array: 4743-4747 GHz

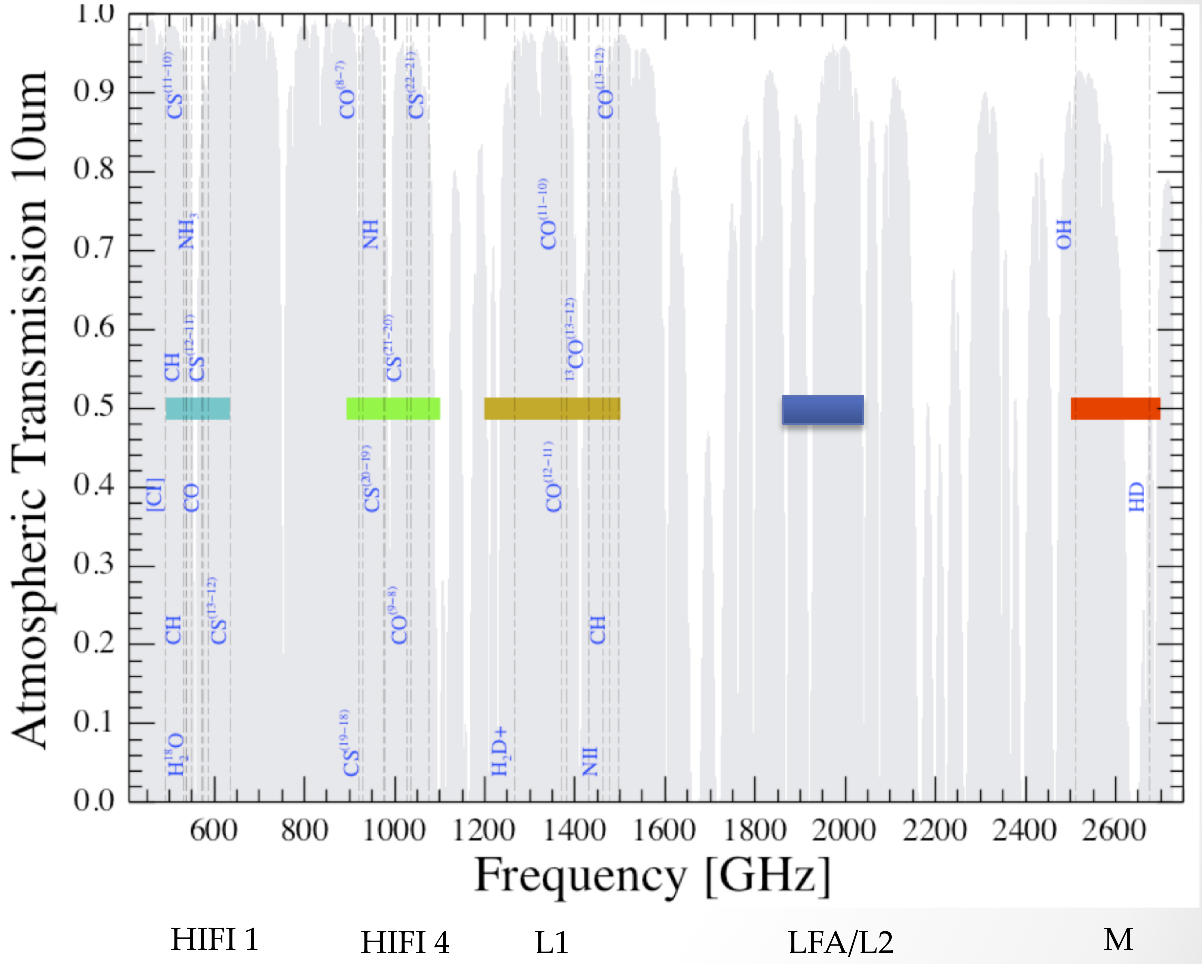
- For [OI] observations
- Poor atmosphere on low frequencies end
- Beam ~ 6 arcsec

Hexagonal geometry with central pixel (HFA, LFA) with 4GREAT pixels overplotted.

Bands (4GREAT)

4GREAT is designed for simultaneous observations in 4 bands. The 4 pixels are co-aligned on the sky.

- Band 1 (HIFI band 1)
  - 0.49-0.63 THz (472-612 µm)
  - Beam size ~ 50 arcsec
  - Lines: NH_3, [CI]
- Band 2 (HIFI band 4)
  - 0.89-1.10 THz (272-337 µm)
  - Beam size ~ 30 arcsec
  - Lines: CH, CS
- Band 3 (L1 channel)
  - 1.24-1.50 THz (200-242 µm)
  - Beam size ~ 20 arcsec
  - Lines: NII, CO, OD, SH, H_2D^+
- Band 4 (M channel)
  - 2.49-2.59 THz (116-120 µm)
  - Beam size ~ 12 arcsec
  - Lines: ^{18}OH, $^2\Pi_{3/2}$



Contact the SOFIA helpdesk (sofia_help@sofia.usra.edu) regarding non-standard tunings.

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Configurations

Two configurations are offered:

- upGREAT HFA (7 sky pixels [OI] line) and upGREAT LFA (2x7 sky pixels [CII] line)
- upGREAT HFA (7 sky pixels [OI] line) and 4GREAT (4 co-aligned sky pixels, 4 frequencies)

Band	THz
HFA	4.7
M	2.6
LFA/L2	1.9
L1	1.4
HIFI 4	1.0
HIFI 1	0.55

GREAT configurations change every cycle.
Some configurations are not offered is there is not enough demand.

Preparation: temperature estimation

The intensity scale in the online tool is brightness temperature T_R^*.

To convert to antenna temperature: $T_R^* = T_A^*/\eta_{fss}$

For GREAT $\eta_{fss} = 0.97$. *The GREAT estimator assumes the line in T_R^* and not in main beam brightness temperature (source that fills the main beam).*

To convert brightness temperature in flux density S:

$S\,[Jy] = 2\,k\,\eta_{fss}\,T_A^*/A_{eff} = 971\,T_A^*\,[K]$ approximately, $S[Jy] \sim 1000\,T_A^*\,[K]$

For a line, we can assume a Gaussian profile with a FWHM Δv expressed in km/s.

$F\,[W/m^2] = 1.065\,S_{peak}\,[Jy]\,10^{-26}\,\Delta\nu[Hz] = 1.065\,10^{-26}\,S_{peak}\,[Jy]\,\nu[Hz]\;\Delta v[km/s]/c$

So, if we know the line intensity and we can guess its FWHM Δv, we can derive the T_R^*, as:

$T_R^*\,[K] = S_{peak}\,[Jy]\,/(0.97*971) = F[W/m^2]\,10^{26}\,c/\,(1003\,\nu[Hz]\;\Delta v[km/s])$

Preparation: time estimation

Once we know:

- peak temperature
- line width
- source velocity

We have to choose the best resolution for the proposed program and use the time estimator:

https://great.sofia.usra.edu/cgi-bin/great/great.cgi

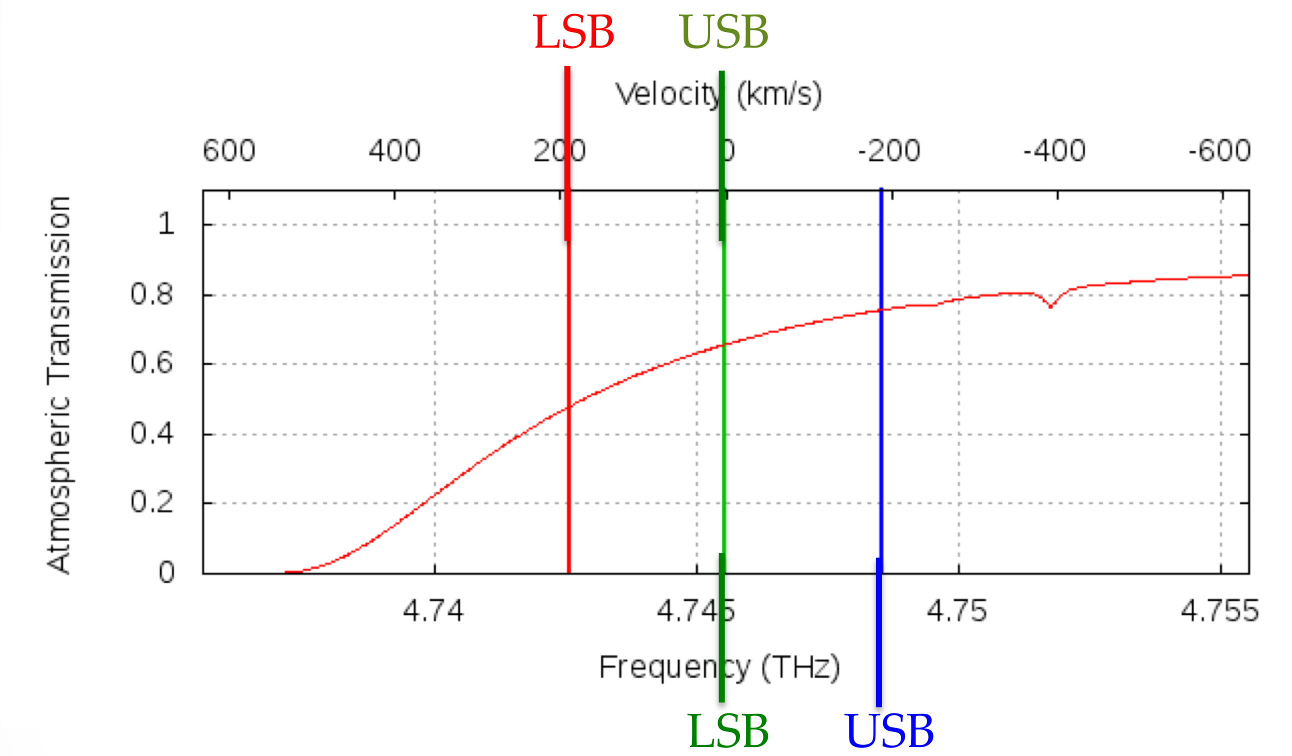
INPUT

Type of Observation :	(•) SinglePoint/BeamSwitch Mapping ( ) TP OTF Mapping		
Observatory Altitude (< 45000 ft):	41000	(•) ft ( ) m	
Water Vapor Overburden (in microns; 0 if unknown):	0		
Telescope elevation (between 20 and 60 deg):	45		
Signal to Noise Ratio / Integration Time (s):	0.55	(•) SNR ( ) Integration Time	
Rest Frequency (in THz, use 7 decimals):	1.8900000		
Source Velocity (in km/s):	100		
(•) **Observer Velocity** (VLSR in km/s):	0	- OR -	( ) **Enter UT Date:** 2017/07/08
Brightness Temperature, T_R*(K) :	.1		
Frequency or Velocity Resolution :	1	( ) MHz (•) km/s	
Line Width (for averaging sky transmission) :	31.8	(•) MHz ( ) km/s	
Comments for the plot :			

OUTPUT

SinglePoint		
Rest Frequency of the line incl. Doppler correction	1.889370	THz
V_LSR	100.000	km/s
Single Sideband System Temperature (LSB tuning)	2996	K
Single Sideband System Temperature (USB tuning)	2674	K
Integration Time (LSB, ON+OFF)	183.1	s
Integration Time (USB, ON+OFF)	145.9	s
Mean Atmospheric Transmission (RestFreq)	0.89	-
Mean Atmospheric Transmission (USB)	0.72	-
Mean Atmospheric Transmission (LSB)	0.87	-

Tuning and atmosphere



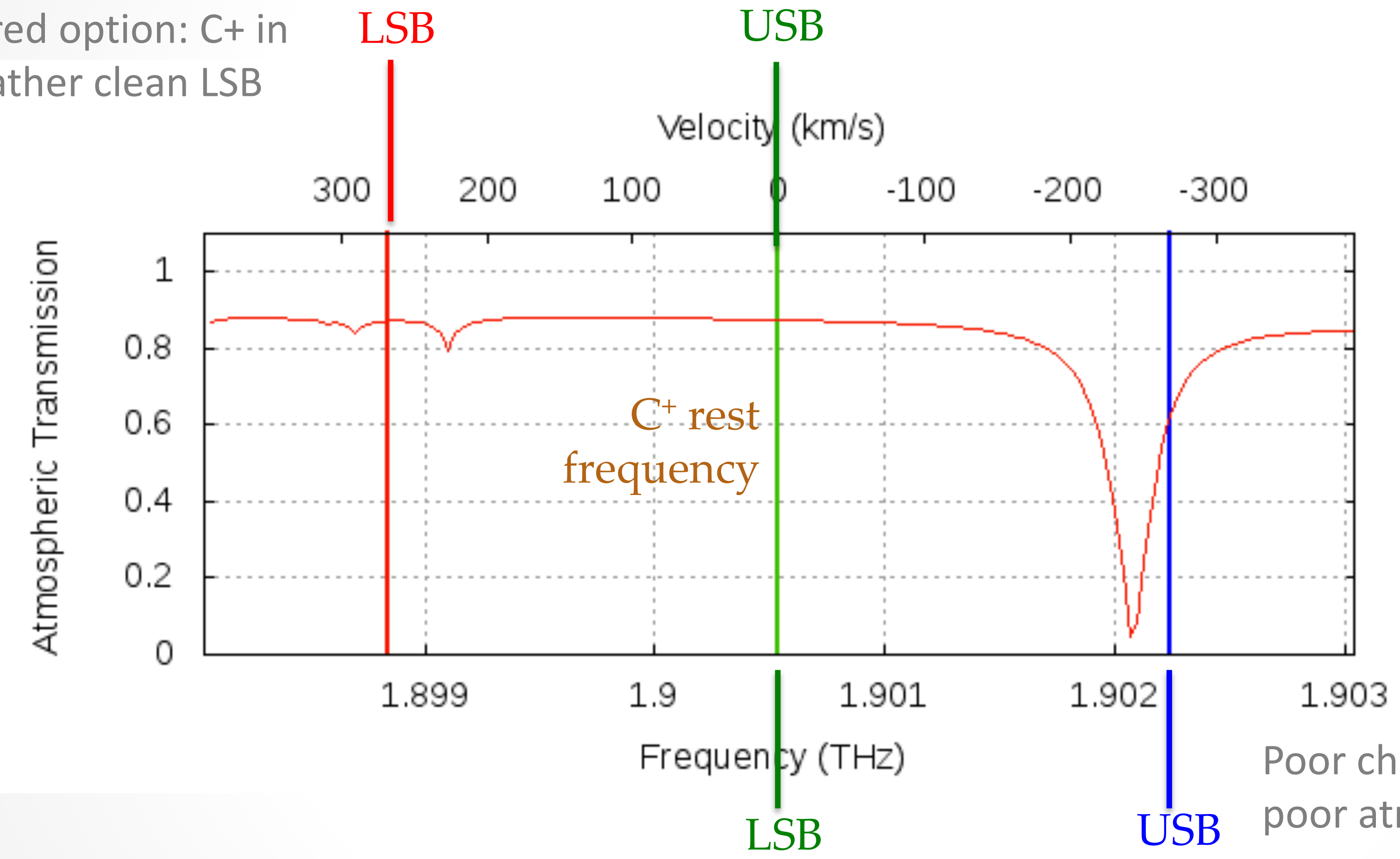
The time estimator gives also a plot of the atmospheric absorption and the possible positions of signal and image bands for a given reference frequency. If the green line corresponds to the position of the line in the signal sideband, blue and red lines are the possible positions of the image sideband if the line is placed in the LSB or USB, respectively.

In the case of [OI], the best choice is to use the blue case (image in the USB). In this way, the noise added to the final spectrum is minimized.

Tuning and atmosphere

At low Doppler shifts, the C+ line is best observed in the upper sideband (USB)

Preferred option: C+ in USB, rather clean LSB

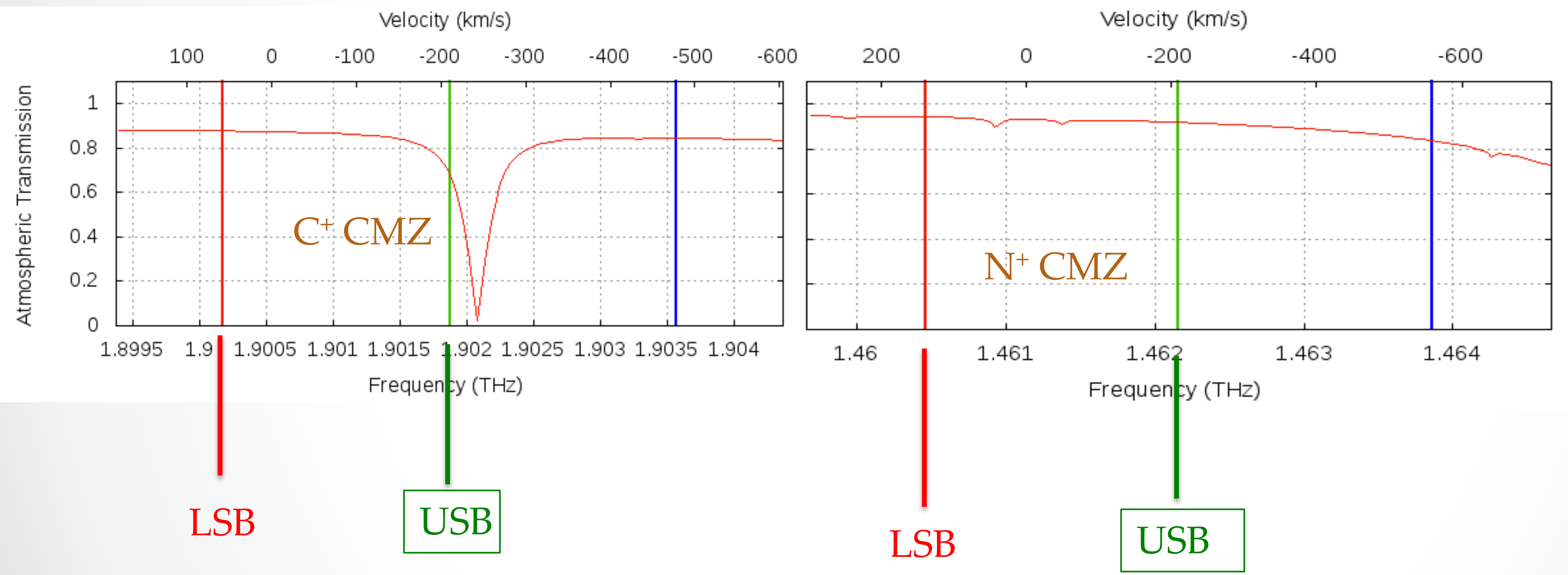


Poor choice: C^+ in LSB, poor atmosphere USB

Note that at this high resolutions, the velocity of the observer can be important to evaluate the best solution. This can be on the order of tens of km/s, depending on source and time of year.

Tuning and atmosphere

At large, negative Doppler shifts, the sideband choice for C+ is less relevant, though USB slightly preferred, similar to N+ (better transmission in image sideband)



Decision on USB vs. LSB is made by the GREAT team prior to flight.

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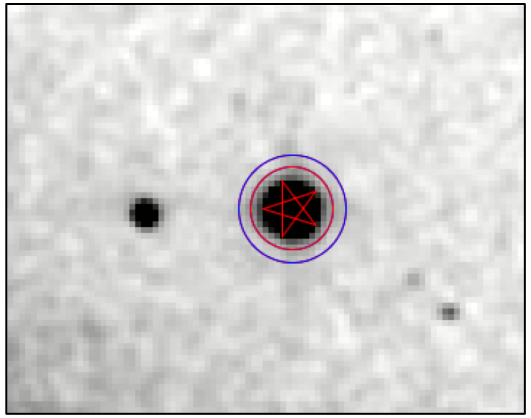
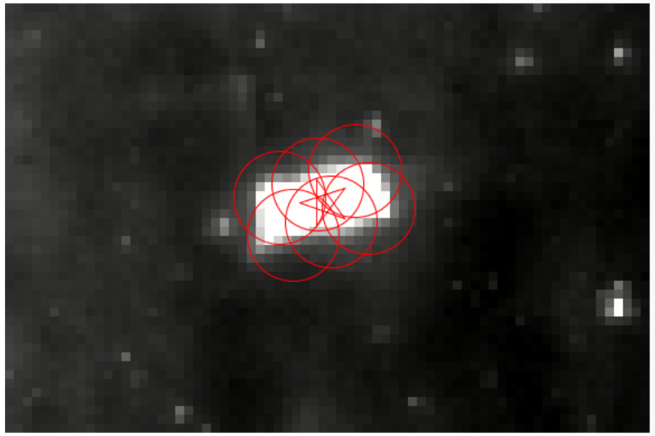
Observing templates

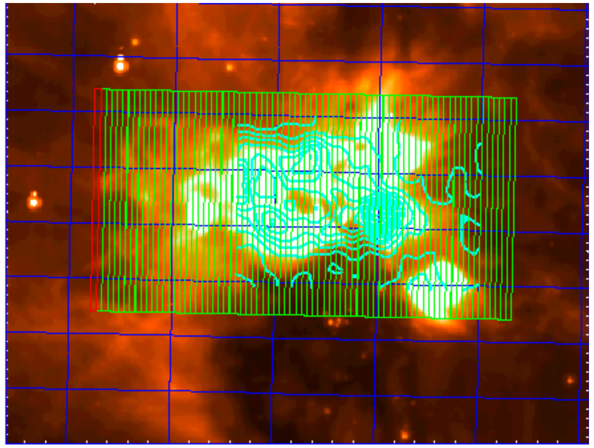
- **Single Point**
  Use for:
  -faint sources (long integration times $\gtrsim$30 s)
  -sources smaller than the beam



- **Raster Map**
  Use for:
  -faint or bright sources
  -compact sources (few beam widths)



- **On-the-fly (array) Map**:
  Use for:
  -bright sources
  -extended sources



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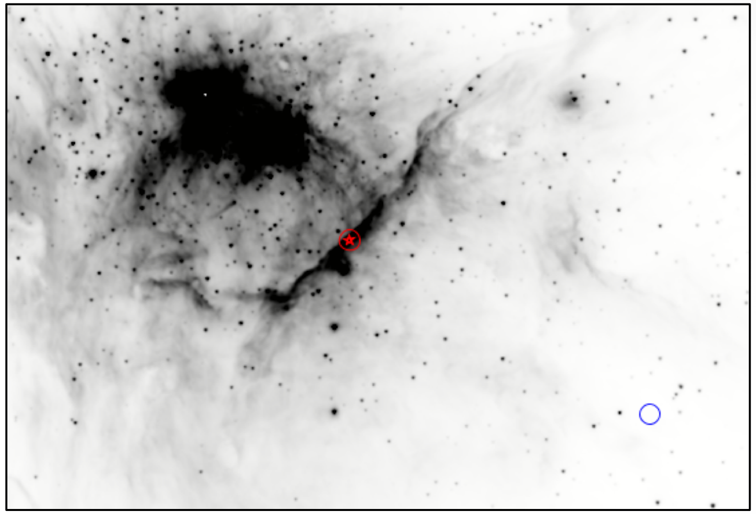
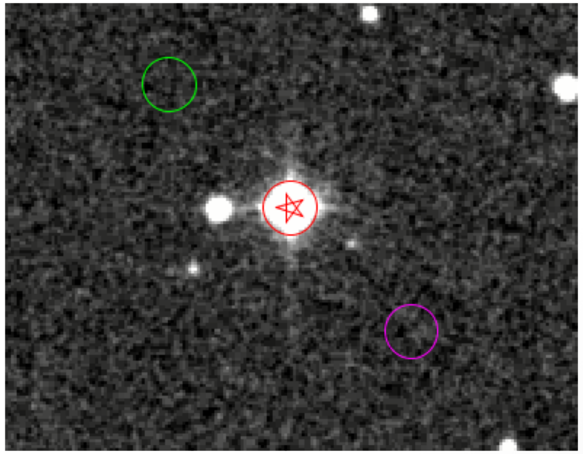
Observing modes

All templates can be observed in the following modes:

Total Power (TP):
-The telescope alternates between the target and a nearby reference position that is (hopefully) free of emission
-On-source time is usually 20 – 30 seconds (equal to off-source time)
-Use when observing in an extended source or a crowded region

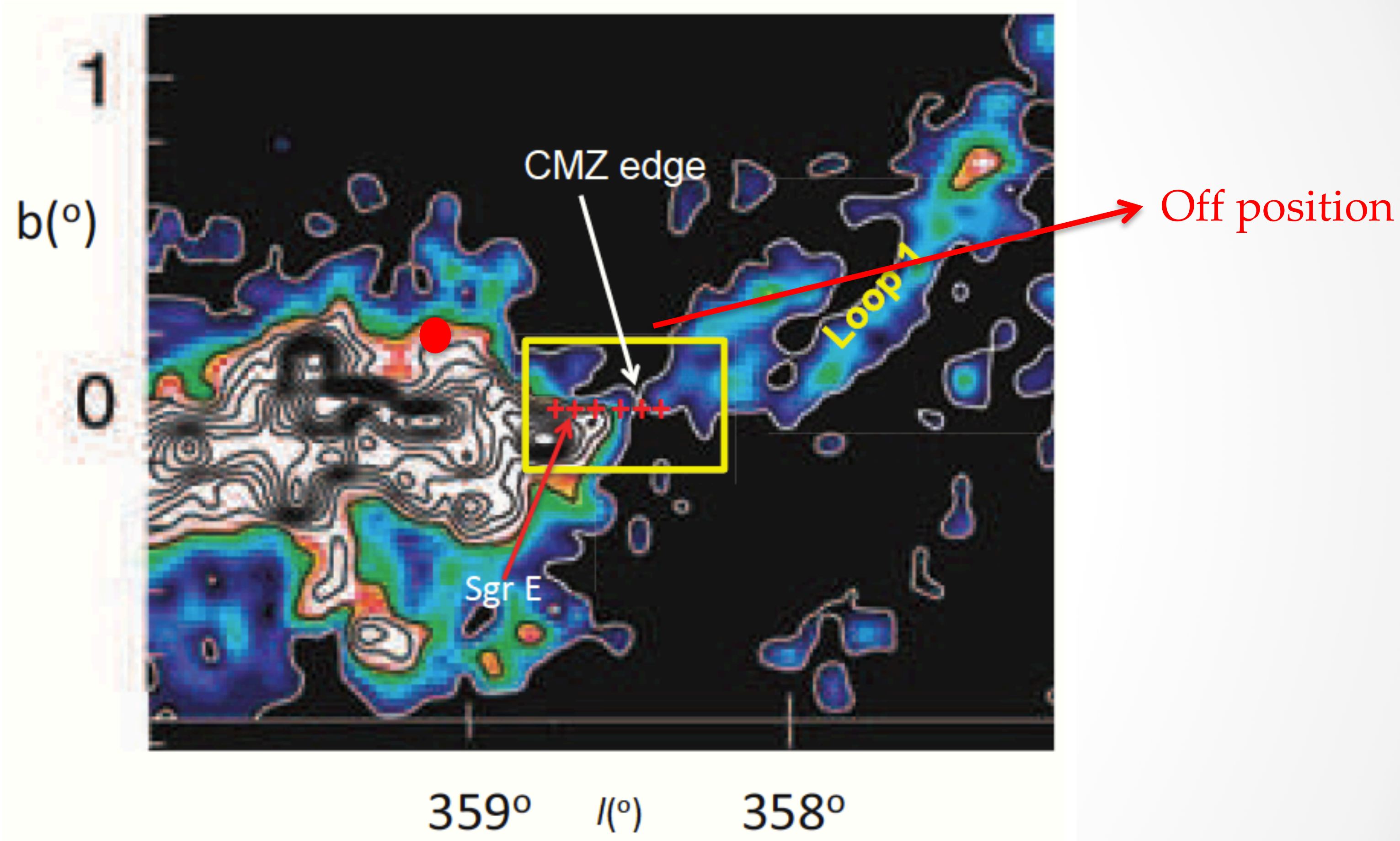
Beam-switched (BSW):
-The secondary mirror ‘chops’ and ‘nods’ between the target (signal) and two sky positions (reference) that are determined by a chop throw and a chop angle.
-Chopping is usually done at 1– 2.5 Hz
-Use when observing point-like or isolated sources





Off position

It is important to find a sky 'off' position that is clean (or as clean as possible). Requires literature search (and sometimes trial and error at the telescope):



NANTEN CO(1-0) map (Fukui et al. 2006)

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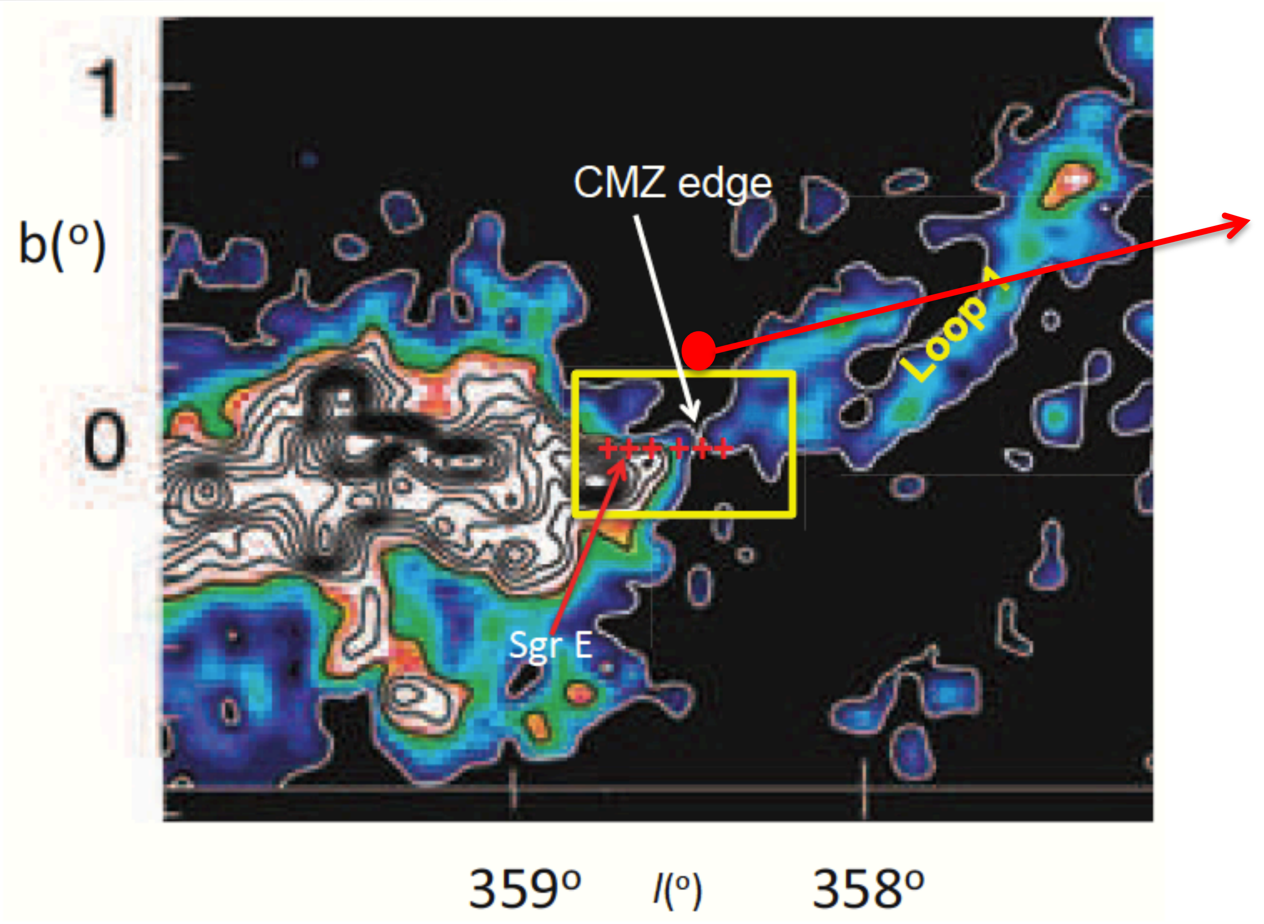
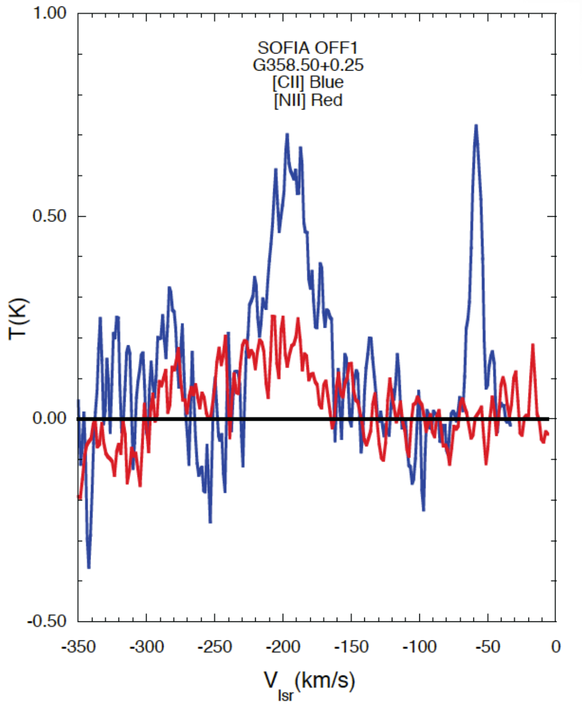
Off position





In this example, the off position is not clean but it is still acceptable in data reduction. This effect can sometimes be mitigated by using the internal reference.

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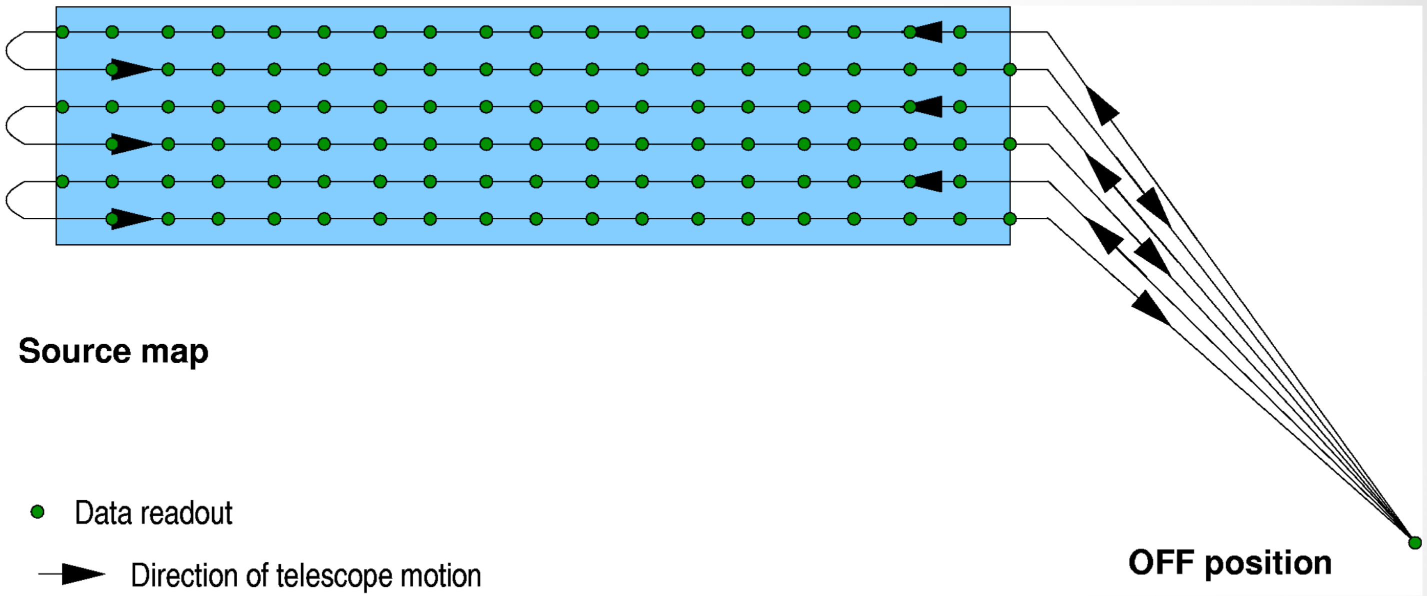
On-the-fly mapping (4GREAT)

Due to the LO stability, each scan must be < 30 s for LFA/4GREAT and < 20 s for HFA in total power mode.

In case of beam switch, there is no such restriction.

We can compute the scan length:



- Integration time can vary between $0.3 - 2\ s$ per spatial point
- Typical scan length is ~30 or ~20 read-outs ($\sim 30 \cdot 6'' = 3'$ and $\sim 20 \cdot 3'' = 1'$) using an half beam step.
- It is possible to combine several ON position with a single OFF position. This allows one to save time and noise, but introduces spatially correlated noise. The time spent in the OFF position depends on the number of readouts and integration time per point:

$\sqrt{30} \cdot 1s = 5.5s$ or $\sqrt{20} \cdot 1s = 4.5s$

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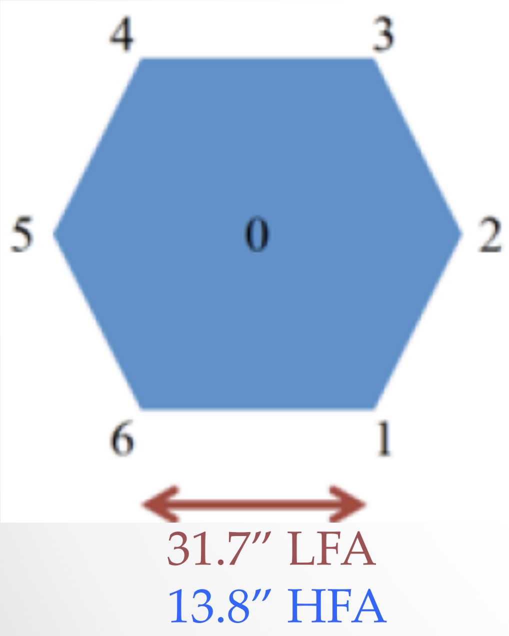
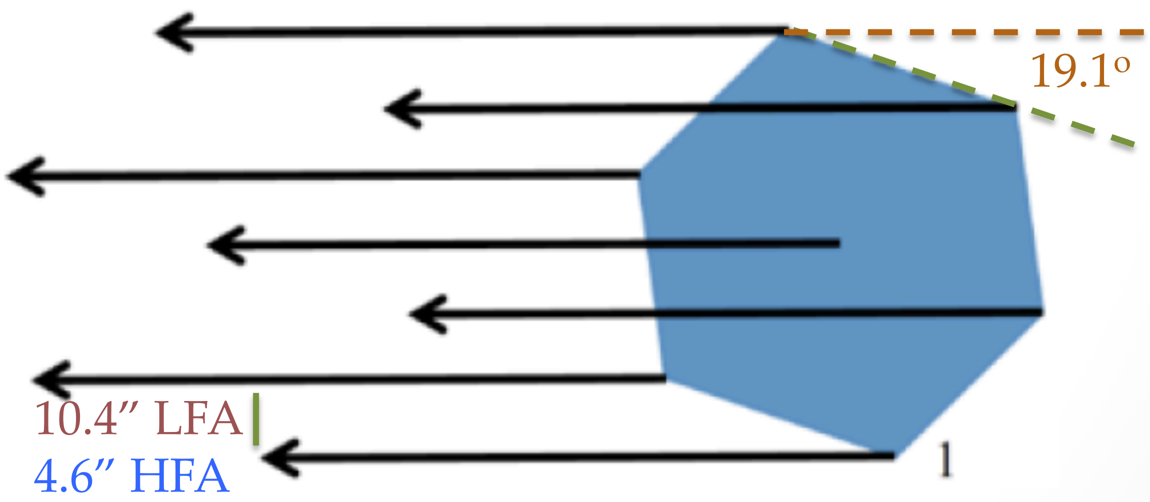
LFA/HFA mapping

- LFA: Array of 14 pixels on 7 sky positions in 2 polarizations
- HFA: Array of 7 pixels on 7 sky positions in 1 polarization
- Pixels separated by approximately 2 beams
- Array tilted by 19.1 deg w.r.t. scan direction for maximum efficiency
- Mapping simultaneously in LFA and HFA





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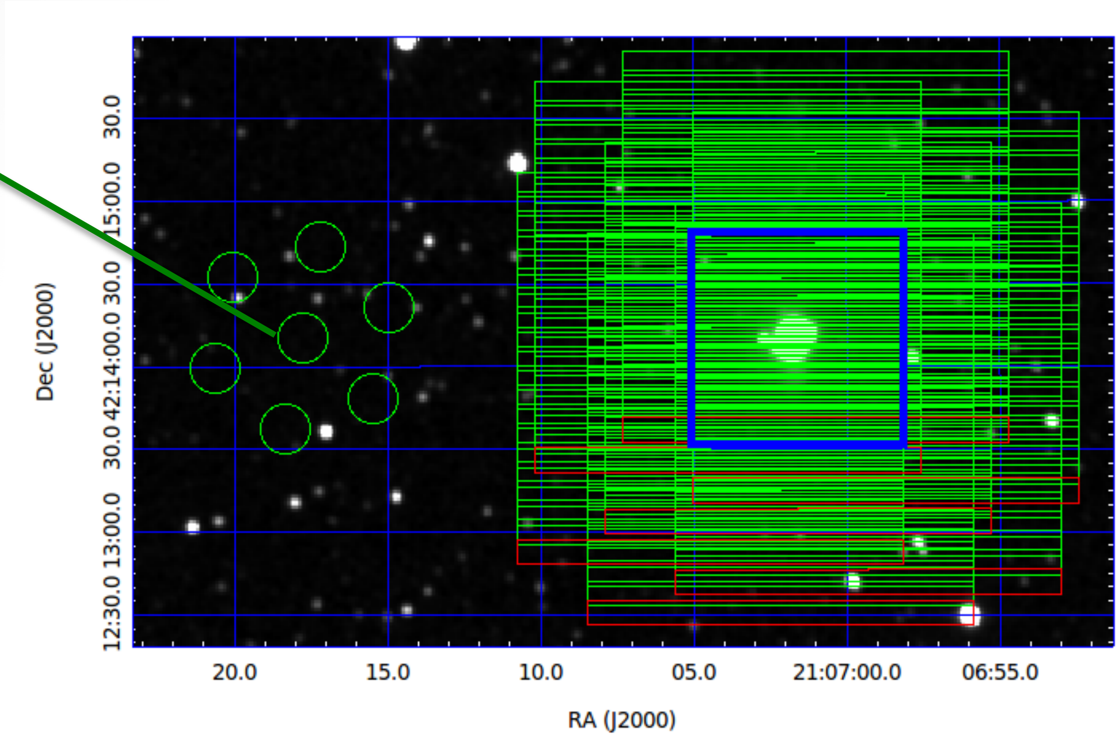
LFA/HFA mapping (medium size map)

Off position



- Central region mapped by each pixel
- Scanning in only one direction
- Scans separated by half beam
- Need to add half an array width on all 4 sides for all pixels to sample box
- Benefit: 7 (or 14) independent maps of the same area, deeper integration

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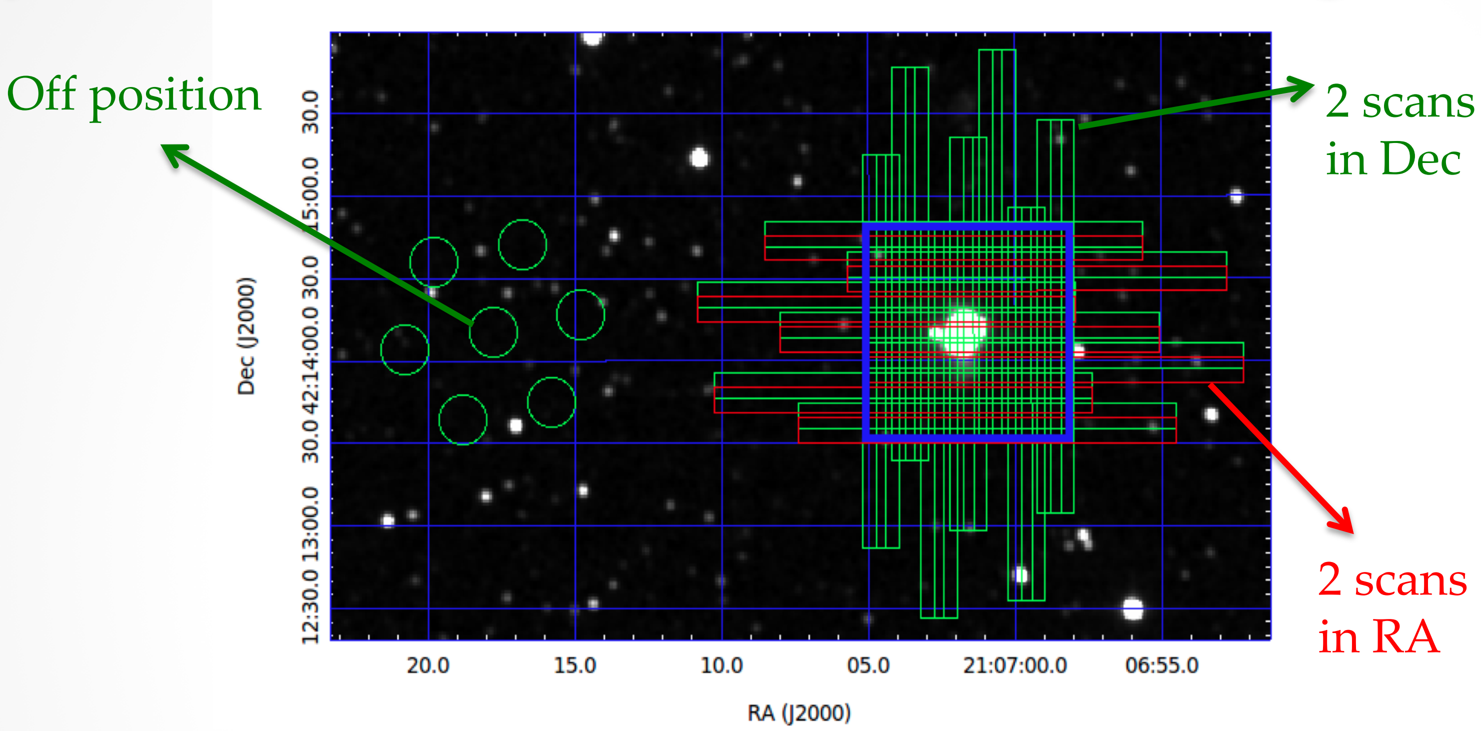
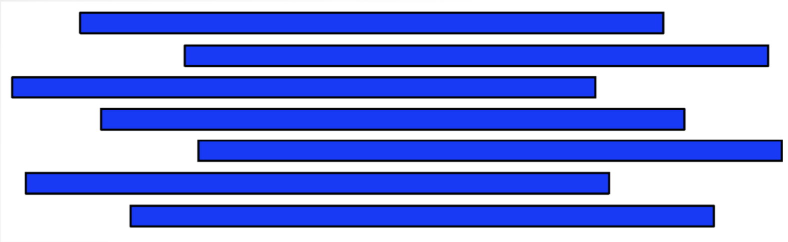
Array OTF mode (element of large map)



- On The Fly (OTF) mode efficient: reference measurement before each scan
- Scanning in RA and Dec avoids striping
- Scans separated by half projected pixel distance
- Need to add half an array width before and after for all pixels to sample box
- Benefit: greater mapping speed

LFA/HFA mapping: Mapping blocks

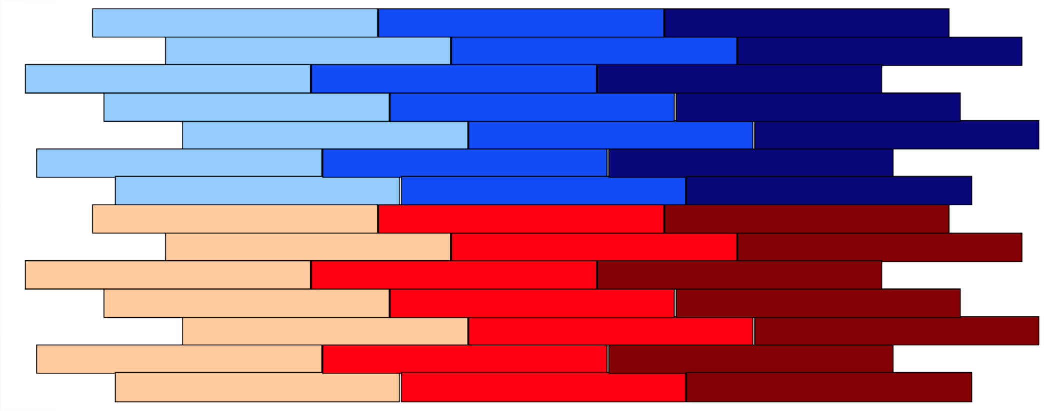
Sparsely sampled block



Fully sampled block

5.2" spacing for LFA
2.3" spacing for HFA

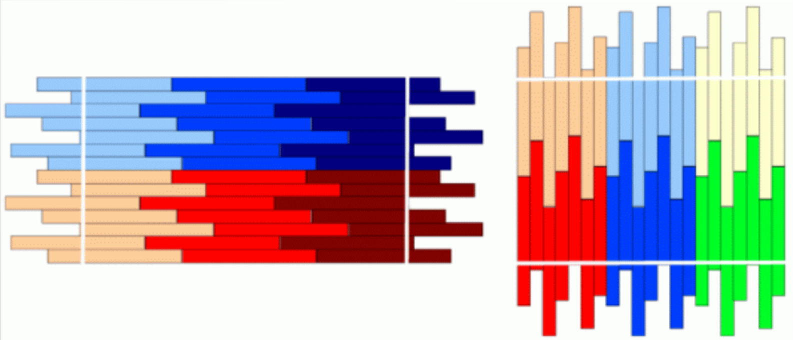
Mosaic of blocks to map large region

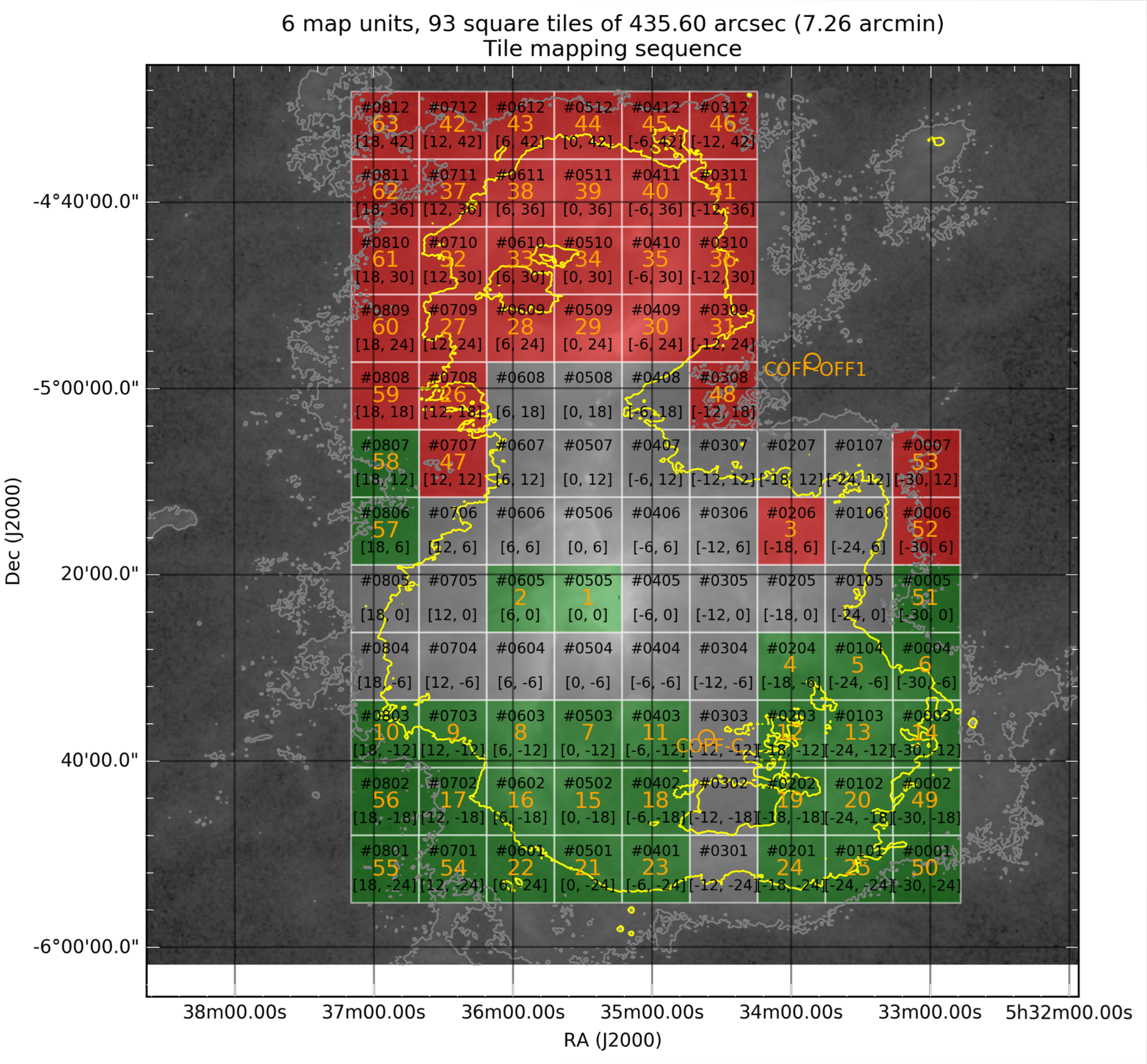


To map a large area is better organizing the observations in *blocks*.

Tiling

In this example (map of Orion) each tile is composed by 6 blocks (see previous slide) in each direction.





Orion map

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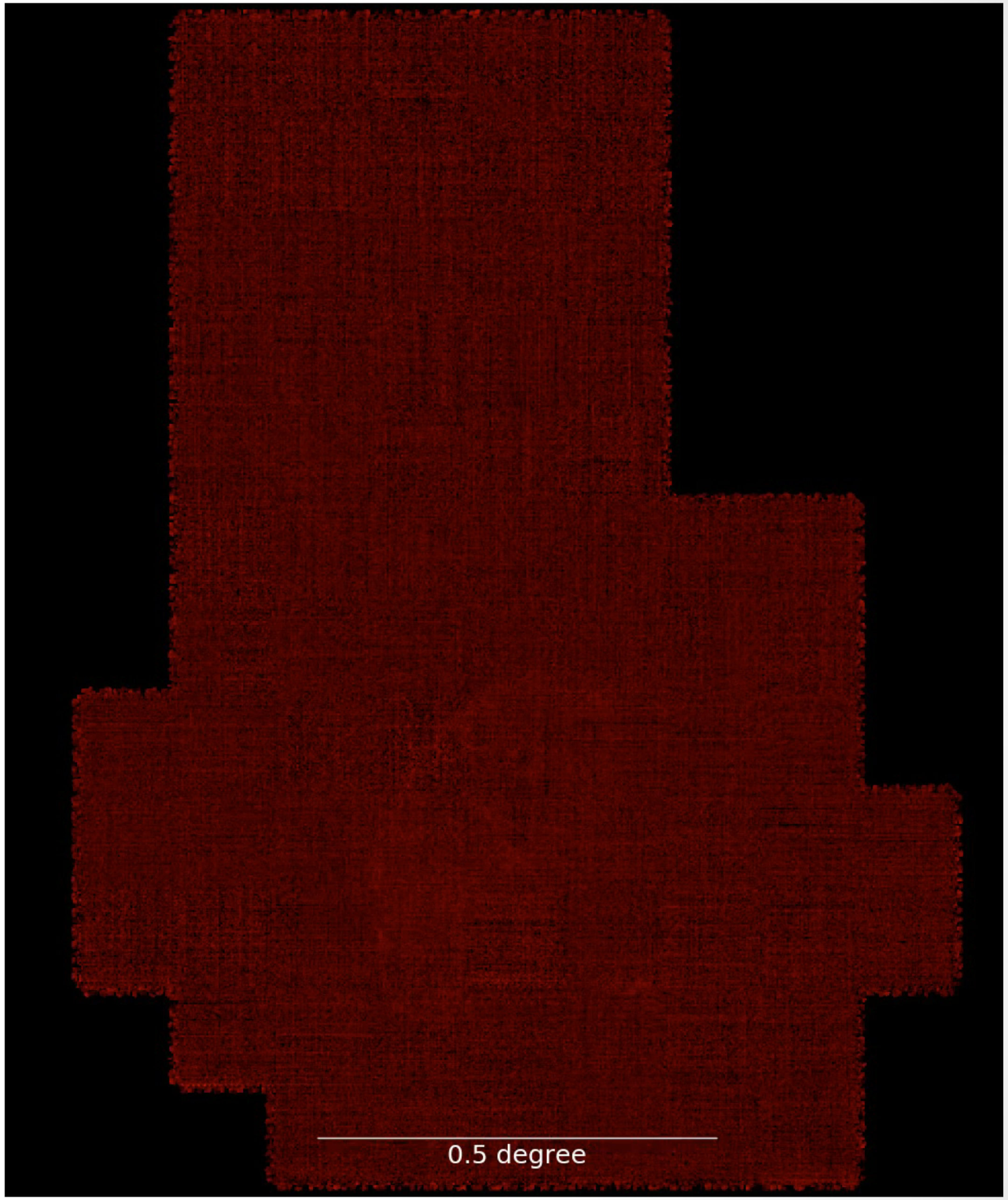
The Orion map

The Large Scale [CII] Emission from the Orion Molecular Cloud (Tielens, A., et al., in prep)

The [CII] 185 µm line is a powerful diagnostic tool for evaluating the physical conditions of PDRs and is used as a tracer of star formation in both normal and starburst galaxies.

The goal of this study was to further examine the use of the [CII] line as a tracer of star formation rate, measure the amount of molecular cloud mass not measured by CO (known as "CO-dark" gas), and semi-empirically determine the photo-electric heating efficiency over a wide range in incident UV fields.



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GREAT vs HIFI

GREAT mixers improved over HIFI, in system temperature and baseline quality (standing waves).

Despite atmosphere, GREAT (nearly) as sensitive as HIFI:

- C^+ line at 1900.5369 GHz, at rest velocity, 41,000 ft, smoothed over 2 km/s, 1000 s ON+OFF on T_R^* scale, fully extended emission:
  - GREAT: RMS=53 mK, T_{sys}=2840 K (T_{sys} incudes atmosphere!)
  - HIFI: RMS=45 mK, T_{sys}=2760 K
- Same after smoothing to 50 km/s (stability for broad lines):
  - GREAT: RMS=11 mK
  - HIFI: RMS=12 mK
- GREAT wins with factor of 10 larger mapping speed (array receiver). Also, HIFI had no mixers for N^+ and OI, and … Herschel is out of He
- However, HIFI more sensitive for point source emission (galaxies) due to the smaller size mirror (3.5 vs 2.5 m).

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GREAT vs FIFI-LS

- GREAT has high resolution (10^5) than FIFI-LS (500-2000)
- FIFI-LS has continuous coverage between 50 and 200μm, while GREAT covers this wavelength range in four narrow bands (L1,L2/LFA,M,HFA)
- FIFI-LS has an array of 5x5 spaxels which is efficient for mapping in two parallel arrays (blue and red). GREAT can map large regions in approximately 4x longer time at least in one frequency.
- When observing large regions, the best strategy is to use FIFI-LS to map the entire region and eventually GREAT to map regions with brighter flux and/or more complicate velocity fields (which require an higher resolution).

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Resources online

- GREAT Cookbook:
  /https://www.sofia.usra.edu/sites/default/files/USpot_DCS_DPS/Documents/GREAT_cookbook.pdf
- GREAT Instrument Flyer:
  https://www.sofia.usra.edu//sites/default/files/Instruments/GREAT/Documents/GREAT%20Flyer.pdf
- Observer's Handbook:
  https://www.sofia.usra.edu/science/proposing-and-observing/sofia-observers-handbook-cycle-6/7-great
- USPOT Manual:
  https://www.sofia.usra.edu/science/proposing-and-observing/uspot-manual
- MPIfR sub-millimeter group (GREAT instrument team):
  http://www3.mpifr-bonn.mpg.de/div/submmtech/
- SOFIA Help Desk: mailto:sofia_help@sofia.usra.edu