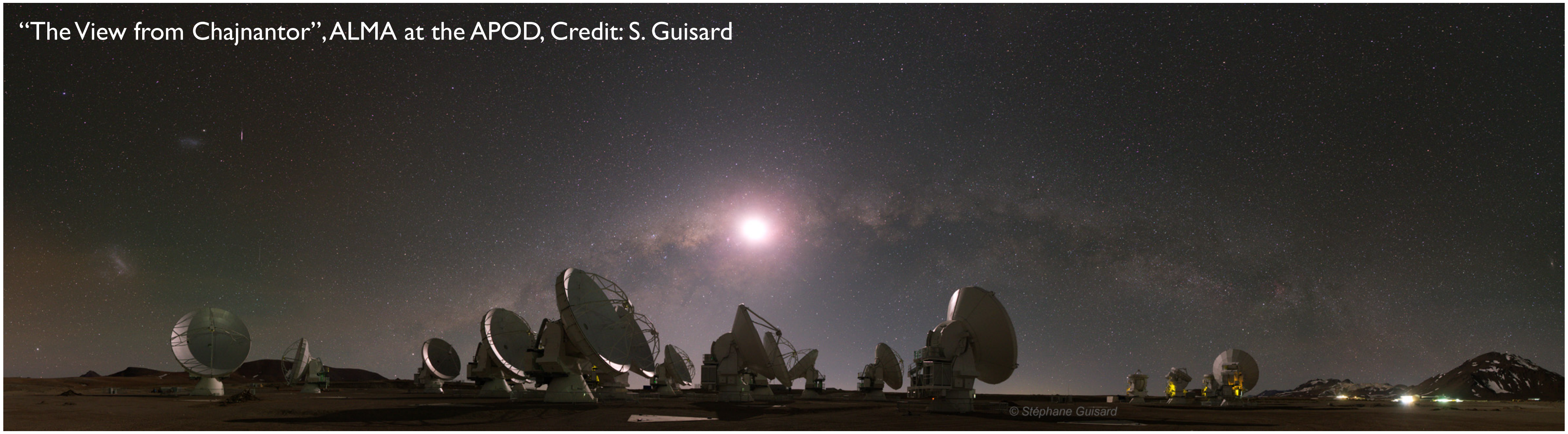


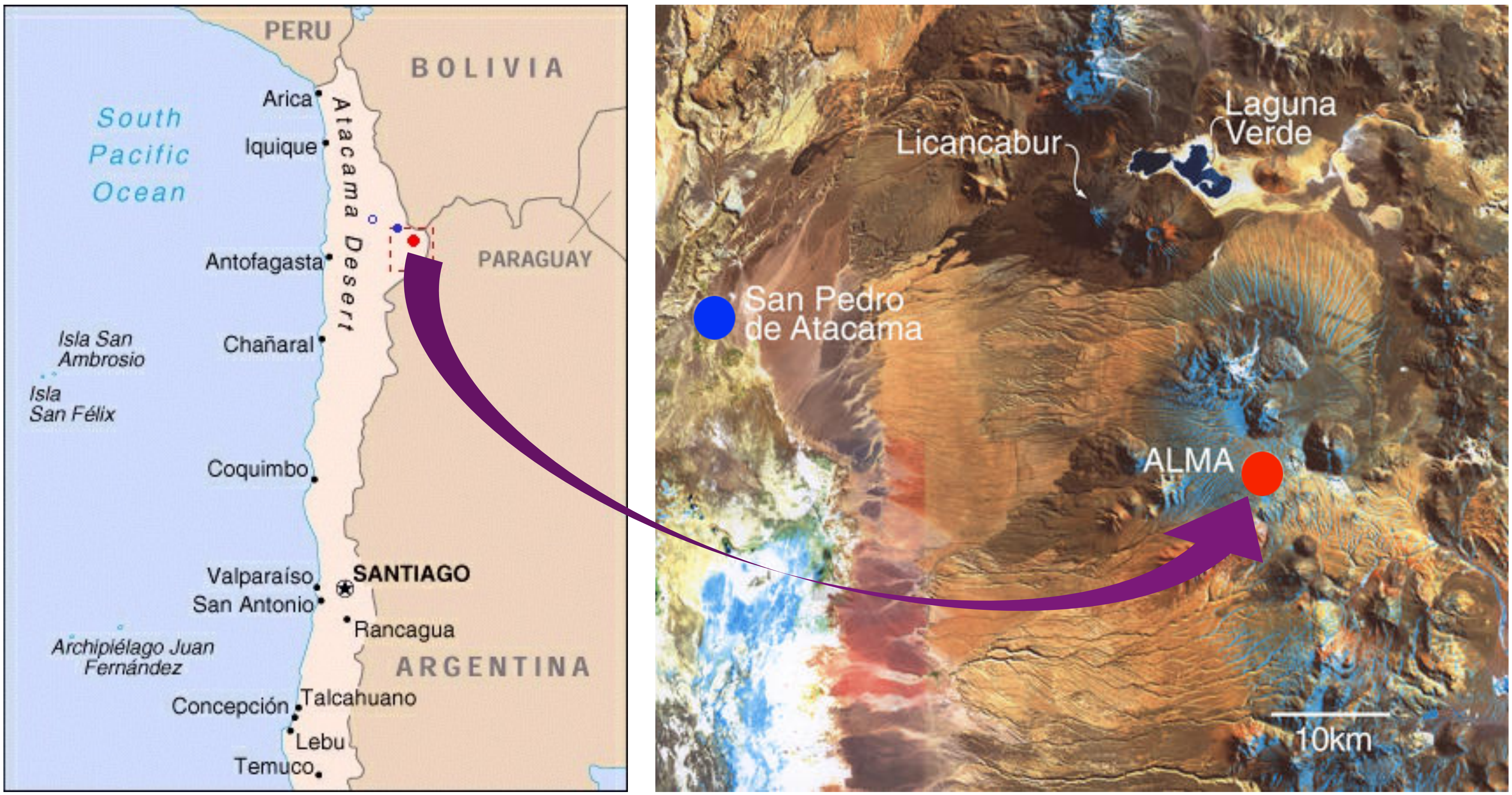
ALMA Data Reduction Path

Laura Pérez, Caltech

Talk heavily borrowed from: **Crystal Brogan, Ed Fomalont, Al Wootten**
https://science.nrao.edu/facilities/alma/naasc-workshops

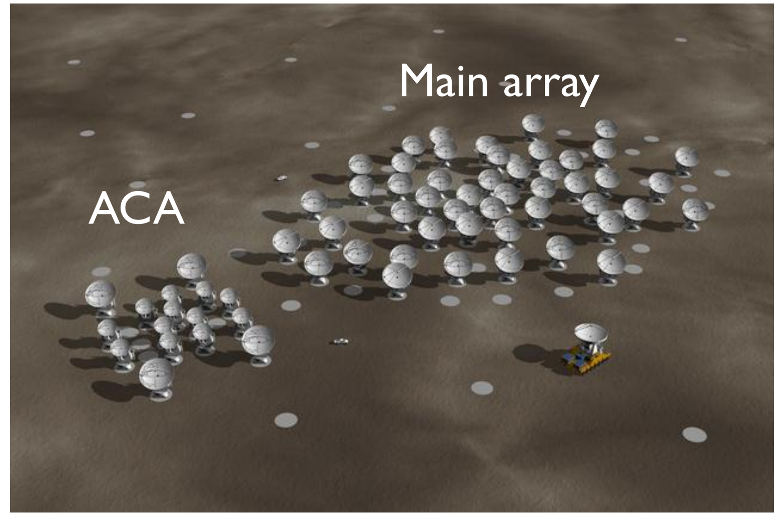
Atacama Large Millimeter/sub-Millimeter Array

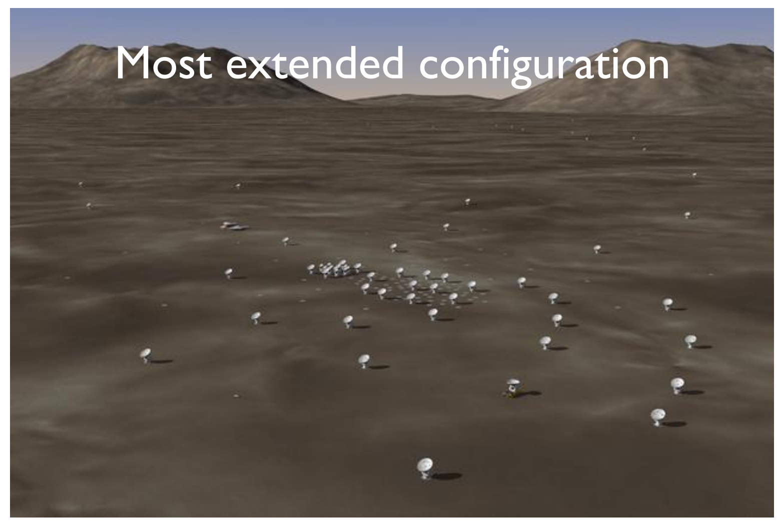
- Global partnership: Europe, North America and East Asia in cooperation with the Republic of Chile
- 5000 m (16500 ft.) site in Atacama Desert, Chile



ALMA Overview (Full Science)

- Main Array: 50 x 12m antennas
  - Total Power Array 4 x 12m
  - Atacama Compact Array (ACA): smaller array of 12 x 7m antennas
- Baselines up to 15 km
  - 0.015” at 300 GHz
- Sensitive, precision imaging
  - 84 to 950 GHz (3 mm to 315 μm)
- Low-noise, wide-band SIS receivers (8 GHz bandwidth)
- Flexible correlator
  - High spectral resolution at wide bandwidth
- Full polarization capabilities





ALMA Status (Early Science)

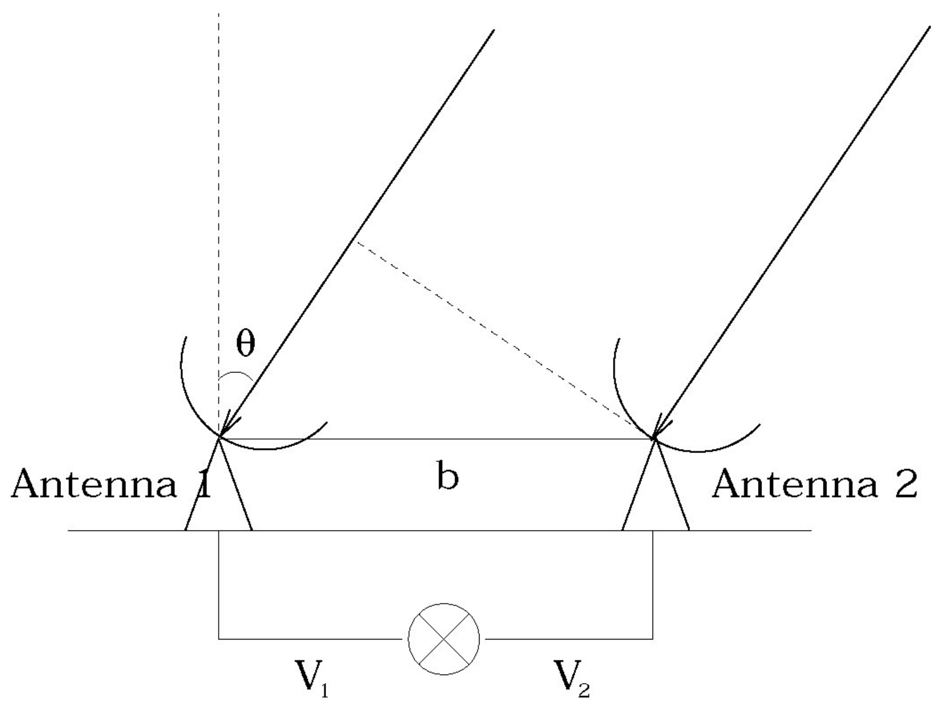
- 6 out of those 30 are 7m ACA antennas
- Early science started September 30, 2011
- Several "Science Verification" datasets available online
  - We will use some in hands-on session!
- Call for Proposals for Cycle 1: spring 2012

https://almascience.nrao.edu/call-for-proposals

ALMA and EVLA: similar data reduction!

- Both telescopes are interferometers, hence measuring:
  - Complex visibility
  - Amp/Phase: as a function of time, baseline, and frequency
  - Difference: ALMA operates at a **higher frequency**

A. Isella's talk



ALMA and EVLA: similar data reduction!

- Baseline calibration
- Examine data, flag if necessary
- Flux calibration
- Bandpass calibration
- Gain calibration
- Apply calibration tables to science target
- Imaging

Discussed in J. Lazio's lecture (Baseline calibration through Apply calibration tables to science target)

Imaging → To be discussed in J. Carpenter's lecture

ALMA and EVLA: similar data reduction!

- Baseline calibration
- Water Vapour Radiometry (WVR) Calibration
- Tsys calibration
- Examine data, flag if necessary
- Flux calibration
- Bandpass calibration
- Gain calibration
- Apply calibration tables to science target
- Imaging

Part of ALMA tutorials (WVR Calibration, Tsys calibration)

Discussed in J. Lazio's lecture (Examine data, flag if necessary; Flux calibration; Bandpass calibration; Gain calibration; Apply calibration tables to science target)

Imaging → To be discussed in J. Carpenter's lecture

ALMA and EVLA: similar data reduction!

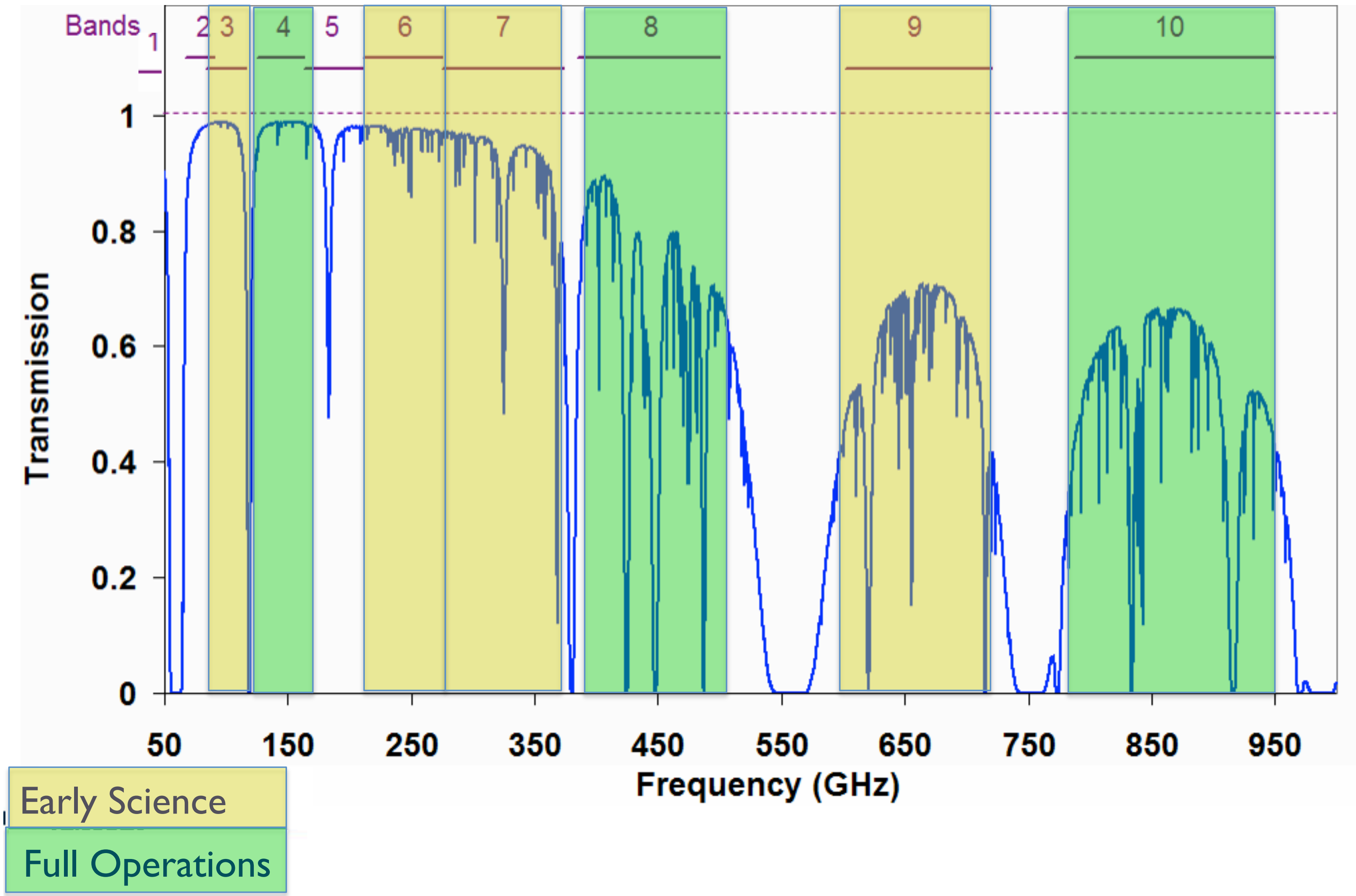
- Baseline calibration
- Water Vapour Radiometry (WVR) Calibration
- Tsys calibration
- Examine data, flag if necessary
- Flux calibration
- Bandpass calibration
- Gain calibration
- Self-calibration
- Apply calibration tables to science target
- Imaging

Part of ALMA tutorials (WVR and Tsys calibration)

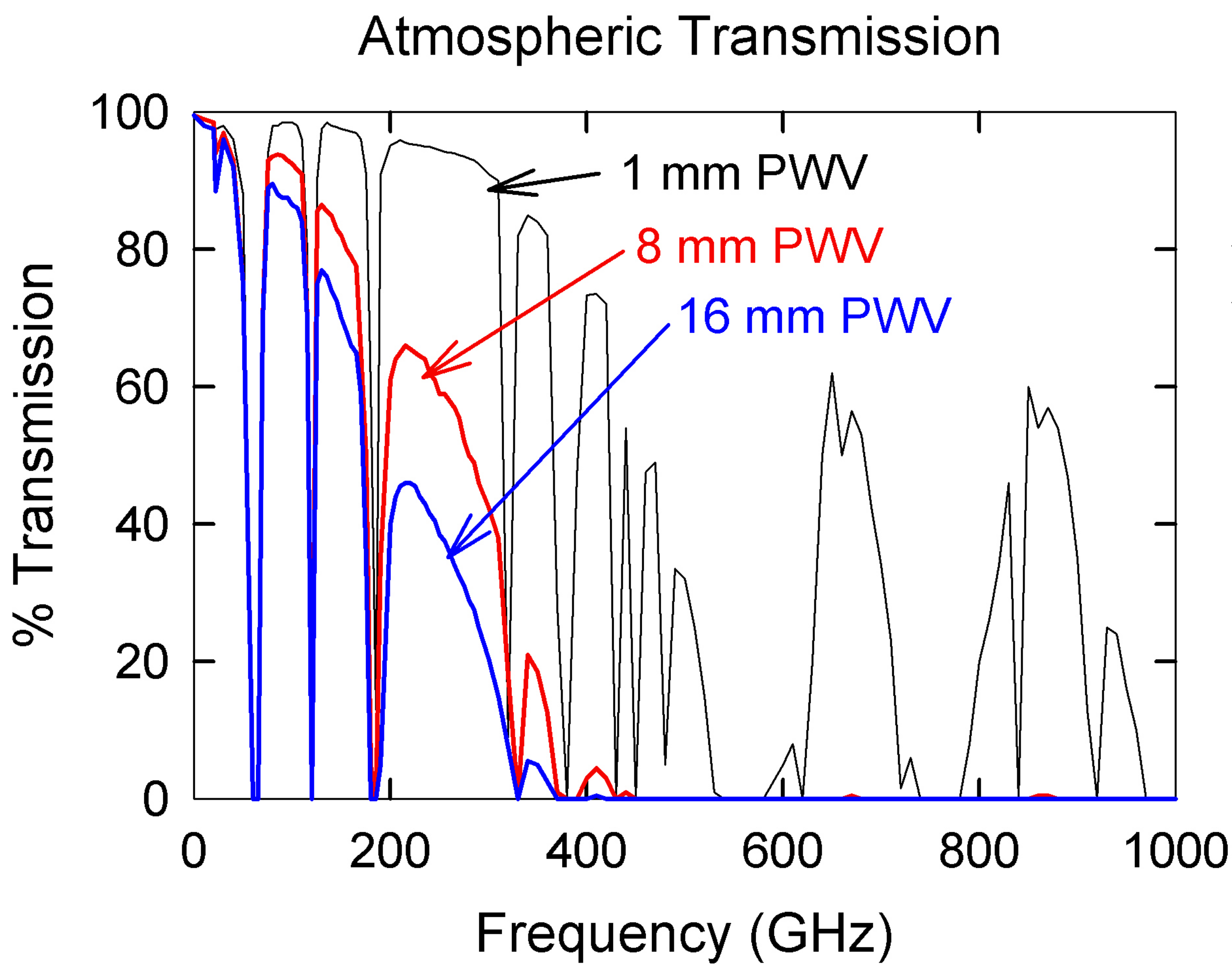
Separate tutorial, try it out! (Self-calibration)

Sensitivity and System Temperature

ALMA Receiver Bands



Atmospheric opacity



PWV = Precipitable Water Vapor

Sensitivity drops as opacity increases

- Before entering atmosphere the source signal $S = T_{source}$
- After attenuation by atmosphere the signal is $S = T_{source}\, e^{-\tau}$
- Consider the signal-to-noise ratio:

$$S / N = (T_{source}\, e^{-\tau}) \;/\; T_{noise} = T_{source} \;/\; \underbrace{(T_{noise}\, e^{\tau})}_{T_{sys}}$$

- What contributes to T_{noise}?
  - Receiver noise (T_{rx})
  - At millimeter wavelengths the atmosphere has a significant brightness temperature (T_{sky})

$$T_{noise} \approx T_{rx} + T_{sky}$$

where $T_{sky} = T_{atm}\,(1 - e^{-\tau}) + T_{bg} e^{-\tau}$

> T_{atm} = temperature of the atmosphere ≈ 300 K
>
> T_{bg} = 3 K cosmic background

System Sensitivity: characterized by T_{sys}

- The system sensitivity drops exponentially (!!!) as opacity increases

$$S / N = T_{source} / T_{sys}$$
$$T_{sys} = T_{noise} e^{\tau} \approx T_{atm}(e^{\tau} - 1) + T_{rx} e^{\tau}$$

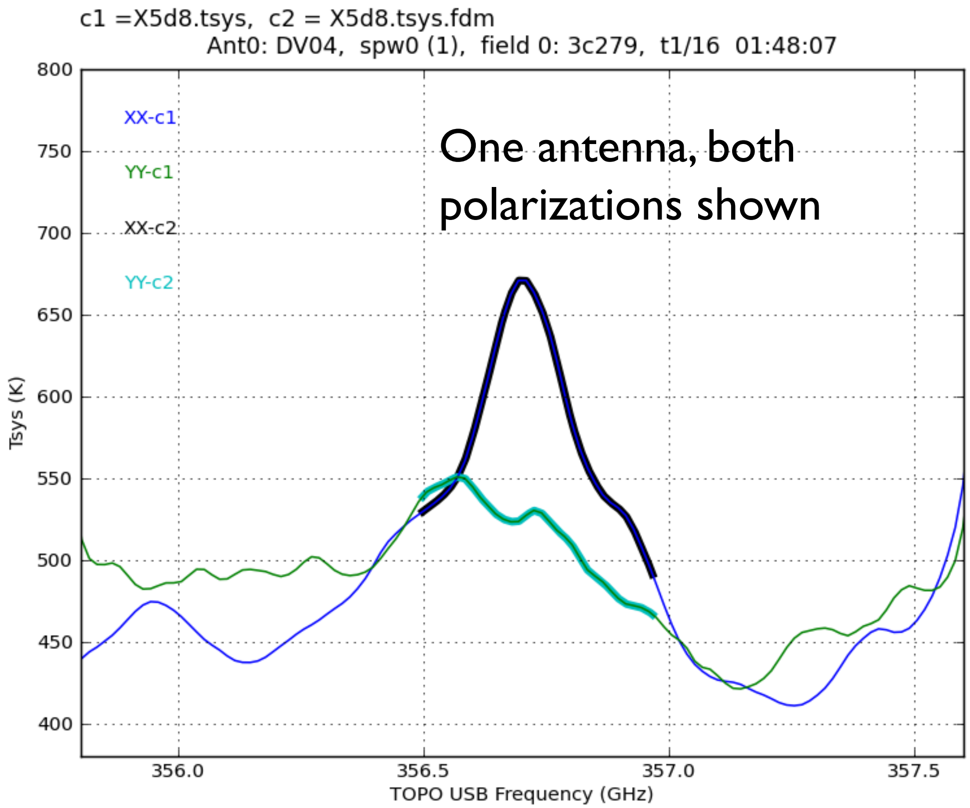
- Typical optical depth at 230 GHz:
  - τ_{225} = 0.15 = 3 mm PWV (zenith), at elevation = 30° $\Rightarrow$ τ_{225} = 0.3

$$T_{sys} = e^{\tau}(T_{atm}(1-e^{-\tau}) + T_{rx}) = 1.35(77 + 75) \sim 200 \text{ K}$$

assuming T_{atm} = 300 K and T_{rx} = 75 K

⇨ Atmosphere adds considerably to T_{sys} and since the opacity can change rapidly, T_{sys} must be measured often

Examples of ALMA T_{sys} measurements

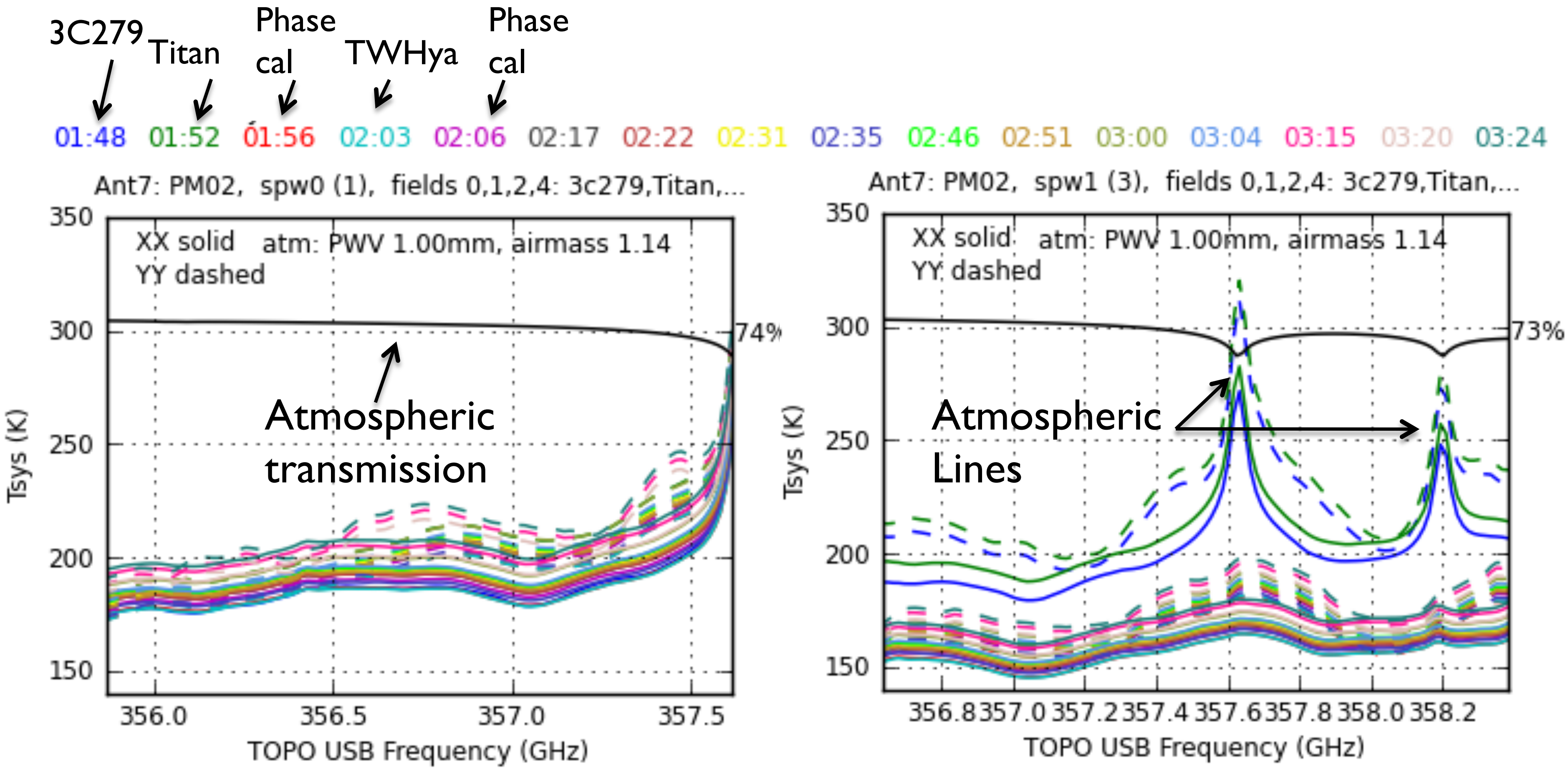


Example: TWHya Band 7

- Science data taken with 0.5 GHz high spectral resolution windows
- Tsys measured in 2 GHz low-spectral resolution mode and interpolated to "science" resolution mode

Examples of ALMA T_{sys} vs time

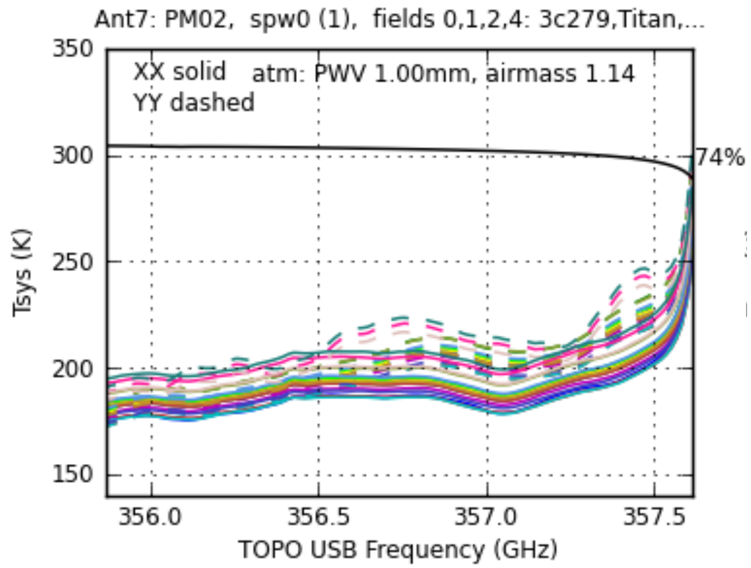
Colors = scans with Tsys measurements = variations with time and elevation for one antenna



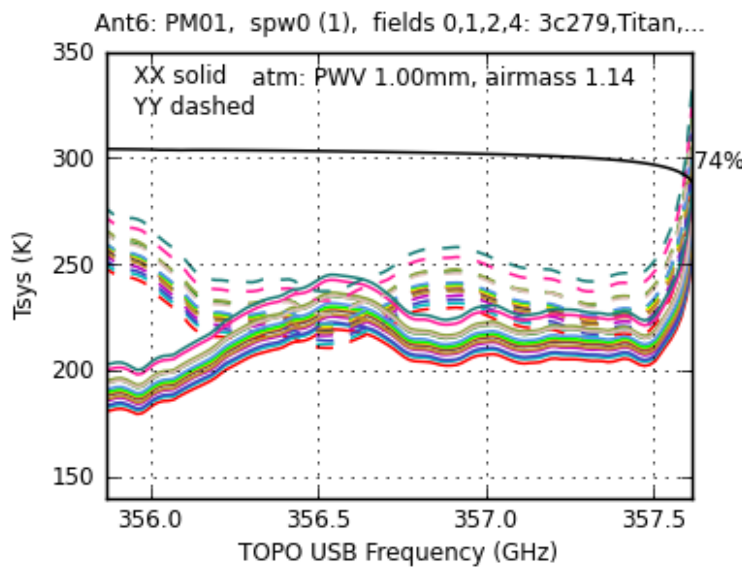
Spw=0

Spw=1

Examples of ALMA Tsys: two antennas



Antenna PM02



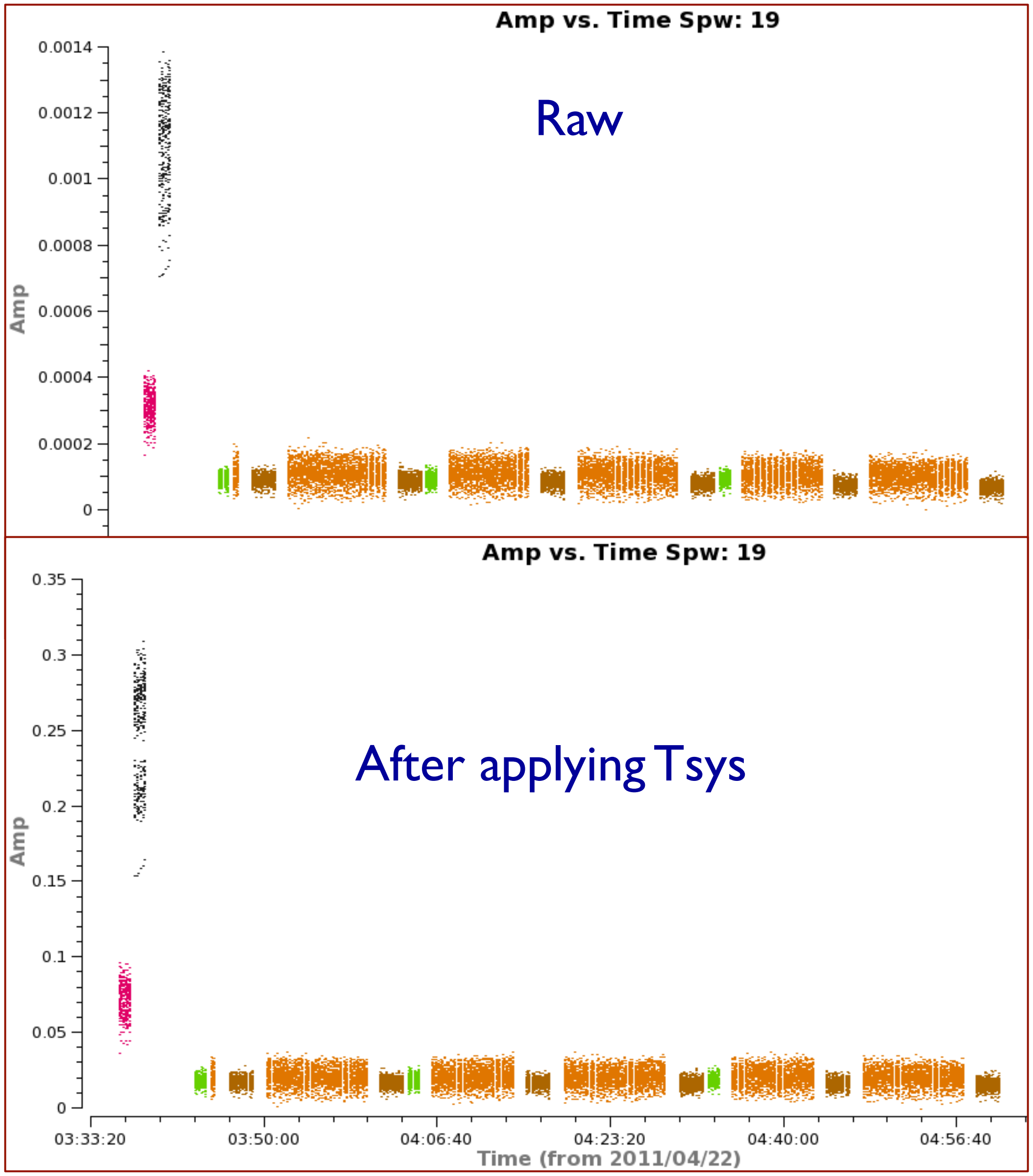
Antenna PM01

$$VisibilityWeight \propto \frac{1}{T_{sys}(i)T_{sys}(j)}$$

→ Baselines with good Tsys get up-weighted

→ Baselines with poor Tsys get down-weighted

Before and After applying Tsys



- Notice change in Amp scale.
- Amplitudes multiplied by:

$$S = S_o * [T_{sys}(1) * T_{sys}(2)]^{0.5}$$

To estimate approximate Jy scale, multiply by ALMA antenna efficiency factor:

about 40 Jy/K

CASA: applying Tsys measurements

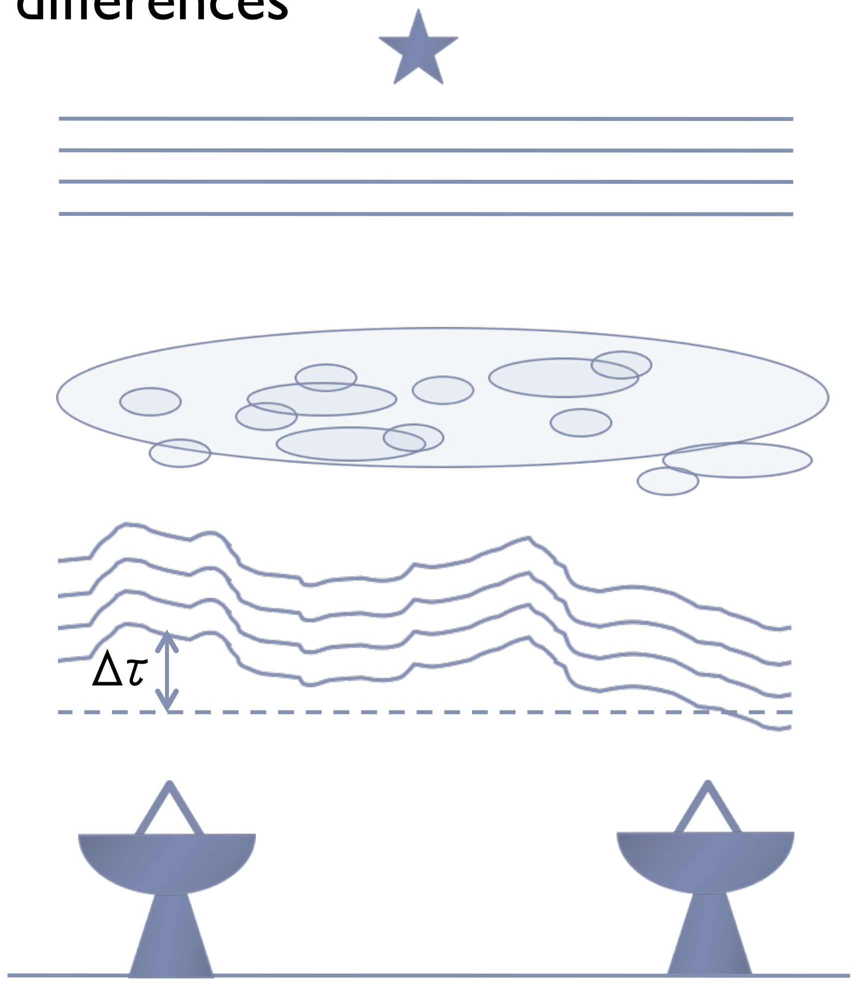
- What you get from the observatory:
  - Calibration tables with Tsys measurements in two modes
    - Time Division Mode (TDM, wide BW)
    - Frequency Division Mode (FDM, narrow BW)
- Generated along observations, will be provided to the user
- In CASA use "applycal" task to apply Tsys tables

Water Vapor Radiometry Corrections

Atmospheric phase fluctuations

- Variations in the amount of PWV across the atmosphere cause random delay differences

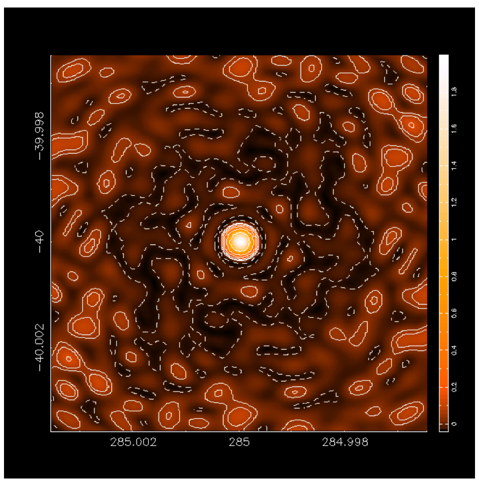
$$\Delta\phi = 2\pi \cdot \nu \cdot \Delta\tau$$



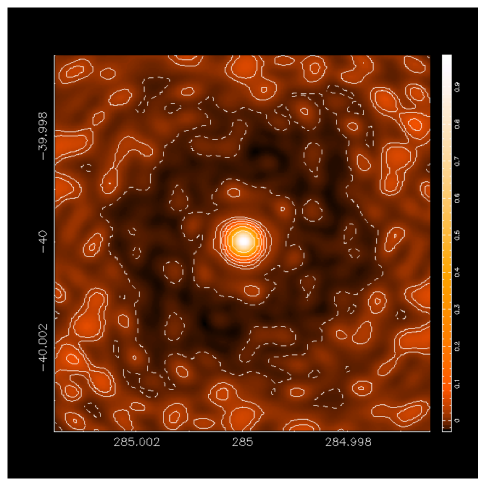
Phase fluctuations corrupt data

- Reduce angular resolution of observations
  - Introducing “seeing”
- Reduce sensitivity of observations

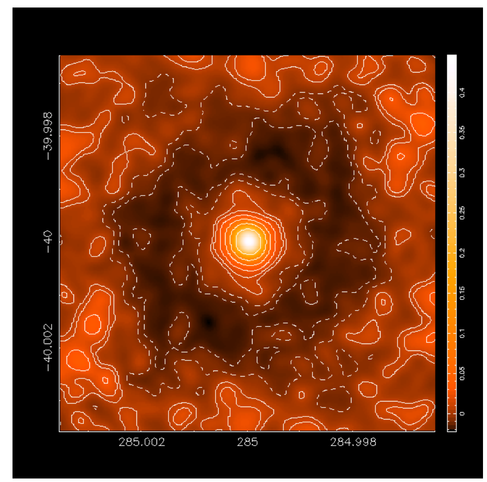
2 Jy peak



0.98 Jy peak



0.45 Jy peak

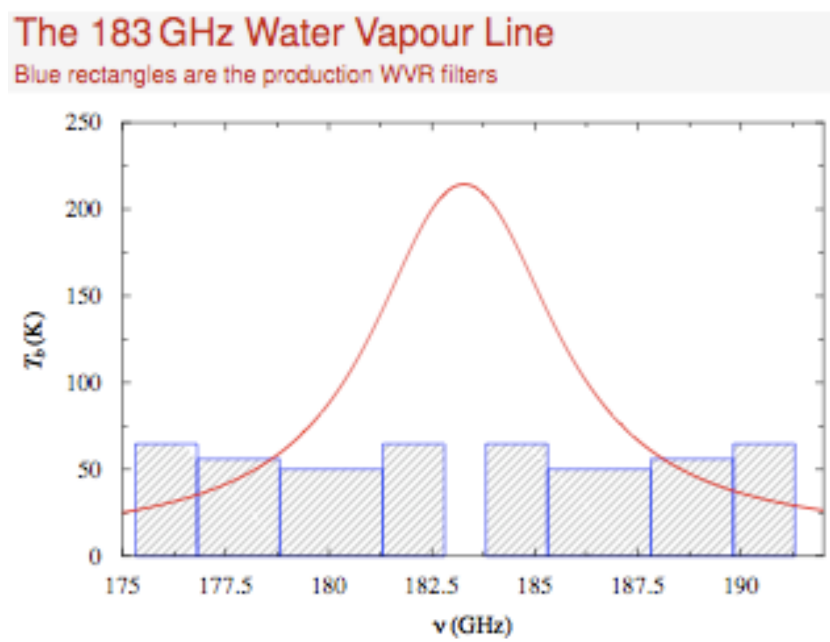


Increasing magnitude of atmospheric phase fluctuations

http://www.mrao.cam.ac.uk/projects/alma/fp6/index.html

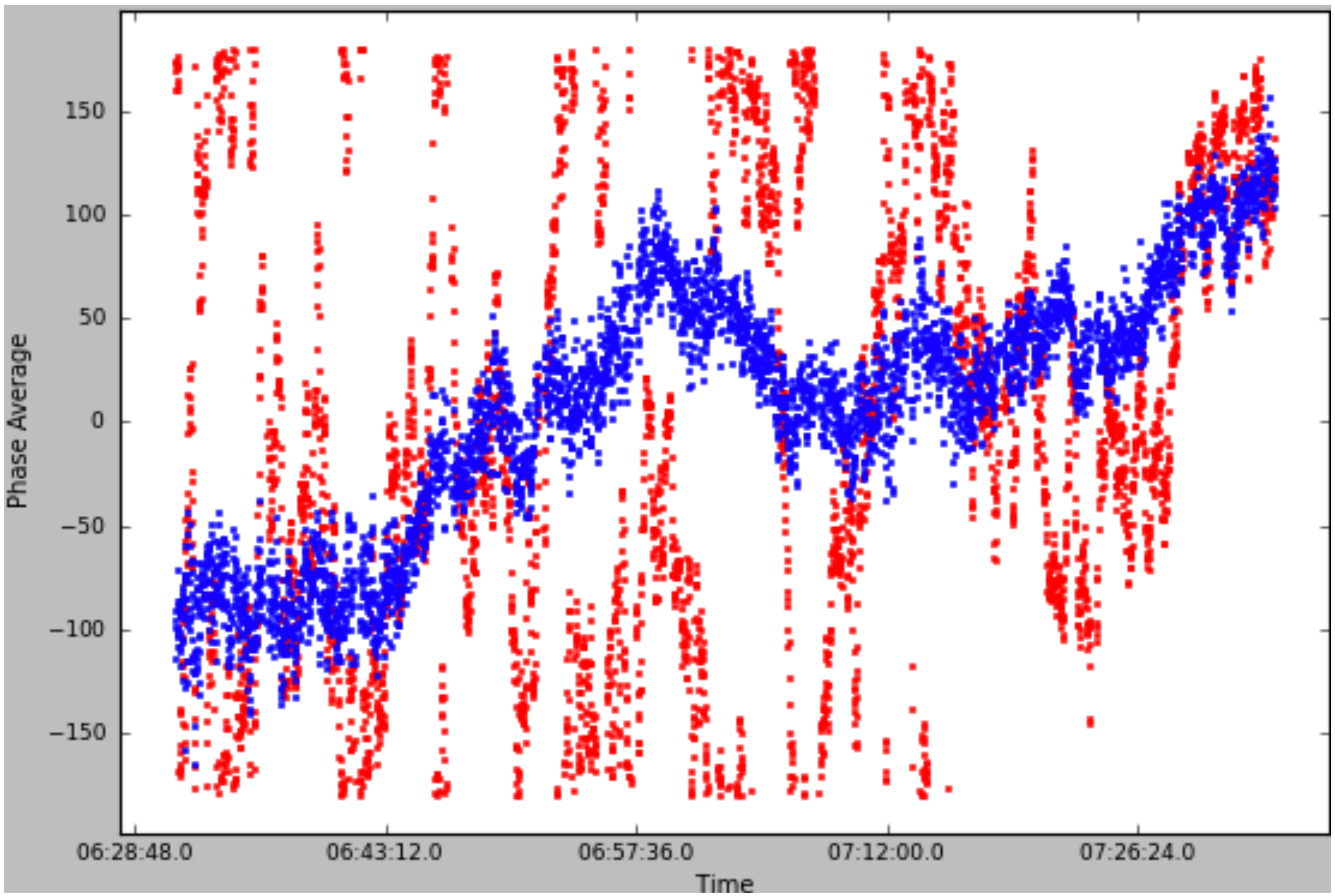
ALMA WVR System

- Water Vapor Radiometry (WVR)
  - Radiometer (on each antenna) measures rapid fluctuations in T^B_{atm}
  - From T^B_{atm} → water vapor column → phase corrections
- 4 channels flanking 183 GHz water line
  - Data taken each second
  - Need to perfect models for relating WVR data to the phase correction beyond simplified method



WVR calibration example

600m baseline, Band 6, Mar 2011
(red=raw data, blue=corrected)



1 hr

CASA: applying WVR measurements

- What you get from the observatory:
  - Calibration tables with phase corrections derived from WVR measurements

- Generated along observations, will be provided to the user

- In CASA use “applycal” task to apply WVR tables

Self-calibration

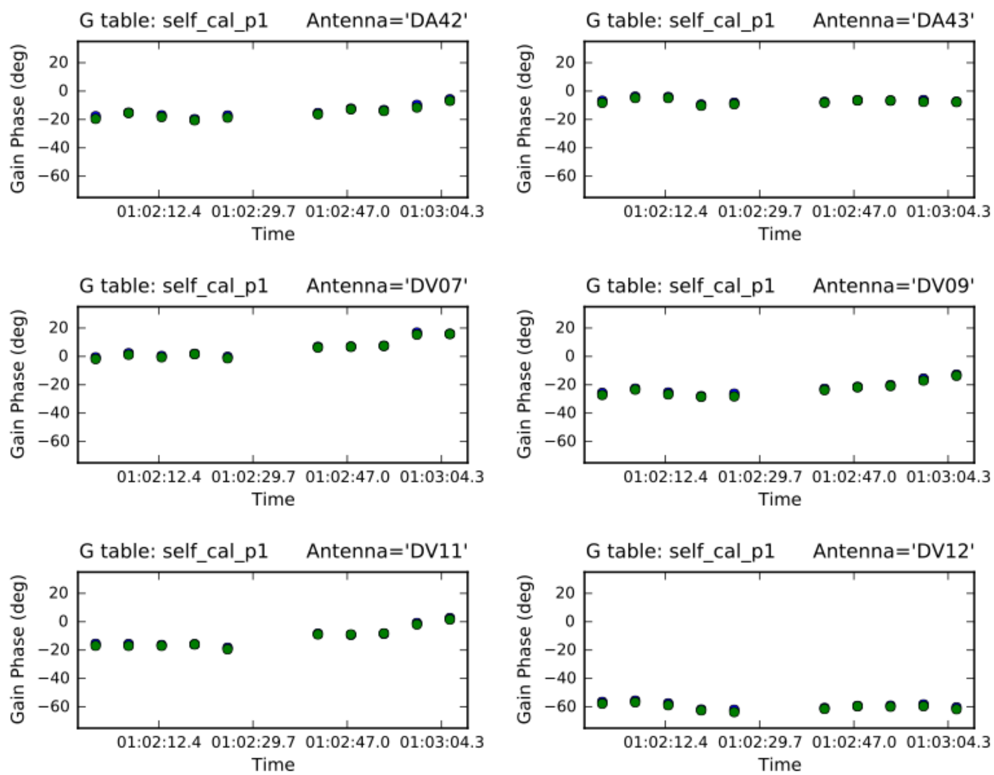
Self-calibration Procedure

- Basic calibration involves observing "calibrators" of known brightness, position and morphology.
  - Usually quasars, bright point sources, or solar system objects with accurately known models
- Apply basic calibrations from the calibrator to target
  - J. Lazio's talk
- Produce an image for the target (i.e. you have a known model!)
  - J. Carpenter's talk
- With this "known model" determine additional gains to "self-calibrate" target data

Self-calibration issues

- How much do you really know your target?
  - Are you modeling noise?
- Interval for gain calibration solution must be carefully chosen
  - Too short (low SNR) and you will be calibrating noise!
- Beware of extended sources
  - ALMA is very sensitive → many targets will be strong, but we will also detect extended emission.
  - This make self-cal much more difficult since initial model may have missing flux density

Self-calibration examples



Gain phase solutions for several antennas
Note that interval is 6sec

- General Comments for ALMA selfcal :
  - Phase offsets biggest problems, not short-term phase noise (WVR)
  - Solution interval of minutes can remove phase offsets
- Solutions must be continuous in time!! This is the ultimate test of success.

Self-calibration examples

Basic gain cal

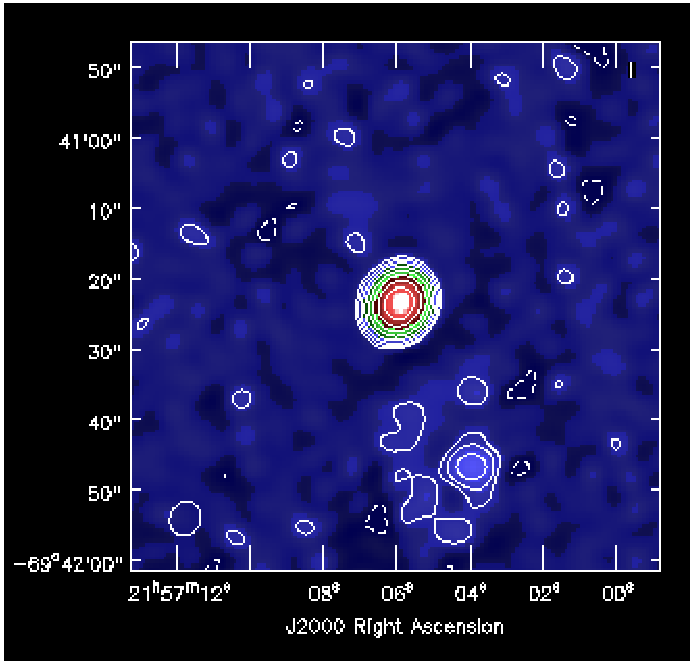


Image of 2157-694 after phasecal 1

Pk = 120 mJy Jy, clev=0.5 mJy; d_i ~240

Image noise = ***0.22 mJy***

Expected noise = 0.05 mJy

Basic gain cal + selfcal

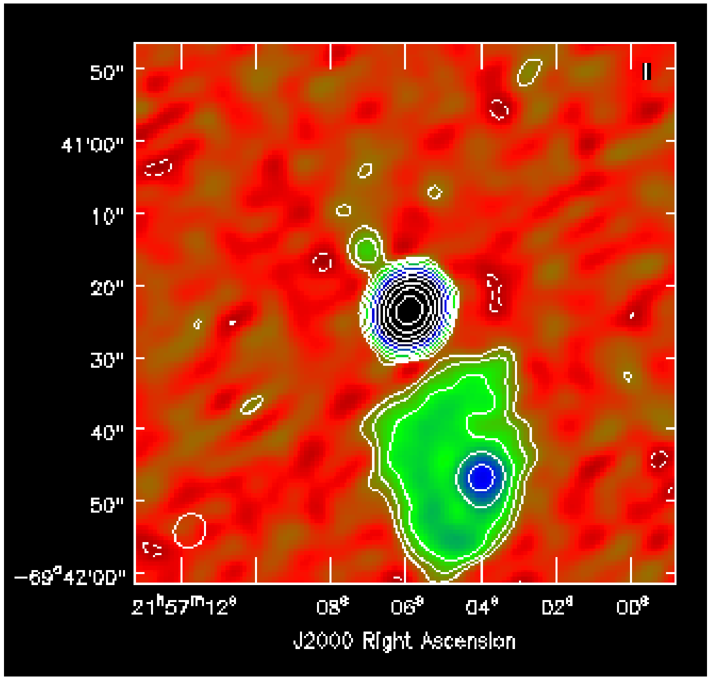


Image of 2157-694 after phasecal 2 and amplitude selfcal, over entire scan

Pk = 122 mJy Jy, clev=0.15 mJy; d_i~2000

Image noise = ***0.06 mJy***

Final Remarks

- High frequency observations are strongly affected by the atmosphere
- They require additional calibrations
  - Tsys corrections
  - WVR corrections
  - Perhaps even try self-calibration!

- Tsys and WVR calibration tables will be provided and can be simply applied to the data (using "applycal" in CASA)

- Self-calibration is a fundamental tool: can obtain order-of-magnitude increase sensitivity and image fidelity
  - Self-calibration tables will not be included in the data shipped to PI's.
  - So learn how to do it!

From Power to Temperature

- An antenna measures Power

$$P_A = \tfrac{1}{2}\ A\ S\ \Delta\nu$$

- The signal measured is generally noise-like

- A resistor at physical temperature T will deliver a noise power level of P (Nyquist 1928) that is given by:

$$P = k_B T\ \Delta\nu$$

- It is often ‘convenient’ to express this random noise power in terms of an equivalent temperature (in RJ limit)

$$P_A = k_B T_A\ \Delta\nu$$

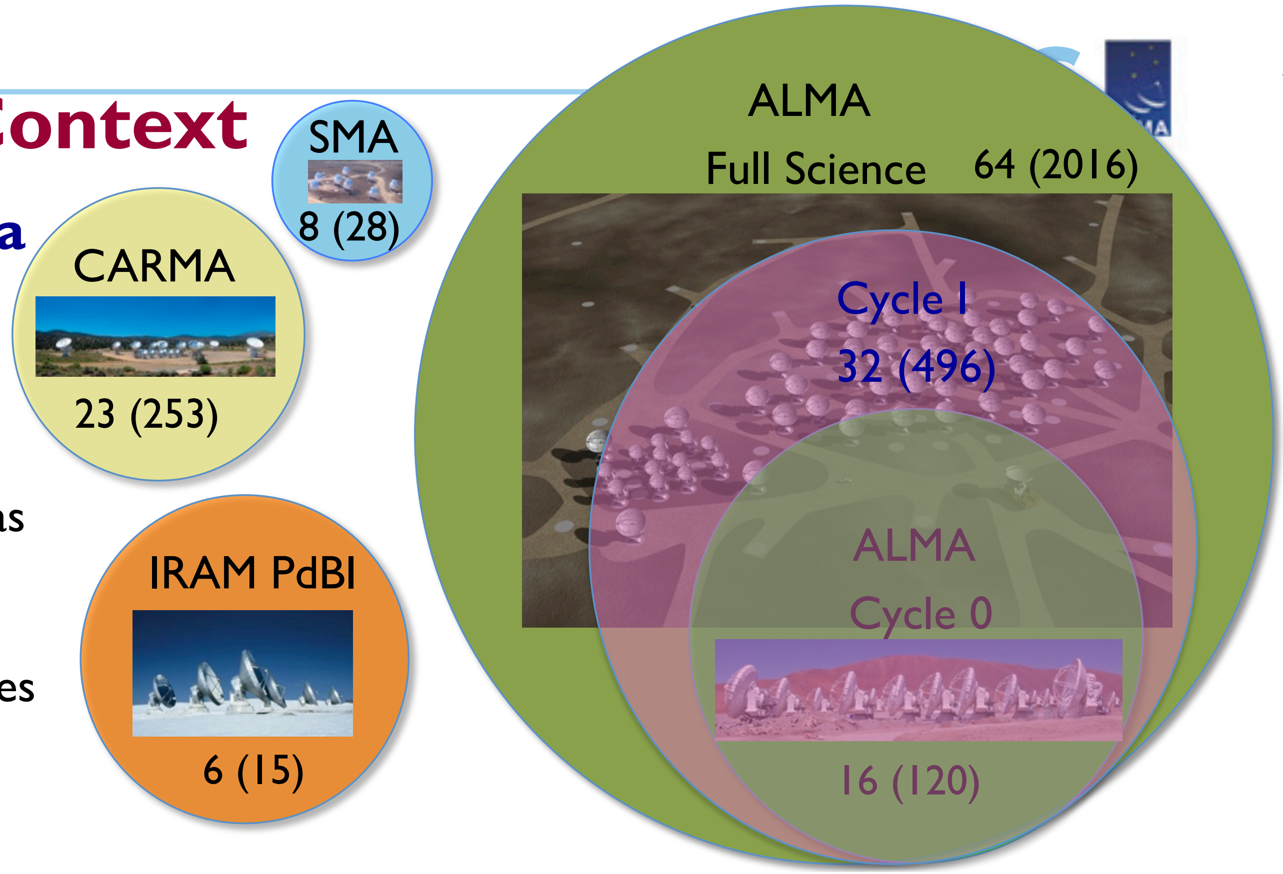
From A. Wooten's talk

ALMA in Context

Collecting Area

of Antennas

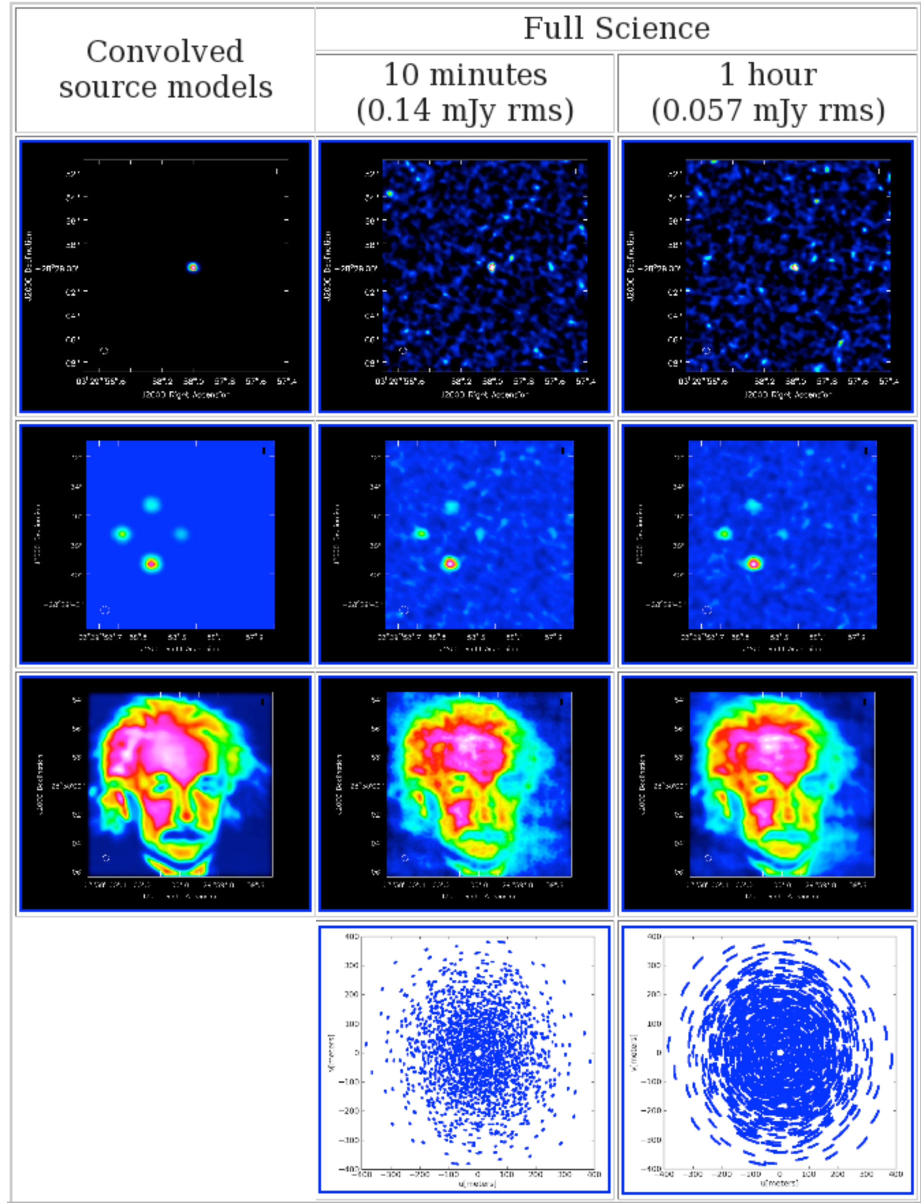
(# of baselines)



- Sensitivity goes as collecting area
- Image fidelity goes as # of baselines

Total Power Array

- "Fill in" the range of low spatial frequencies not sampled by the array
  - Since antennas cannot be put closer than their diameter
- Goal: Sample large-scale emission by scanning over fields in total power mode



What Data Were Taken (2)?

The following CASA task will print a summary of the observations, optionally making a hardcopy text file if *listfile* is set

listobs(vis='your.ms',listfile='your.ms.listobs',verbose=T)

- In the Order they are encountered in the data:
  - Each position that is observed is given a **field id**; inside CASA objects can be selected via their **Names** (* wildcard use possible) or **field id**
  - The spectral setups are indicated by a **spectral window (spw) id**
  - Each antenna used in the observing array is given an **Antenna id**
  - Each distinct target is also given a **source id – i.e. only different for mosaics** (not currently used inside CASA)

Example TDM: SV data NGC3256

- Top portion of verbose *listobs*
- In next slides we zoom in on different parts

```
           MeasurementSet Name:  /export/data_1/data_2/SV_data/NGC3256_Band3_UnCalibratedMSandTablesForReduction/uid___A002_X1d54a1_X174.ms      MS Version 2
================================================================================
   Observer: Unknown     Project: T.B.D.
Observation: ALMA
Data records: 205961       Total integration time = 3782.5 seconds
   Observed from   16-Apr-2011/04:05:36.4   to   16-Apr-2011/05:08:38.9 (UTC)

   ObservationID = 0         ArrayID = 0
  Date        Timerange (UTC)          Scan  FldId FieldName           nRows   Int(s)   SpwIds       ScanIntent
  16-Apr-2011/04:05:39.4 - 04:06:20.2     1      0 1037-295            1463    2.87     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:06:44.6 - 04:07:37.3     2      0 1037-295            2415    2.89     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_POINTING#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:08:32.7 - 04:09:11.8     3      1 Titan               1456    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:09:35.0 - 04:13:05.7     4      1 Titan               14532   2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_AMPLI#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:13:40.6 - 04:17:11.0     5      0 1037-295            14532   2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:17:30.1 - 04:18:08.6     6      0 1037-295            1449    2.89     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:18:28.2 - 04:19:13.2     7      0 1037-295            2905    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:19:54.1 - 04:20:32.6     8      2 NGC3256             1449    2.89     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:20:57.0 - 04:30:36.3     9      2 NGC3256             38752   2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
              04:30:55.3 - 04:31:33.9    10      0 1037-295            1456    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:31:53.3 - 04:32:38.4    11      0 1037-295            2905    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:32:57.3 - 04:33:36.0    12      2 NGC3256             1456    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:33:56.7 - 04:43:36.2    13      2 NGC3256             38773   2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
              04:44:03.1 - 04:44:41.9    14      0 1037-295            1456    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:45:05.2 - 04:45:51.0    15      0 1037-295            2905    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:46:09.3 - 04:46:47.4    16      2 NGC3256             1456    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:47:08.3 - 04:56:47.6    17      2 NGC3256             38752   2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
              04:57:06.7 - 04:57:45.2    18      0 1037-295            1463    2.87     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:58:04.2 - 04:58:49.7    19      0 1037-295            2912    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              04:59:16.2 - 04:59:55.4    20      2 NGC3256             1463    2.87     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
              05:00:19.2 - 05:07:31.6    21      2 NGC3256             29106   2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
              05:07:53.3 - 05:08:38.4    22      0 1037-295            2905    2.88     [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
           (nVis = Total number of time/baseline visibilities per scan)
Fields: 3
  ID   Code Name                RA               Decl           Epoch   SrcId nVis
  0    none 1037-295            10:37:16.07900 -29.34.02.8130 J2000   0     38766
  1    none Titan               00:00:00.00000 +00.00.00.0000 J2000   1     15988
  2    none NGC3256             10:27:51.60000 -43.54.18.0000 J2000   2     151207
   (nVis = Total number of time/baseline visibilities per field)
Spectral Windows:  (9 unique spectral windows and 2 unique polarization setups)
  SpwID  #Chans Frame Ch1(MHz)     ChanWid(kHz)  TotBW(kHz)  Corrs
  0          4 TOPO  184550       1500000       7500000     I
  1        128 TOPO  113211.988  15625         2000000     XX  YY
  2          1 TOPO  114188.55   1796875       1796875     XX  YY
  3        128 TOPO  111450.813  15625         2000000     XX  YY
  4          1 TOPO  112427.375  1796875       1796875     XX  YY
  5        128 TOPO  101506.187  15625         2000000     XX  YY
  6          1 TOPO  100498.375  1796875       1796875     XX  YY
  7        128 TOPO  103050.863  15625         2000000     XX  YY
```

Example TDM: SV data NGC3256

```
        MeasurementSet Name:  /export/data_1/data_2/SV_data/NGC3256_Band3_UnCalibr
================================================================================
   Observer: Unknown     Project: T.B.D.
Observation: ALMA
Data records: 205961       Total integration time = 3782.5 seconds
   Observed from   16-Apr-2011/04:05:36.4   to   16-Apr-2011/05:08:38.9 (UTC)

   ObservationID = 0         ArrayID = 0
  Date        Timerange (UTC)          Scan  FldId FieldName          nRows   Int(s)
  16-Apr-2011/04:05:39.4 - 04:06:20.2     1      0 1037-295           1463   2.87
              04:06:44.6 - 04:07:37.3     2      0 1037-295           2415   2.89
              04:08:32.7 - 04:09:11.8     3      1 Titan              1456   2.88
              04:09:35.0 - 04:13:05.7     4      1 Titan              14532  2.88
              04:13:40.6 - 04:17:11.0     5      0 1037-295           14532  2.88
              04:17:30.1 - 04:18:08.6     6      0 1037-295           1449   2.89
              04:18:28.2 - 04:19:13.2     7      0 1037-295           2905   2.88
              04:19:54.1 - 04:20:32.6     8      2 NGC3256            1449   2.89
              04:20:57.0 - 04:30:36.3     9      2 NGC3256            38752  2.88
              04:30:55.3 - 04:31:33.9    10      0 1037-295           1456   2.88
              04:31:53.3 - 04:32:38.4    11      0 1037-295           2905   2.88
              04:32:57.3 - 04:33:36.0    12      2 NGC3256            1456   2.88
              04:33:56.7 - 04:43:36.2    13      2 NGC3256            38773  2.88
              04:44:03.1 - 04:44:41.9    14      0 1037-295           1456   2.88
              04:45:05.2 - 04:45:51.0    15      0 1037-295           2905   2.88
              04:46:09.3 - 04:46:47.4    16      2 NGC3256            1456   2.88
              04:47:08.3 - 04:56:47.6    17      2 NGC3256            38752  2.88
              04:57:06.7 - 04:57:45.2    18      0 1037-295           1463   2.87
              04:58:04.2 - 04:58:49.7    19      0 1037-295           2912   2.88
              04:59:16.2 - 04:59:55.4    20      2 NGC3256            1463   2.87
              05:00:19.2 - 05:07:31.6    21      2 NGC3256            29106  2.88
              05:07:53.3 - 05:08:38.4    22      0 1037-295           2905   2.88
```

Sequence of observing with scan and field ids, and intrinsic integration time

```
Fields: 3
  ID   Code Name          RA               Decl           Epoch   SrcId nVis
  0    none 1037-295      10:37:16.07900 -29.34.02.8130 J2000   0     38766
  1    none Titan         00:00:00.00000 +00.00.00.0000 J2000   1     15988
  2    none NGC3256       10:27:51.60000 -43.54.18.0000 J2000   2     151207
   (nVis = Total number of time/baseline visibilities per field)
```

Summary of of sources observed

Example TDM: SV data NGC3256

NAASC

```
FldId FieldName     SpwIds        ScanIntent
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_POINTING#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    1 Titan         [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    1 Titan         [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_AMPLI#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
    2 NGC3256       [1, 3, 5, 7, 2, 4, 6, 8, 0] OBSERVE_TARGET#ON_SOURCE
    0 1037-295      [1, 3, 5, 7, 2, 4, 6, 8, 0] CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
```

Intents for each scan

Summary of spws for each scan

```
Spectral Windows:  (9 unique spectral windows and 2 unique polarization setups)
  SpwID  #Chans Frame Ch1(MHz)    ChanWid(kHz)  TotBW(kHz)  Corrs
  0           4 TOPO  184550      1500000       7500000     I
  1         128 TOPO  113211.988  15625         2000000     XX  YY
  2           1 TOPO  114188.55   1796875       1796875     XX  YY
  3         128 TOPO  111450.813  15625         2000000     XX  YY
  4           1 TOPO  112427.375  1796875       1796875     XX  YY
  5         128 TOPO  101506.187  15625         2000000     XX  YY
  6           1 TOPO  100498.375  1796875       1796875     XX  YY
  7         128 TOPO  103050.863  15625         2000000     XX  YY
```

Summary of spectral setup

WVR data

Example TDM: SV data NGC3256

```
Antennas: 7:
  ID    Name   Station    Diam.     Long.           Lat.
  0     DV04   J505       12.0 m    -067.45.18.0   -22.53.22.8
  1     DV06   T704       12.0 m    -067.45.16.2   -22.53.22.1
  2     DV07   J510       12.0 m    -067.45.17.8   -22.53.23.5
  3     DV08   T703       12.0 m    -067.45.16.2   -22.53.23.9
  4     DV09   N602       12.0 m    -067.45.17.4   -22.53.22.3
  5     PM02   T701       12.0 m    -067.45.18.8   -22.53.22.2
  6     PM03   J504       12.0 m    -067.45.17.0   -22.53.23.0
```

Summary of antenna ids, antenna names, and station (pad) names. Note: it is always best to use antenna names in your data reduction to avoid confusion.

When necessary, antenna position corrections can be generated using *gencal* and applied like any other calibration table

Example FDM: SV data TWHya

NAASC

Spectral Windows: (25 unique spectral windows and 2 unique polarization setups)

SpwID	#Chans	Frame	Ch1(MHz)	ChanWid(kHz)	TotBW(kHz)	Corrs
0	4	TOPO	184550	1500000	7500000	I
1	128	TOPO	355740.062	15625	2000000	XX YY
2	1	TOPO	356716.625	1796875	1796875	XX YY
3	128	TOPO	356507.813	15625	2000000	XX YY
4	1	TOPO	357484.375	1796875	1796875	XX YY
5	128	TOPO	346792.187	15625	2000000	XX YY
6	1	TOPO	345784.375	1796875	1796875	XX YY
7	128	TOPO	345182.438	15625	2000000	XX YY
8	1	TOPO	344174.625	1796875	1796875	XX YY
9	128	TOPO	344386.763	15625	2000000	XX YY
10	1	TOPO	343378.95	1796875	1796875	XX YY
11	128	TOPO	346324.263	15625	2000000	XX YY
12	1	TOPO	345316.45	1796875	1796875	XX YY
13	128	TOPO	354402.388	15625	2000000	XX YY
14	1	TOPO	355378.95	1796875	1796875	XX YY
15	128	TOPO	356402.388	15625	2000000	XX YY
16	1	TOPO	357378.95	1796875	1796875	XX YY
17	3840	TOPO	356497.936	122.070312	468750	XX YY
18	1	TOPO	356732.189	468750	468750	XX YY
19	3840	TOPO	357734.314	122.070312	468750	XX YY
20	1	TOPO	357499.939	468750	468750	XX YY
21	3840	TOPO	346034.314	122.070312	468750	XX YY
22	1	TOPO	345799.939	468750	468750	XX YY
23	3840	TOPO	343955.936	122.070312	468750	XX YY
24	1	TOPO	344190.189	468750	468750	XX YY

TDM used for Tsys measurements

TDM used for pointing (in ES would have been done in Band 3)

FDM "Science"

Scan	FldId	FieldName	SpwIds	ScanIntent
1	0	3c279	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
2	0	3c279	[9, 11, 13, 15, 10, 12, 14, 16, 0]	CALIBRATE_POINTING#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
3	1	Titan	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
4	1	Titan	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_AMPLI#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
5	0	3c279	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
6	2	TW Hya	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
7	2	TW Hya	[9, 11, 13, 15, 10, 12, 14, 16, 0]	CALIBRATE_POINTING#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
8	3	J1147-382=QSO	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
9	2	TW Hya	[17, 19, 21, 23, 18, 20, 22, 24, 0]	OBSERVE_TARGET#ON_SOURCE
10	4	J1037-295=QSO	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
11	4	J1037-295=QSO	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
12	2	TW Hya	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
13	2	TW Hya	[17, 19, 21, 23, 18, 20, 22, 24, 0]	OBSERVE_TARGET#ON_SOURCE
14	4	J1037-295=QSO	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
15	4	J1037-295=QSO	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
16	3	J1147-382=QSO	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
17	2	TW Hya	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
18	2	TW Hya	[17, 19, 21, 23, 18, 20, 22, 24, 0]	OBSERVE_TARGET#ON_SOURCE
19	4	J1037-295=QSO	[1, 3, 5, 7, 2, 4, 6, 8, 0]	CALIBRATE_ATMOSPHERE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE
20	4	J1037-295=QSO	[17, 19, 21, 23, 18, 20, 22, 24, 0]	CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE

Example FDM Mosaic:
SV data Antennae

NAASC

```
Fields: 26
  ID   Code Name                RA               Decl           Epoch   SrcId nVis
  0    none 3c279               12:56:11.16657 -05.47.21.5247 J2000   0     61726
  1    none Titan               12:41:48.13907 -01.42.05.4897 J2000   1     16296
  2    none NGC4038 - Antennae *12:01:53.17008 -18.52.37.9200 J2000   2     7406
  3    none NGC4038 - Antennae *12:01:51.90301 -18.51.49.9437 J2000   2     9884
  4    none NGC4038 - Antennae *12:01:52.43086 -18.51.49.9437 J2000   2     9856
  5    none NGC4038 - Antennae *12:01:52.95871 -18.51.49.9437 J2000   2     9870
  6    none NGC4038 - Antennae *12:01:53.48656 -18.51.49.9436 J2000   2     9870
  7    none NGC4038 - Antennae *12:01:54.01441 -18.51.49.9436 J2000   2     9856
  8    none NGC4038 - Antennae *12:01:52.16693 -18.51.56.4319 J2000   2     9884
  9    none NGC4038 - Antennae *12:01:52.69478 -18.51.56.4318 J2000   2     9870
  10   none NGC4038 - Antennae *12:01:53.22263 -18.51.56.4318 J2000   2     9870
  11   none NGC4038 - Antennae *12:01:53.75049 -18.51.56.4318 J2000   2     9884
  12   none NGC4038 - Antennae *12:01:51.90301 -18.52.02.9201 J2000   2     9870
  13   none NGC4038 - Antennae *12:01:52.43086 -18.52.02.9200 J2000   2     9870
  14   none NGC4038 - Antennae *12:01:52.95871 -18.52.02.9200 J2000   2     7406
  15   none NGC4038 - Antennae *12:01:53.48656 -18.52.02.9200 J2000   2     7392
  16   none NGC4038 - Antennae *12:01:54.01441 -18.52.02.9199 J2000   2     7392
  17   none NGC4038 - Antennae *12:01:52.16694 -18.52.09.4082 J2000   2     7420
  18   none NGC4038 - Antennae *12:01:52.69479 -18.52.09.4082 J2000   2     7406
  19   none NGC4038 - Antennae *12:01:53.22264 -18.52.09.4082 J2000   2     7392
  20   none NGC4038 - Antennae *12:01:53.75049 -18.52.09.4081 J2000   2     7406
  21   none NGC4038 - Antennae *12:01:51.90301 -18.52.15.8964 J2000   2     7392
  22   none NGC4038 - Antennae *12:01:52.43087 -18.52.15.8964 J2000   2     7392
  23   none NGC4038 - Antennae *12:01:52.95872 -18.52.15.8963 J2000   2     7420
  24   none NGC4038 - Antennae *12:01:53.48657 -18.52.15.8963 J2000   2     7392
  25   none NGC4038 - Antennae *12:01:54.01442 -18.52.15.8963 J2000   2     6356
   (nVis = Total number of time/baseline visibilities per field)
Spectral Windows:  (9 unique spectral windows and 2 unique polarization setups)
  SpwID  #Chans Frame Ch1(MHz)    ChanWid(kHz)  TotBW(kHz)  Corrs
  0          4 TOPO  184550      1500000       7500000     I
  1       3840 TOPO  344845.586  488.28125     1875000     XX  YY
  2          1 TOPO  343908.086  1875000       1875000     XX  YY
  3       3840 TOPO  354971.074  488.28125     1875000     XX  YY
  4          1 TOPO  343908.086  1875000       1875000     XX  YY
  5        128 TOPO  344900.518  15625         2000000     XX  YY
  6          1 TOPO  343892.705  1796875       1796875     XX  YY
  7        128 TOPO  354916.143  15625         2000000     XX  YY
```

- Every unique position observed gets a unique field id
- For mosaics, the source id will be the same for all the pointings in a mosaic
- Source ids are not currently used in CASA

NOTE: CASA's *clean* task in *imagermode='mosaic'* will attempt to mosaic ALL fields given to it, whether they were observed that way or not!

NRAO

Data Package for Cycle 0

You will receive a tar file containing the following directories

1. 'raw' contains an ms that has ALREADY been calibrated for WVR, Tsys, and any antenna position corrections, and only the "science" spectral windows.
   A. It also contains the calibration tables (bandpass, phase, amplitude, flux) and backup flag tables from each stage of reduction (the data itself contain the final flag state so you don't need to do anything if you are happy with it).
2. 'calibrated' contains the fully calibrated ms (i.e. ready for imaging).
3. 'science' contains fits files for the **reference** images.
4. 'script' contains the CASA data reduction script.
5. 'qa' contains the Quality Assurance "2" report (estimates of achieved rms noise etc).
6. 'logs' contains the CASA log files.

➔ Attempt to loosely replicate what the pipeline will serve in Full Science (items A, 3-6 + raw ASDM)

➔ It is likely that you will want to perfect the images to suit your science goals

NAASC

- Extra slides

Interferometric MM Measurement of T_{sys}

- How do we measure $T_{sys} = T_{atm}(e^{\tau} - 1) + T_{rx} e^{\tau}$ without constantly measuring T_{rx} and the opacity?

- The "chopper wheel" method: putting an ambient temperature load (T_{load}) in front of the receiver and measuring the resulting power compared to power when observing sky T_{atm} (Penzias & Burrus 1973).

Load in $V_{in} = G\, T_{in} = G\, [T_{rx} + T_{load}]$

Load out $V_{out} = G\, T_{out} = G\, [T_{rx} + T_{atm}(1 - e^{-\tau}) + T_{bg} e^{-\tau} + T_{source} e^{-\tau}]$

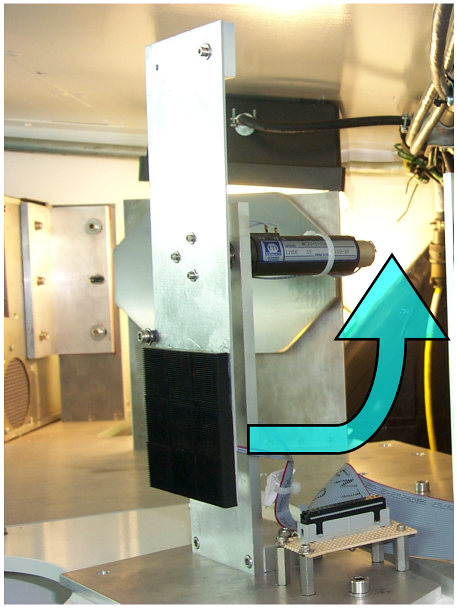
assume $T_{atm} \approx T_{load}$

Comparing in and out $$\frac{V_{in} - V_{out}}{V_{out}} = \frac{T_{load}}{T_{sys}}$$

$$T_{sys} = T_{load} * T_{out} / (T_{in} - T_{out})$$

Power is really observed but is $\propto$ T in the R-J limit

- IF $T_{atm} \approx T_{load}$, and T_{sys} is measured often, changes in mean atmospheric absorption are corrected. ALMA will have a two temperature load system which allows independent measure of T_{rx}



SMA calibration load swings in and out of beam