How to observe with upGREAT on SOFIA

Volker Ossenkopf-Okada, I. Physikalisches Institut, Universität zu Köln

Overview

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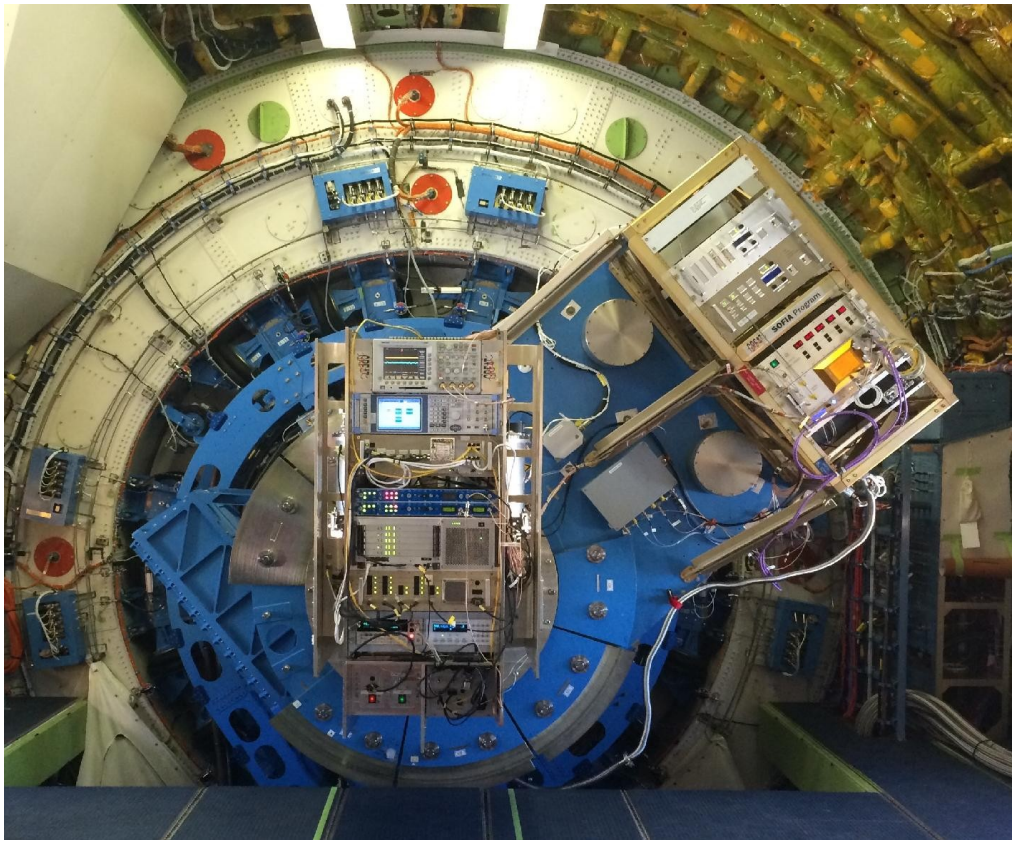
MPS
DLR-Pf

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



Prerequisite – good science driver

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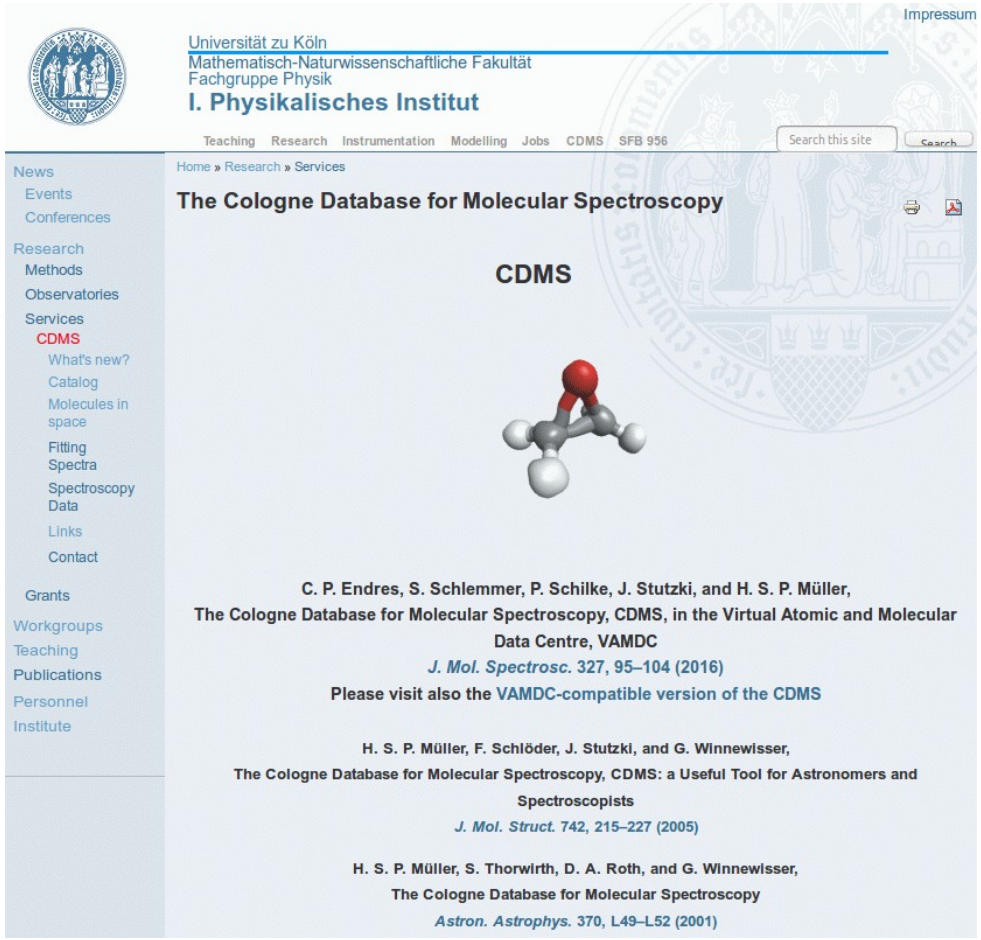
See tutorial of W.T. Reach

- 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?



Main sources of info

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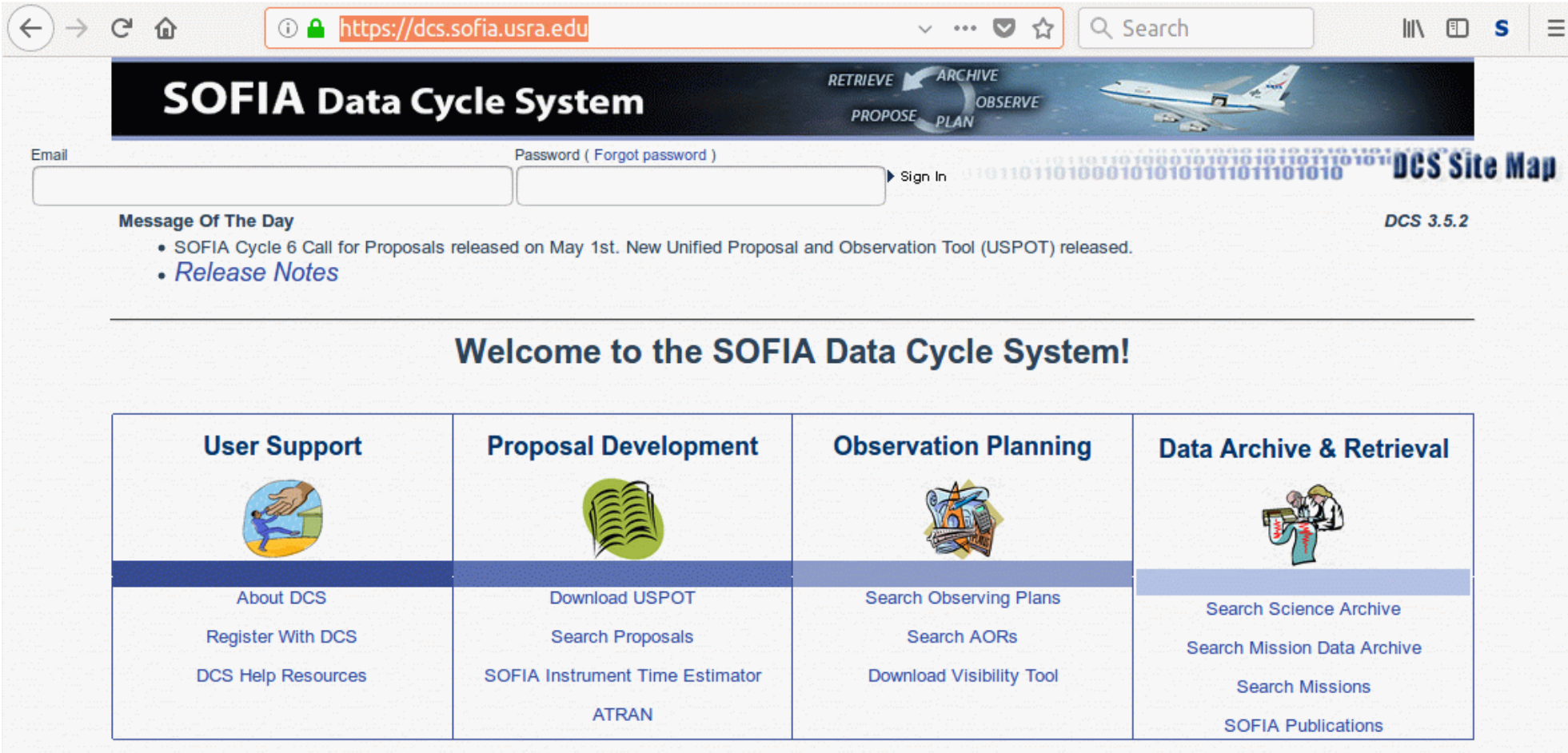

- GREAT time estimator: https://great.sofia.usra.edu/cgi-bin/great/great.cgi
- VT (Visibility tool)
- USPOT (Proposal handling system)

Main sources of info

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- SOFIA Observers Handbook
  - https://www.sofia.usra.edu/science/proposing-and-observing/sofia-observers-handbook-cycle-6

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

GREAT

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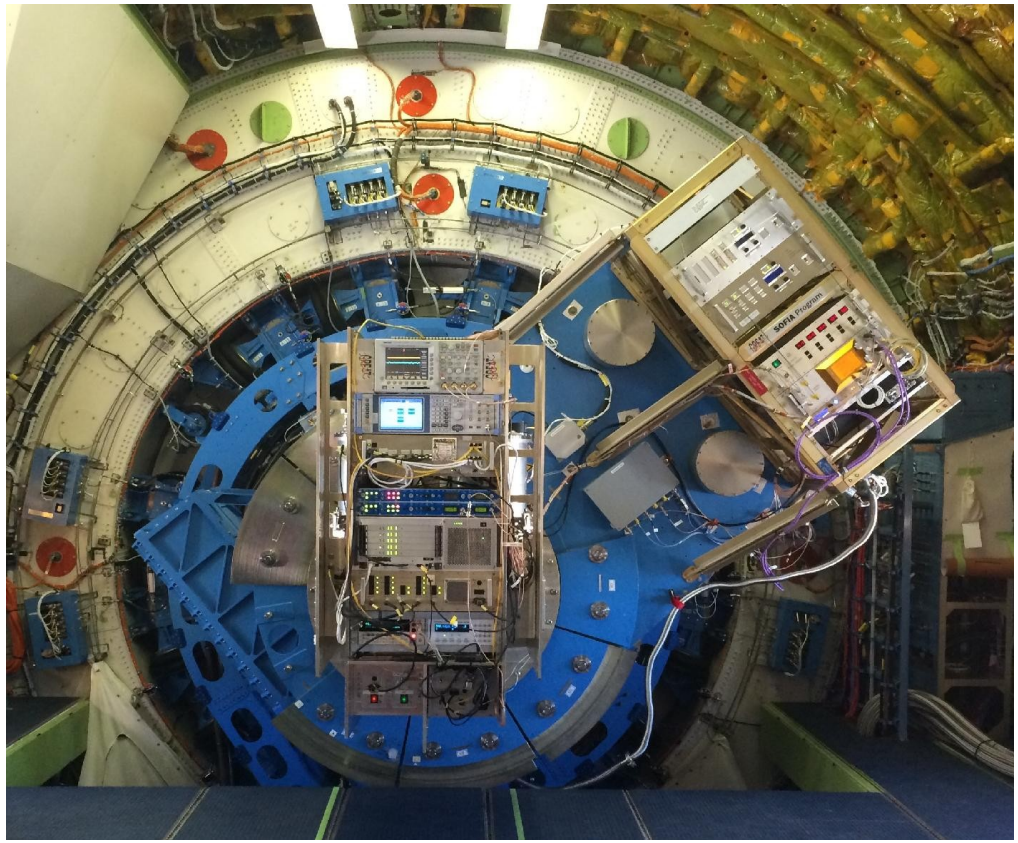
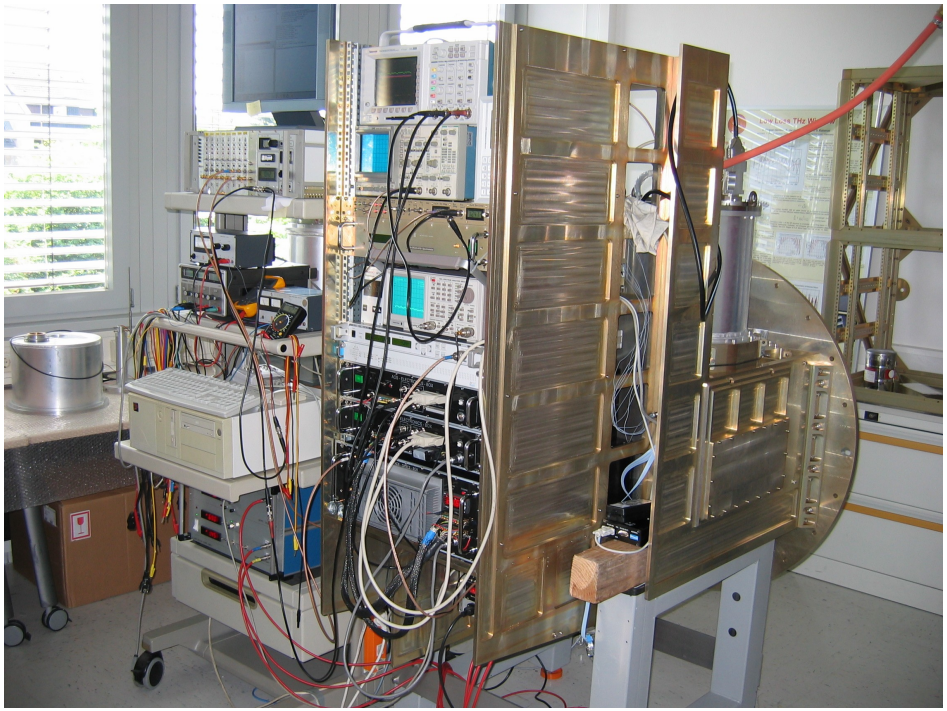
German REceiver for Astronomy at Terahertz-Frequencies

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



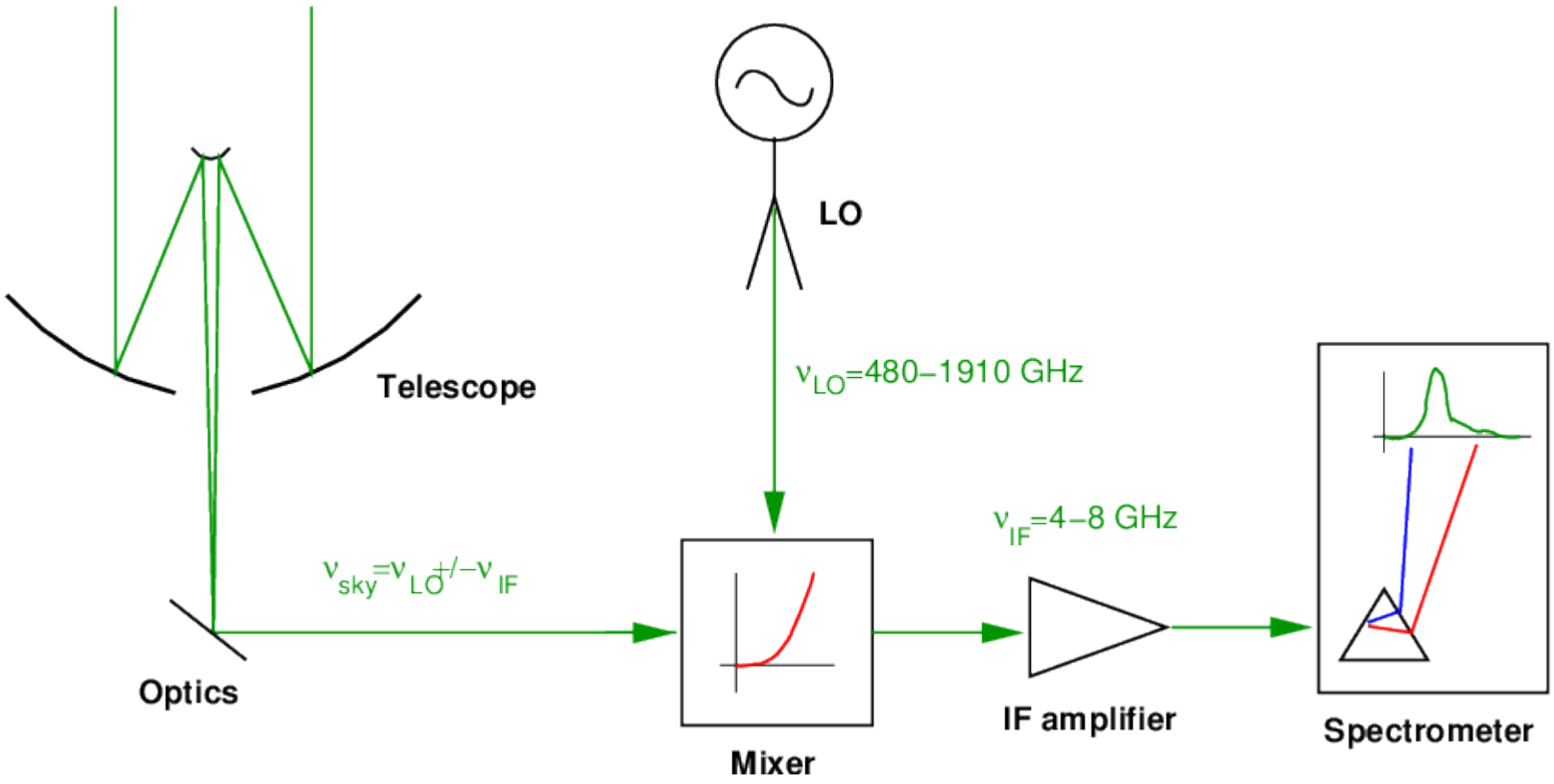


- Spectrometers: FFTS4G
  - 16k channels
  - Bandwidth: 4GHz
  - Resolution: 283kHz ($R = 10^7$)

Basics

Heterodyne principle

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



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

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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

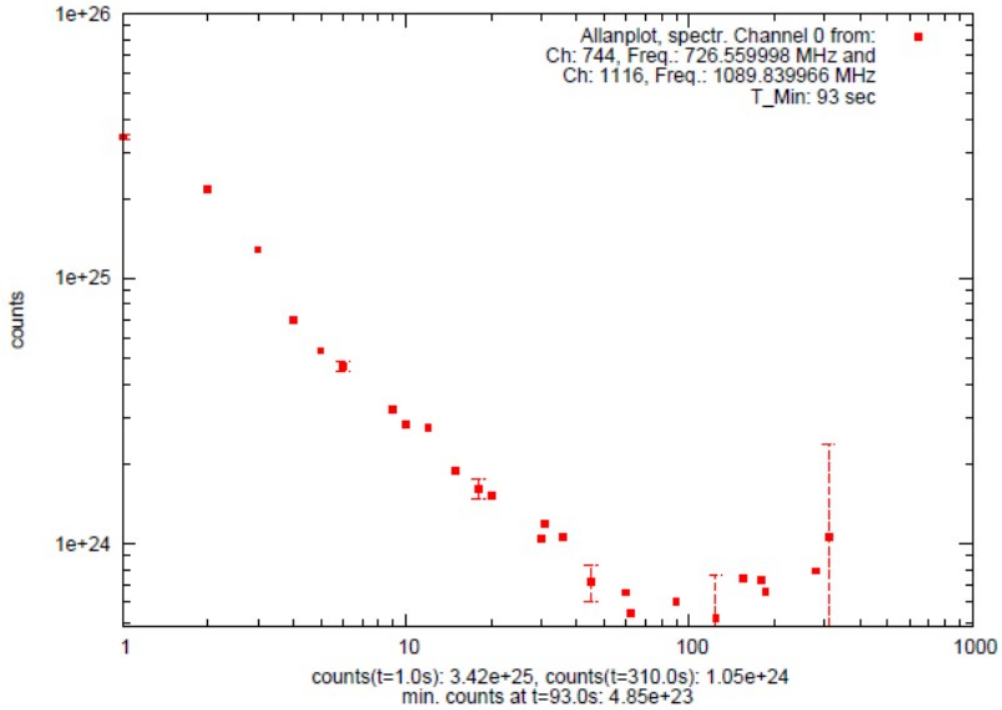
$$T_{\rm rms,ssb} = \frac{T_{\rm sys,ssb}}{\sqrt{t_{\rm int} \times \Delta\nu}}$$

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

Basics

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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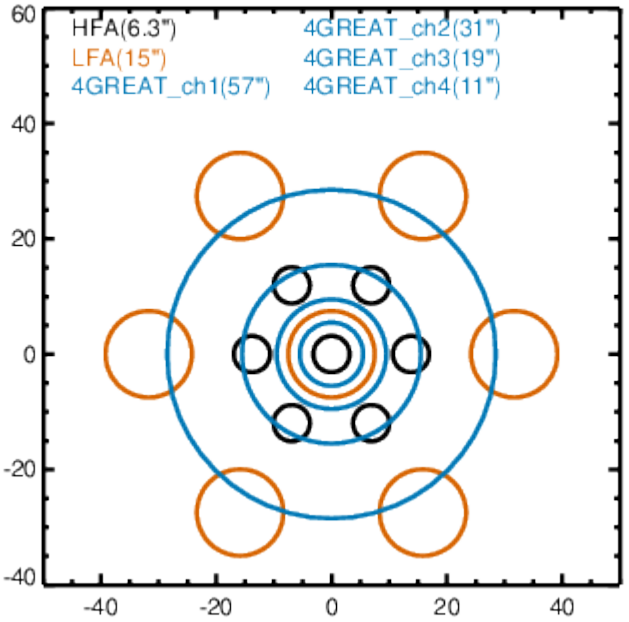
Frequencies:

Channel		Frequencies [THz]	Pixels	Lines of interest	$T_{rec,dsb}$[K]
4GREAT	4G1	0.490-0.635	1	[CI], CH, CO, NH_3, $H_2{}^{18}O$	120
4GREAT	4G2	0.890-1.100	1	NH, OH^+, CO, HDO	350
4GREAT	4G3	1.20-1.53	1	[NII], CO, OD, SH, H_2D^+	1100
4GREAT	4G4	2.48-2.69	1	OH	1700
upGREAT	LFA	1.83 – 2.01	2x7	CO, [CII], [OI], OH	1050
upGREAT	HFA	4.74	7	[OI]	1100

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



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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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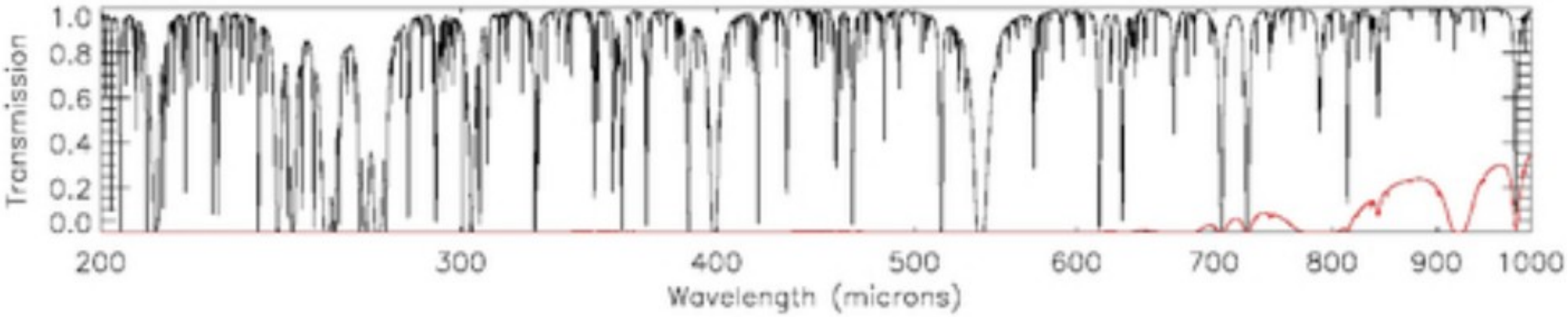
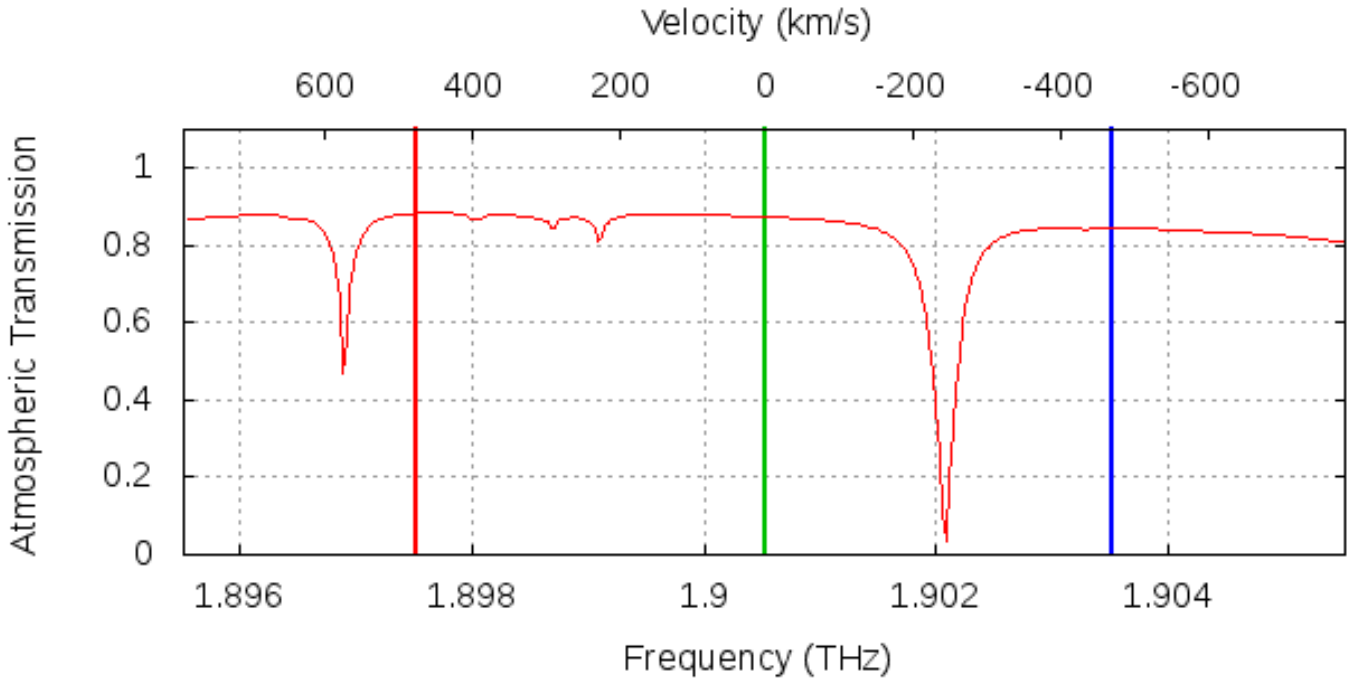
But: Be aware the atmosphere!



- Atmospheric lines cover parts of the bands
- Coverage depends on observing date
- Selection of the sideband



Atmosphere

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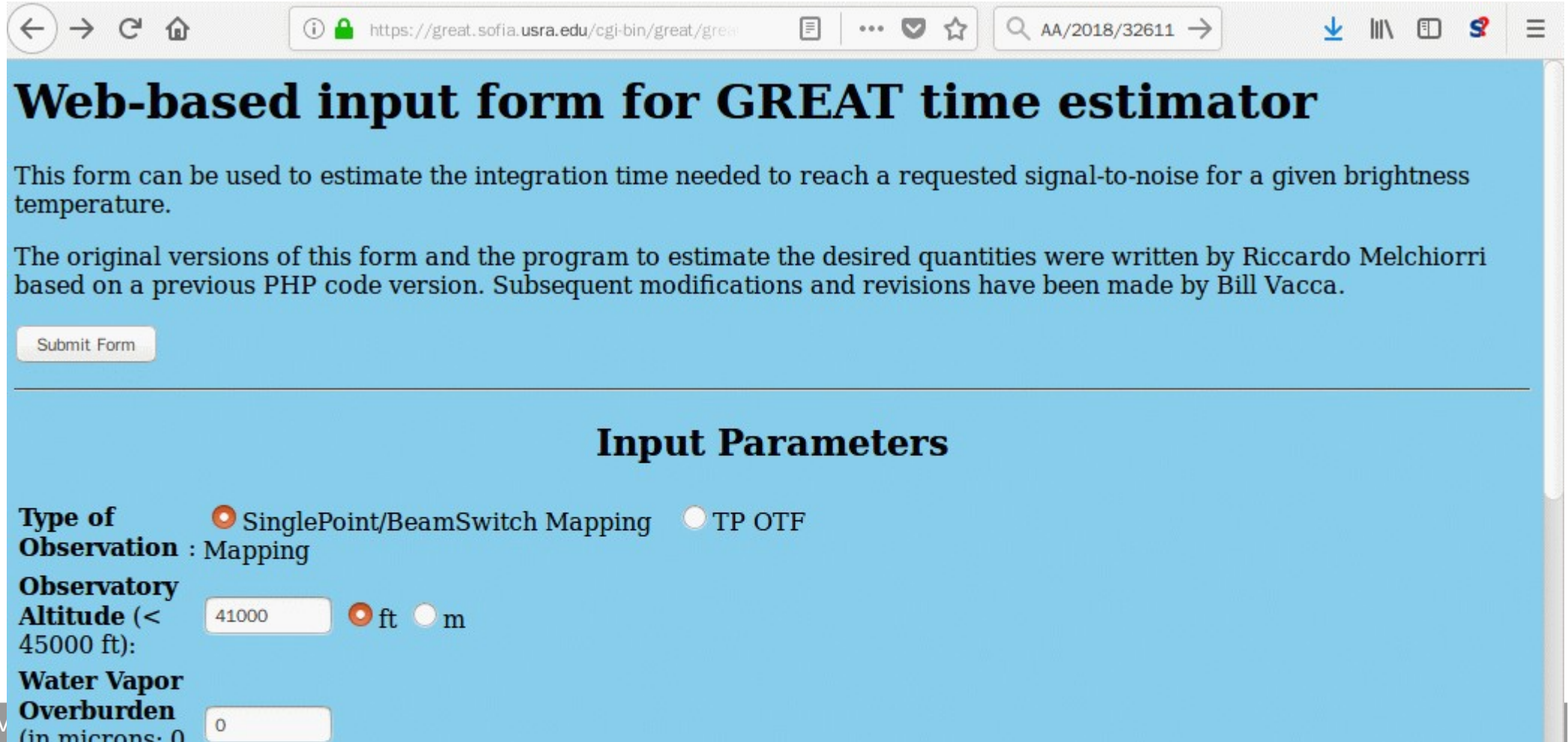
- Check the atmospheric transmission:
  - GREAT time estimator:
    - https://great.sofia.usra.edu/cgi-bin/great/great.cgi



Planning

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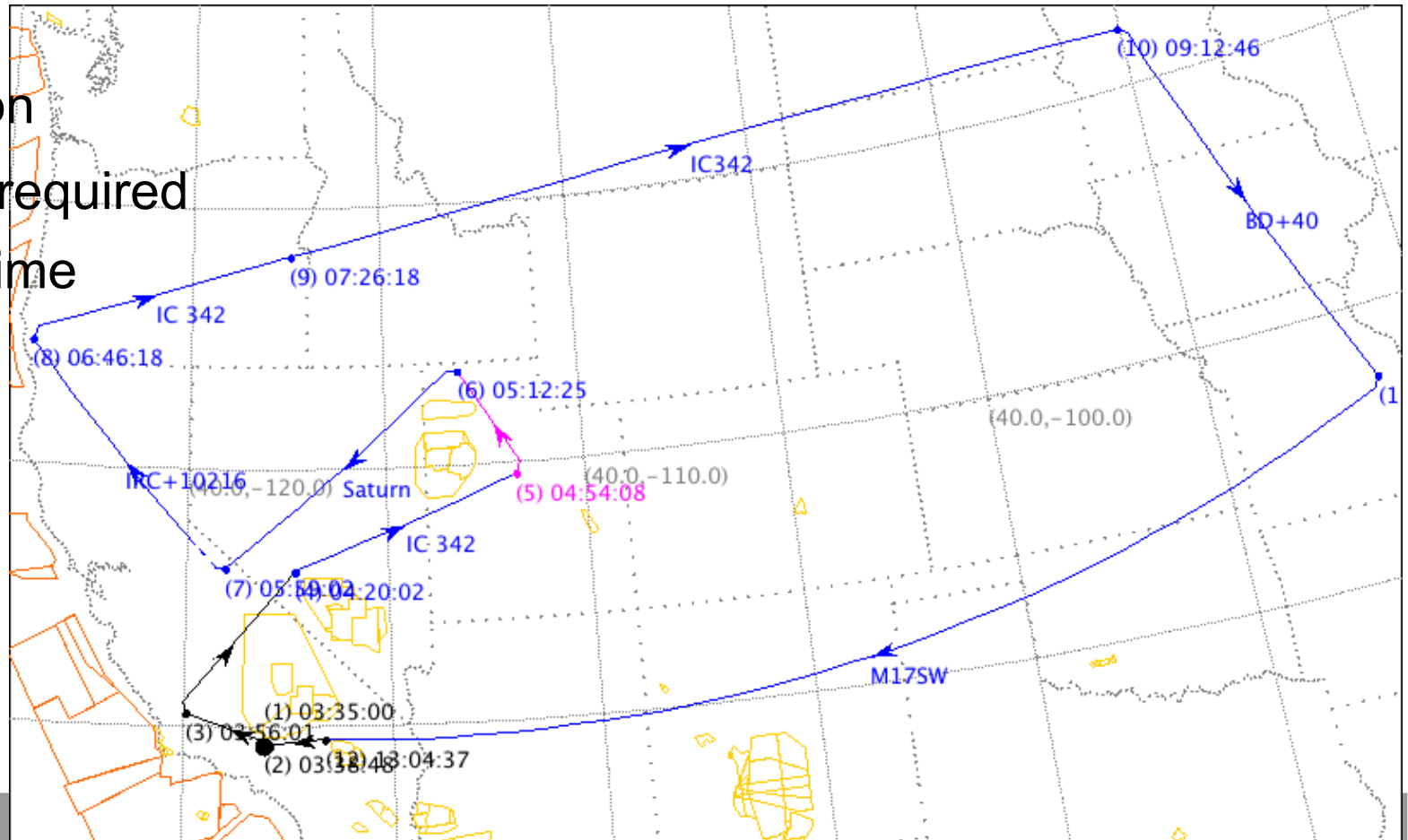
- Time constraints:
  - LSR velocity of source relative to atmospheric features
    - GREAT time estimator
  - Visibility at observing altitude
    - 20°-60°
  - Flight direction
    - Round-trip required
    - Maximum time per lag ~3h



Planning

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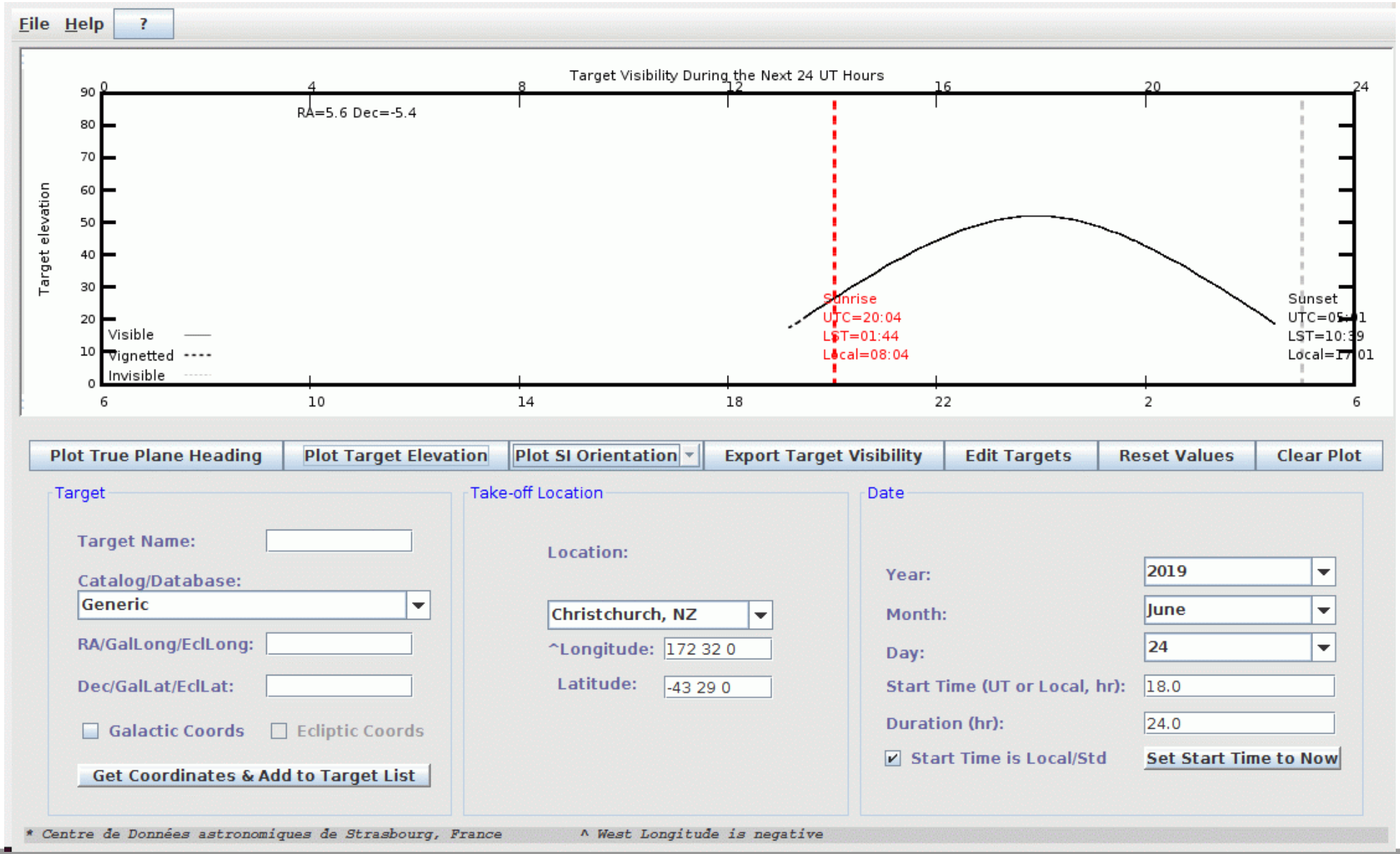
- Visibility Tool (3.5.1):



Observing modes

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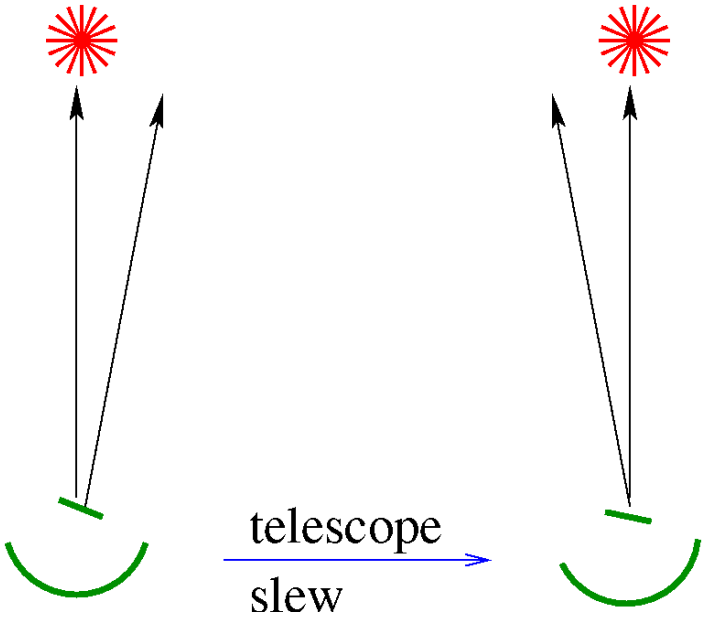
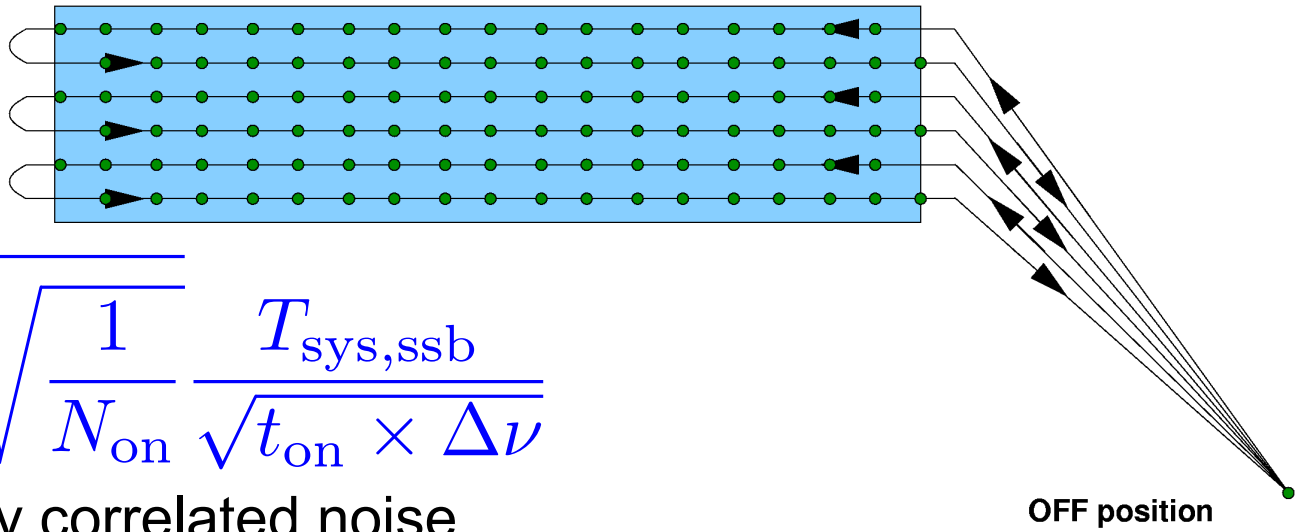
- Symmetric modes $t_{\rm on} = t_{\rm off}$
  - e.g. double-beam switch (=chop-nod)
  - for broad lines/instable frequencies

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



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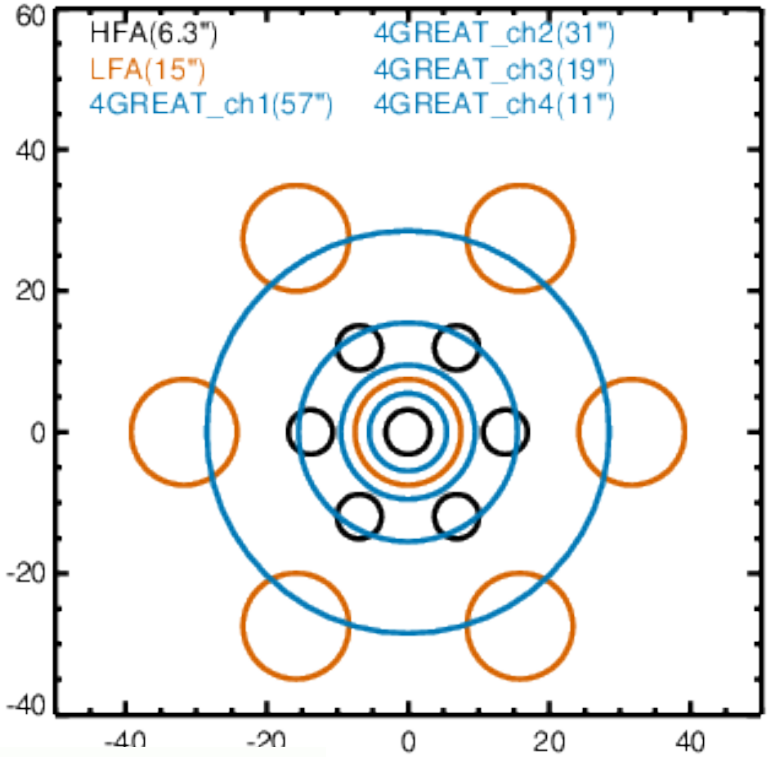
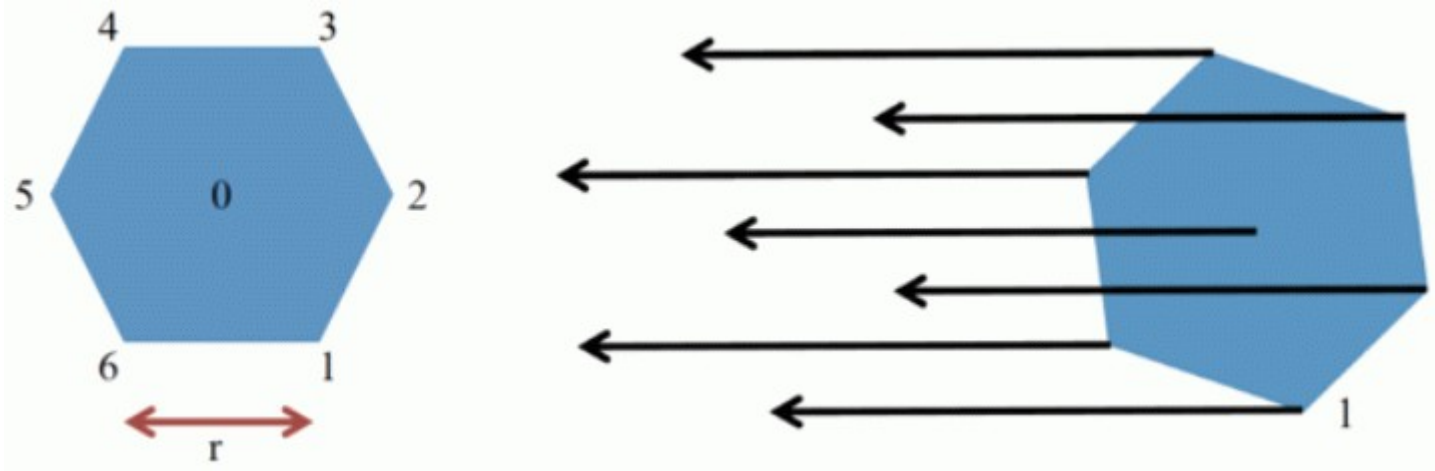
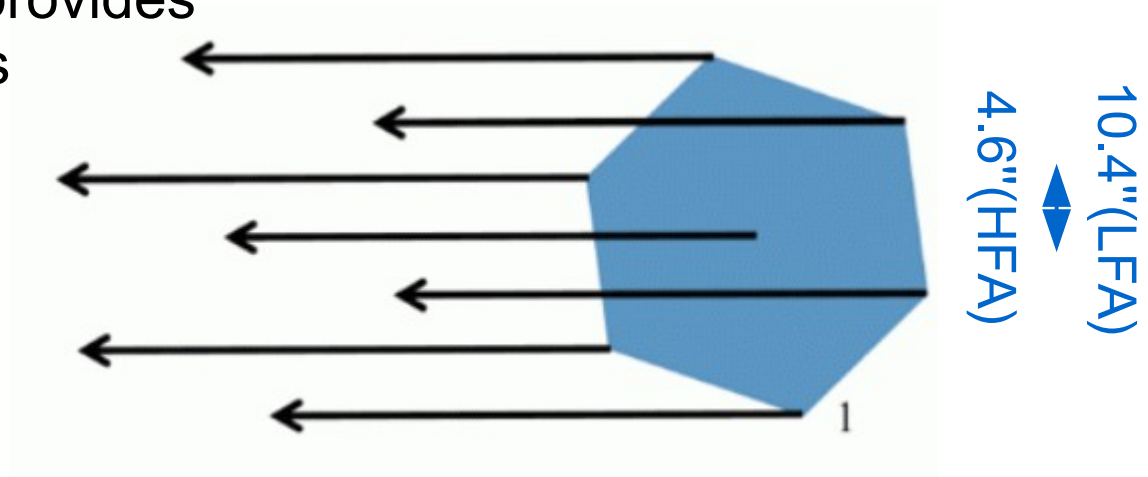
- Combine with receiver geometry
  - Single pixels (4GREAT)
    - Use Nyquist sampling or half-beam sampling depending on beam width
  - Array mapping (LFA, HFA)
    - Array tilt by 19.1 degrees provides equal spacing of scan lines



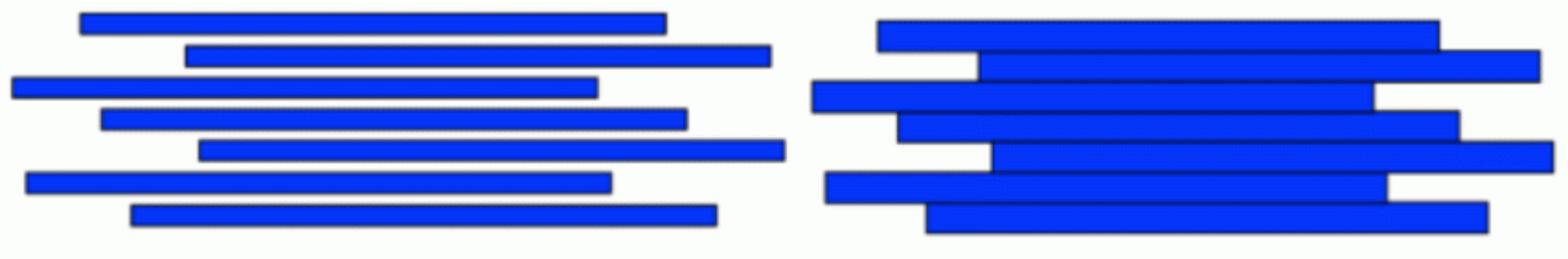


Mapping modes

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



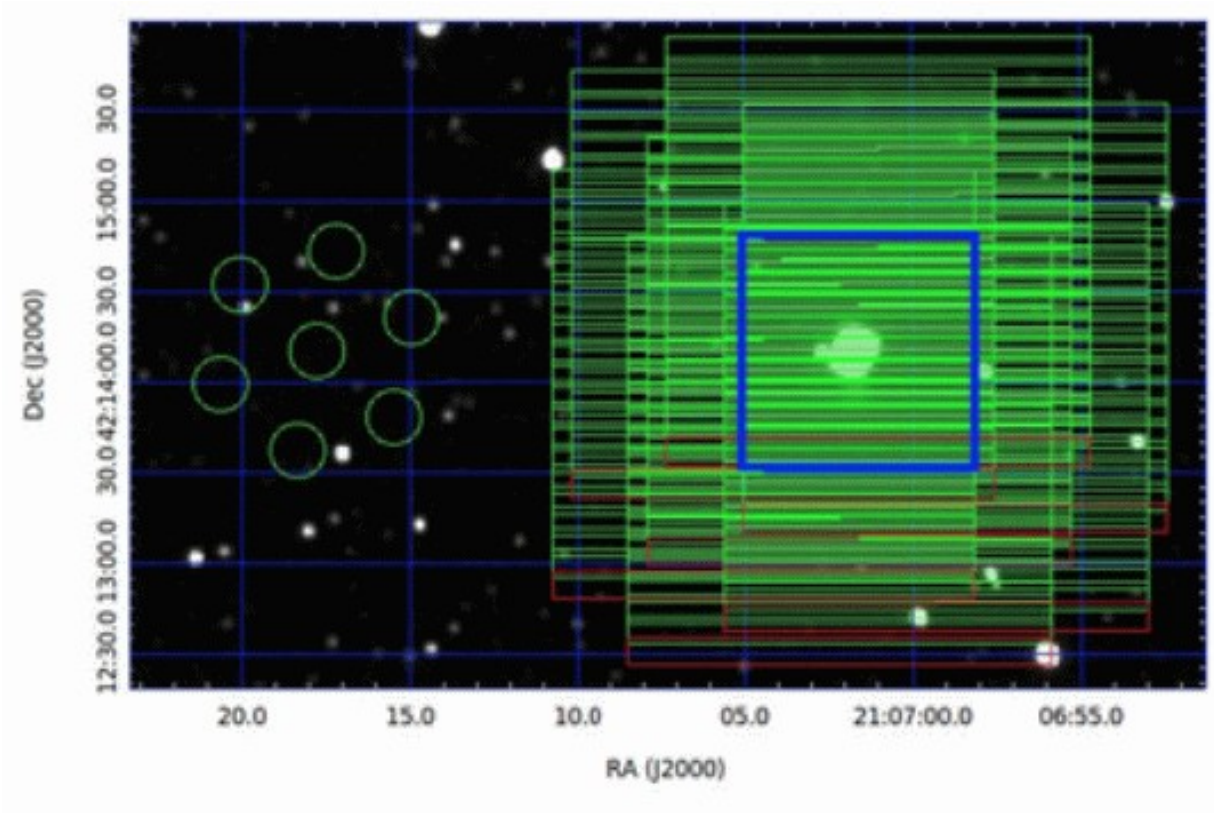
  - Two adjacent scans provide fully sampled maps



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

Mapping modes

- Classical OTF
  - Every pixel covers every part of the map
  - Allows to compensate for different pixel sensitivities
  - Arbitrary map size
  - Ideal for weak, small sources



Mapping modes

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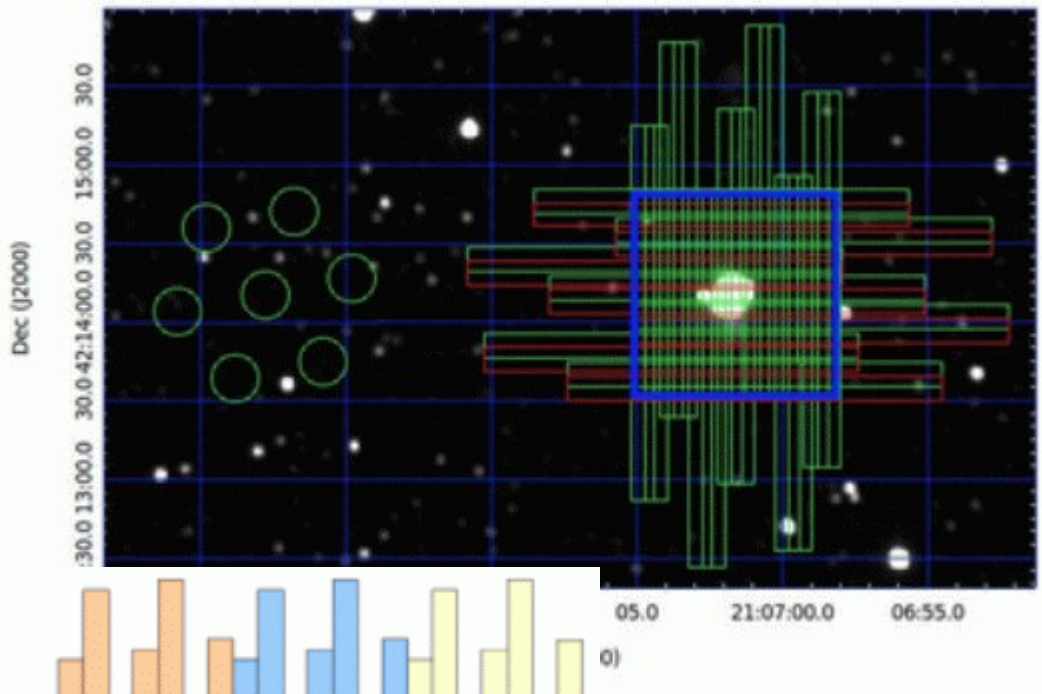
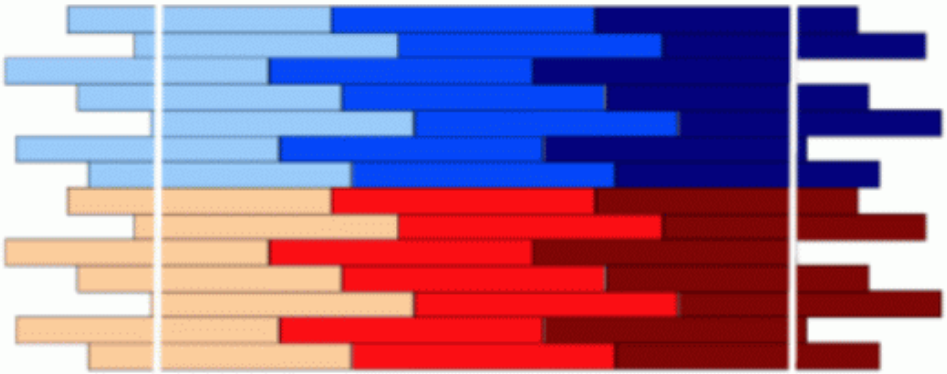
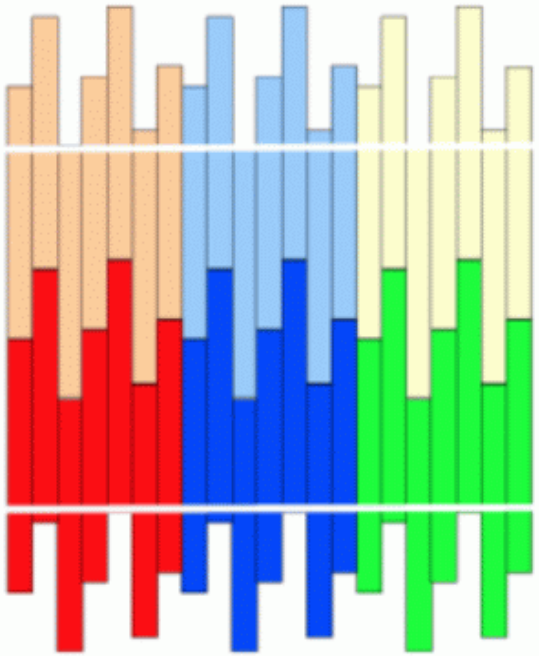
- Array OTF
  - Assembly of map from minimum array coverages
  - Mosaicing for large areas
    - 73.8" (LFA), 32.2" (HFA)
  - Ideal for strong extended sources
  - Not in HFA-LFA combination







Visualization

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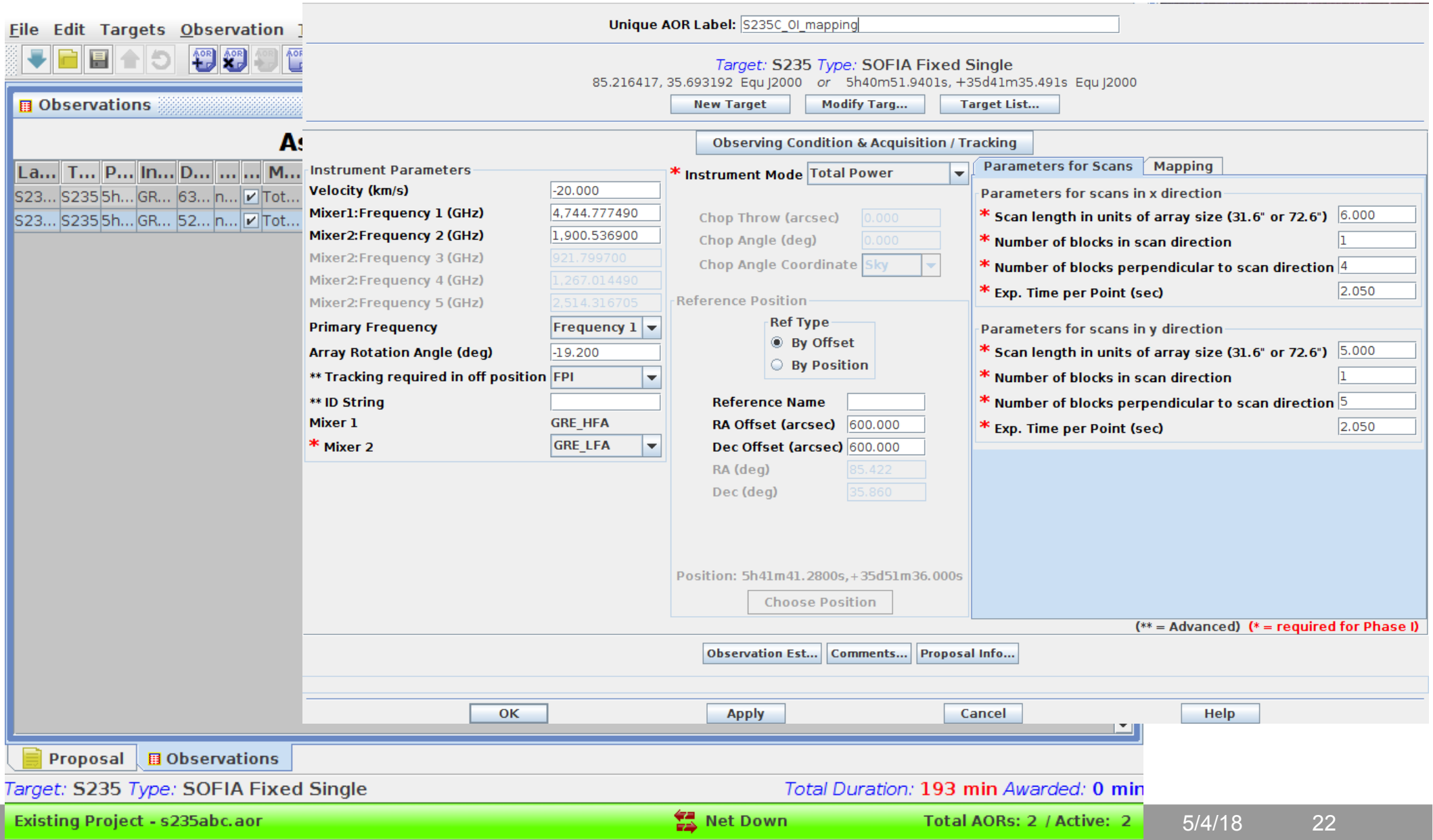
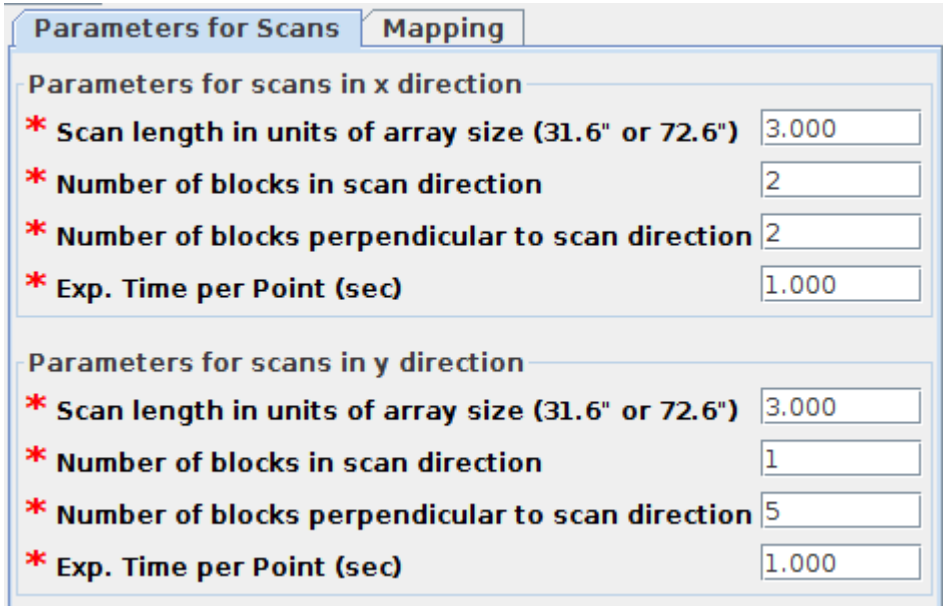
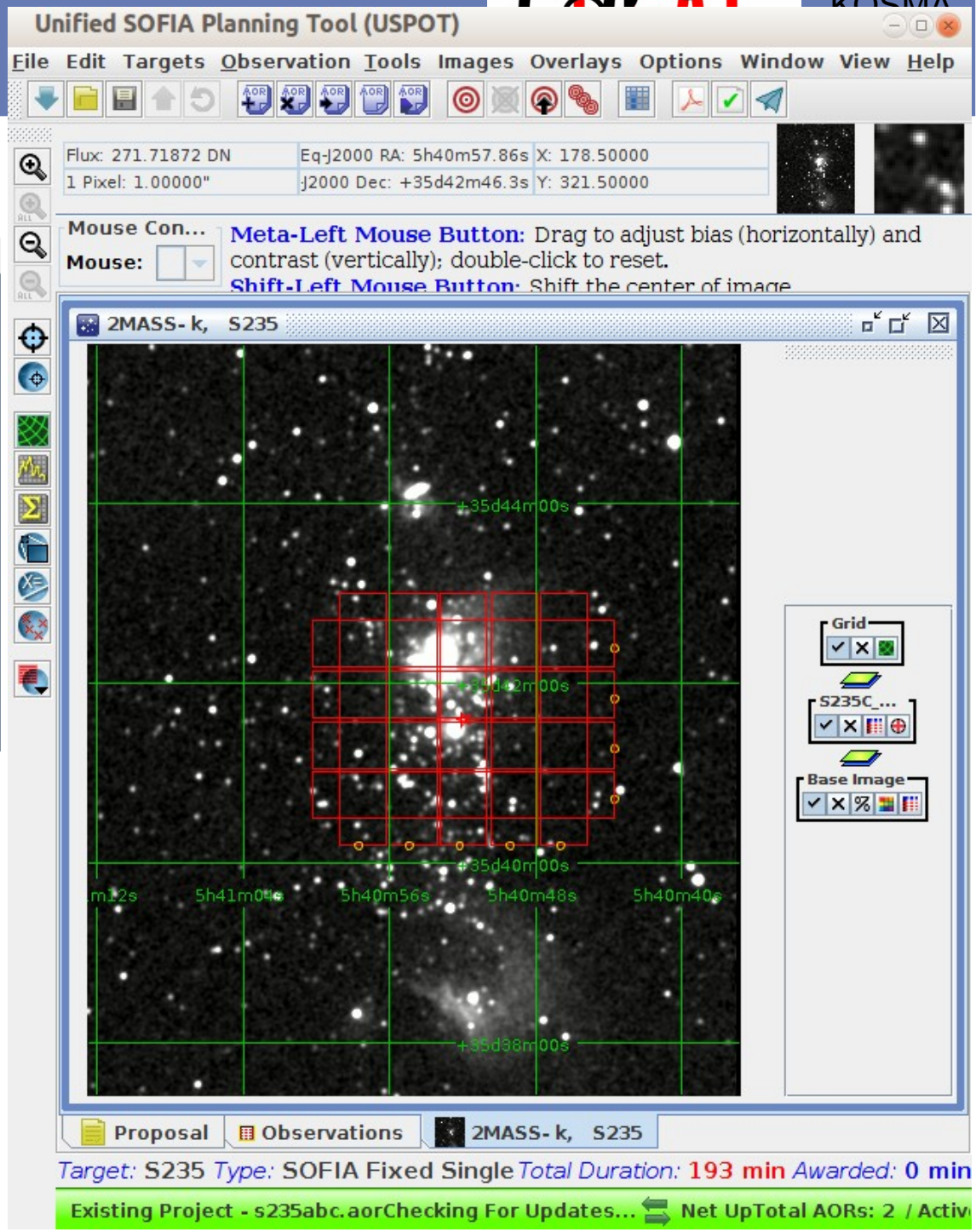
- USPOT (3.5.2):



Visualization

- Array OTF:





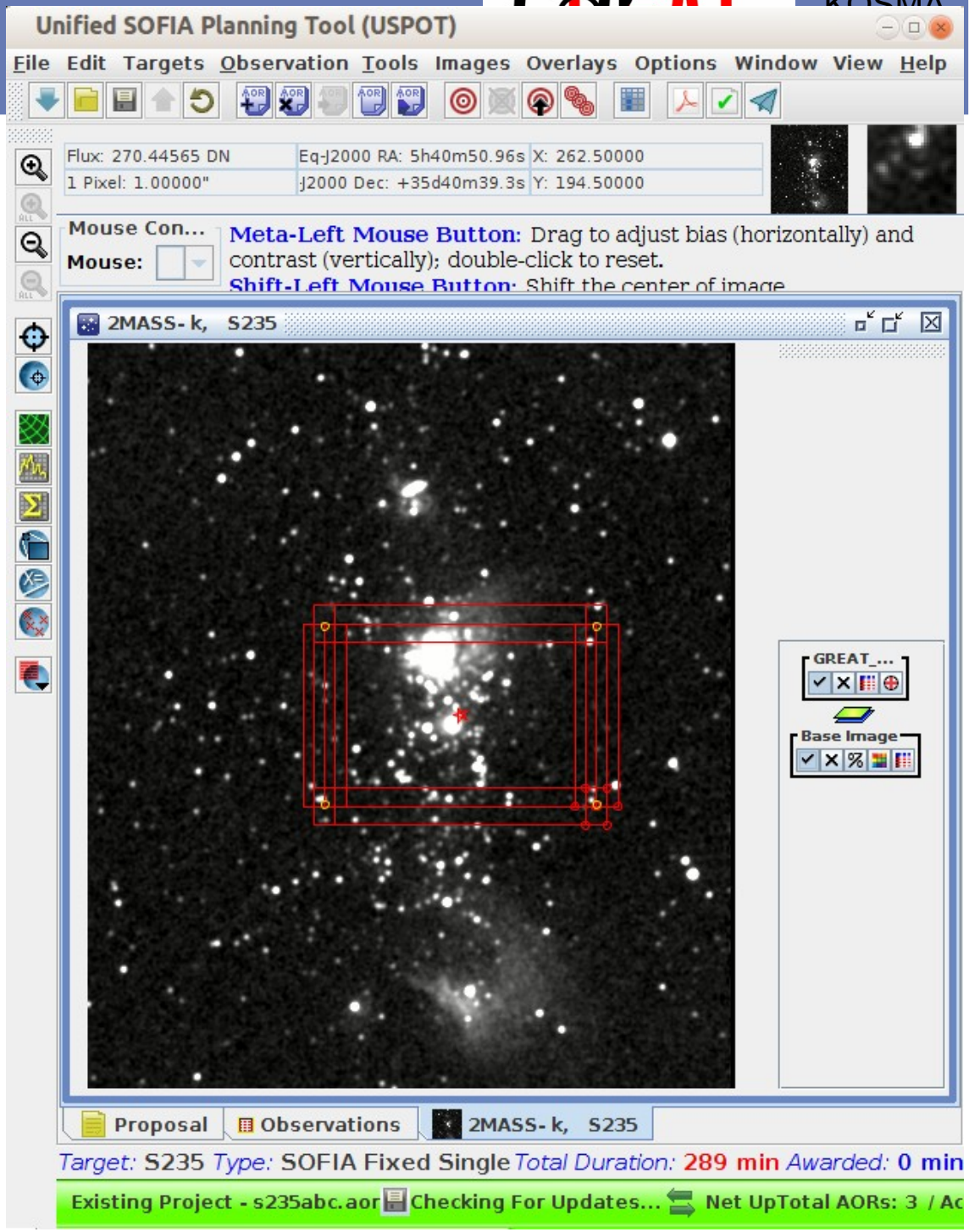
Visualization

- Classical OTF:

Mapping Parameters

Exposure Time Per Cycle (sec)	2821.22
* On-source Exp. Time Per Point (sec)	1.000
* Cycles	1
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)	3.000
Step size in the y-direction (arcsec)	3.000
* Num Steps in the x-direction	61
* Num Steps in the y-direction	41
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)



Time estimates

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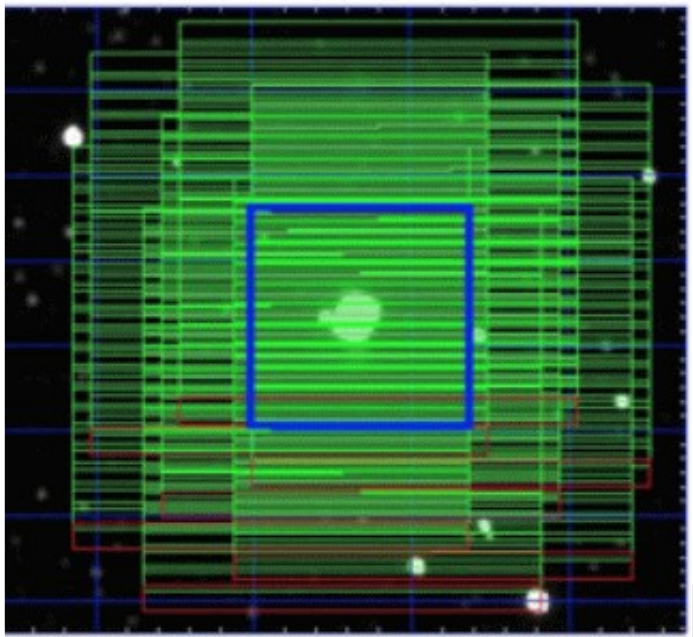
- Output from GREAT time estimator → USPOT (3.5.2)
  - Single point observations
    - Use $t_{on+toff}$ in USPOT as given by time estimator
  - Single beam switch / double beam switch mapping
    - Divide $t_{on}+t_{off}$ by 2 for input as t_{on} in USPOT
  - Array-OTF
    - Use t_{on} in USPOT as given 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
      - Smaller reduction for noise goal at edges



Data delivery

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- 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

- 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 Imv
go view
```

Example

MPIfR
KOSMA
MPS
DLR-Pf

let name Horsehead_CII
let type lmv
go view