Analysing ALMA data - the *CASA* software package

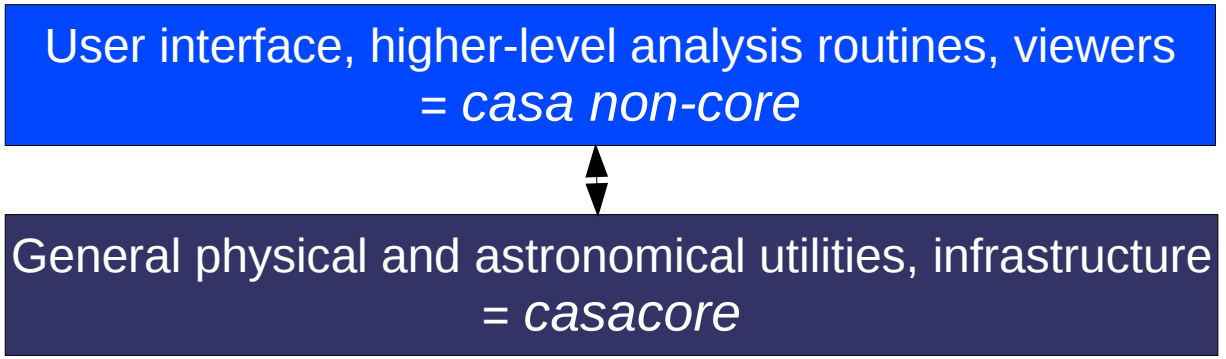
Dirk Petry (ESO), June 2010

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
→ How does CASA look and feel?	- the typical analysis session
→ CASA status and release plans	

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)**
- **1.5 Million lines of code (mostly C++)**
- **In public release under GNU Public License since December 2009**

CASA – development team

CASA Developers Meeting, NRAO, Socorro, May 2010

CASA – development team

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

CASA – development team

Originally only developed at NRAO (Socorro, NM), now

approx. 17 FTE developers are at work at

US (NRAO and others): 10.5
Japan (NAOJ): 3.0
Europe (ESO and others): 3.5

+ 1 CASA manager (NRAO Socorro) = Nick Elias

+ 1 Project Scientist (NRAO Socorro) = Jürgen Ott

+ a few 5% FTEs at ASTRON, ATNF, and other places
Also involved:
ALMA Computing Managers = B. Glendenning (NRAO), G. Raffi, 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 → MS, FITS → Image, UVFITS → MS, VLA → MS, etc.
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 set of C++ classes
   for radio astronomical calibration and imaging
5) A set of high-level analysis procedures ("tasks")
   special procedures for each required task such as CLEAN etc.
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 for users and developers

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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

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

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)

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 design and implementation

CASA special features:

b) the *Measurement Equation* (Hamaker, Bregman, & Sault 1996 + Sault, Hamaker, & Bregman 1996) implemented as a set of C++ classes for radio astronomical calibration and imaging

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

where

the vectors are: V = visibility = $f(u, v)$, I = Image to be calculated,

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

P = paralactic angle

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 design and implementation

***CASA* special features:**

b) the *Measurement Equation* (Hamaker, Bregman & Sault 1996)
implemented as a set of C++ classes for radio astronomical calibration and imaging
(continued)

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

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

ideal visibility known from calibrator source

⇒ have set of linear equations.

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

The calibrater (cb) tool contains a set of ***solvers*** for the different calibration components.

CASA design and implementation

***CASA* special features:**

c) A programmable command line interface with scripting

Framework Architecture of 17 tools can be bound to any scripting language, presently selected is ***Python (augmented by IPython)***

at – atmosphere library
ms – Measurement Set utilities
mp – Measurement Set Plotting, e.g. data (amp/phase) versus other quantities
cb – Calibration utilities
cp – Calibration solution plotting utilities
im – Imaging utilities
ia – Image analysis utilities
fg – flagging utilities
tb – Table utilities (selection, extraction, etc.)
me – Measures utilities
tp – table plot
vp – voltage patterns
qa – Quanta utilities
cs – Coordinate system utilities
pl – matplotlib functionality
sd - ASAP = ATNF Spectral Analysis Package (single-dish analysis imported from ATNF)
sm - simulation

CASA design and implementation

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 design and implementation

CASA special features:

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

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

toolkit (implemented in C++) ⟶ tasks (implemented in Python)

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 3.0.1 comes with 91 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 3.0.2 published this month

- Development platforms: Linux (RHEL) + Mac OS X
- Supported platforms (binary distribution): RHEL, Fedora, openSuSE, Ubuntu, Max OS X

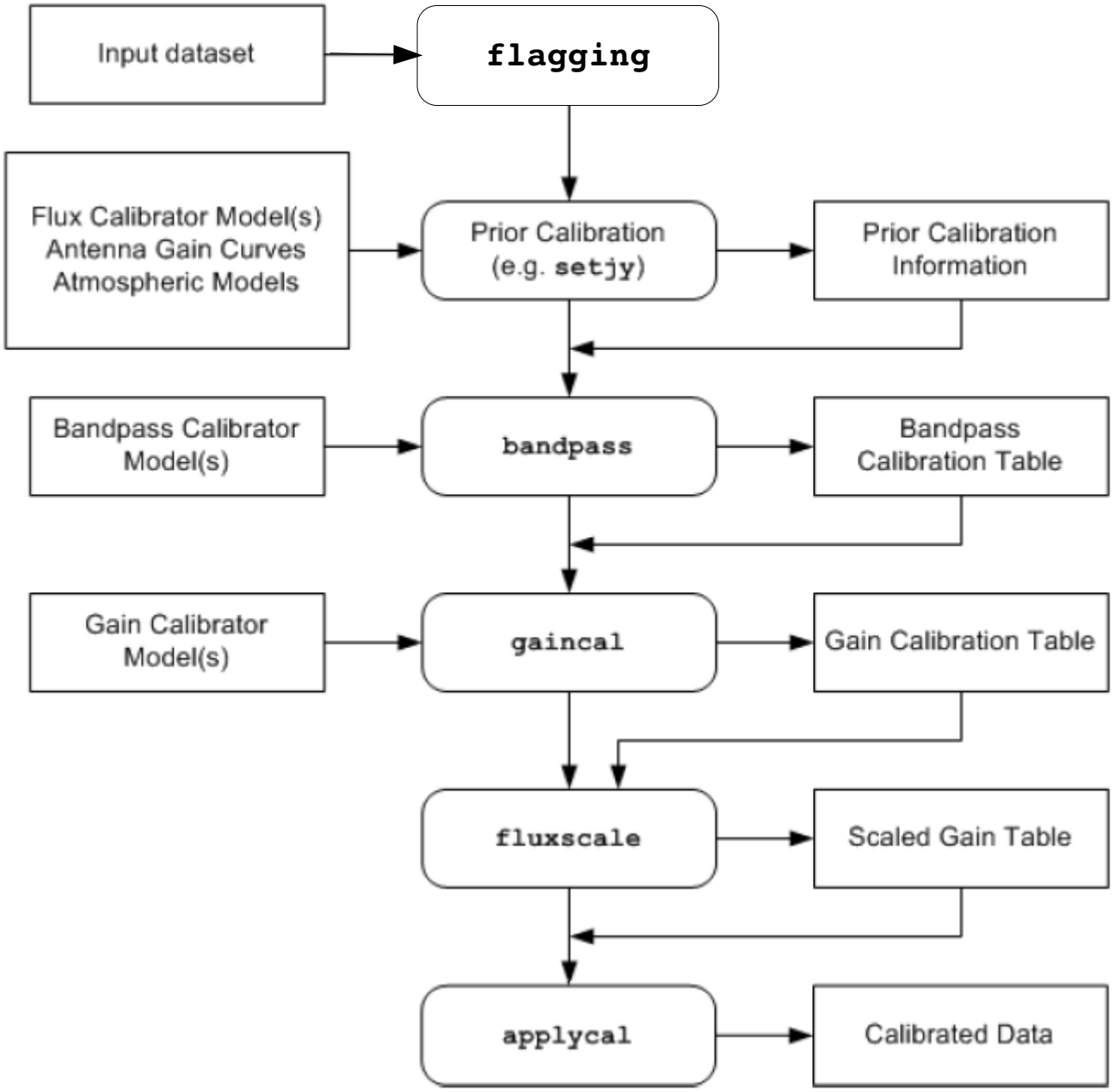
- Code kept in *svn* repository at NRAO, Socorro
- Presently have approx. 4300 modules, 1.5E6 lines of code, 1E6 lines of comments
- The core functionality (*casacore,* also available at http://code.google.com/p/casacore/)
  is also used by other projects

- *Hot topics*:
  - Support for High Performace Computing and Parallelisation
  - Advanced Imaging: wide fields, continuum imaging over wide spectral ranges
  - Interoperability: using CASA for other observatories and VLBI

How does *CASA* look and feel?

A typical analysis session

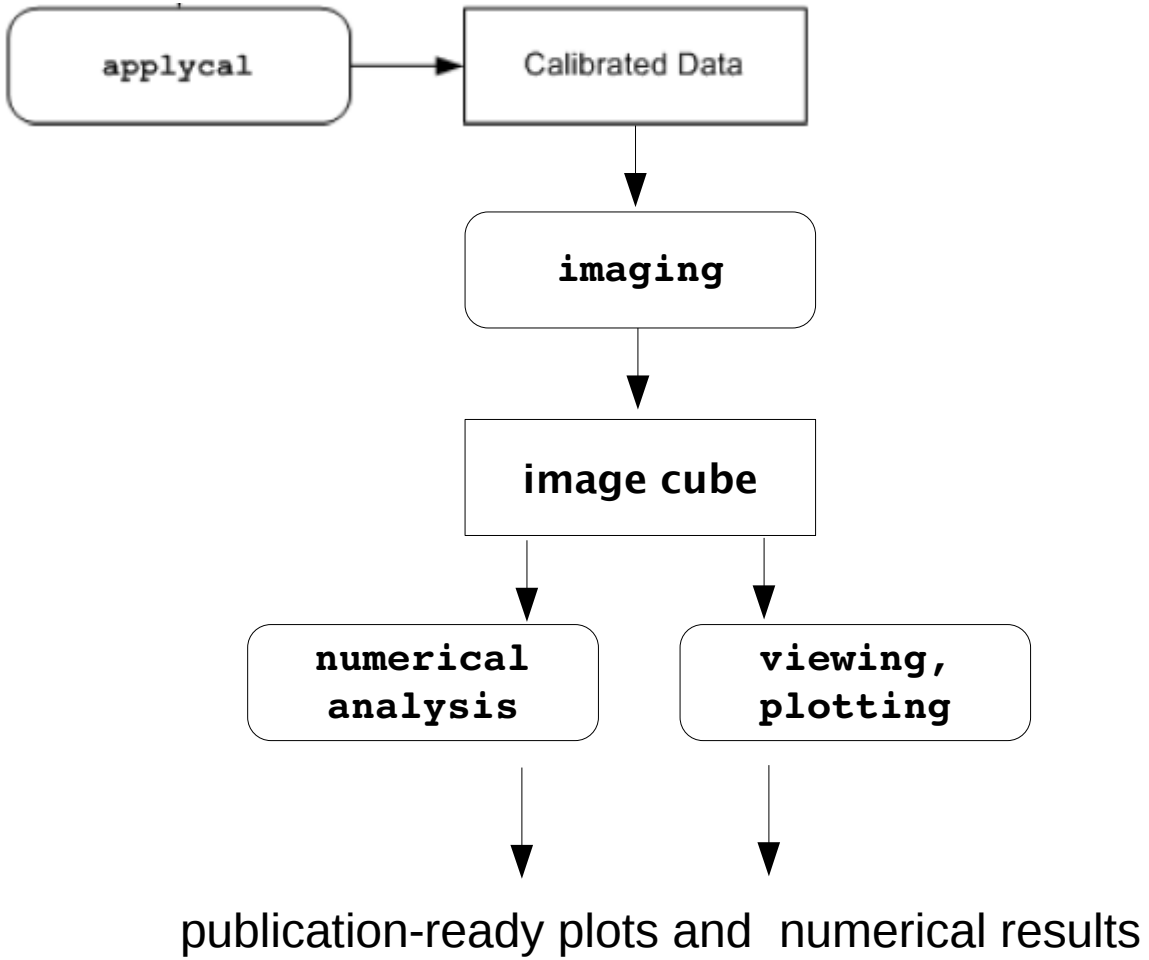
Part 1: flagging and calibration



How does *CASA* look and feel?

A typical analysis session

Part 2: imaging and
image analysis

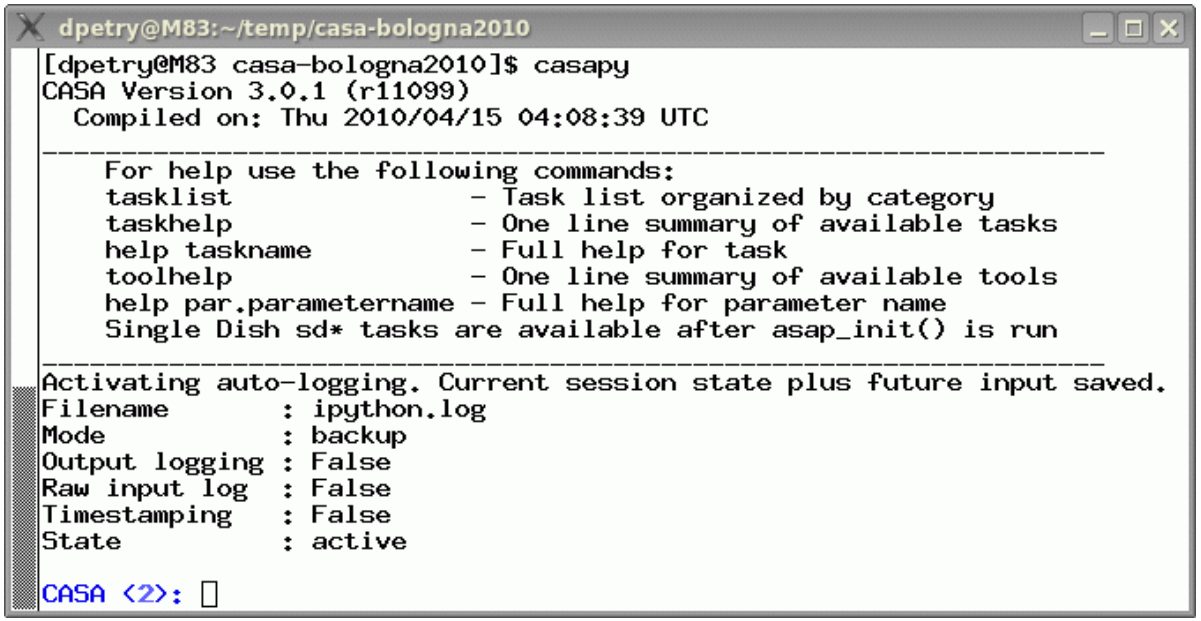


How does *CASA* look and feel?

Pictures from a typical analysis session

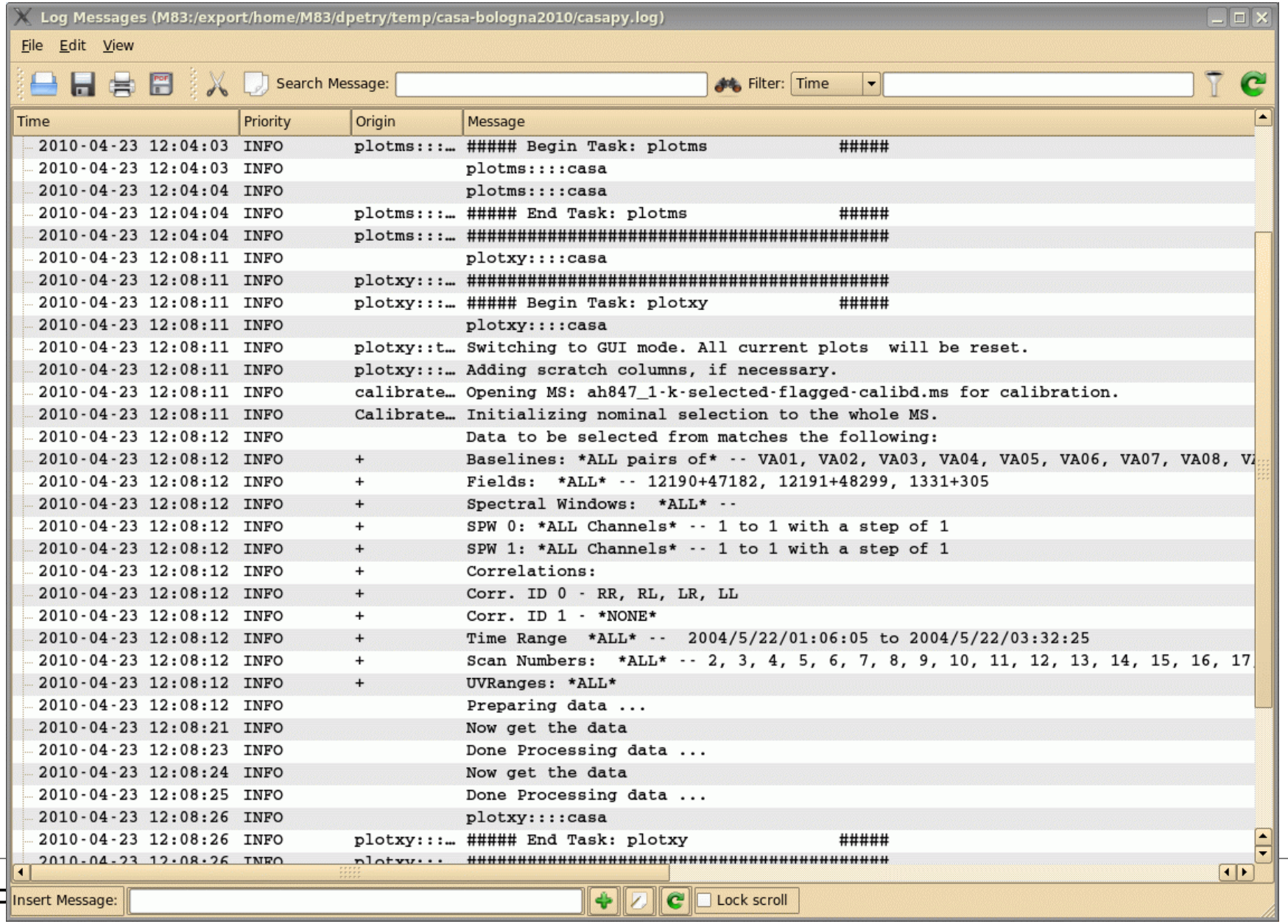
1) Startup:
open terminal and start *casapy*

Available tasks and tools are listed and the logger window is opened.



The *CASA* user interface

The logger provides functionality for monitoring and debugging command execution.



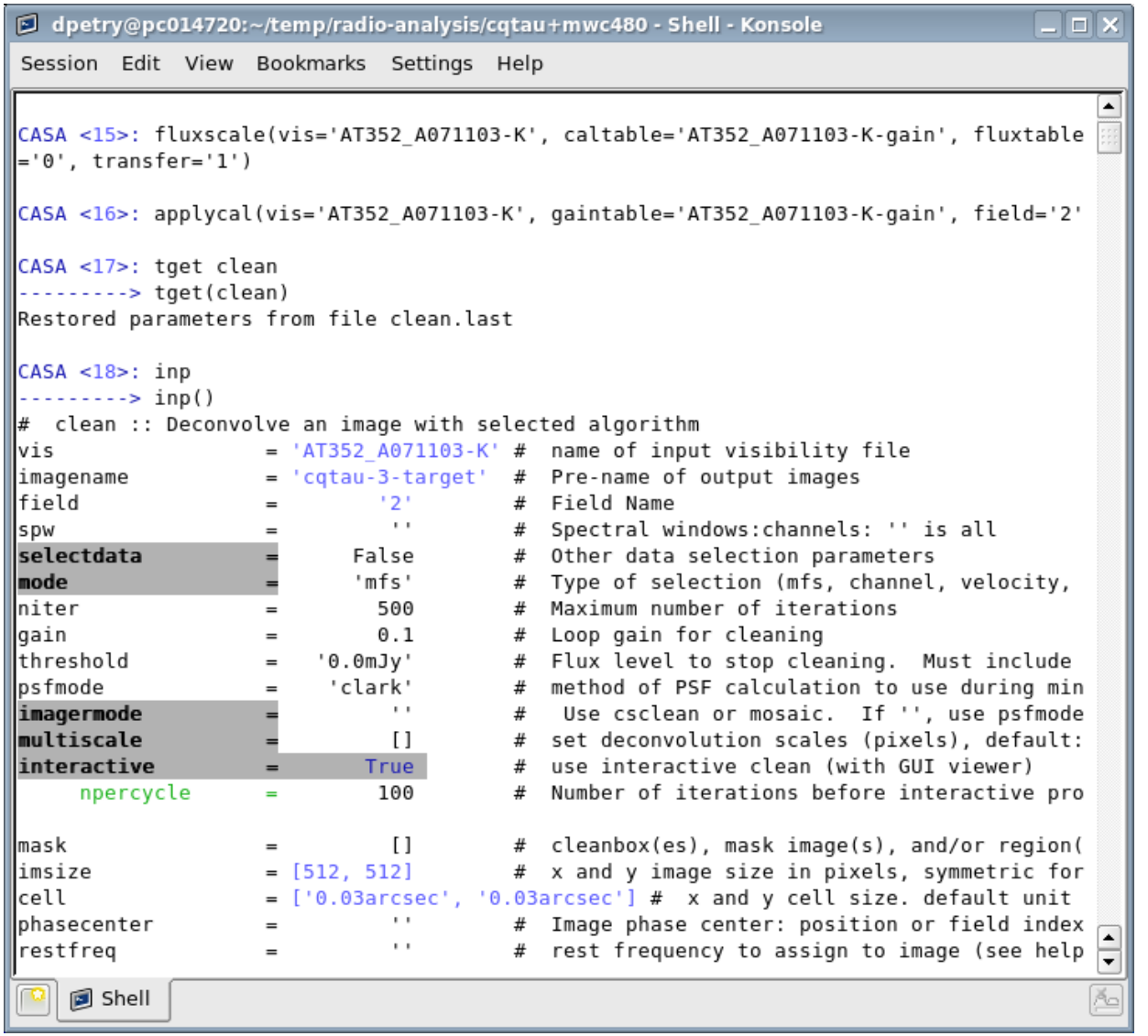
The *CASA* user interface

Pictures from a typical analysis session

2) enter commands in a MATLAB-like environment

recall previous settings

list present settings for given task (includes parameter verification)



The *CASA* user interface

Pictures from a typical analysis session

3) where needed, tools have GUIs:

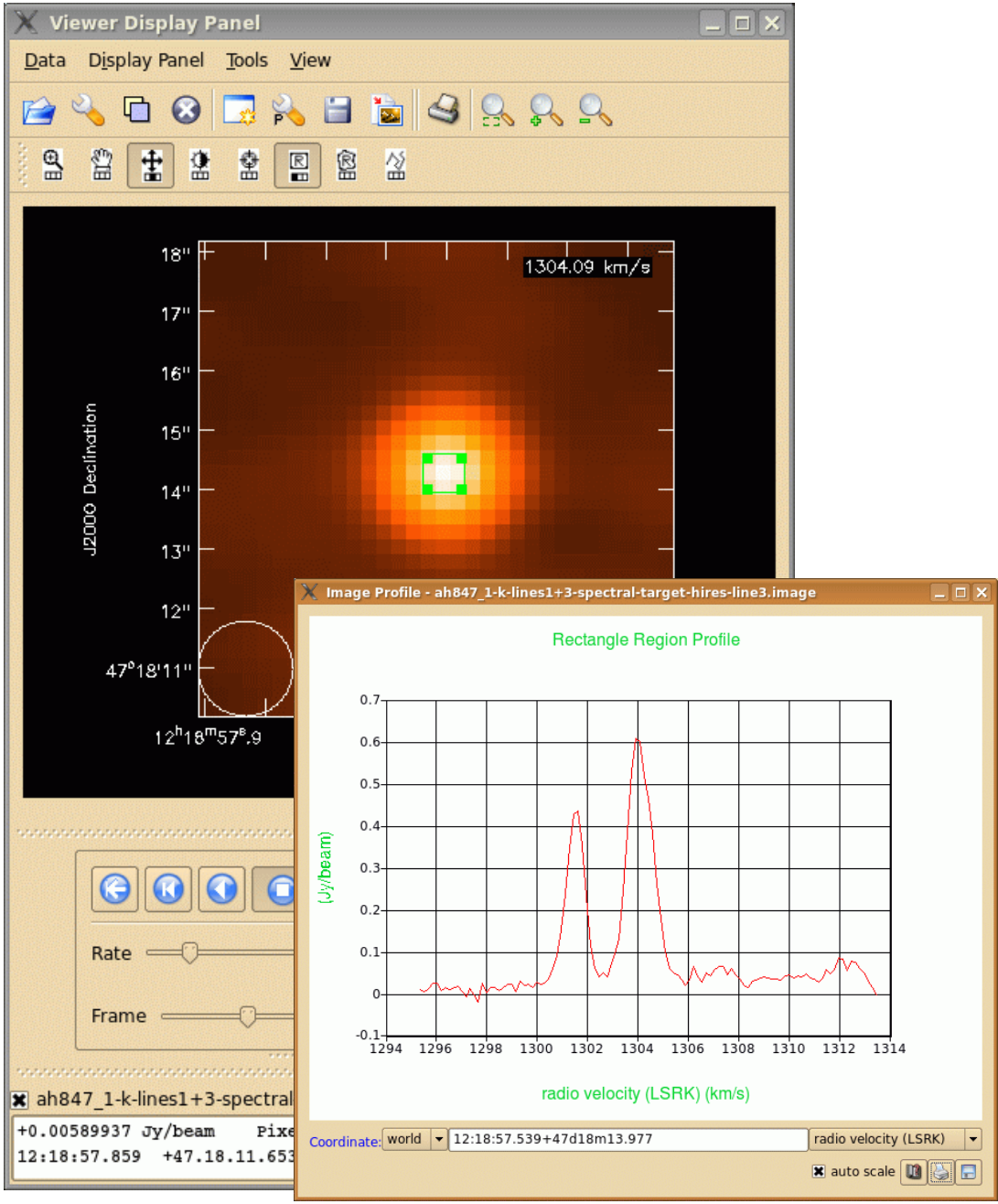
plotxy, plotcal, browsetable, viewer, clean

(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



The *CASA* user interface

A typical analysis session

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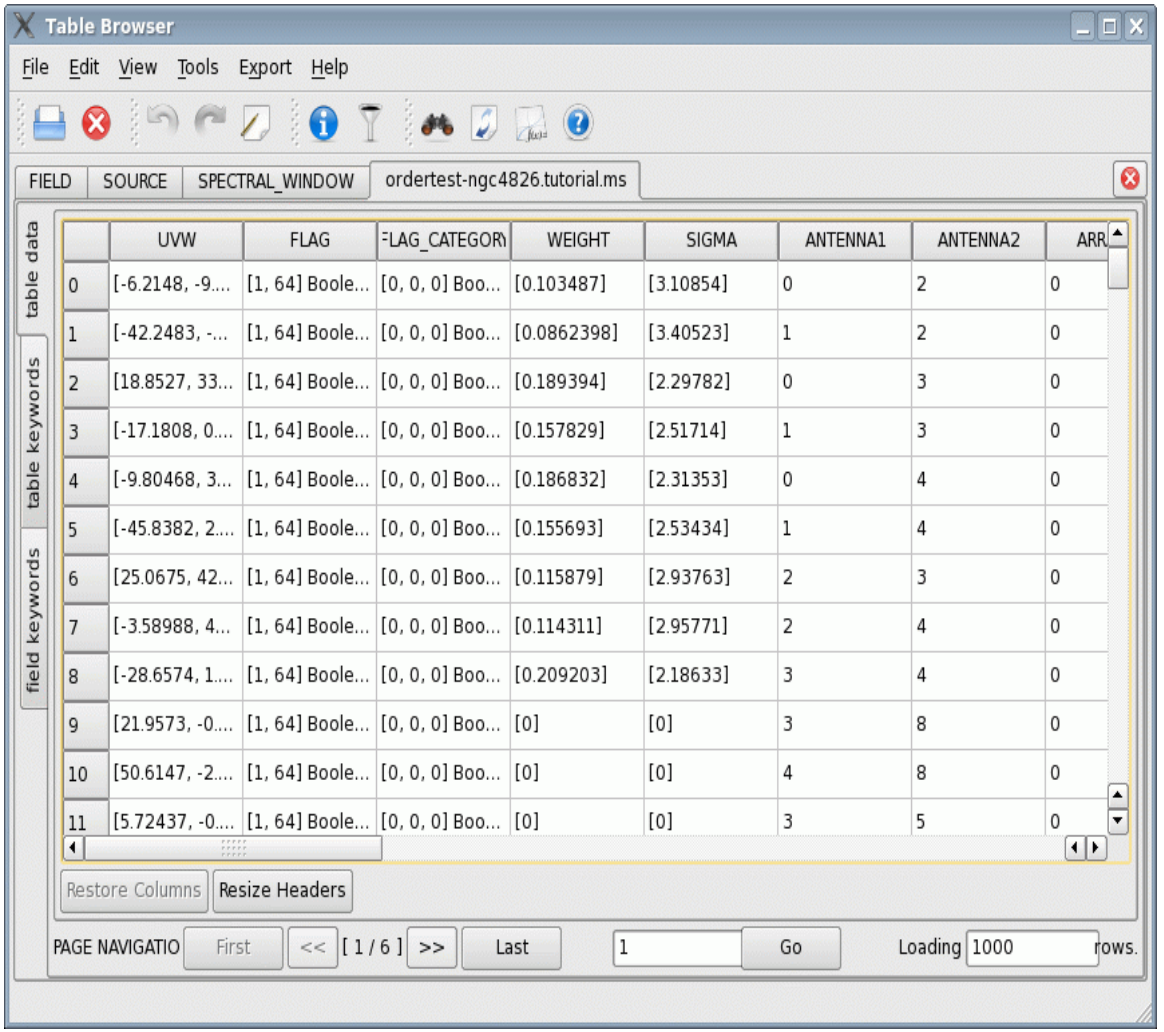
browsetable permits you to explore any CASA table, e.g. Measurement Sets

Also Qt-based.



The *CASA* user interface

A typical analysis session

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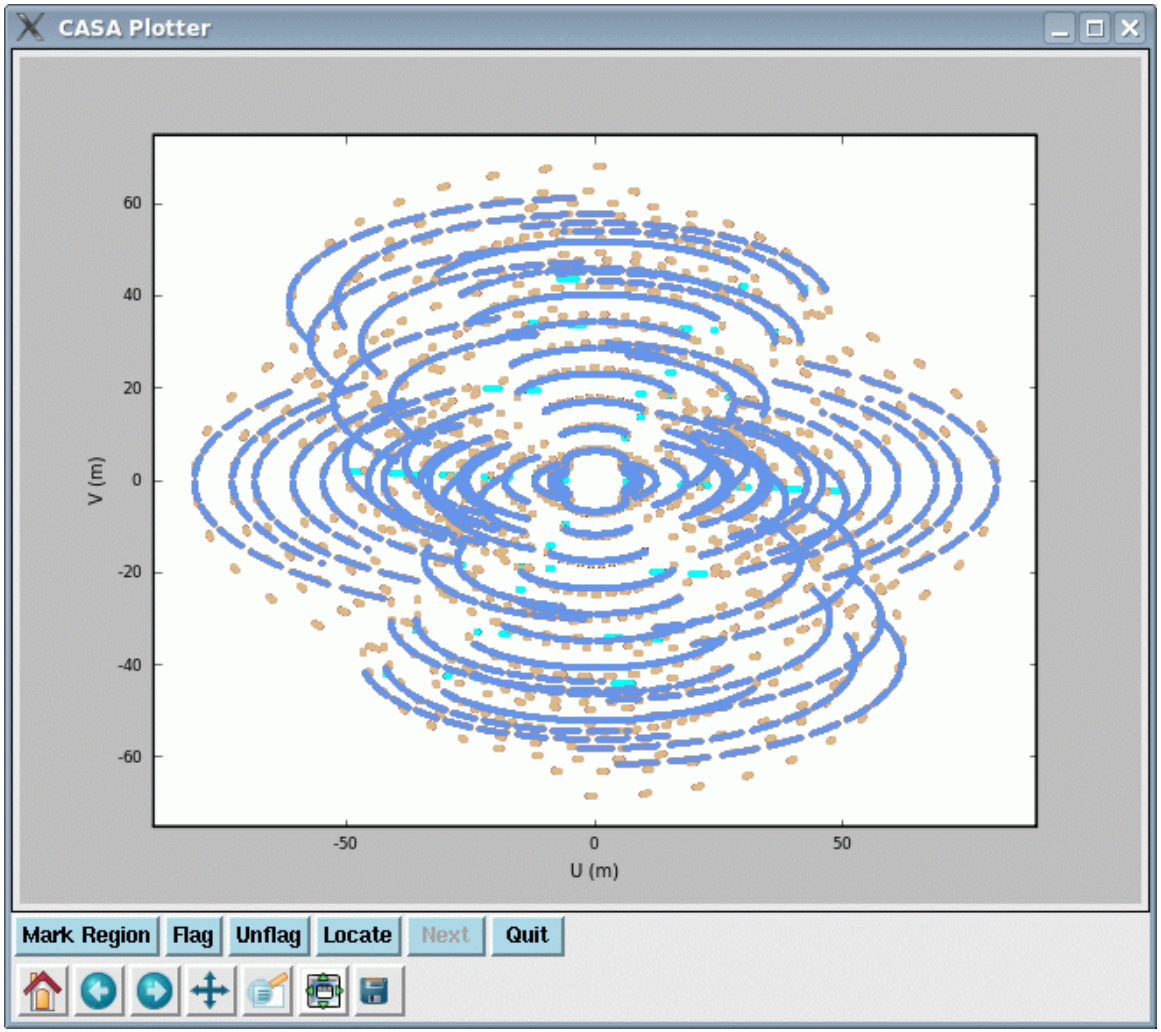
plotxy is a specialized tool for diagnostic plots and data selection

To be phased out.



The *CASA* user interface

A typical analysis session

3) where needed, tools have GUIs:

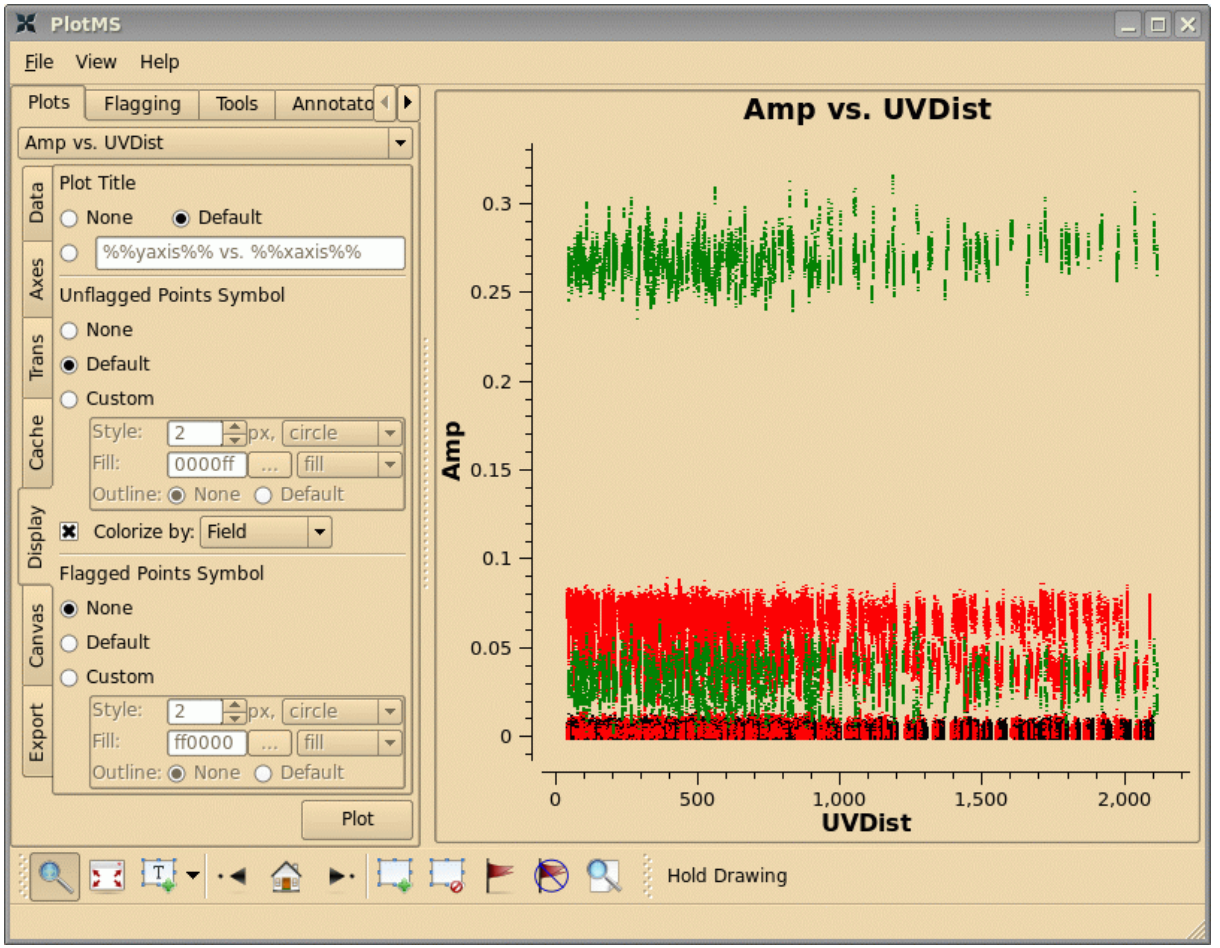
plotxy, plotcal, browsetable, viewer, clean

(started in separate threads)

plotms is going to replace plotxy. Release 3.0.2 contains beta version.

plotms is Qt-based and much faster than plotxy.

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



Summary

- **The standard science data analysis package for ALMA and EVLA is *CASA***
- **Data from other observatories can also be processed, e.g. VLA, BIMA, ATCA, ...**
- ***CASA* derives from AIPS++ (partially survives in *casacore*)**
- **approx. 20 people are working on *CASA***
  in North America, Europe, and Japan
- ***CASA* is a toolbox with**
  - **MATLAB-like user interface**
  - **GUI tools for data selection, browsing, and image processing**
- **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**
  (it is technically a Table with several well-defined sub-tables)
- ***CASA* is publicly available under GPL for Linux and Mac OS X**

- **The first public release of *CASA* (version 3.0.0) became available in December 2009**
- **The latest release is version 3.0.2**