The *CASA* software package

Dirk Petry (ESO/ARC), February 2012

Outline

→ What is *CASA?* - main features

→ Who develops *CASA*? - development team

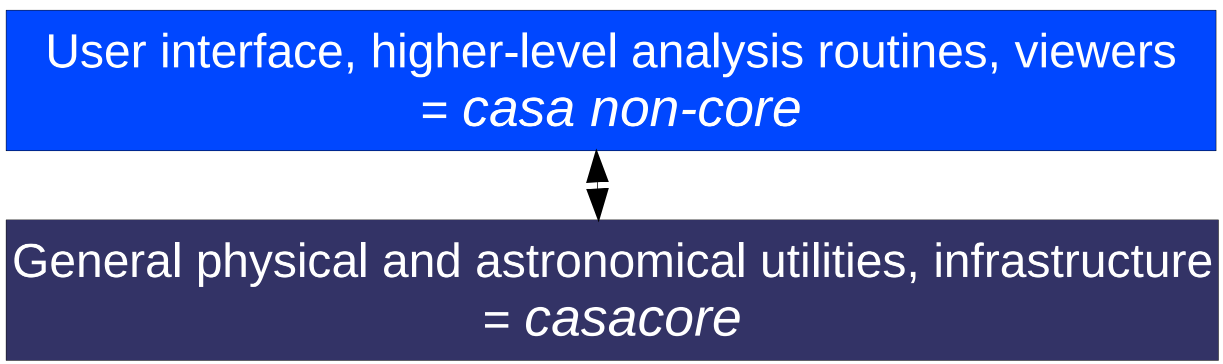
→ What are the main requirements and how does *CASA* meet them? - design and implementation

→ CASA status and release plans

→ How does CASA look and feel? - installation and the typical analysis session

CASA main features

- *CASA* **= Common Astronomy Software Applications**
- **Development started in the 90s as the next generation of AIPS**
- **Refocussed in 2003 to be *the ALMA/EVLA analysis package***
- **Has the intention to be a *general software package to reduce both interferometer and single-dish data***
- **Internally consists of two parts:**



- **Implements the “Measurement Equation” (Hamaker, Bregman & Sault 1996)**
- **Internal data format is the “Measurement Set” (Kemball & Wieringa 2000)**
- **more than 1.5 Million lines of code (mostly C++)**
- **In public release under GNU Public License since December 2009**

CASA – development team

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Since mid 2008, two CASA developers at ESO, since Sept. 2009 three

CASA – development team

Originally only developed at NRAO (Socorro, NM) ,
now approx. 19 FTE developers are at work at

US (NRAO and others):	**12**
Japan (NAOJ):	**3**
Europe (ESO and others):	**4**

+ 1 CASA manager (NRAO Socorro) = Jeff Kern

+ 1 CASA Project Scientist (NRAO Socorro) = Jürgen Ott

+ 1 ALMA CASA subsystem scientist (NRAO CV) = Crystal Brogan

+ 1 EVLA CASA subsystem scientist (NRAO Socorro) = Steve Myers

+ 2 ARC CASA leads (ESO: D. Petry, NAOJ: A. Higuchi)

+ a few 5% FTEs at ASTRON, ATNF, and other places
Also involved:
ALMA Computing Managers = B. Glendenning (NRAO), E. Schmid, P. Ballester (ESO)

CASA design and implementation

Overall architecture:

1) A data structure

2) A set of data import/export facilities

3) A set of tools for data access, display, and editing

4) A set of tools for science analysis

5) A set of high-level analysis procedures ("tasks")

6) A programmable command line interface with scripting

7) Documentation

CASA design and implementation

Overall architecture:

1) A data structure
   Tables: Images, Caltables, and the *Measurement Set* (MS)
2) A set of data import/export facilities
   the so-called *fillers*: (ASDM, UVFITS, FITS-IDI, VLA archive) → MS, FITS → Image
3) A set of tools for data access, display, and editing
   tools to load/write data into/from casacore data types,
   Qt-based table browser, viewer, and (beta) x/y plotter, *matplotlib*-based x/y plotter
4) A set of tools for science analysis
   built around the *Measurement Equation* (developed in 1996),
   a toolkit for radio astronomical calibration, imaging, and simulation
5) A set of high-level analysis procedures (“tasks”)
   user-friendly implementations of the solutions for all common analysis problems
6) A programmable command line interface with scripting
   Python (augmented by *IPython*) gives a MATLAB-like interactive language
7) Documentation
   an extensive cookbook (500 pages) + documentation through help commands
   (help, ?, pdoc) + online help pages, See **http://casa.nrao.edu/**

CASA design and implementation

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4) A set of tools for science analysis

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CASA design and implementation

CASA special features:

a) the *Measurement Set* (MS)

- developed by Cornwell, Kemball, & Wieringa between 1996 and 2000

- designed to store both interferometry (multi-dish) and single-dish data

- supports (in principle) any setup of radio telescopes

- supports description and processing of the data via the Measurement Equation

- fundamental storage mechanism: *CASA Tables* (inspired by *MIRIAD*)

- MS = table for radio telescope data (visibilities) + *auxiliary sub-tables*

CASA design and implementation

The Measurement Set

Table Name	Key defined in this table	key definition method	referenced by	referenced keys
MAIN	none	-	-	ANTENNA_ID FEED_ID DATA_DESC_ID PROCESSOR_ID (PHASE_ID) FIELD_ID (PULSAR_GATE_ID) ARRAY_ID OBSERVATION_ID STATE_ID
(FREQ_OFFSET)	none	-	-	ANTENNA_ID FEED_ID SPW_ID
(SYSCAL)	none	-	-	ANTENNA_ID FEED_ID SPW_ID
POINTING	none	-	-	ANTENNA_ID POINTING_MODEL_ID
(WEATHER)	none	-	-	ANTENNA_ID
HISTORY	none	-	-	OBSERVATION_ID OBJECT_ID
FLAG_CMD	none	-	-	none

Table Name	Key defined in this table	key definition method	referenced by	referenced keys
ANTENNA	ANTENNA_ID	row number	MAIN FEED FREQ_OFFSET POINTING SYSCAL WEATHER	(ORBIT_ID) (PHASED_ARRAY_ID)
FEED	FEED_ID	explicit	MAIN FREQ_OFFSET SYSCAL	ANTENNA_ID SPW_ID BEAM_ID (PHASED_FEED_ID)
DATA_DESCRIPTION	DATA_DESC_ID	row number	MAIN	SPW_ID POLARIZATION_ID (LAG_ID)
PROCESSOR	PROCESSOR_ID	row number	MAIN	TYPE_ID MODE_ID (PASS_ID)
FIELD	FIELD_ID	row number	MAIN	SOURCE_ID (EPHEMERIS_ID)
OBSERVATION	OBSERVATION_ID	row number	MAIN HISTORY	none
STATE	STATE_ID	row number	MAIN	none
SPW	SPW_ID	row number	DATA_DESCRIPTION FEED FREQ_OFFSET SOURCE SYSCAL	(RECEIVER_ID) (DOPPLER_ID) (ASSOC_SPW_ID)

Table Name	Key defined in this table	key definition method	referenced by	referenced keys
POLARIZATION	POLARIZATION_ID	row number	DATA_DESCRIPTION	none
(SOURCE)	SOURCE_ID	explicit	(DOPPLER) FIELD	SPW_ID (PULSAR_ID)
(DOPPLER)	DOPPLER_ID	explicit	SPW_ID	SOURCE_ID TRANSITION_ID

Legend:

[Table Name]	[Key defined in this table]	[key definition method]	[referenced by]	[referenced keys] (optional) reference to table outside the MS definition

Level 1: Tables not referenced by other tables

Level 2: Tables referenced by level 1

Level 3: Tables referenced by level 2

V1, D.Petry, 13.2.09

CASA special features:

b) A toolkit for radio astronomical calibration, imaging, and simulation built around the *Measurement Equation* (Hamaker, Bregman, & Sault 1996 + Sault, Hamaker, & Bregman 1996)

$$\vec{V}_{ij} = \vec{M}_{ij}\vec{B}_{ij}\vec{G}_{ij}\vec{D}_{ij}\int \vec{E}_{ij}\vec{P}_{ij}\vec{T}_{ij}\vec{F}_{ij}\; S\vec{I}_{\nu}(l,m)\, e^{-i2\pi(u_{ij}l+v_{ij}m)}\, dl\, dm + \vec{A}_{ij}$$

where

the vectors are: V = observed visibility = $f(u, v)$, I = Image to be derived,
A = additive baseline-based error component

the matrices are:
M = multiplicative, baseline-based error component
B = bandpass response
G = generalised electronic gain
D = polarisation leakage
E = antenna voltage pattern, i.e. primary beam effects
P = parallactic angle dependence
T = tropospheric effects
F = ionospheric Faraday rotation
S = mapping of I to the polarization basis of the observation

other variables and indices are:

l, m = image plane coordinates, i, j = telescope ID pairs = baseline, u, v = Fourier plane coordinates

CASA special features:

b) A toolkit for radio astronomical calibration, imaging, and simulation built around the *Measurement Equation* (Hamaker, Bregman, & Sault 1996 + Sault, Hamaker, & Bregman 1996) (continued)

Assuming, e.g., independence of the matrices from (l,m), the ME can be solved for individual calibration components.

$$\vec{V}_{ij}^{obs} = \overleftrightarrow{B}_{ij}\overleftrightarrow{G}_{ij}\overleftrightarrow{D}_{ij}\overleftrightarrow{P}_{ij}\overleftrightarrow{T}_{ij}\overleftrightarrow{F}_{ij}\,\vec{V}_{ij}^{ideal}$$

ideal visibility known from calibrator source

⇒ have set of linear equations.

The actual calculation of the component is then a χ^2 minimization.

(For wide-field imaging the above assumption doesn't hold and the solution is more complex but still possible.)

CASA contains a set of ***solvers*** for the different calibration components.

CASA design and implementation

CASA special features:

b) A toolkit for radio astronomical calibration, imaging, and simulation (continued)

Imaging in CASA: Combinations of Major and Minor Cycle Algorithms

Imaging (Major Cycle):

1) Standard (no dir.-dep. effects, uv-grid sampling uses convolutional regridding)
2) with dir.-dep. effects:
   a) W-term (image domain faceting, uv domain faceting, W projection)
   b) PB correction (image domain, A projection)
   c) Pointing Offset correction by phase gradient
   d) Mosaicing (linear (separate) deconvolution,
      joined deconv. of combined dirty images,
      mosaicing by regridding all uv data onto one grid)

Deconvolution (Minor Cycle):

1) CLEAN (delta function model)
2) MS-CLEAN (blob model)
3) MSMFS CLEAN (model of blobs with polynomial spectrum)
4) MEM (maximum entropy method using prior image and delta function model)

see nice overview compiled by Urvashi Rau: https://safe.nrao.edu/wiki/bin/view/Software/AlgorithmList

CASA special features:

b) A toolkit for radio astronomical calibration, imaging, and simulation (continued)

A sophisticated radio-astronomical data simulator: ***simdata***

- Create Measurement Sets of simulated data
(and for convenience: analyse the simulated MS to create simulated image)

- Input:

a) FITS image

b) "antenna list" file describing your interferometer (incl. site name)
sites: *browsetable(os.getenv("CASAPATH").split(' ')[0]+"/data/geodetic/Observatories")*
arrays: *ls os.getenv("CASAPATH").split(' ')[0]+"/data/alma/simmos/"*

c) observation setup parameters
(central direction, time, mosaicing, spectral, integration time, etc.)

d) corrupting effect parameters
(thermal noise from atmosphere and receiver)

- *uses realistic site-dependent troposphere model*
- *knows about ALMA and EVLA receiver parameters*
- *phase noise and gain drift can be applied to the MS later via CASA tools*

e) for convenience: clean task parameters for output image creation

CASA design and implementation

CASA special features:

c) A programmable command line interface with scripting

Framework Architecture of 20 tools bound to ***Python (augmented by IPython)***

```
at : ATM - atmosphere simulation library
cb : Calibration utilities
cp : Calibration solution plotting utilities
cs : Coordinate system utilities
fg : Flagging/Flag management utilities
ia : Image analysis utilities
im : Imaging utilities
me : Measures utilities
ms : MeasurementSet (MS) utilties
mp : MS plotting (data (amp/phase) versus other quantities)
pm : PlotMS utilities
rg : Region manipulation utilities
tb : Table utilities (selection, extraction, etc)
tp : Table plotting utilities
qa : Quanta utilities
sl : Spectral line import and search
sm : Simulation utilities
vp : Voltage pattern/primary beam utilities
pl : pylab (matplotlib) functionality
sd : (after running asap_init()) Single dish utilities
```

CASA special features:

c) A programmable command line interface with scripting (continued)

Python (augmented by IPython)

Gives features such as

- tab completion
- autoparenthesis
- command line numbering
- access to OS, e.g.
  Lines starting with '!' go to the OS.
  `a = !ls *.py` to capture the output of '`ls *.py`'.
  `!cmd $myvar` expands Python var `myvar` for the shell.
- history
- execfile()
- comfortable help

CASA special features:

c) A programmable command line interface with scripting
(continued)

In addition to toolkit: high-level tasks for the standard user

tasks (implemented in Python) → **tools** (implemented in C++)

e.g. the task *importfits* is based on the tool ***ia*** (image analysis):

```
#Python script
casalog.origin('importfits')
ia.fromfits(imagename,fitsimage,whichrep,whichhdu,zeroblanks,overwrite)
ia.close()
```

CASA 3.3 comes with 109 implemented tasks.

CASA status

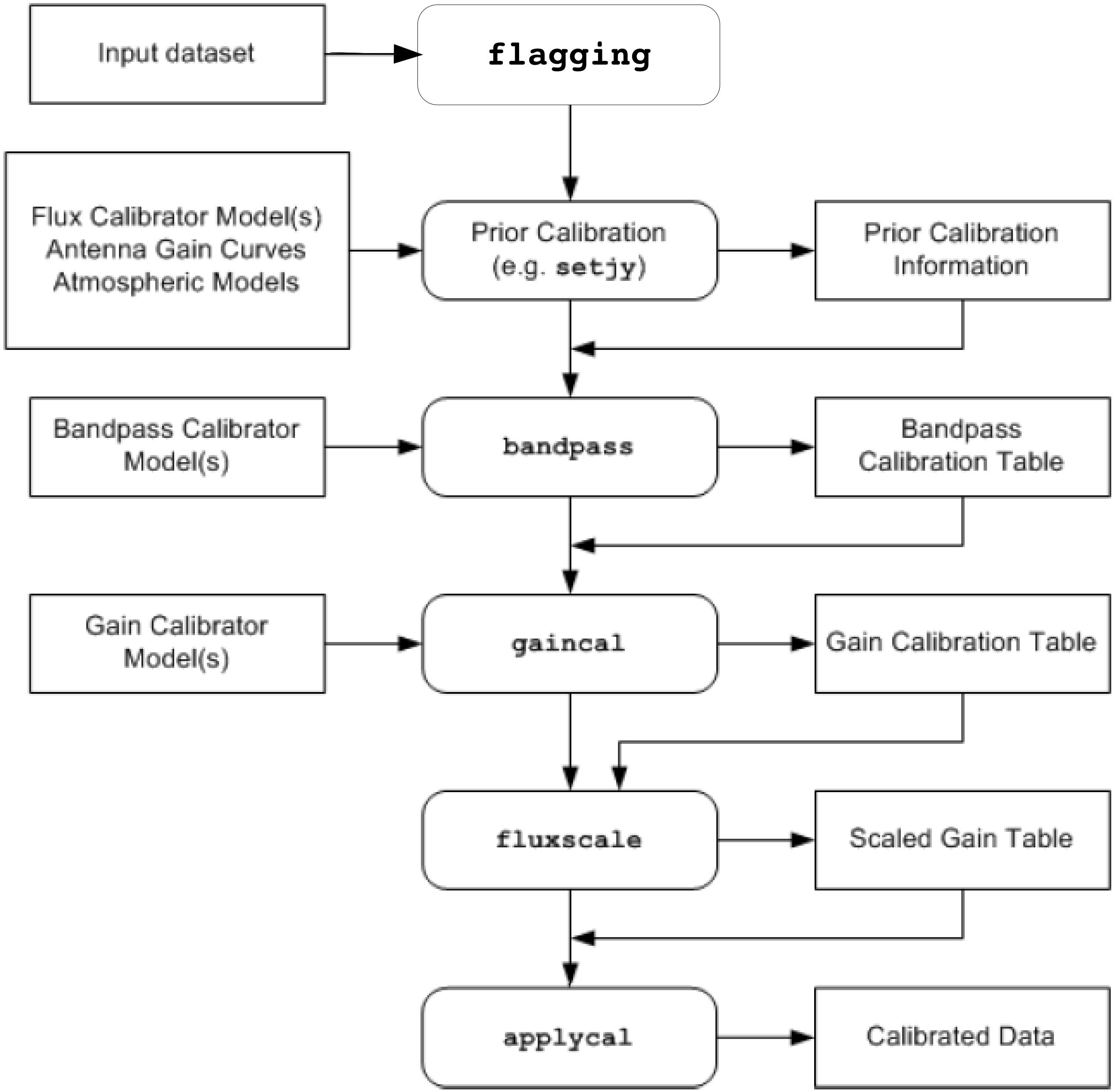
- Since Dec 2009 in public release under GPL = anybody can download,
  no warranty (see http://casa.nrao.edu),
  limited support (help desk, needs registration)
- Tutorials for the user community regularly given
- The first public release was CASA 3.0.0 (Dec 2009), release 3.3.0 out Nov 2011

- Development platforms: Linux (RHEL) + Mac OS X
- Supported platforms (binary distribution): RHEL, Fedora, openSuSE, Ubuntu, Mac OS X
  (10.6 and 10.7, no longer 10.5)
- Code kept in *svn* repository at NRAO, Socorro
- Have approx. 4300 modules, > 1.5E6 lines of code, > 1E6 lines of comments
- The core functionality (*casacore,* also available at http://code.google.com/p/casacore/)
  is also used by other projects
- *Hot topics*:
  - Support for High Performance Computing and Parallelisation
  - Advanced Imaging: wide fields, continuum imaging over wide spectral ranges

How does *CASA* look and feel?

A typical analysis session

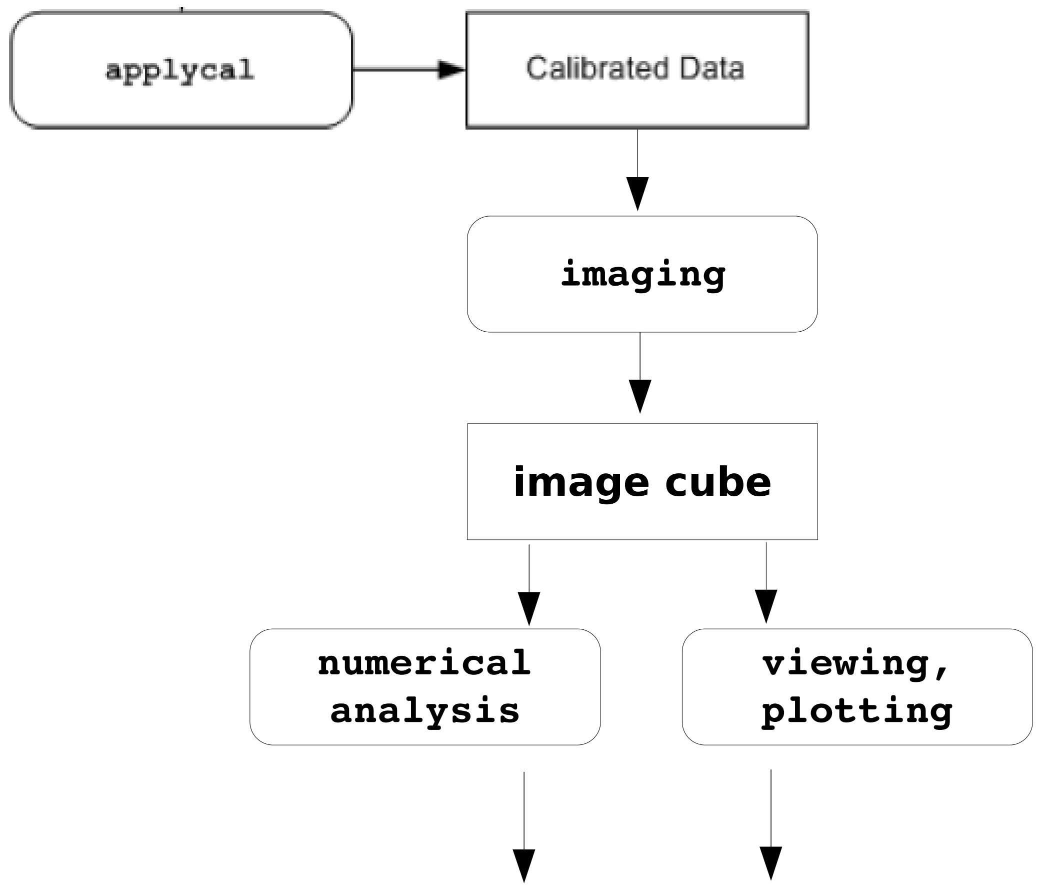
Part 1: flagging and calibration



How does *CASA* look and feel?

A typical analysis session

Part 2: imaging and
image analysis



publication-ready plots and numerical results

How does *CASA* look and feel?

Installation - CASA comes as a tgz-file for Linux or a dmg-file for Mac OS-X

See "Obtaining CASA" link on http://casa.nrao.edu/

Download latest version at
https://svn.cv.nrao.edu/casa/linux_distro
or
https://svn.cv.nrao.edu/casa/osx_distro

Linux:
Unpack tgz file in a location of your choice.
cd into the created casapy directory.

```
export PATH=$PWD:$PATH
```

Mac OS-X:
Open the CASA disk image file (if your browser does not do so automatically).
Read the README for special instructions!
Drag the CASA application to the Applications folder of your hard disk.
Eject the CASA disk image.
Double-click the CASA application to run it for the first time.

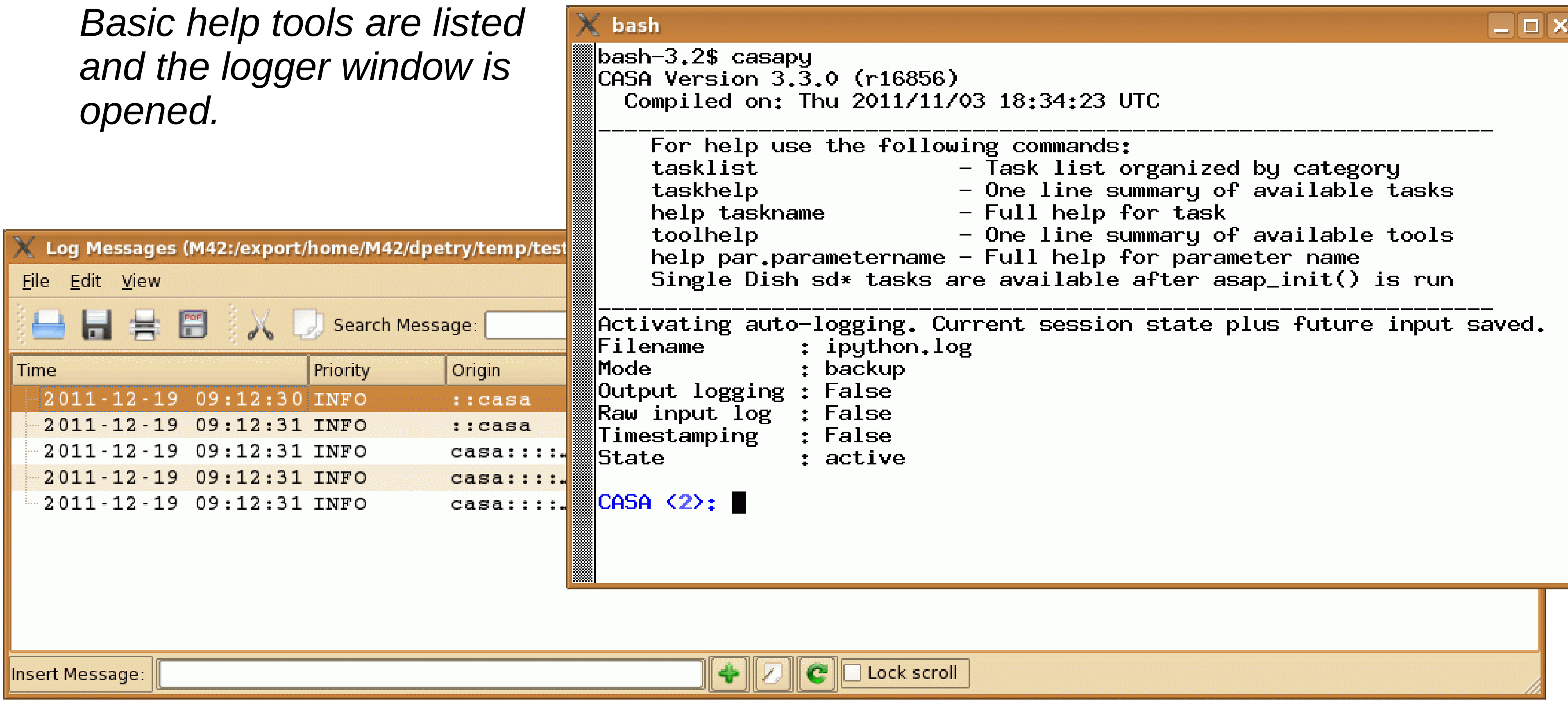
Distribution contains all necessary libraries and Python. No external packages needed.
Exception: Ubuntu users should install Xvfb!

How does *CASA* look and feel?

Pictures from a typical analysis session

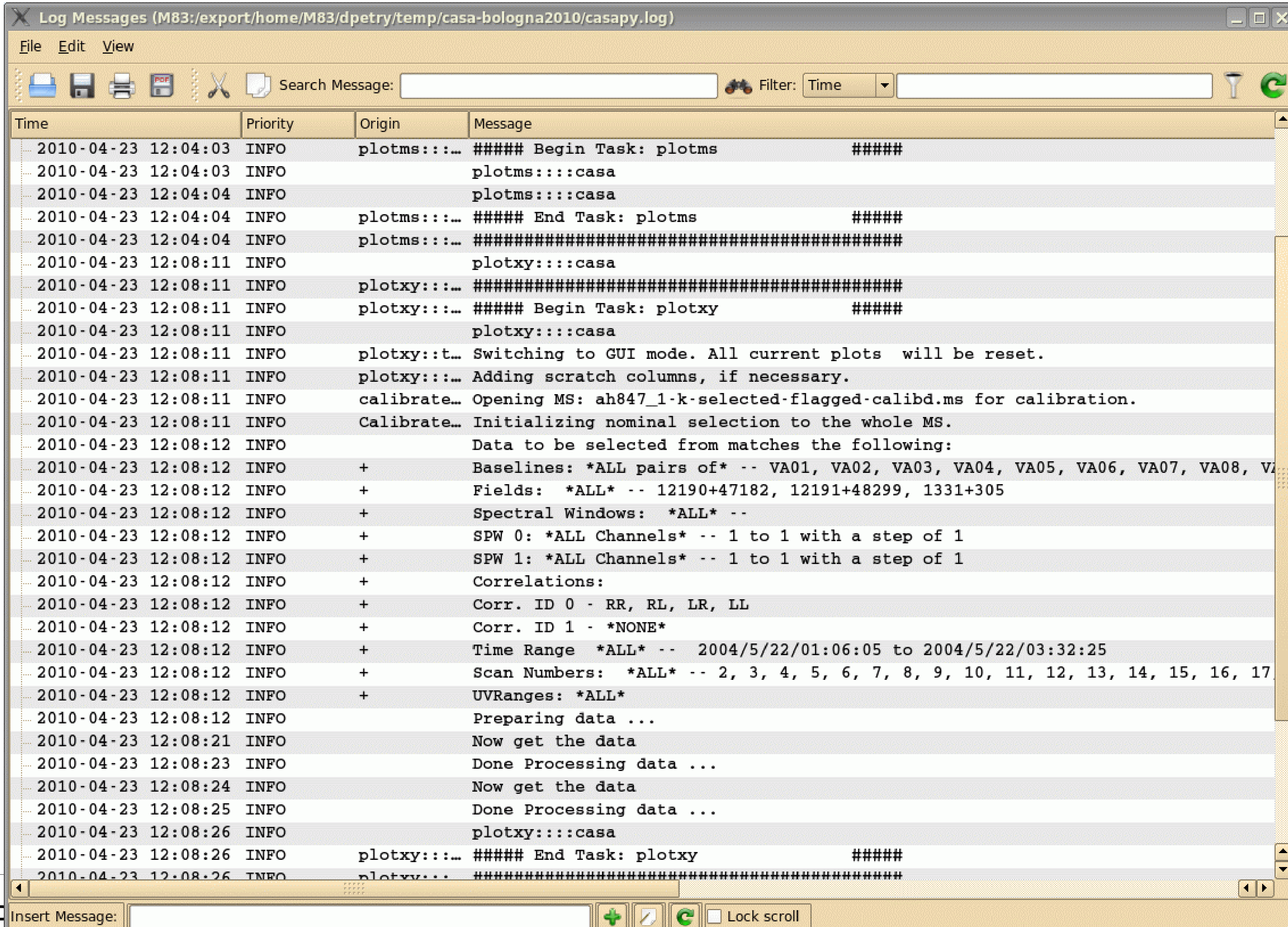
1) Startup:
open terminal and start *casapy*

Basic help tools are listed and the logger window is opened.



The *CASA* user interface

The logger provides functionality for monitoring and debugging command execution.

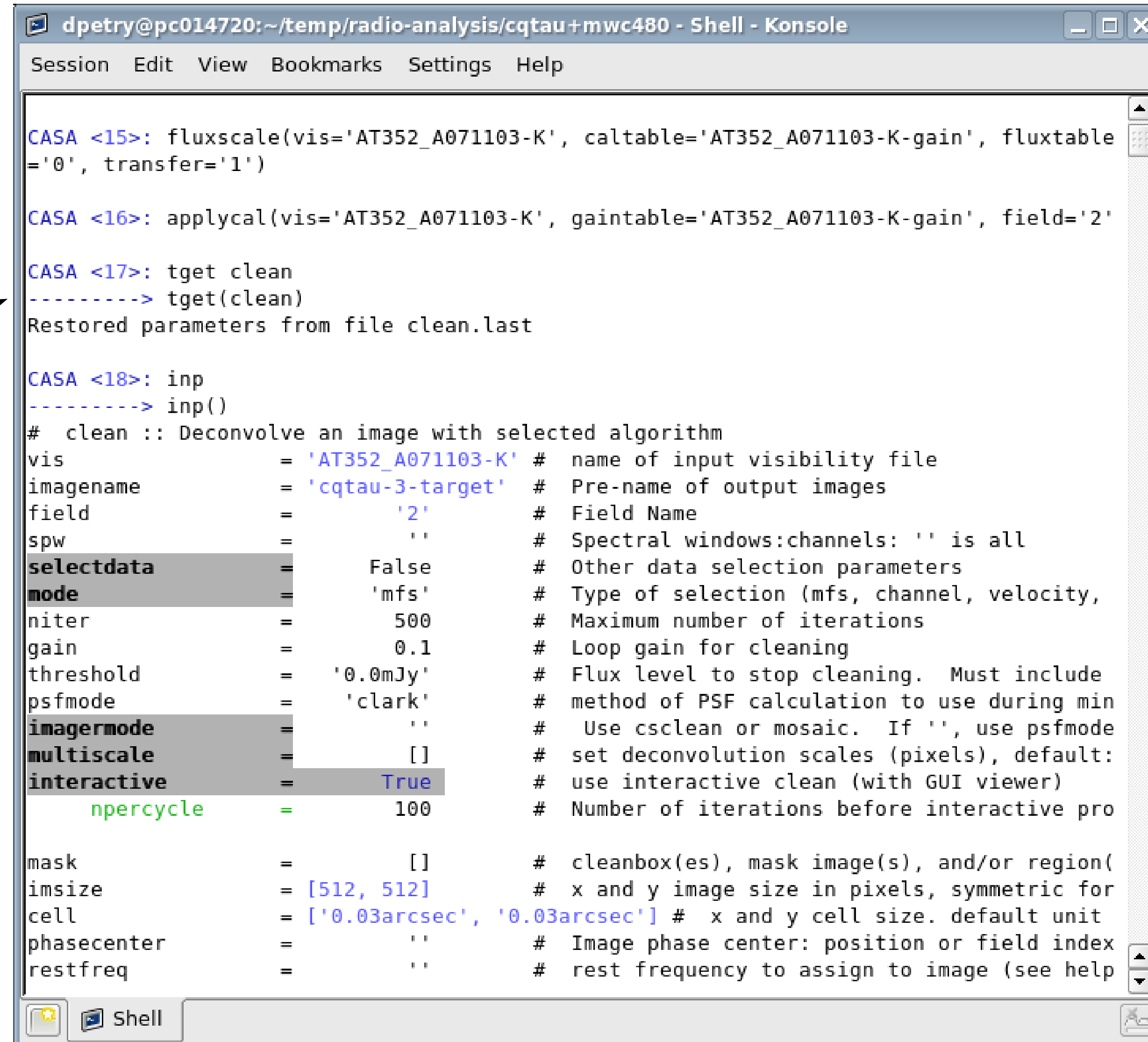


Pictures from a typical analysis session

2) enter commands in a MATLAB-like environment

recall previous settings

list present settings for current task (includes parameter verification)



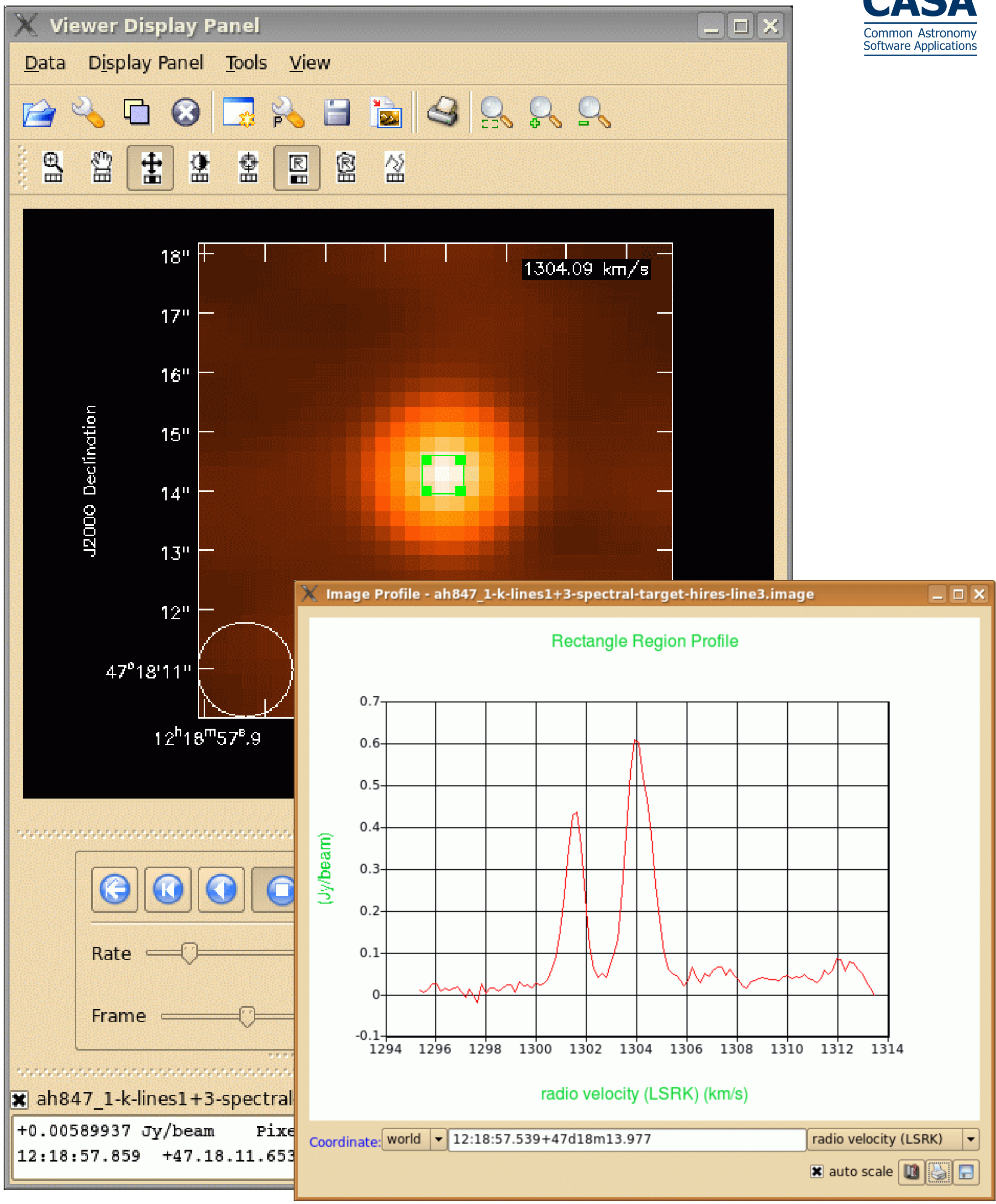
The *CASA* user interface

Pictures from a typical analysis session

3) where needed, tools have GUIs:

plotxy, plotcal, browsetable,
viewer, clean, plotms

(started in separate threads)



The ***viewer*** is a powerful multi-function tool for data selection and visualization.

Uses Qt widget set
(but 80% independent)

Rendering based on pgplot

A typical analysis session

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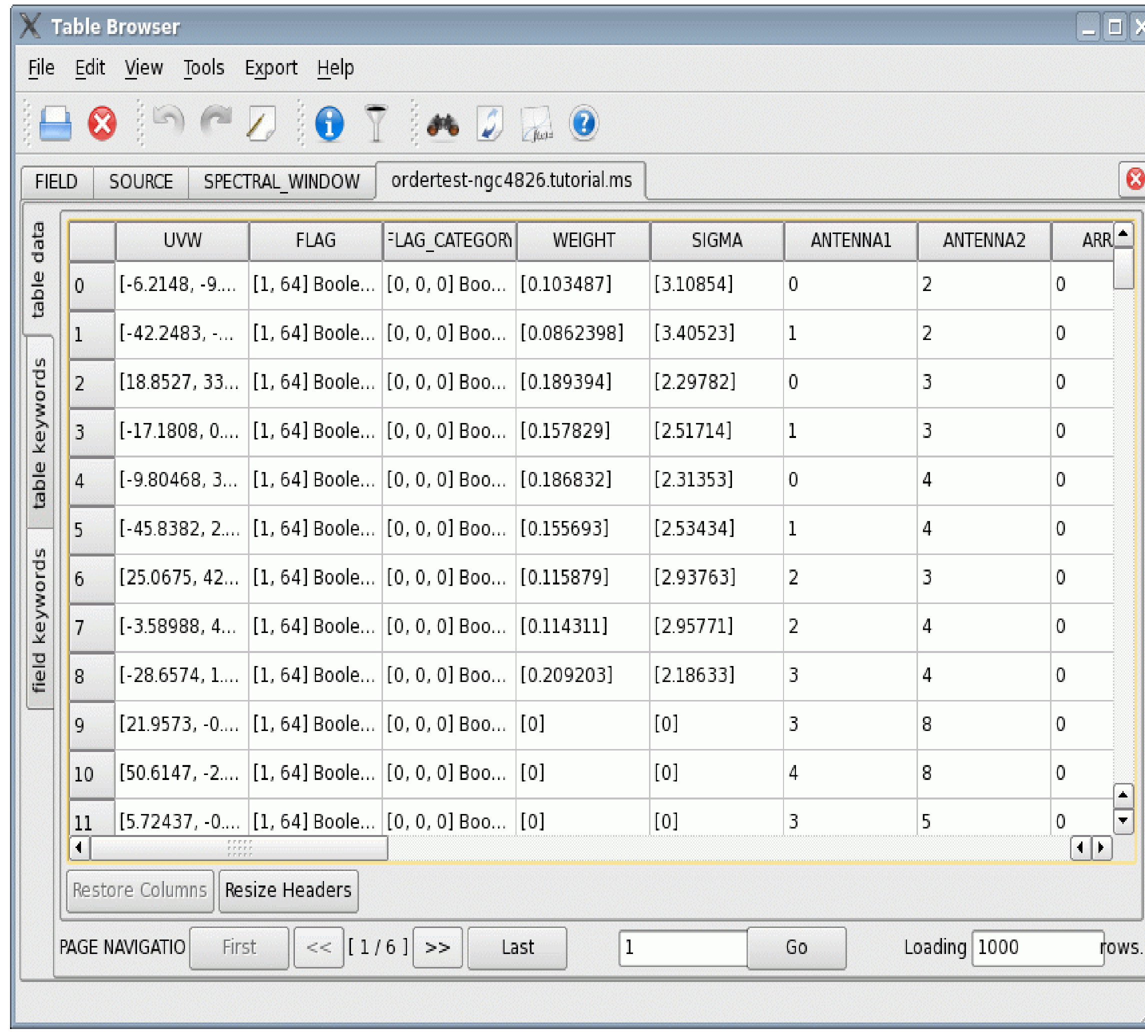
plotxy, plotcal, browsetable, viewer, clean, plotms

(started in separate threads)

browsetable permits you to explore any CASA table, e.g. Measurement Sets

Also Qt-based.



A typical analysis session

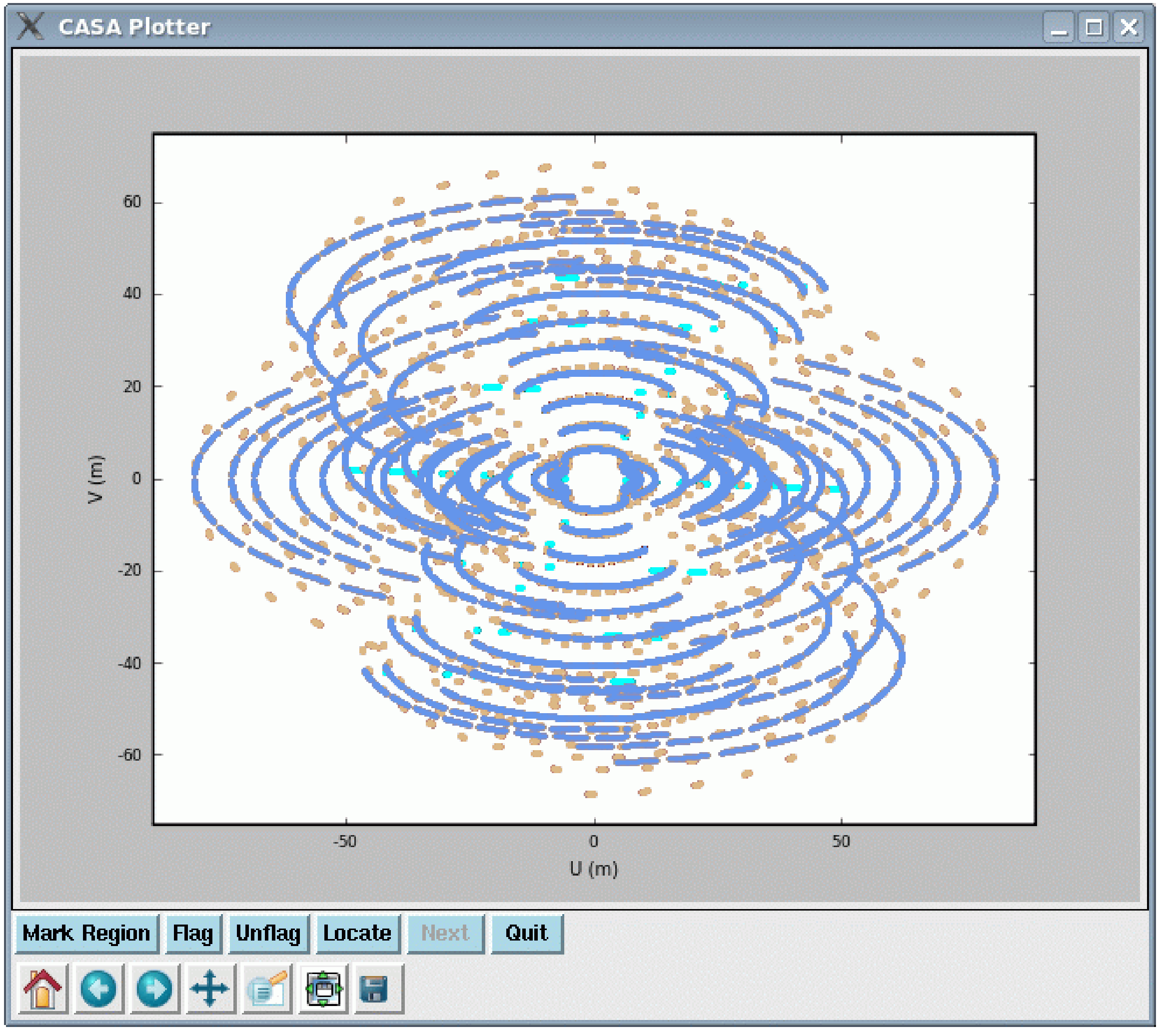
3) where needed, tools have GUIs:

plotxy, plotcal, browsetable, viewer, clean, plotms

(started in separate threads)

plotxy is a specialised tool for diagnostic plots and data selection

To be phased out.



The *CASA* user interface

A typical analysis session

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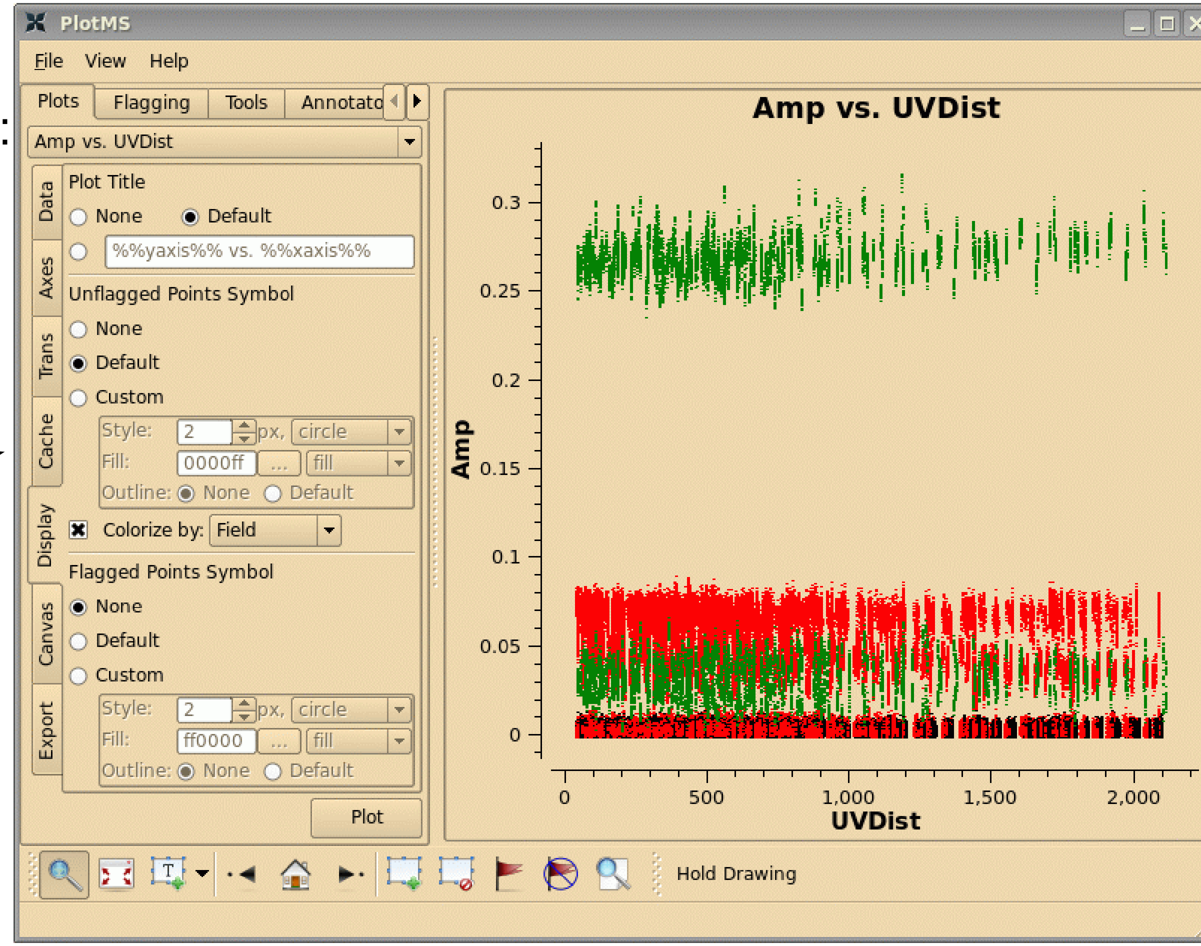


plotms is going to replace plotxy. Release 3.3 contains first useful version.

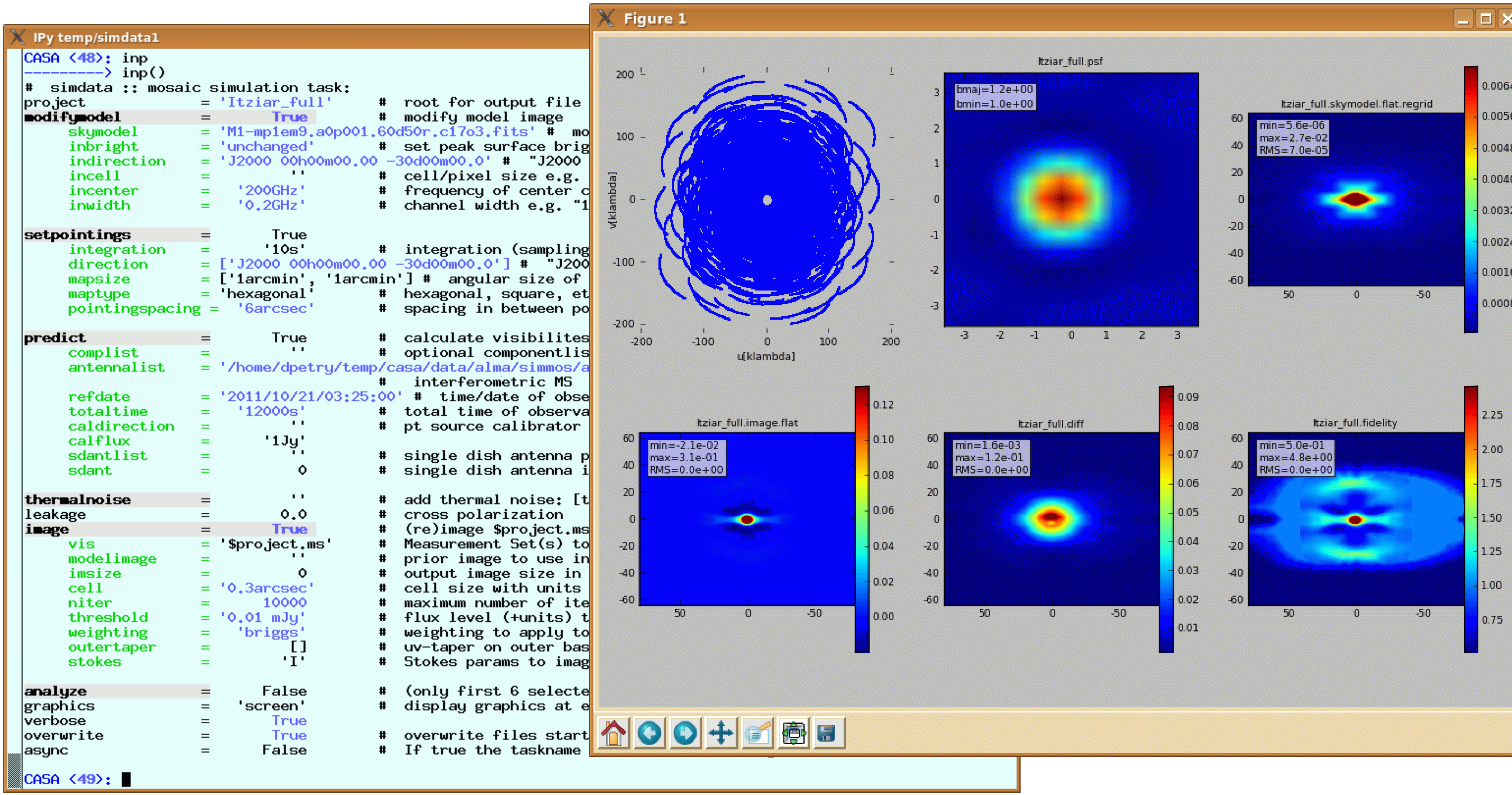
plotms is Qt-based and much faster than plotxy.

Uses generic plotting class which in turn uses **Qwt**.

The *CASA* user interface

A typical analysis session

4) A sophisticated radio-astronomical data simulator: ***simdata***



Summary

- The standard science data analysis package for ALMA and EVLA is *CASA*
- Data from other observatories can also be processed, e.g. BIMA, ATCA, CARMA, SMA
- *CASA* is mostly C++ code (libraries for general use available as *casacore*)
- approx. 22 people are working on *CASA* in North America, Europe, and Japan
- *CASA* is a *comprehensive toolbox* with
  - MATLAB-like, scriptable user interface using *Python/iPython*
  - procedures for calibration, imaging, spectral and spatial analysis, simulation and more
  - GUI tools for data selection, browsing, plotting, and image processing
- The command-line interface has two levels:
  - *tasks* for the common analysis problems
  - *tools* for everything else including *your own tasks*
- the heart of the science analysis code is the *Measurement Equation*
- the internal data format are *CASA Tables*
- the *Measurement Set* is the *CASA* data format for visibility data
- *CASA* is publicly available under GPL for Linux and Mac OS X, installation is simple, see http://casa.nrao.edu/
- The latest release is version 3.3 (November 2011)