How to observe with upGREAT on SOFIA

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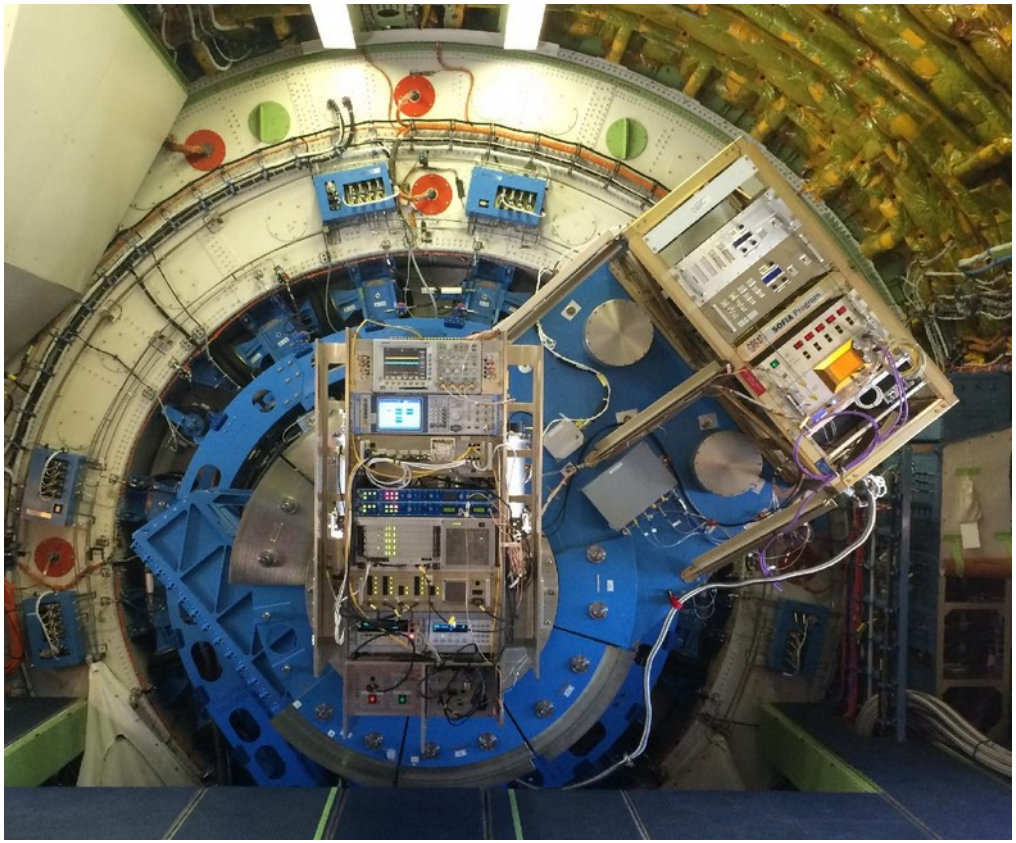
Overview

MPIfR
KOSMA
MPS
DLR-Pf

- Main references
- What to observe?
  - Constraints
    - Instrument
    - Atmosphere
    - Flight tracks
- How to observe?
  - Noise
  - Observing modes
- How to use the data?
  - Data release
  - Data reduction



Main source of info

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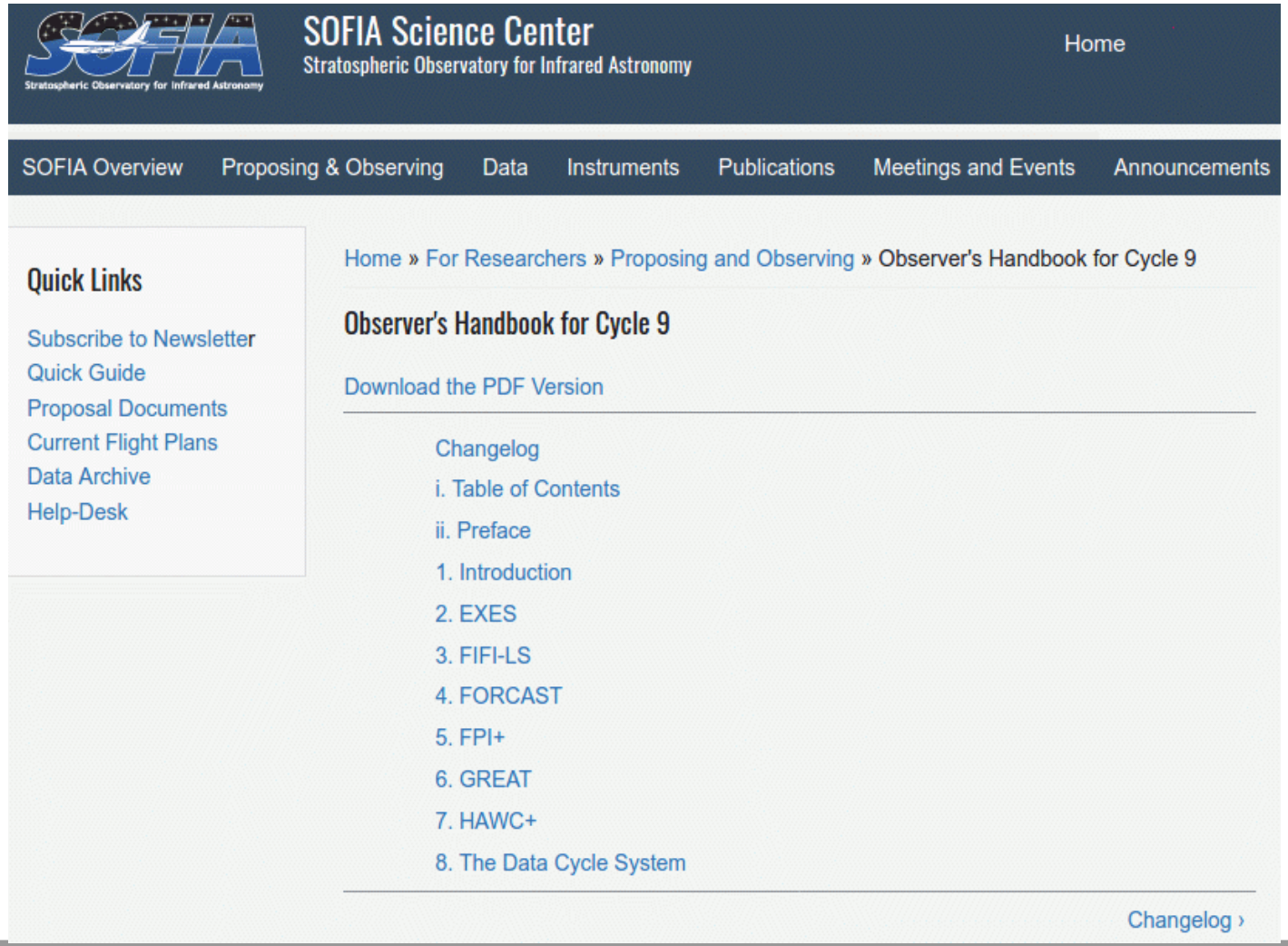
DLR-Pf

- SOFIA Observers Handbook
  - https://www.sofia.usra.edu/science/proposing-and-observing/observers-handbook-cycle-9



SOFIA Toolbox

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Main source of info

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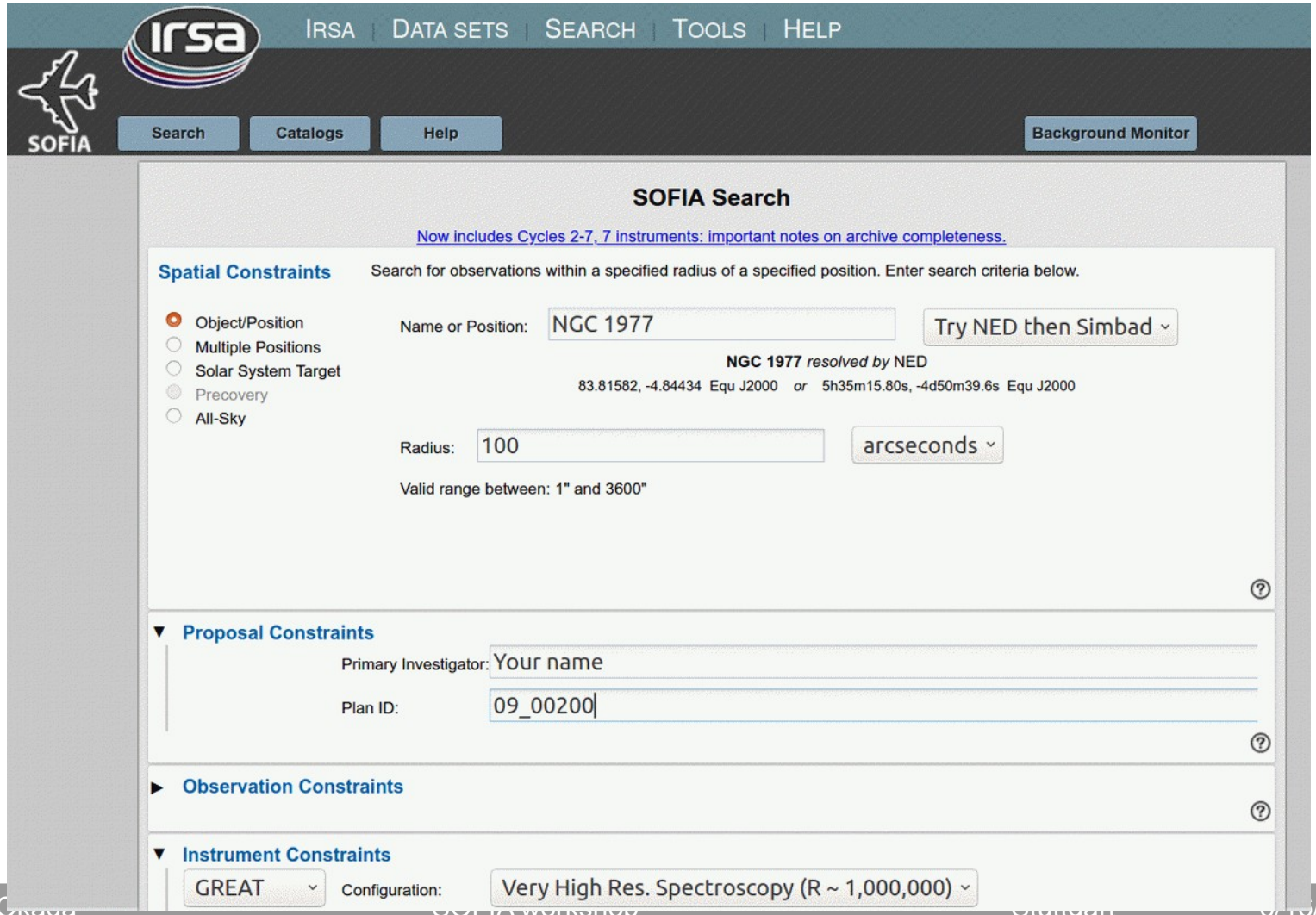
- Data release
  - Science archive at IRSA
    https://irsa.ipac.caltech.edu/applications/sofia/



Main source of info

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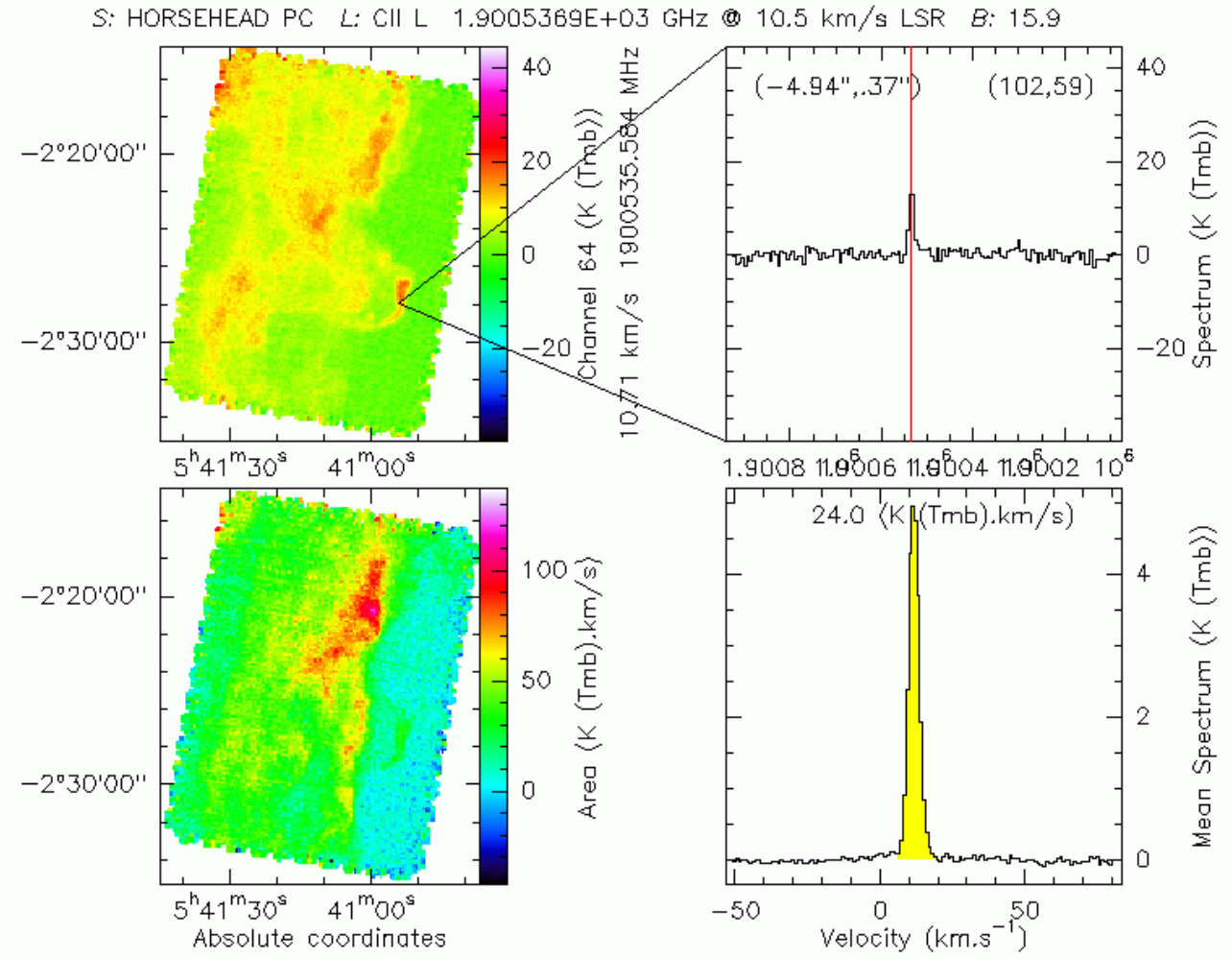
- Data release
  - Data reduction: CLASS (GILDAS):
    - https://www.iram.fr/IRAMFR/GILDAS/gildasli2.html



Prerequisite

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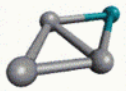
Good science driver is the key!

- What line(s) do I want to observe?
  - What is the line frequency?
- What source(s)?
  - coordinates, area
- What line intensity do I expect?
- Where is a good reference position?

The Cologne Database for Molecular Spectroscopy
CDMS



Documentation | Entries | Description | Search | Partition Function | Archive

See the General part for a description of the content and the home page for citation!

Entries having an asterisk after the version number have been included in the database after acceptance of our new article on the CDMS, *J. Mol. Struct.*, **742** 215-227 (2005), in January, 2005. It can not be ruled out completely that recent entries contain errors.

Note: Entries having an asterisk after the tag state the temperature independent $S\mu^2$ instead of the intensity *I* at 300 K !!

For some entries, where, for example, hyperfine splitting was important for the laboratory data, but is expected to be of minor importance for radioastronomical observations, separate predictions are available. Values of the partition function given in the respective documentation refer to the vibrational ground state only – unless stated otherwise.

Get one list of partition functions for the price of a half.
Currently 1019 entries.

Tag	Name	# lines	Ver.	Catalog	Documentation	Date of entry	Entry in cm^{-1}
003501	HD	20	2*	HTML | ASCII	e003501.cat	Dec. 2011	w003501.cat
004501	H_2D^+	196	3*	HTML | ASCII	e004501.cat	Mar. 2017	w004501.cat
005501	HD_2^+	163	3*	HTML | ASCII	e005501.cat	Jan. 2018	w005501.cat
005502	HeH^+	18	1*	HTML | ASCII	e005502.cat	April 2008	w005502.cat
012501	C	2	1*	HTML | ASCII	e012501.cat	Sep. 2005	w012501.cat
012502	BH	15	1*	HTML | ASCII	e012502.cat	July 2008	w012502.cat
012503	C^+	1	1*	HTML | ASCII	e012503.cat	Aug. 2010	w012503.cat
013501	^{13}C	7	1*	HTML | ASCII	e013501.cat	Sep. 2005	w013501.cat

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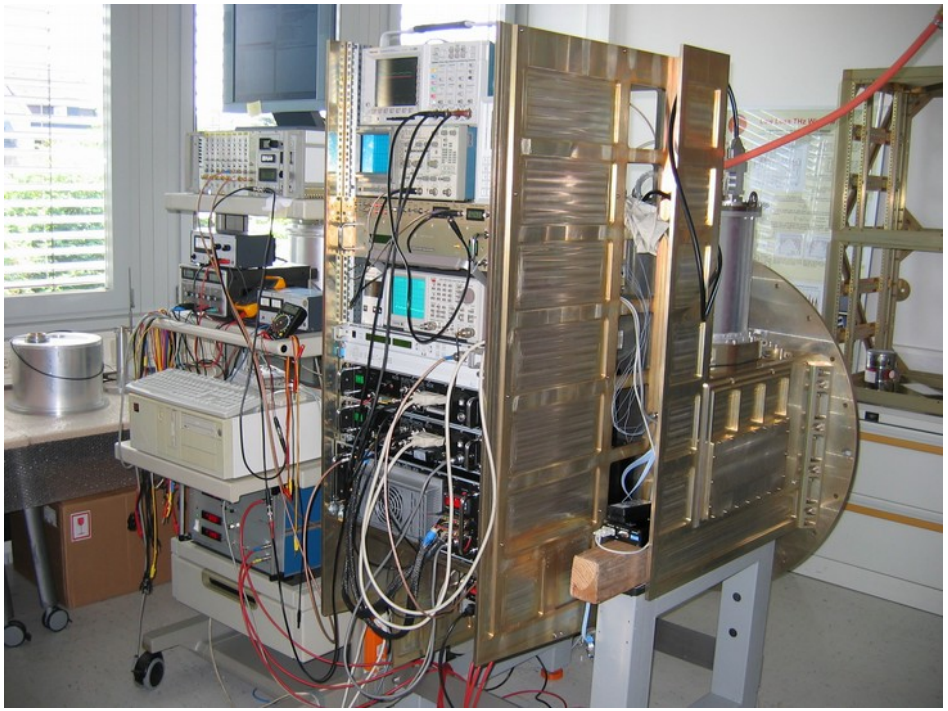
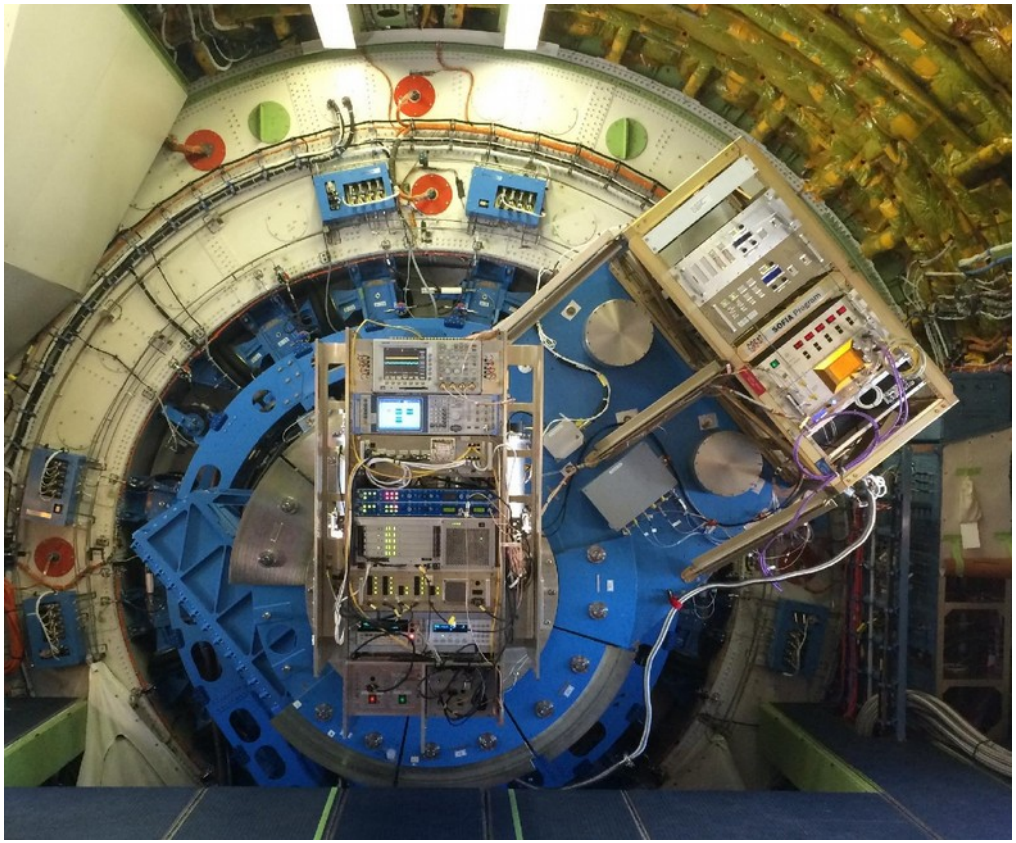
German REceiver for Astronomy at Terahertz-Frequencies

- Heterodyne receiver
  - Dual channel
    - 2-5 frequencies simultaneously
  - 0.5 – 4.7 THz
    - in 6 frequency-bands





- Spectrometers: FFTS4G
  - 16k channels
  - Bandwidth: 4GHz
  - Resolution: 283kHz ($R = 10^7$)

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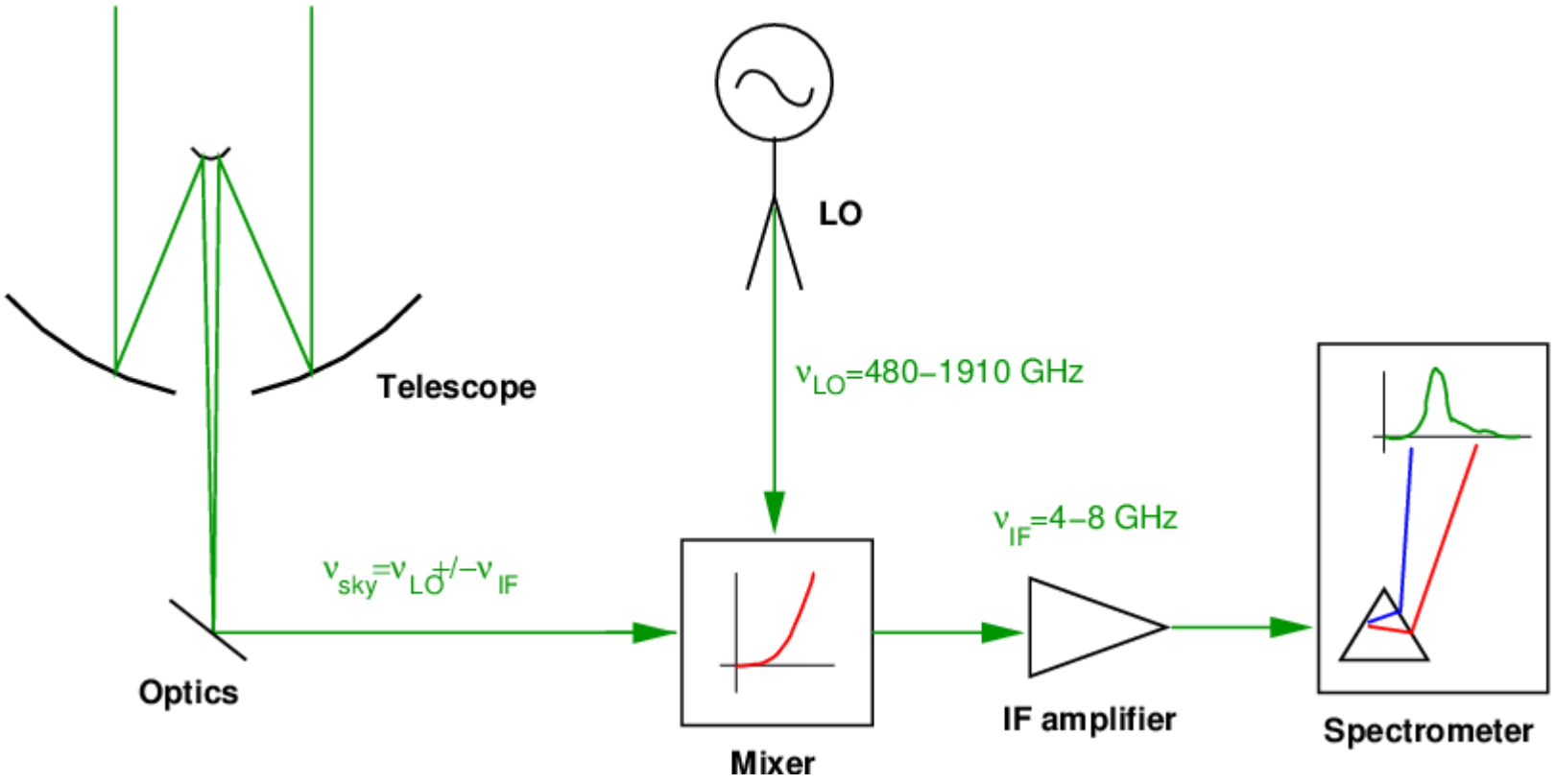
Heterodyne principle

- Mixing of sky signal with reference frequency
- Amplification of difference (IF) frequency



→ double-sideband sensitivity: $\nu_{\rm sky} = \nu_{\rm LO} \pm \nu_{\rm IF}$

Radiometry

- Noise determined by
  - Forward efficiency, main beam efficiency $\eta_{\rm fwd} \approx 0.96, \eta_{\rm mb} \approx 0.7$
  - Receiver temperature (double sideband) $T_{\rm rec,dsb}$
  - Atmospheric transmission in signal + image sideband $\eta_{\rm sky,ssb}, \eta_{\rm sky,isb}$
  - Frequency resolution
  - Integration time

$$T_{\rm rms,ssb} = \frac{T_{\rm sys,ssb}}{\sqrt{t_{\rm int} \times \Delta\nu}}$$

$$T_{\rm sys,ssb} \approx \frac{2}{\eta_{\rm mb}\eta_{\rm sky,ssb}} \left[T_{\rm rec,dsb} + (1-\eta_{\rm fwd}) T_{\rm tel} + \frac{1-\eta_{\rm sky,ssb}}{2} T_{\rm sky} + \frac{1-\eta_{\rm sky,isb}}{2} T_{\rm sky} \right]$$

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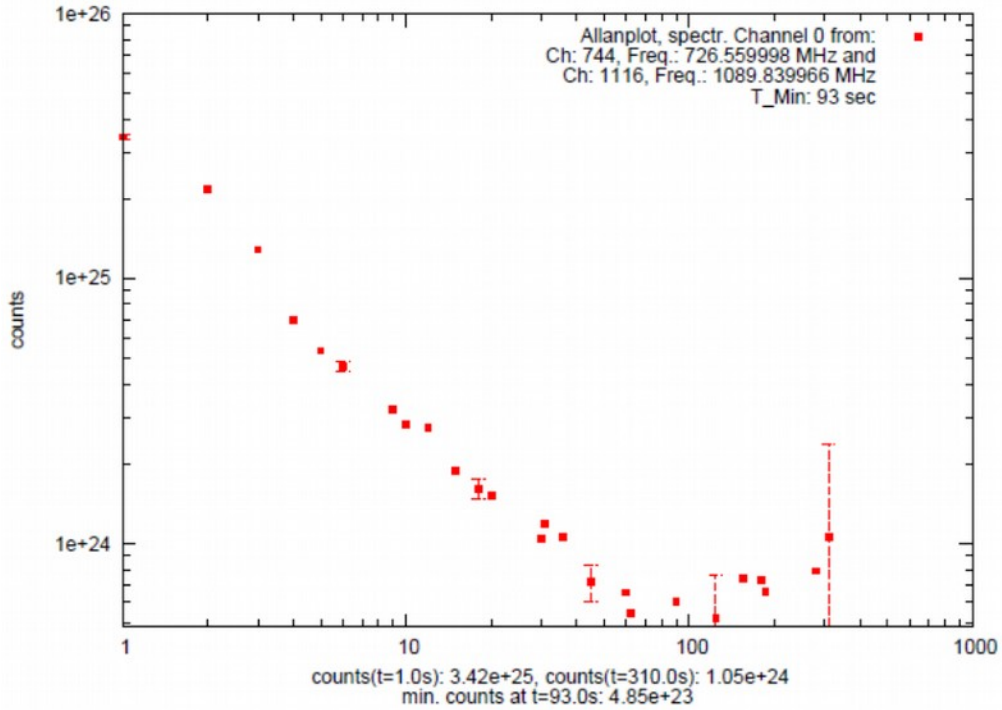
Radiometry

- Stability of heterodyne instruments ~ 100s



4G3 stability Feb. 2018

- Requires repeated OFF measurements
  - Eat time and add noise
  - Factor 2 for symmetric schemes with $t_{\rm on} = t_{\rm off}$

$$T_{\rm rms,ssb} = \frac{2 \times T_{\rm sys,ssb}}{\sqrt{(t_{\rm on} + t_{\rm off}) \times \Delta\nu}}$$

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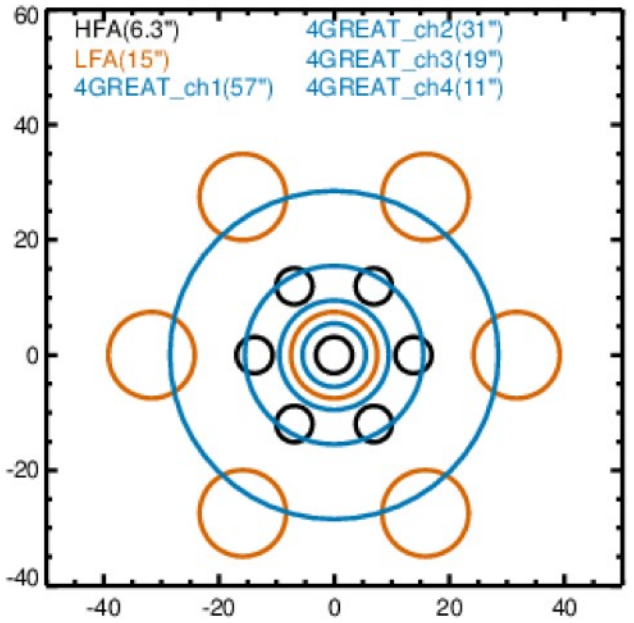
Frequencies:

Channel		Frequencies [THz]	Pixels	Lines of interest	$T_{rec,dsb}$[K]
4GREAT	4G1	0.491-0.555, 0.560-0.635	1	[CI], CH, CO, NH_3, $H_2{}^{18}O$	120
4GREAT	4G2	(0.890)-0.984, 0.990-1.092	1	NH, OH^+, CO, CS, HDO	350
4GREAT	4G3	1.2030-1.395, 1427-1.525	1	[NII], CO, OD, SH, H_2D^+	1100
4GREAT	4G4	2.490-2.590	1	OH	3300
upGREAT	LFA	1.835-2.007	2x7	CO, [CII], [OI], OH, CH	1050
upGREAT	HFA	4.74	7	[OI]	1250

Gaps in coverage from atmospheric blocking

- Beams:
  - 57" (0.5 THz) ... 6.6" (4.74 THz):



Frequencies

Tested lines (incomplete):

4G-1

IF Offset	6	
Specie	Rest (GHz)	SB
HDO(110-101)	509.29242	
CH_559	536.7610	USB
H218O(110-101)	547.67644	USB
NH3(100-001)	572.49816	
CO J = 5–4	576.26793	
HCl(1-0)	625.91876	

4G-2

IF Offset	6	
Specie	Rest	SB
HDO(111-000)	893.63867	
OH+(10-01)	909.1588	
CO(8–7)	921.7997	
OH+(12-01)	971.8038	
NH	974.47861	USB
H3O+(000-101)	984.71191	USB
13CO(9-8)	991.32935	LSB
H218O(202-111)	994.67513	LSB
OH+(11-00)	1033.1186	USB
CO(9-8)	1036.9124	LSB
H2S(221-110)	1072.8365	LSB

- Check for your own lines of interest in covered frequency range

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4G-3		
IF Offset	2	
Specie	Rest	SB
HF(1-0)	1232.476	
HCN(14-13)	1239.890	
HCO+(14-13)	1247.735	
HCL(2-1)	1251.4519	
CO(11-10)	1267.0145	
H2O2(1274)	1274.577	USB
H2O(743-652)	1278.265	USB
H2O(827-734)_L	1296.4111	
H2F+(111-000)	1305.315	
HCN(15-14)_U	1328.3022	USB
7LiH(3-2)_U	1329.414	USB
PH3(5-4)_L	1333.2	LSB
HCO+(15-14)_L	1336.7149	LSB
6LiH(3-2)	1356.928	
H2D+(101-000)	1370.0849	
CO(12-11)	1381.9951	
SH	1383.08	
OD_LOW	1390.614	USB
OD_HIGH	1391.4947	USB

4G-4		
IF Offset	2	
Specie	Rest	SB
18OH2PI32_L	2494.6951	
18OH2PI32_H	2498.9945	
OH2PI32_L	2509.949	
OH2PI32_H	2514.3167	
CO(22-21)	2528.1721	
HD(1-0)_L	2674.9861	

LFA		
IF Offset	1.5	
HCN(14-13)	1239.8903	LSB
HCO+(14-13)	1247.7350	LSB
CO(11-10)	1267.0145	USB
OD	1391.4947	USB
CO(16-15)	1841.3455	USB
CII	1900.5369	LSB
CH_149	2006.7625	USB
OI_145	2060.0688	USB

Frequencies

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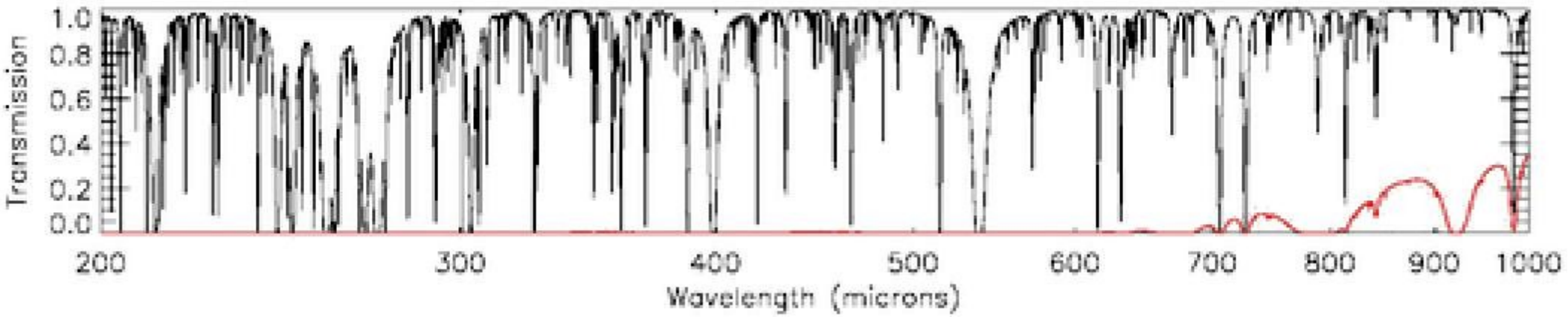
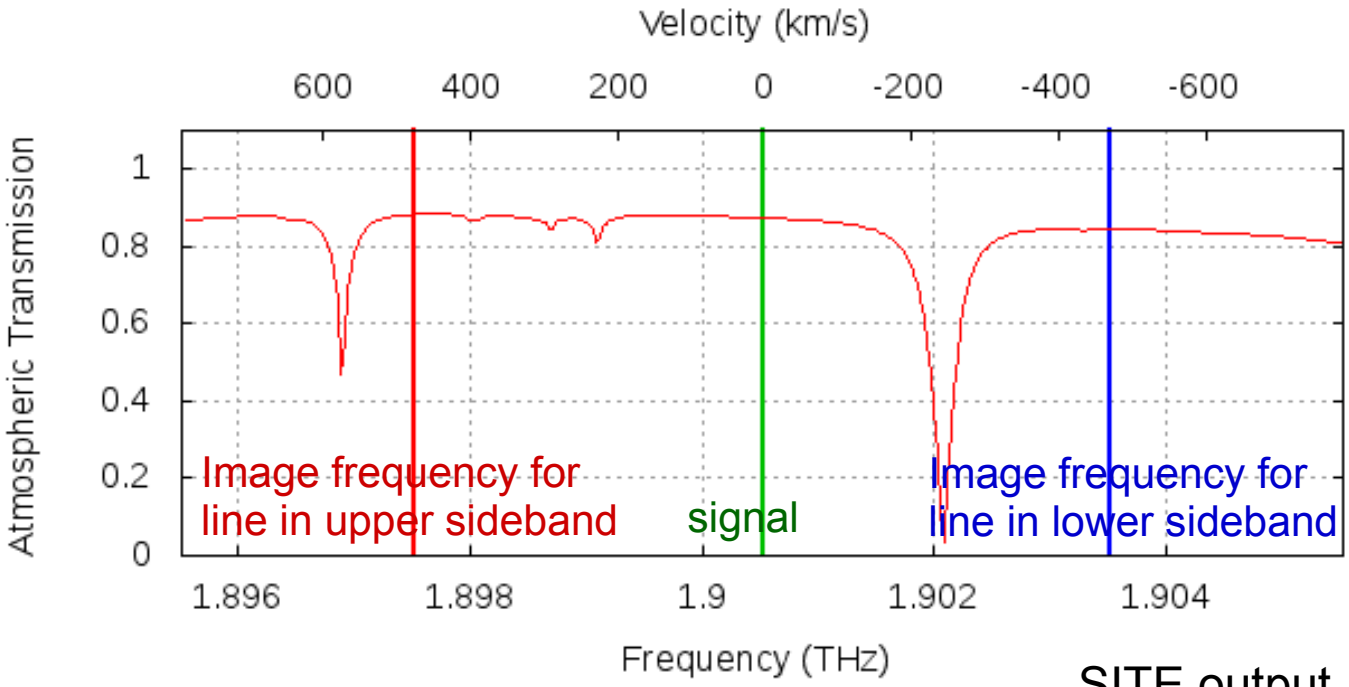
But: Be aware the atmosphere!



- Atmospheric lines cover parts of the bands
- Coverage depends on observing date
- Selection of the sideband where atmospheric noise from image sideband is minimized



SITE output

Atmosphere

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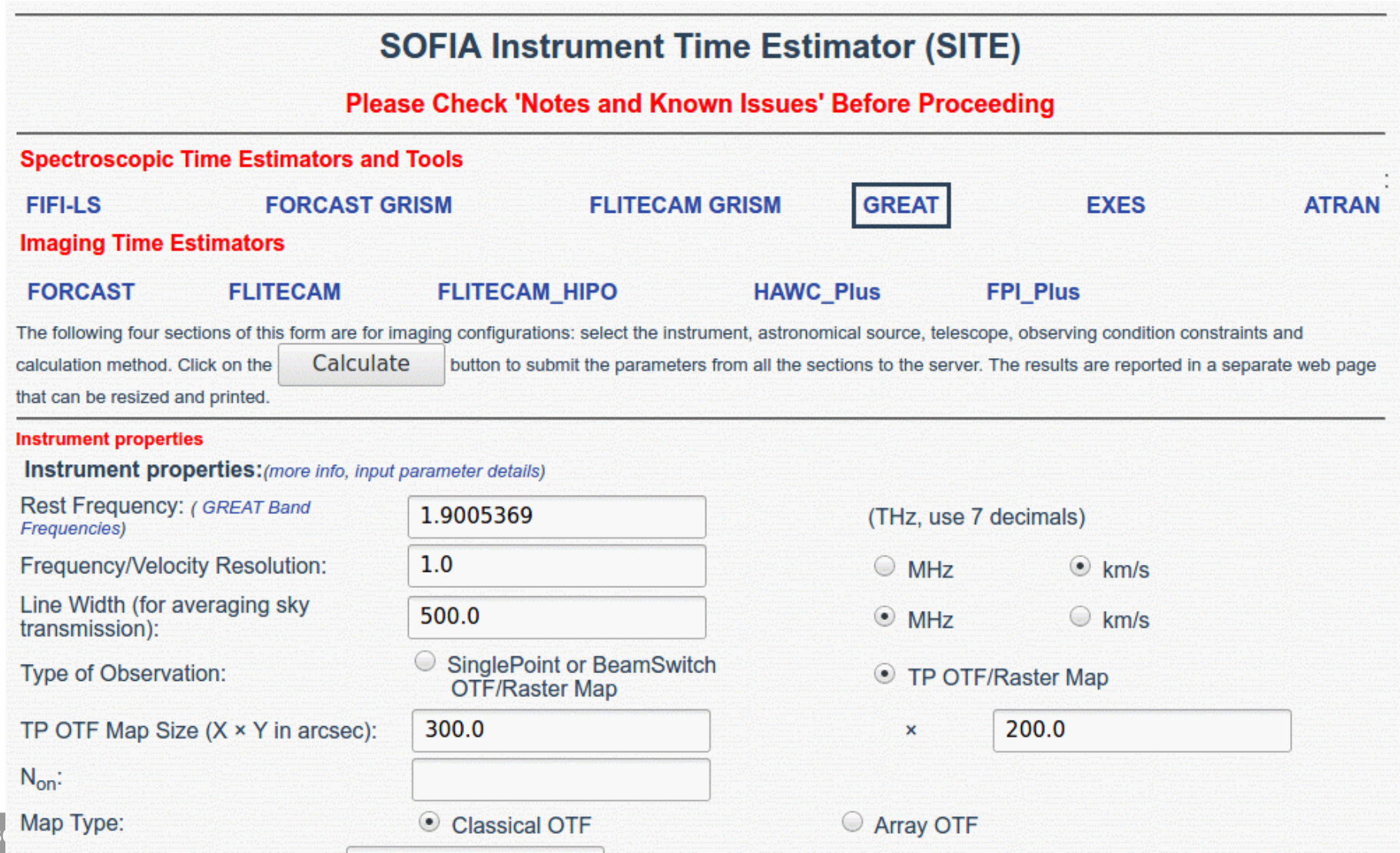
- Check the atmospheric transmission in the time estimator:
  - https://dcs.arc.nasa.gov/proposalDevelopment/SITE/index.jsp



SOFIA Instrument Time Estimator (SITE)

Please Check 'Notes and Known Issues' Before Proceeding

Spectroscopic Time Estimators and Tools

FIFI-LS | FORCAST GRISM | FLITECAM GRISM | GREAT | EXES | ATRAN

Imaging Time Estimators

FORCAST | FLITECAM | FLITECAM_HIPO | HAWC_Plus | FPI_Plus

The following four sections of this form are for imaging configurations: select the instrument, astronomical source, telescope, observing condition constraints and calculation method. Click on the Calculate button to submit the parameters from all the sections to the server. The results are reported in a separate web page that can be resized and printed.

Instrument properties

Instrument properties: *(more info, input parameter details)*

Rest Frequency: *(GREAT Band Frequencies)*	1.9005369	(THz, use 7 decimals)
Frequency/Velocity Resolution:	1.0	○ MHz ◉ km/s
Line Width (for averaging sky transmission):	500.0	◉ MHz ○ km/s
Type of Observation:	○ SinglePoint or BeamSwitch OTF/Raster Map	◉ TP OTF/Raster Map
TP OTF Map Size (X × Y in arcsec):	300.0	× 200.0
N_{on}:		
Map Type:	◉ Classical OTF	○ Array OTF

Atmosphere

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- Check the atmospheric transmission in the time estimator:

Output Parameters

N_{on}	50	
Rest Frequency of the line incl. Doppler correction	1.899933	THz
V_LSR	95.250	km/s
Single Sideband System Temperature (LSB tuning)	2795	K
Single Sideband System Temperature (USB tuning)	3412	K
Integration Time (LSB, ON source per map point)	37.4	seconds
Integration Time (USB, ON source per map point)	55.7	seconds
Mean Atmospheric Transmission (RestFreq)	0.87	
Mean Atmospheric Transmission (USB)	0.83	
Mean Atmospheric Transmission (LSB)	0.60	

Assumed Parameters

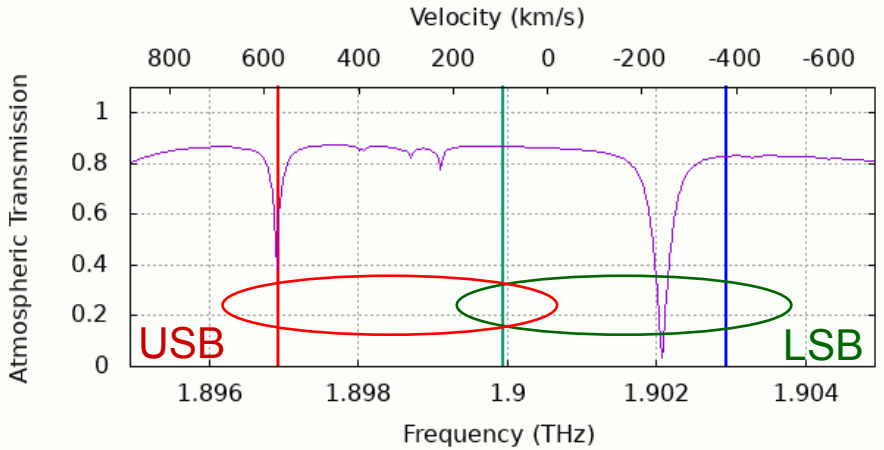
Ambient temperature for the atmosphere	178.0	K
Physical Temperature of the Telescope	188.0	K
Telescope Efficiency incl. ohmic losses and spillover	0.92	
Double Side Band Receiver Temperature	1050.0	K
Forward Scattering Efficiency	0.97	

Input Parameters

Observation Type	TP OTF Mapping	
Rest Frequency	1.900537	THz
Spectral Resolution	1.000	km/s
Line Width	10.000	km/s
OTF Map Size	300.0 X 200.0	arcseconds
Map Type	Classical OTF	
Calculation Method	Estimate Integration Time for given SNR and line strength	
Total signal to noise	5.0	
Brightness Temperature	1.0	K
Source Velocity	80.0	km/s

Observer Velocity Type - Computed value of 15.249691507352562 km/s based on

Plot of Atmospheric Transmission



The green line shows the position of the line in the signal sideband.
The red line shows where the image band would be if the line is placed in the upper sideband.
The blue line shows where the image band would be if the line is placed in the lower sideband.

Planning

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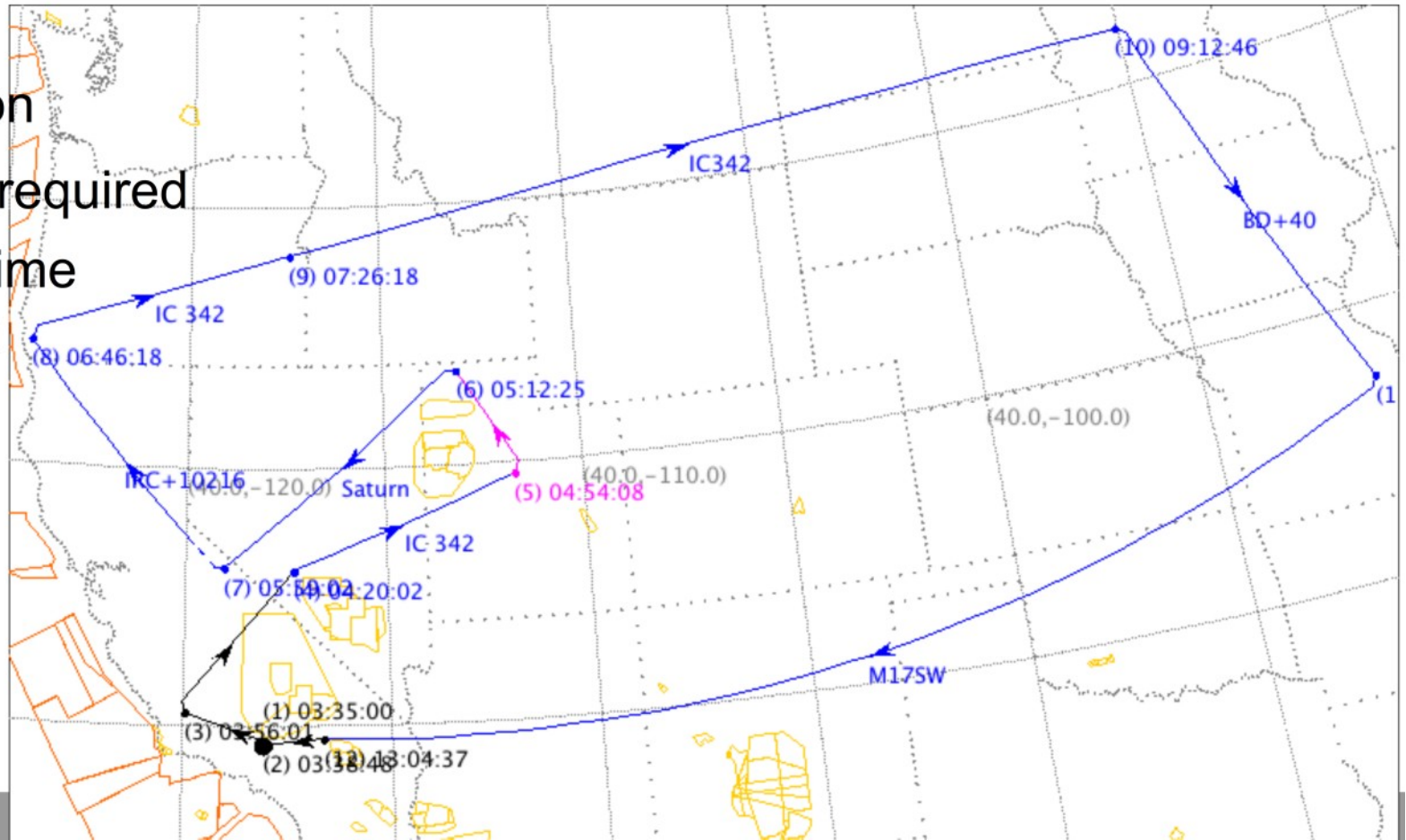
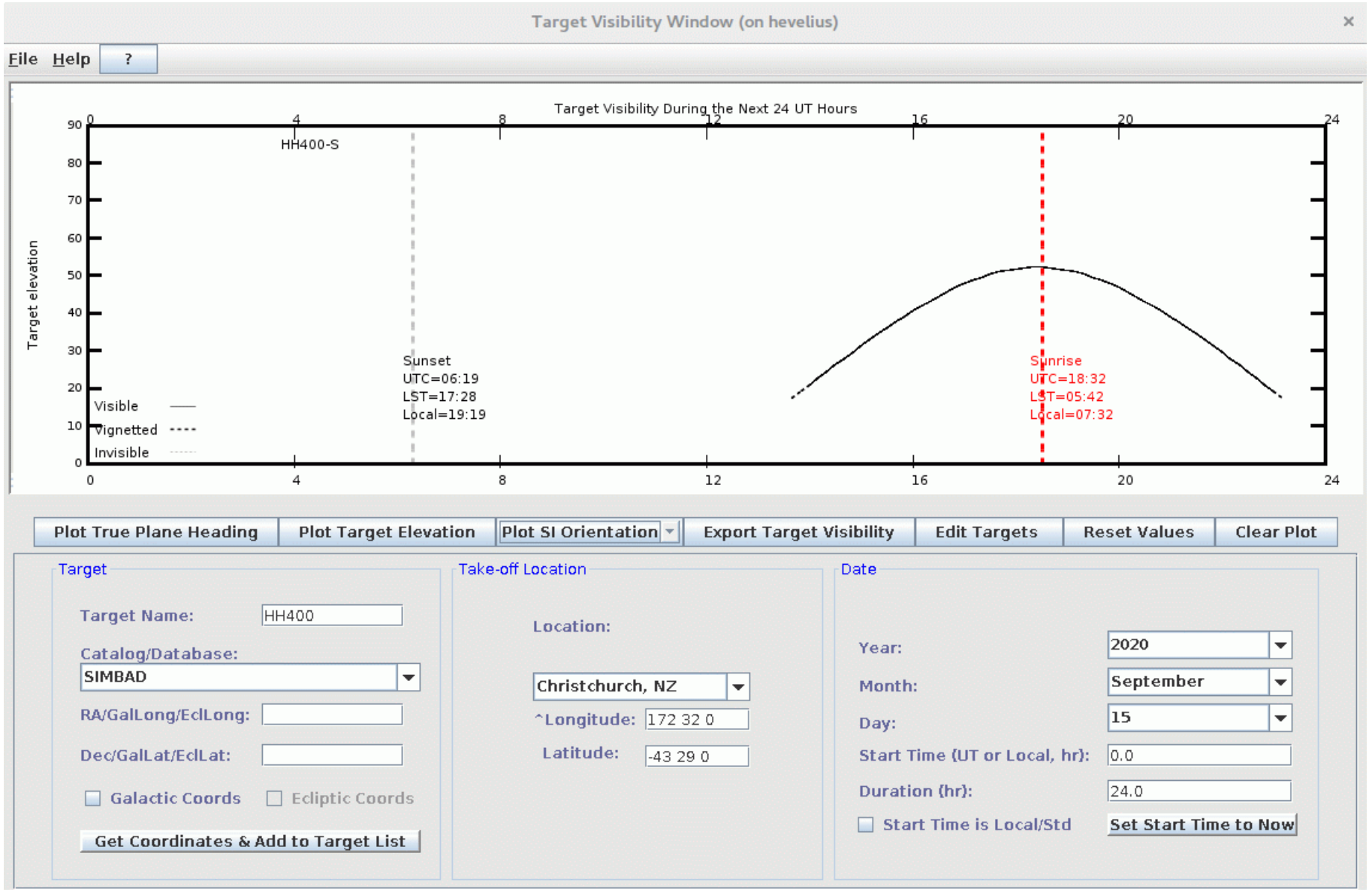
- Time constraints:
  - LSR velocity of source relative to atmospheric features
    - GREAT time estimator
  - Visibility at observing altitude
    - 20°-60°
  - Flight direction
    - Round-trip required
    - Maximum time per lag ~3h



Planning

- Visibility Tool (in USPOT):



Observing modes

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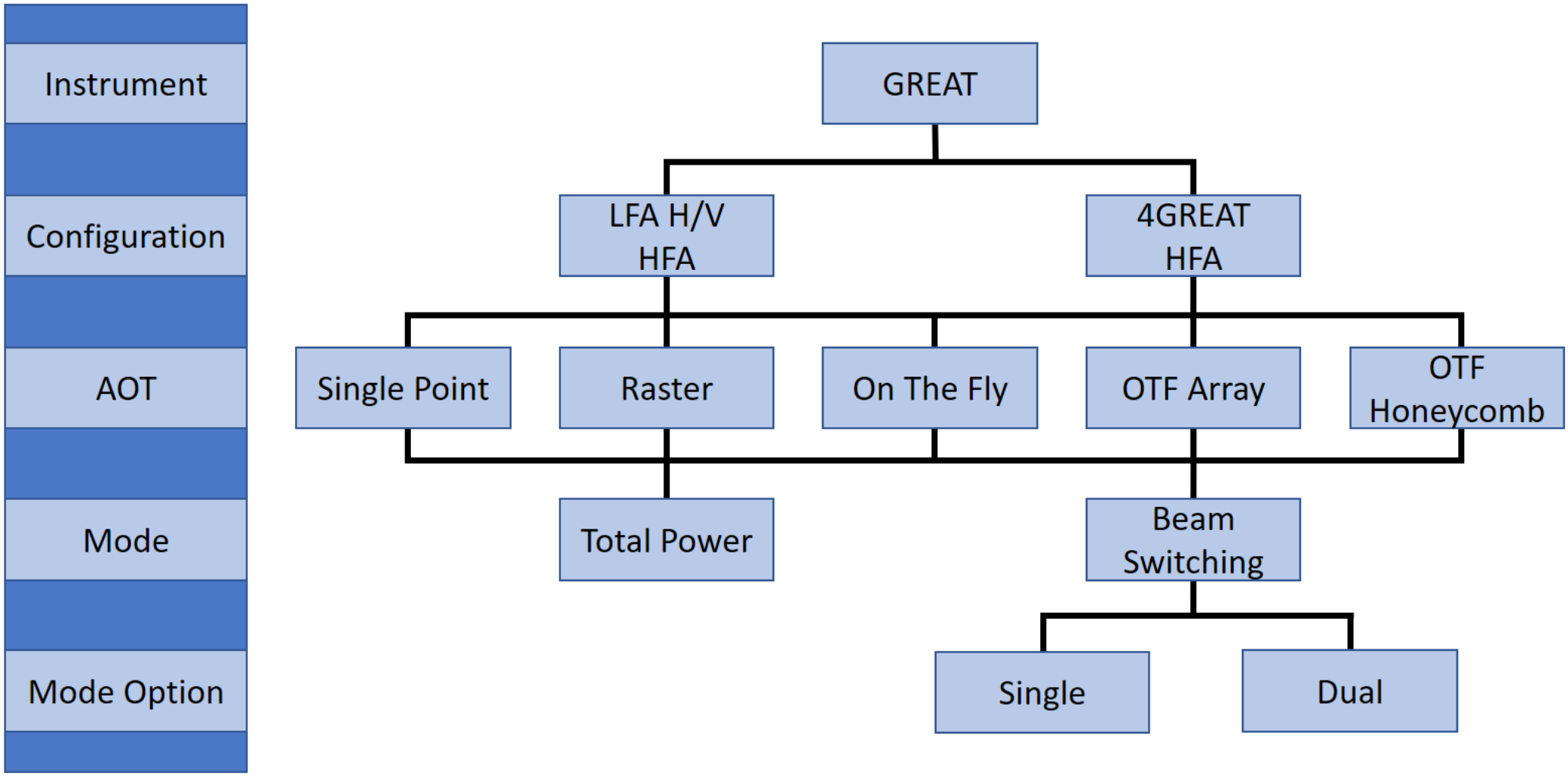
- Detector arrays only in fixed combinations offered:



Observing modes

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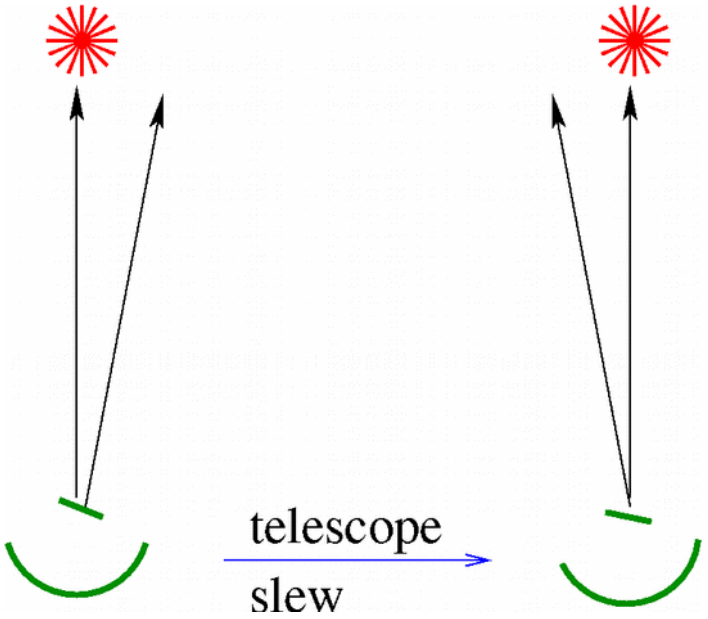
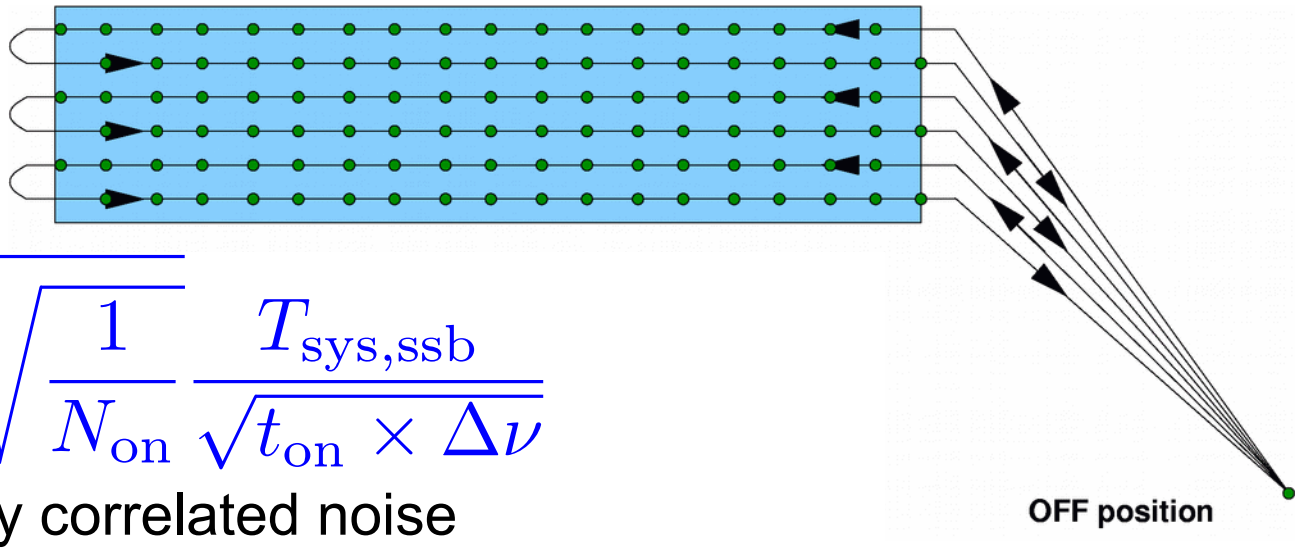
- Symmetric modes $t_{\rm on} = t_{\rm off}$
  - e.g. double-beam switch (=chop-nod)
  - for broad lines/instable frequencies

$$T_{\rm rms,ssb} = \frac{2 \times T_{\rm sys,ssb}}{\sqrt{(t_{\rm on} + t_{\rm off}) \times \Delta\nu}}$$



- OTF mapping
  - Combines $N_{\rm on}$ map points with a single OFF measurement
  - Saves time and noise



$$T_{\rm rms,ssb} = \sqrt{1 + \sqrt{\frac{1}{N_{\rm on}}}} \frac{T_{\rm sys,ssb}}{\sqrt{t_{\rm on} \times \Delta\nu}}$$

  - But introduces spatially correlated noise

Mapping modes

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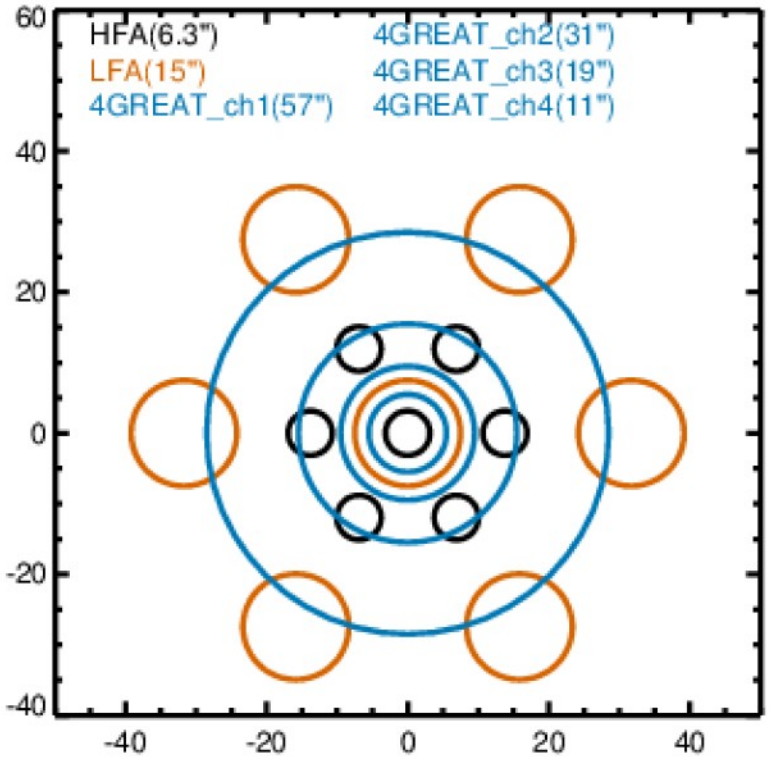
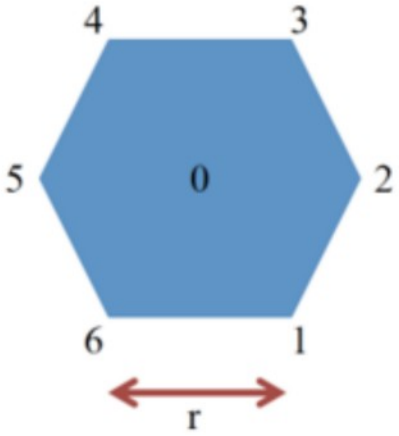
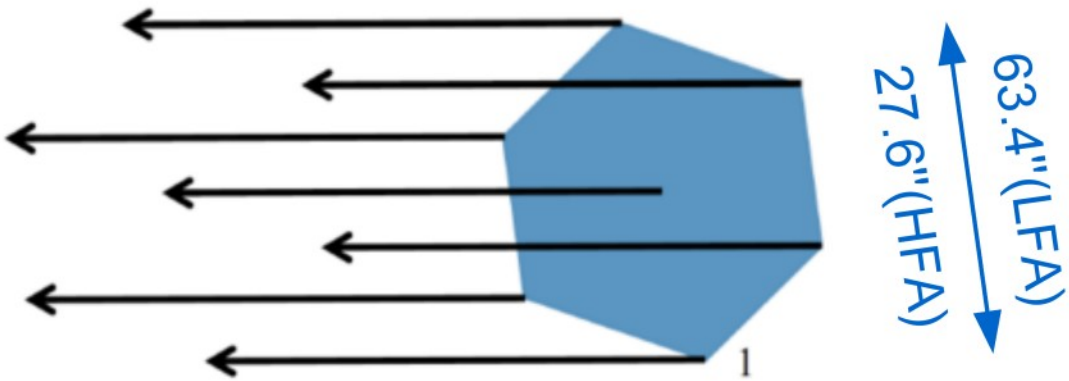
DLR-Pf

- Combine with receiver geometry
  - Single pixels (4GREAT)
    - Use Nyquist sampling or half-beam sampling depending on beam width
  - Array mapping (LFA, HFA)
    - Array tilt by 19.1 degrees provides equal spacing of scan lines

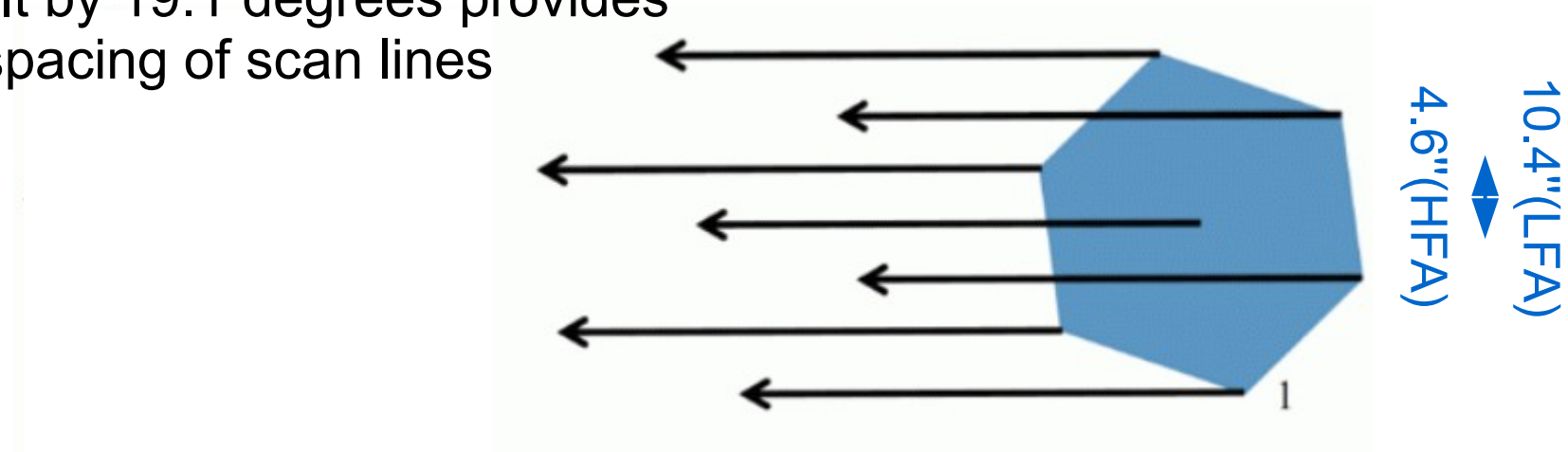




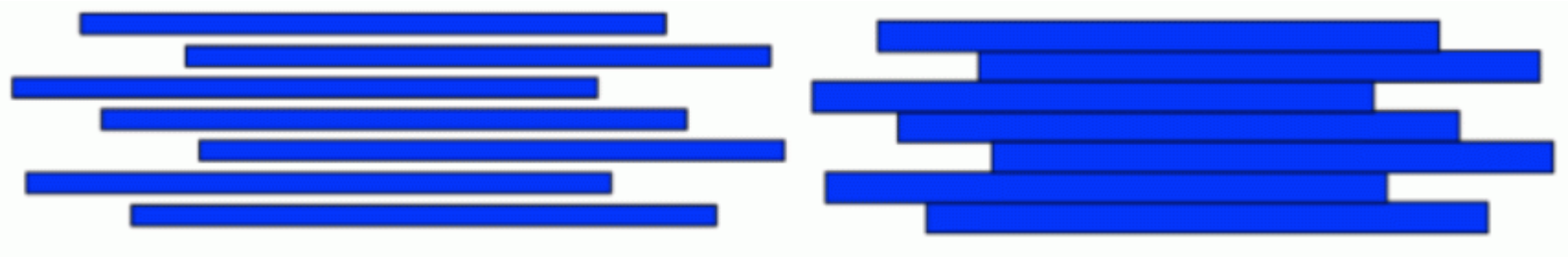


Mapping modes

- Array mapping (LFA, HFA)
  - Array tilt by 19.1 degrees provides equal spacing of scan lines



  - Two adjacent scans provide fully sampled maps



- 5.2" spacing for LFA
- 2.3" spacing for HFA

Mapping modes

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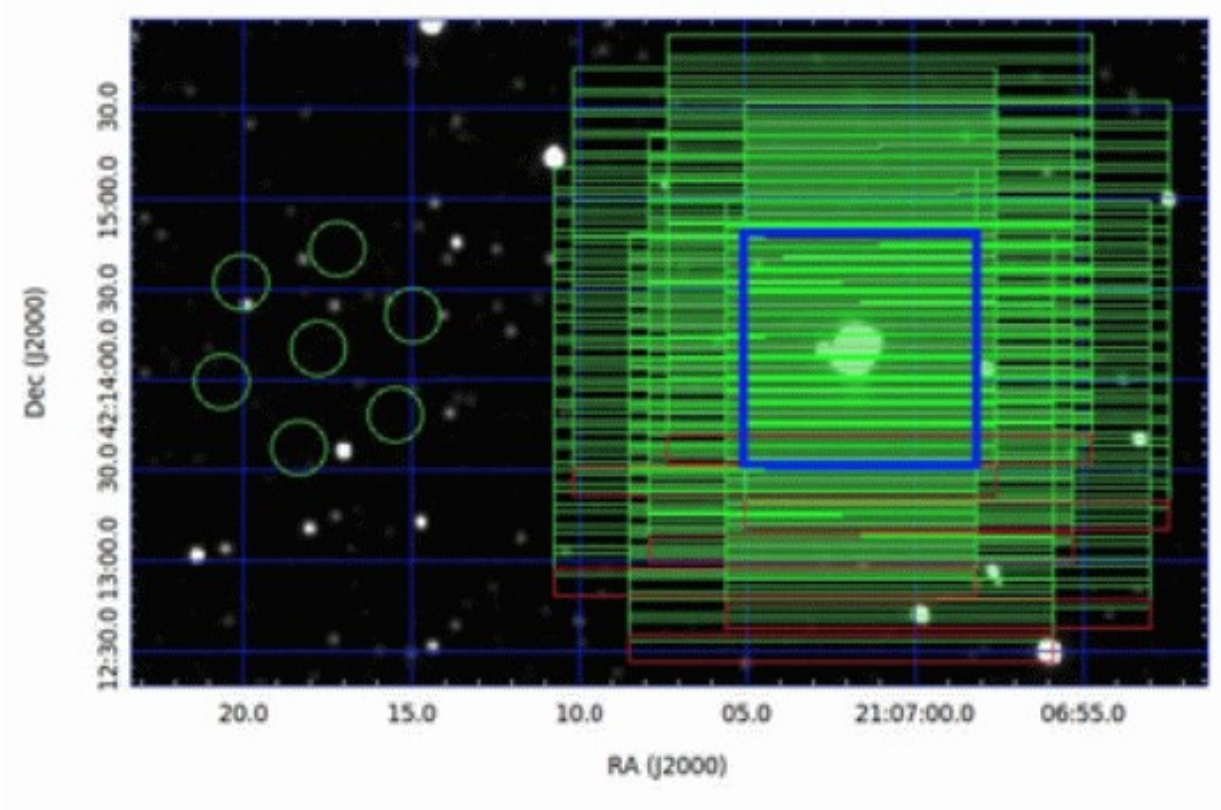
- Classical OTF
  - Every pixel covers every part of the map
  - Allows to compensate for different pixel sensitivities
    - Provides uniform noise over the map
    - Gradual increase at the edges
  - Arbitrary map size
  - Best mode for majority of observations



Mapping modes

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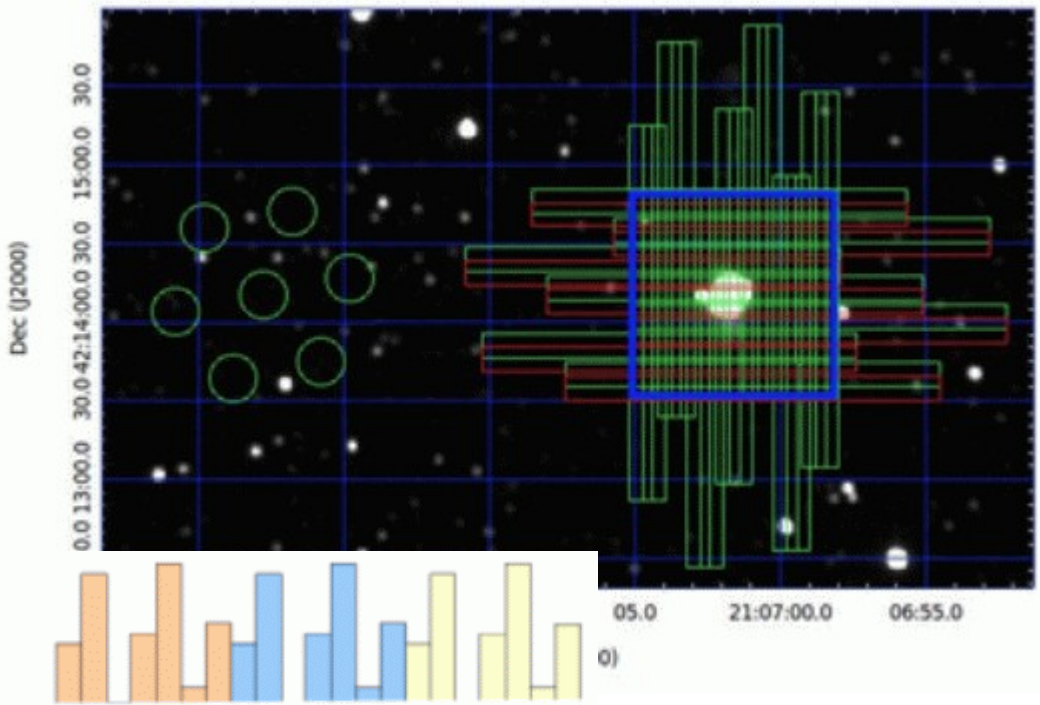
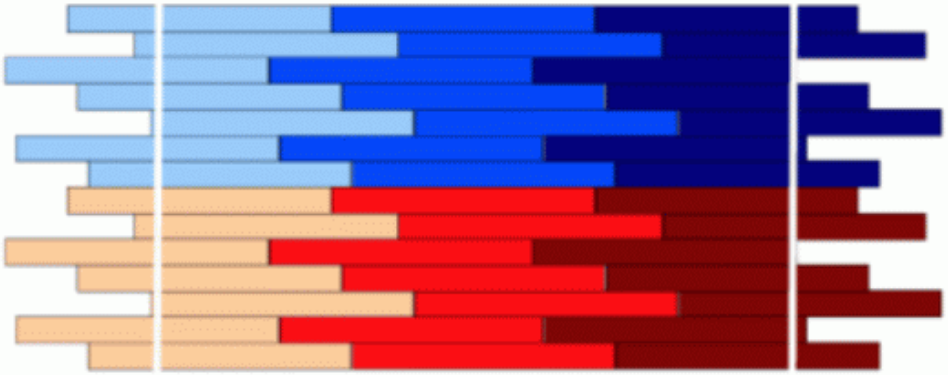
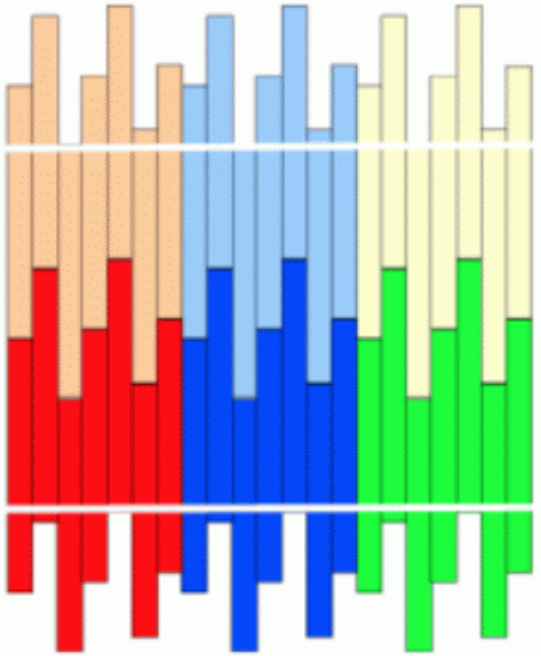
DLR-Pf

- Array OTF
  - Assembly of map from fastest array coverages
  - Mosaicing for large areas
    - 73.8" (LFA), 32.2" (HFA)
  - Possible stripes in noise pattern for varying pixel sensitivities
  - Not in HFA-LFA combination







  - For strong extended sources with short integration time

Mapping modes

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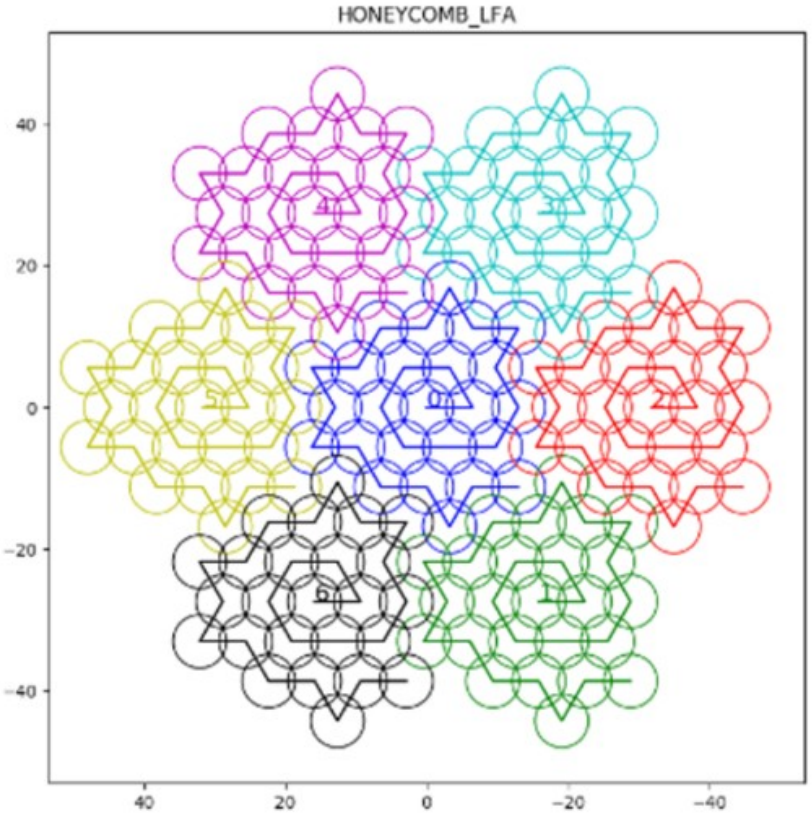
DLR-Pf

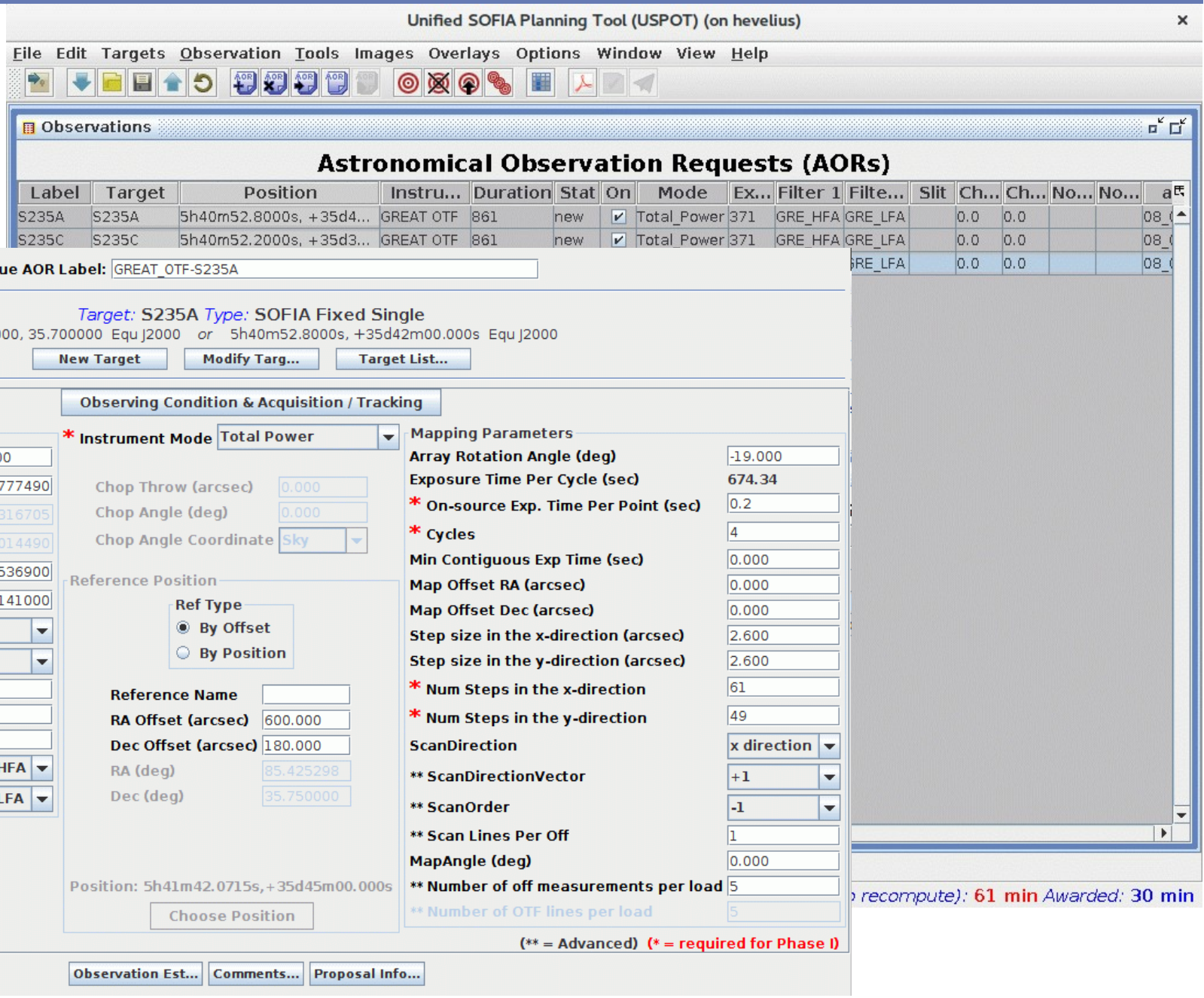
- Honeycomb-OTF
  - Fills in the spaces between the array pixels by quasi-spiral motion
  - Avoids irregular map edges
  - Hexagonal pattern
    - Mosaicing for larger areas possible
  - Patchy noise pattern possible in case of varying pixel sensitivities
  - Not in HFA-LFA combination
  - Ideal for sources with about the size of the arrays



Visualization

MPIfR
KOSMA
MPS
DLR-Pf

- USPOT (4.3.1):



Visualization

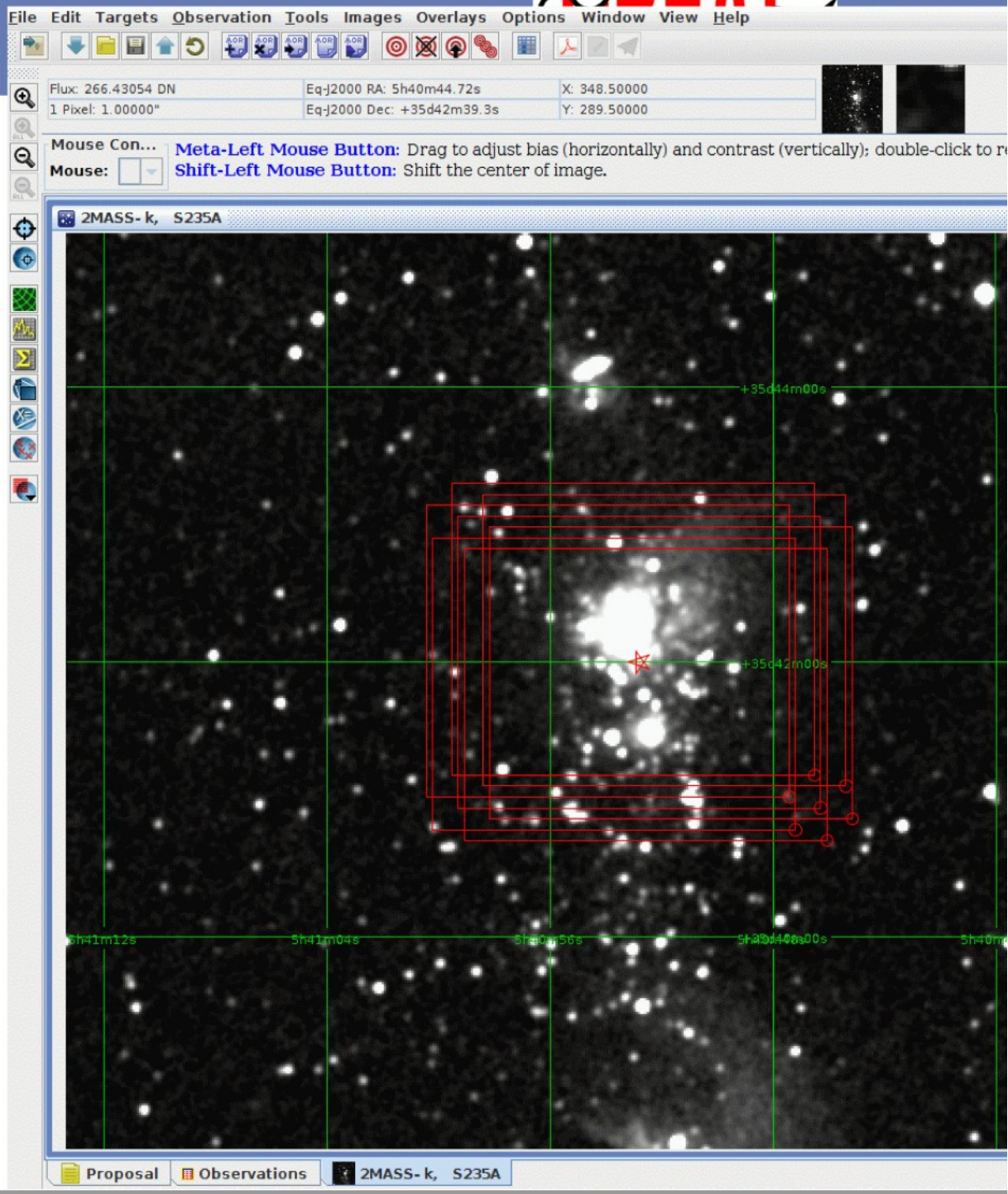
MPIfR
KOSMA

- Classical OTF:

Mapping Parameters

Array Rotation Angle (deg)	-19.000
Exposure Time Per Cycle (sec)	674.34
* On-source Exp. Time Per Point (sec)	0.2
* Cycles	4
Min Contiguous Exp Time (sec)	0.000
Map Offset RA (arcsec)	0.000
Map Offset Dec (arcsec)	0.000
Step size in the x-direction (arcsec)	2.600
Step size in the y-direction (arcsec)	2.600
* Num Steps in the x-direction	61
* Num Steps in the y-direction	49
ScanDirection	x direction
** ScanDirectionVector	+1
** ScanOrder	-1
** Scan Lines Per Off	1
MapAngle (deg)	0.000
** Number of off measurements per load	5
** Number of OTF lines per load	5

(** = Advanced) (* = required for Phase I)



Visualization

MPIfR
KOSMA

- Array OTF:

Parameters for Scans | Mapping

Parameters for scans in x direction

* Scan length in units of array size (31.6" or 72.6")	5.000
* Number of blocks in scan direction	1
* Number of blocks perpendicular to scan direction	4
* Exp. Time per Point (sec)	0.7

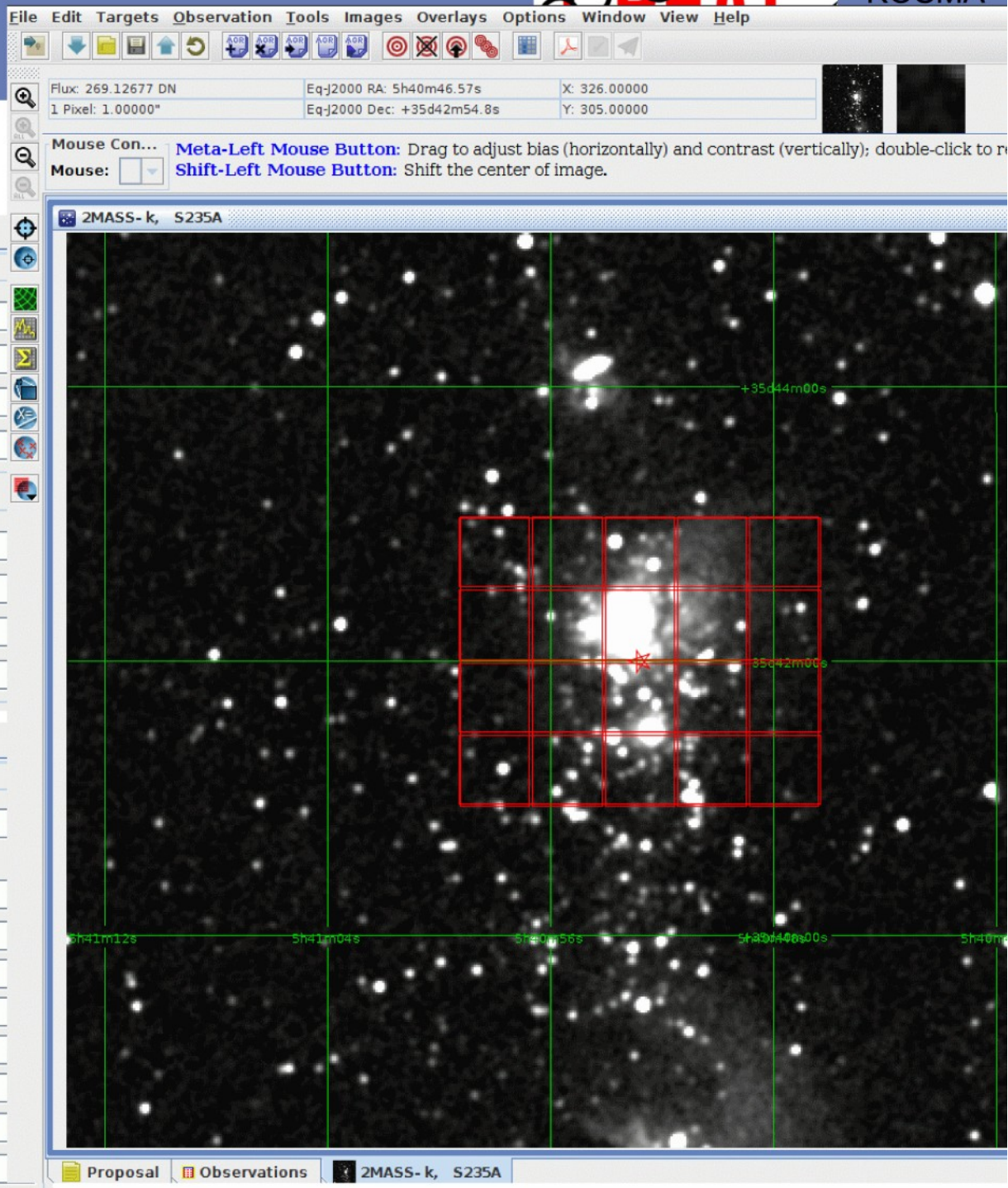
Parameters for scans in y direction

* Scan length in units of array size (31.6" or 72.6")	4.000
* Number of blocks in scan direction	1
* Number of blocks perpendicular to scan direction	5
* Exp. Time per Point (sec)	0.7

Parameters for Scans | Mapping

Mapping Parameters

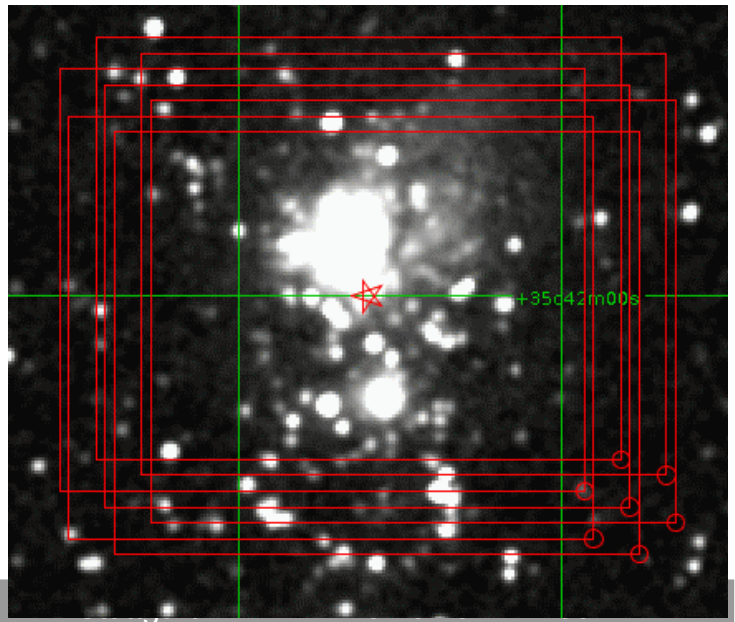
Array Rotation Angle (deg)	-19.000
Exposure Time Per Cycle (sec)	684.471
* Cycles	4
Min Contiguous Exp Time (sec)	0.000
MapAngle (deg)	0.000
Map Offset RA (arcsec)	0.000
Map Offset Dec (arcsec)	0.000
** Number of OTF lines within one block	2
* Step size along OTF line	3.000
** Scan Lines Per Off	1
ScanDirection	x and y directions



Time estimates

MPIfR
KOSMA
MPS
DLR-Pf

- Output from SITE for GREAT → USPOT (4.3.2)
  - Single point observations
    - Use $t_{on+toff}$ in USPOT as given by time estimator
  - Single beam switch / double beam switch mapping
    - Divide $t_{on}+t_{off}$ by 2 for input as t_{on} in USPOT
  - Array-OTF
    - Use t_{on} in USPOT as given by time estimator
  - Classical OTF
    - Divide t_{on} from time estimator by number of pixels for central area
      - 1/14 for LFA
      - 1/7 for HFA
  - But: unavoidable increase of noise at edges



Data delivery

MPIfR
KOSMA
MPS
DLR-Pf

- Release:

Proposal Identification	75_0015	
Project Title	Horsehead and the IC434 PDR interface	
Principle Investigator	E. Young	eyoung@sofia.usra.edu
SMO contact person	G. Sandell, E. Chambers	gsandell@sofia.usra.edu, echambers@sofia.usra.edu
GREAT processing liaison	D. Riquelme (MPIfR)	riquelme@mpifr-bonn.mpg.de

Observations			
Mission Identification	2015-12-11-GR_F266		
Flight date	2015 December 11		
GREAT configuration [1,2]	front-ends: LFA	back-ends: 4GFFT spectrometers	
Astronomical Sources	Horsehead, IC434	Scans: 12715-12790	lines: CII

Calibrated data products	based on: kosma_calibrator ver. December 2015, GILDAS software ver. Nov15a	
product level	file name	description
3a	Cycle3_GR_DDT_75_0015_EYoung_Ta.great	Calibrated to T_A^* scale (η_f = 0.97).
	Cycle3_GR_DDT_75_0015_EYoung_Ta_reduced.great	Calibrated to T_A^* scale, baselines removed as explained in the Data Reduction letter. All scans quality validated.
	Cycle3_GR_DDT_75_0015_EYoung_Tmb_CII.great	Calibrated[3] to T_{mb} scale, using η_{mb} (LFA-V) = (0.67, 0.71, 0.71, 0.70, 0.65, 0.66, 0.71) η_{mb} (LFA-H) = (0.66, --, 0.60, --, 0.66, 0.68, 0.70). Pixel H1 and H3 are not included. Independent fit of dry & wet atmosphere. Created with Cycle3_GR_DDT_75_0015_EYoung.class.
3b	Cycle3_GR_DDT_75_0015_EYoung_CII.lmv	Gridded map for CII (1/σrms2 weighting of individual spectra, σrms baseline noise). See the attached CLASS script for details of the data processing.
	Cycle3__GR_DDT_75_0015_EYoung_CII.fits	Equivalent map in fits format, and
	Cycle3__GR_DDT_75_0015_EYoung_CII_final.fits	with an outer rim (45") removed.

Data delivery

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- Release:

The data were acquired on Dec 11 (SOFIA flight #266), the observing scripts are described in the GREAT flight dossier GP9700066. The large area to be studied was divided into 4 slightly overlapping sub-fields, each field was covered several times (scanning in orthogonal directions), then repeating the cycle with the array orientation rotated by +60 deg. The final map reveals a very uniform noise distribution (~2 K for a spectral resolution of 0.19 km/s). Data was taken fast "on-the-fly" (dump times 0.3-0.4 sec) on a 6" grid (the half-power beam width of upGREAT at the [CII] frequency is 15.1"]. The on-sky reference position was at offset -733,+27.5" (RA,Dec) to the nominal center position of the map.

The data has been processed with the latest version of the GREAT calibrator. The data package (attached as .tar file) does contain

- an overview, providing basic information about your project
- data product level 3, containing
  - (a) the calibrated spectra in standard CLASS format, and
  - (b) the final data product (map) as "lmv"-data cube.
- the *.class script used in CLASS to process the data.
- a read-me file with details of the data reduction
- a brief log of the observations.

If you have questions about the data, the way they were processed or the observations proper, feel free to contact D. Riquelme (riquelme@mpifr-bonn.mpg.de), your data processing liaison.

Data reduction

MPIfR
KOSMA
MPS
DLR-Pf

- GILDAS (CLASS):
  - Change spectral and/or spatial resolution
  - Baseline subtraction
  - Inspection / export

```
file in Cycle3_GT_DDT_75_0015_EYoung_Tmb.great
find
list /toc

file out Horsehead_smoothed.great s /o
for i 1 to found
    get next
    smooth box 5
    base 1
    write
    next

file in Horsehead_smoothed.great
find

set weight sigma
table Horsehead_DDT_CII new /range -50 80 v  /nocheck
let map%beam '15.1'
let map%cell 6.0 6.0
xy_map Horsehead_CII

let name Horsehead_CII
let type lmv
go view
```

Example

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let name Horsehead_CII
let type lmv
go view