2010 PASEO Meeting

July 15-16, 2010 – Socorro, NM

CASA: Common Astronomy Software Applications

Steven T. Myers (EVLA CASA Subsystem Scientist)

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

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EVLA Post-processing Philosophy

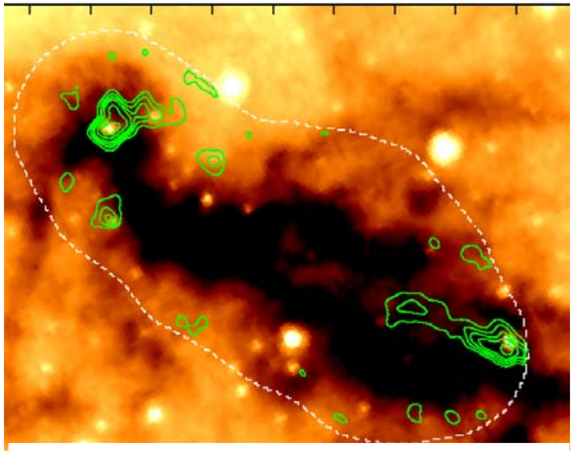
- Enable forefront science with the EVLA through basic and advanced software tools.
  - leverage ALMA co-development and use of CASA package
  - enable pipelines (e.g. for EVLA to produce calibrated data)
  - staged deployment and development, must be within our means
- Stakeholders : EVLA and ALMA
  - first: must support user to process own data (e.g. on workstation or small cluster)
  - second: support pipelines and HPC (e.g. large cluster) processing
  - third: support algorithm development
- Post-processing Software Requirements (2003, updated 2007,2008)
  - guides (but does not dictate) development and implementation

http://www.aoc.nrao.edu/evla/techdocs/computer/workdocs/EVLA_Data_Post-Processing_Software_Requirements_for_CASA.pdf

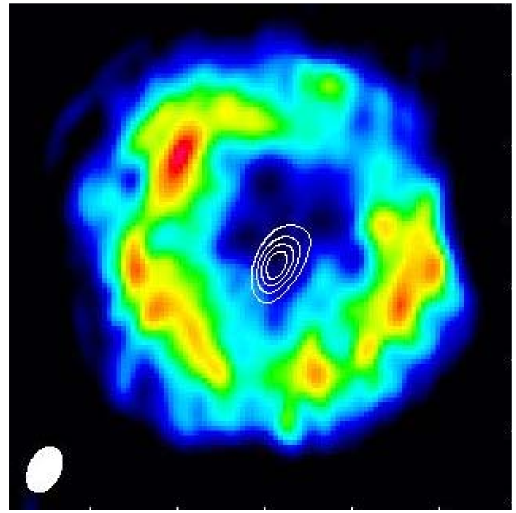
What is CASA? http://casa.nrao.edu

- CASA is the post-processing package for ALMA and EVLA
  - handles interferometric and single dish data
- “Toolkit” code are written in C++; interface & tasks in Python/IPython; GUI displays in Qt/matplotlib
- Fully scriptable (Python), with in-line and web-based help and scientist-written documentation (notably the user manual/cookbook)
- Telescope data (visibility and single-dish) are stored in a MeasurementSet (MS) with a asdm2ms filler (both ALMA & EVLA)
- Tasks for common post-processing operations
  - familiar task parameter input interface as well as call-by-function
- Toolkit-level functionality for manipulating/plotting core infrastructure data types (e.g., Images, Tables, Measures, …)
- Capability for users to “buildmytasks” in Python
  - e.g. used for *importevla* task

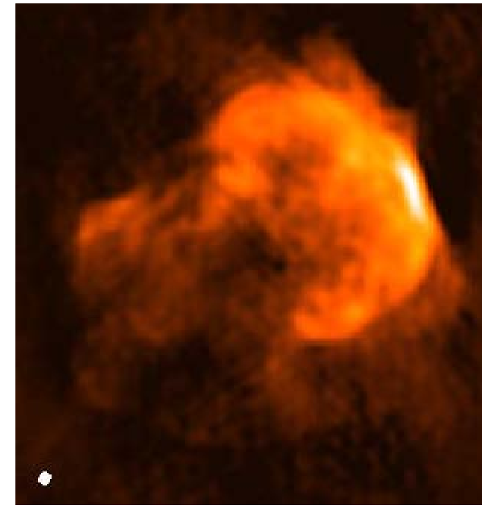
Diverse Data Reduced and Imaged in CASA…



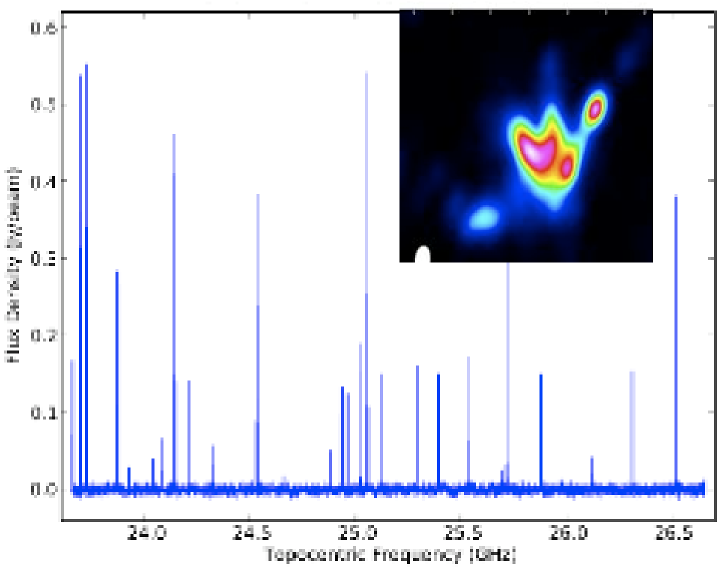
SMA ^{12}CO (2-1) mosaic toward IRDC G19.3+0.07



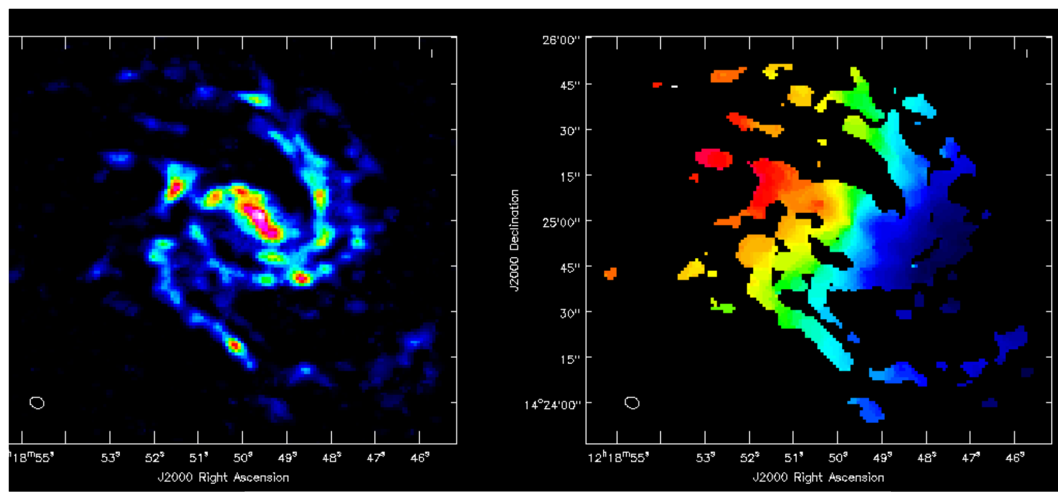
EVLA Ka-band of HC_3N in AGB star IRC+10216



EVLA 6cm mosaic of SNR: 3C391



EVLA demo science: Orion Hot Core this spectrum has 24k channels!



CARMA CO(1-0) mosaic of M99 (data courtesy STINGS team)

Import, Examination, Flagging

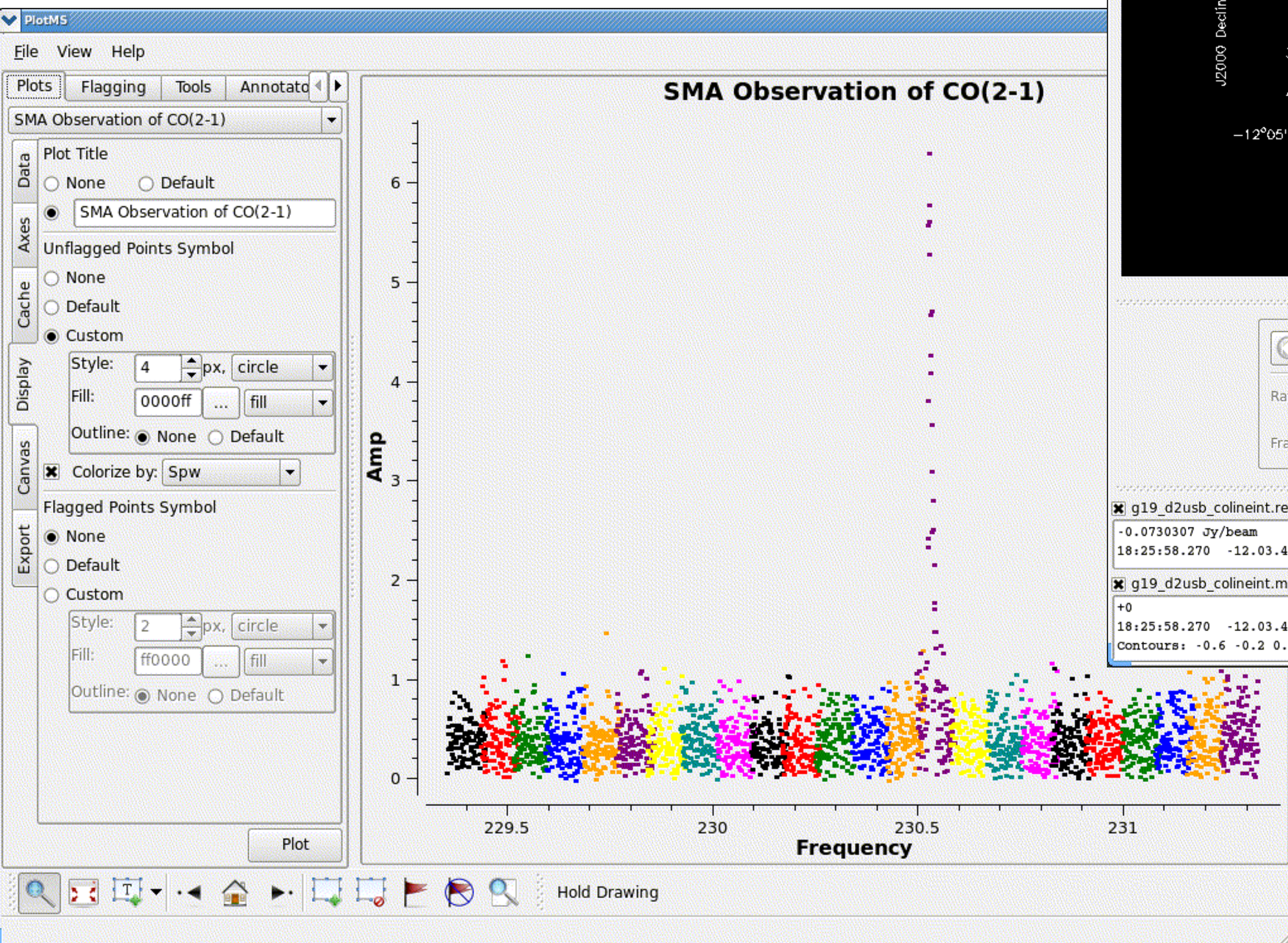
- Full ALMA/EVLA SDM data import (*importasdm*)
  - Raw SDM data formats were designed to be similar to MS
  - ALMA and EVLA use the same underlying format and filler
  - Custom task *importevla* to import and flag EVLA data
  - Importuvfits for data from other telescopes
  - Exportuvfits to AIPS etc. (some limitations)
- Interactive examination and flagging
  - X-Y plotting GUI plotms for visibilities and caltables (soon)
  - Raster (“TV”) display and flagging in *viewer*
- Non-interactive flagging
  - Task *flagdata* for simple flagging (manual, clip, shadow, “quack”)
  - Some experimental auto-flagging options (“rfi”, “autoflag”)
  - Auto-backup of flag columns of MS (access via *flagmanager*)

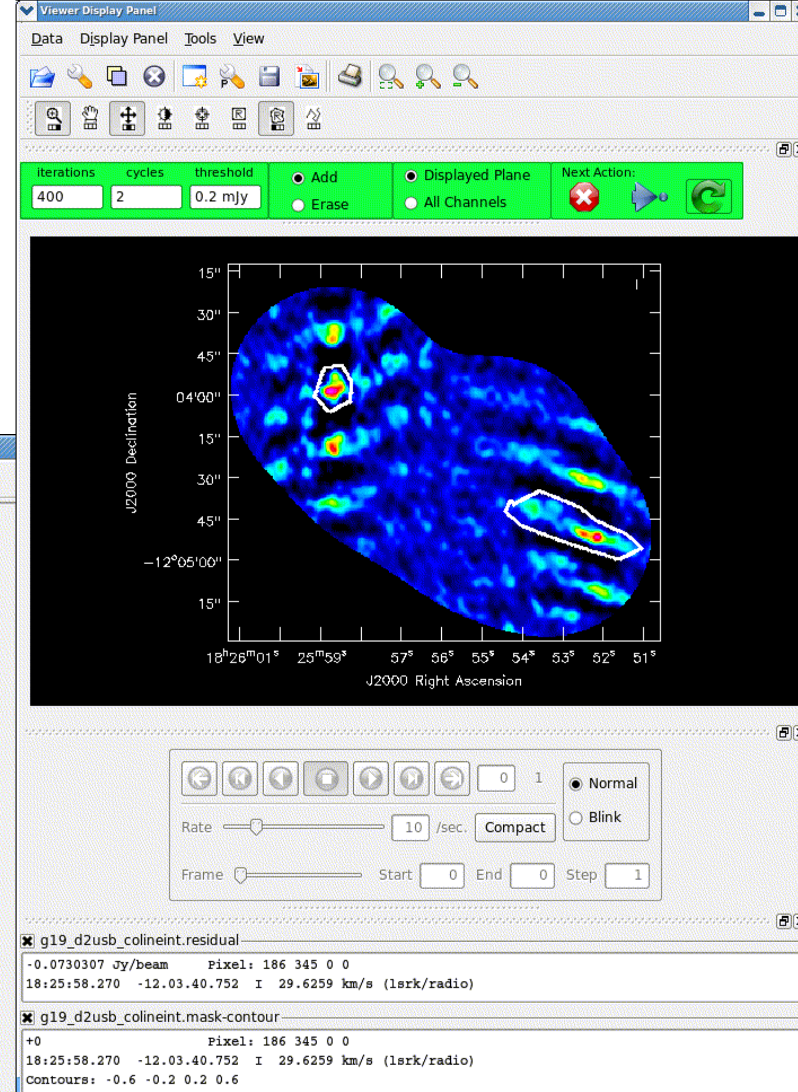
Calibration

- Application of a-priori calibration
  - antenna position, delays, gain curves, zenith optical depth
- Standard gain & bandpass calibration
  - Discrete and Polynominal/Spline solutions available
  - Flux density reference scaling (*setjy* and *fluxscale*)
  - Flexible mapping between spectral windows and/or fields
  - Amp+Phase, Phase, Amp solution modes, solution normalization
  - Auto-interpolation to flagged solutions (e.g. channels in bandpass)
- Polarization calibration
  - For circular RL basis, linear XY basis support under development
  - Linearized instrumental polarization (D-terms) solutions available
  - Channelized for frequency-dependent instrumental polarization
  - Optional solution for source polarization
  - Polarization position-angle solution support (cross-hand phase)

Interactive cleaning and flagging

UV-spectrum in plotms, colorized by spectral window





Imaging & Deconvolution

- Standard CLEAN and Multi-scale CLEAN
- Multi-frequency Synthesis Imaging
  - single term & Taylor series (spectral index,…) (Urvashi thesis)
- Mosaic imaging made simple
  - Joint deconvolution (Miriad style) and gridding convolution (new)
  - Mosaicing with heterogenous arrays (ALMA, CARMA)
- Widefield imaging: W-projection and faceting
  - W-projection more than 1 order of magnitude faster than faceting
  - Widefield can be combined with MFS and multi-scale
- Multiple algorithms for single dish and interferometry combination
- Experimental options:
  - RL “squint” correction & PA-dependent beam effects
  - pointing self-calibration
  - MEM & NNLS (toolkit level only so-far)

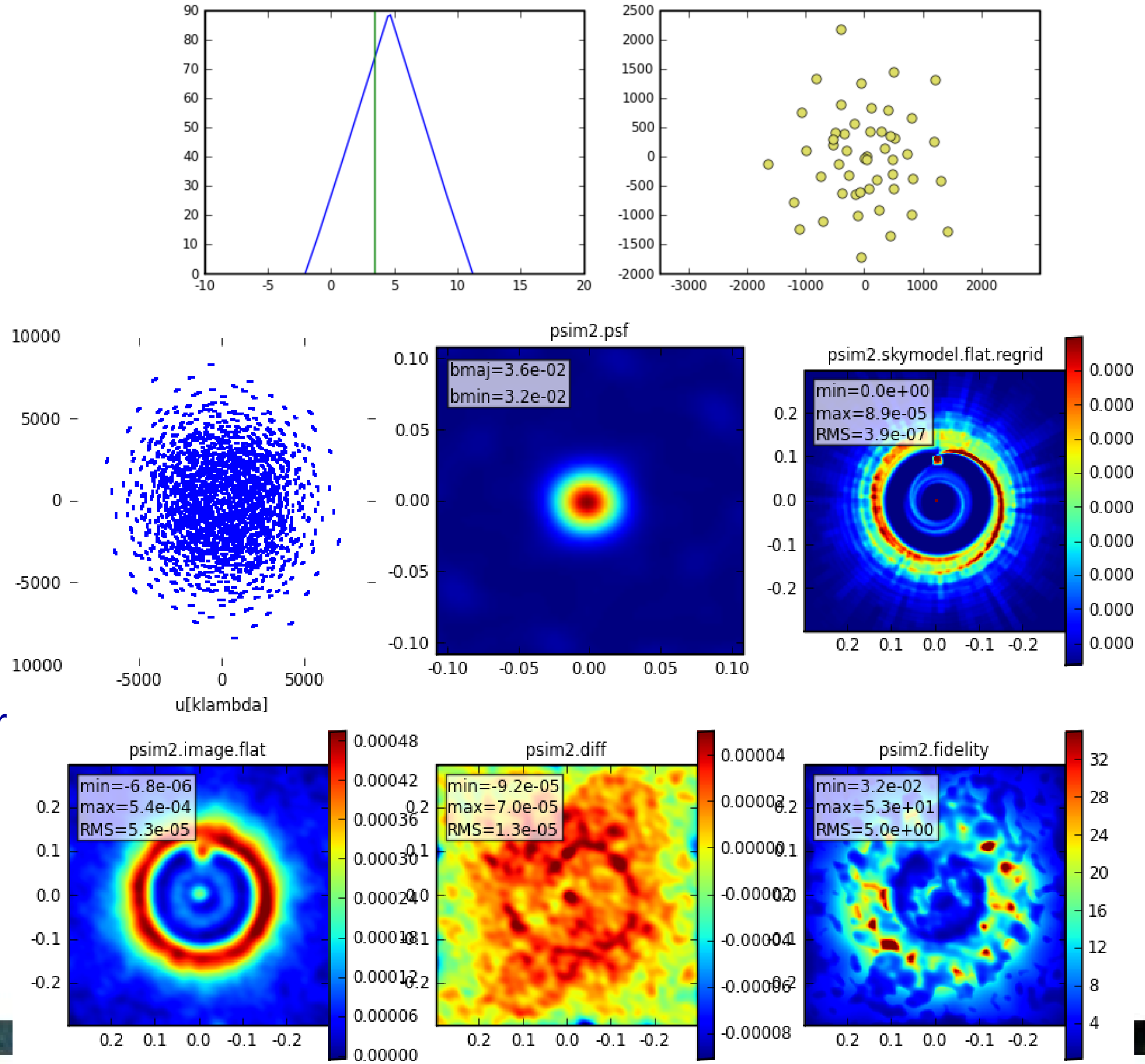
Analysis

- Image viewing in *viewer*
  - supports CASA images and FITS
  - standalone Qt application *casaviewer*
- Facilities for image manipulation
  - moment image calculation in *immoments*
  - *immath* task for combinations, polarization, spectral index
  - "Lattice Expression Language" in toolkit for advanced manipulation
  - other tasks (*specfit,* regridding, convolution) under development
- Access to image information and Python interface
  - can import or write Python functions
  - use of matplotlib
- Development of new analysis tools and tasks is a high priority
  - particularly in spectral line area (fitting, stacking, analysis)
  - user contributions via Python

CASA Simulator: "simdata"

o 1-stop task to simulate ALMA, EVLA, SMA, CARMA, ATCA, SKA

- Simulate continuum, simple spectral cubes
- Create coordinate system for model images
- calculate mosaic pointings (auto or manual)
- Optionally interleave a calibrator
- Simulate total power observations
- Add thermal noise and linear cross-polarization
- Re-image the data, interferometric + total power
- Analyze the difference in output and input images



Primary developer: Remy Indebetouw

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CASA Staff

- Group leader: Nick Elias (since Oct. 2009)
- Development team
  - Currently ~13.5 FTEs (scientific developers and programmers)
  - Distribution of people: NRAO: 8.3, NAOJ: 2.7, ESO: 2.5
  - Two recent vacancies: Application/GUI developer (just filled & started), High performance computing specialist (search underway)
- Overall Project management: Brian Glendenning (ALMA), Brian Butler (EVLA)
- NRAO CASA Science Steering Committee (CSSC)
  - Juergen Ott (Project Scientist)
  - Crystal Brogan (ALMA subsystem scientist)
  - Steve Myers (EVLA subsystem scientist)
  - Ed Fomalont (E2E Scientist)
- External Input:
  - ALMA/EVLA Commissioning teams, RSRO scientists, ASC/NAASC/ARC scientists, and scientific advisory committees (e.g. PASEO,ASAC,ANASAC)

Release Status and Usage

- Have had Beta (patch) releases every ~3-6 months since October 2007
  - Pretty much any recent linux flavor, Mac OSX leopard, snow leopard
  - Available to anyone after registration at http://my.nrao.edu
  - > 400 have downloaded so far
- Being used heavily for EVLA science verification, RSRO visitors, and by outside users for start of early science since March 1, 2010
- Used every day in Chile for ALMA commissioning
- Dec. 18, 2009 was first non-beta release (3.0.0), patch 3.0.1 was released in April, the second patch (3.0.2) was released on June 14. The next major release 3.1.0 will be October 15.

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CASA Tutorials Around the World

- Tutorials this past year:
  - Garching, Germany (May), Hamilton, Canada (June), Bonn, Germany (Oct.), Taiwan (Feb), NAOJ (April), Santiago, Chile (April)
  - May 24, Miami AAS special session with talks/demos
  - June 8-15, NRAO Synthesis Imaging Workshop (~150 students) – all first-day tutorials in CASA (except VLBA)
- Coming up:
  - July 19-20, Oxford, UK preceding the "Molecules in Galaxies" conference
  - Jan. 2011, Seattle AAS, demo/tutorials
  - Soon after ALMA early science decision (late fall) planning for NAASC workshops

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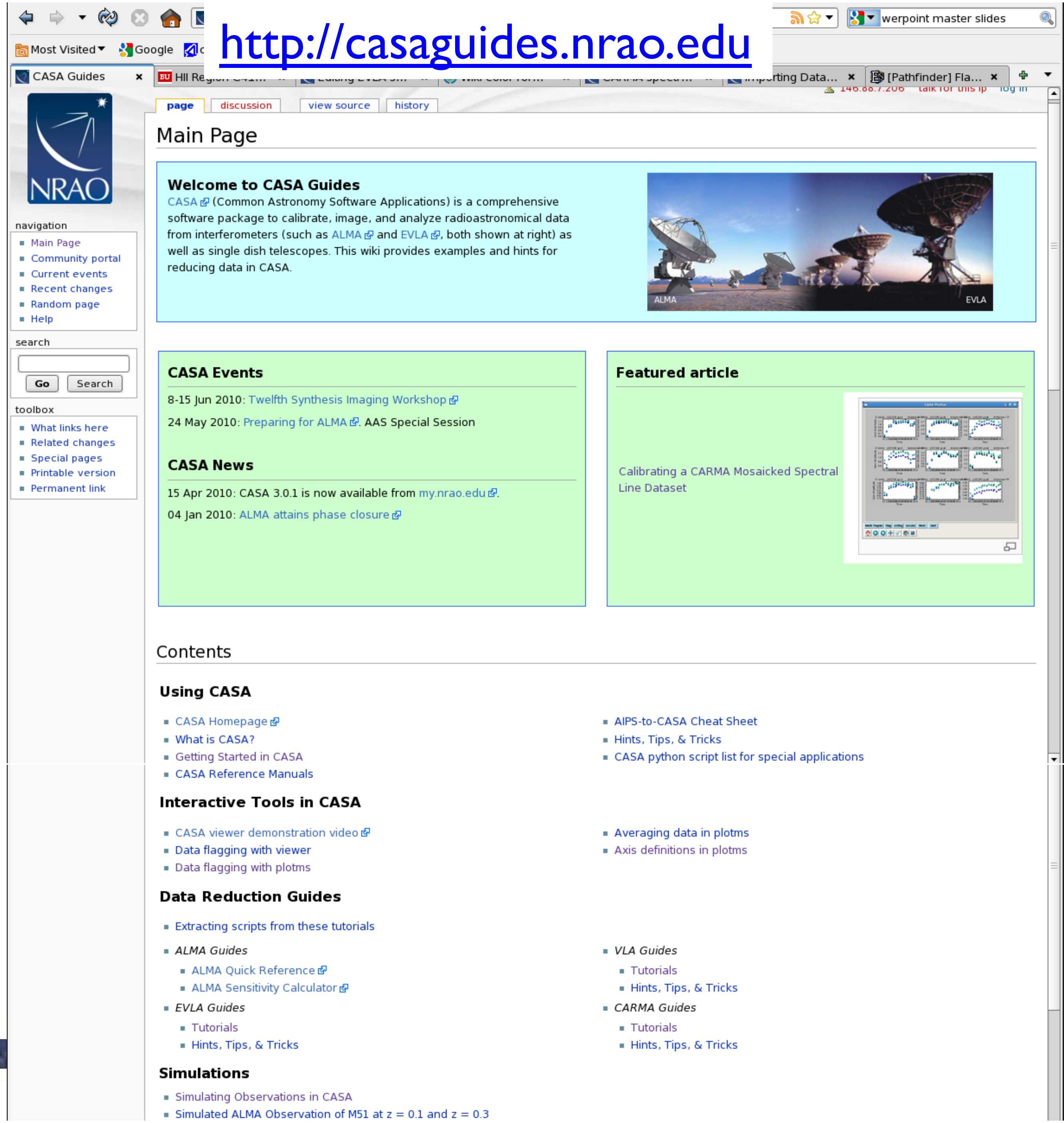
CASAguides

http://casaguides.nrao.edu

- Uses *mediawiki* to enable fully annotated scripts (that can be extracted and run)
- Additional "guides" continue to be added
- NRAO Synthesis Imaging summer school tutorials were successfully delivered this way (written by RSRO scientists)



CASAguides

an example

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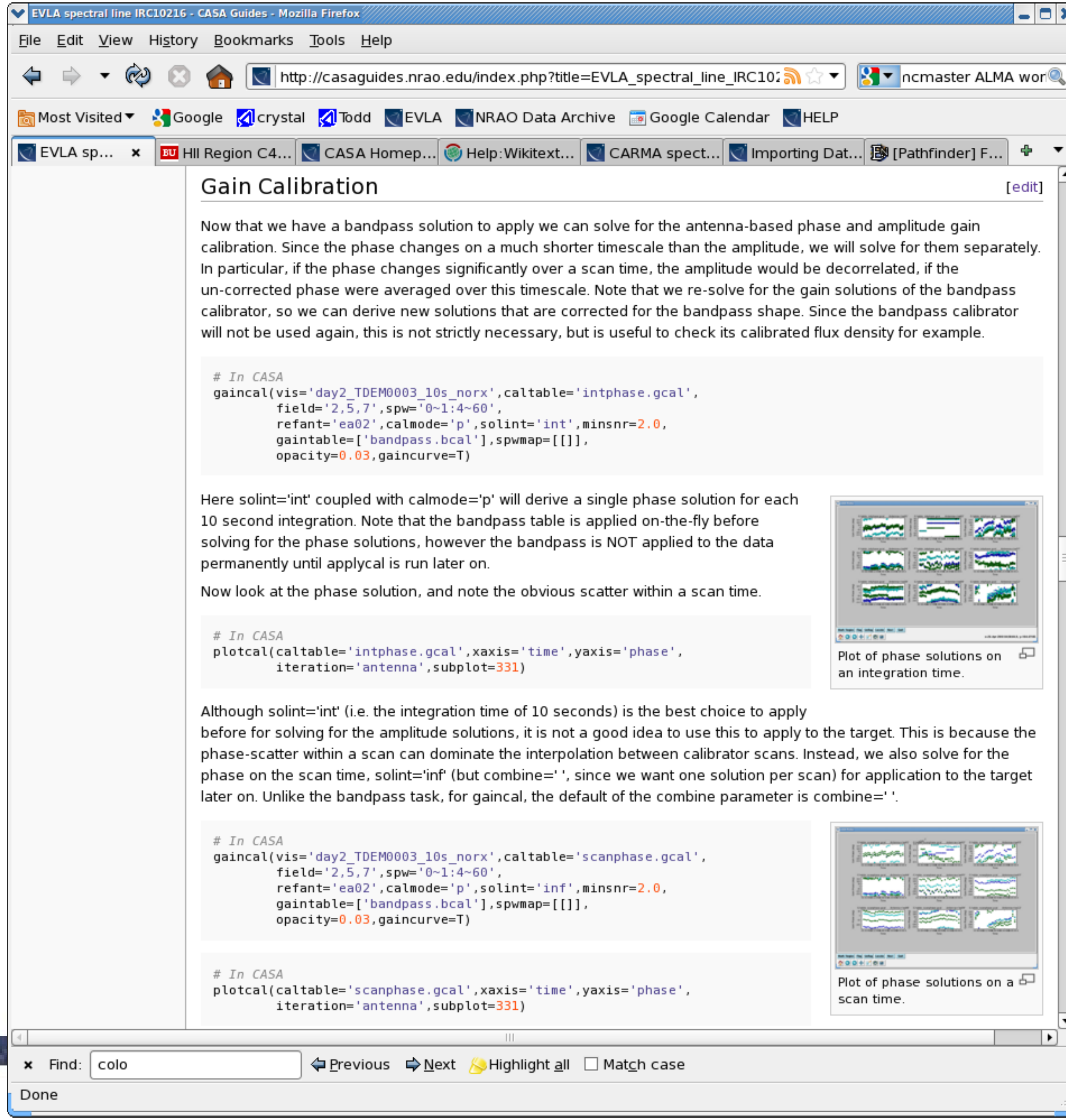
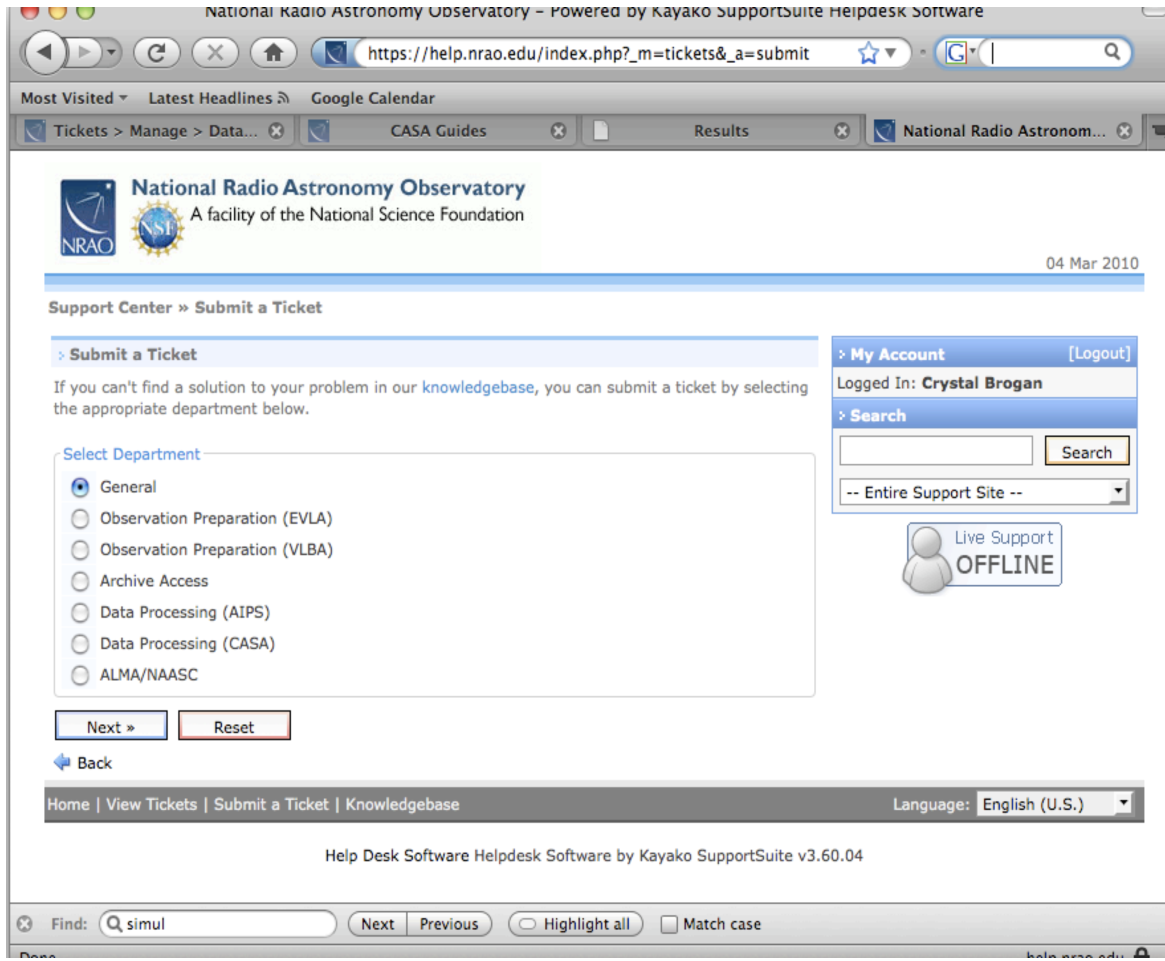


New CASA Helpdesk

- In mid-Feb. NRAO launched Kayako helpdesk at http://help.nrao.edu
- Kayako combines the utilities of managing tickets/user support with a knowledge base
  - Herschel and Spitzer Science Centers
  - top candidate for the ALMA Helpdesk
- Since March 1 used for EVLA and CASA support



CASA Performance

- CASA currently has similar speed to other packages for ~ 10 GB datasets except for a few high nails being aggressively pursued (flagging, plotting)
- For any package the most expensive steps are: Flagging, Calibration (gain, bandpass, polarization, pointing, self-calibration), and Imaging
    - Channelization of data makes the problem “embarrassingly parallelizable”
    - However, particularly for imaging, the problem is I/O and not CPU limited making the problem trickier
- The release of multi-core CASA functionality will be staged.
    - CASA’s architecture has been written with parallelization in mind
    - Simple imaging (single field or simple mosaic <u>cube</u>) well progressed, expected for October release
    - Multi-core flagging and more imaging cases (multi-frequency synthesis continuum) expected June 2011
    - Successful hiring of HPC position critical
- Also pay attention to disk I/O (data rates > standard disk I/O speeds)
    - Investigating use of fast and/or parallel disk systems

Performance in Practice

- Size matters: currently CASA data is ~6 times larger than *miriad* and ~3 times larger than AIPS
  - Double precision 8 byte (Re,Im) floats (same as AIPS and 2x miriad) – essential for high dynamic range. CASA can use 4 byte instead
  - 3 scratch columns for intermediate calculations (AIPS: temporary scratch files on disk, miriad: mostly memory). CASA has high priority target to eliminate permanent scratch columns, reducing disk footprint to 1/3
- A test cluster with 16 nodes (128 cores) was purchased last year (joint EVLA/ALMA) to provide a test-bed for CASA parallelization
  - Recent imaging tests on a 0.1 TB dataset to make a 3600x3600x1024 cube on just one node (8 cores, 16 GB RAM) took ~17 hours
  - 6 hours peak RSRO data rate (75 MB/s) = 1.6 TB, so on 16 nodes, imaging takes ~ 17 hours on the test cluster. But the devil is in the details, and this is only imaging
  - For comparison, the test cluster was $70K. EVLA has ~$400K to purchase operations cluster (+NA ALMA has $250K). Thus the "real" pipeline clusters will be >5x more powerful than the test cluster (speed, memory, #nodes)
    - ➢ The problem is (potentially) within our means

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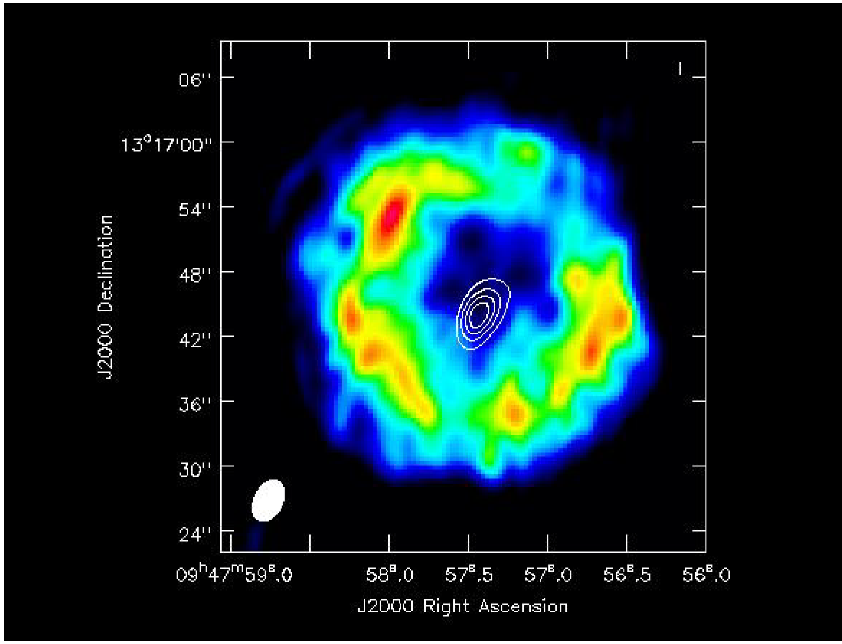
Use Case: Basic Spectral Line

- Example Demo Science dataset: IRC+10216 mosaic at 36GHz

http://casaguides.nrao.edu/index.php?title=EVLA_Spectral_Line_Calibration_IRC+10216

- Dataset (OSRO-1, 26-Apr-2010) TDEM0003_sb1345754_1.55312.131578217595
  - 3hrs (15GB), 2 sub-bands x 64ch x 125kHz (HC_3N, SiO)
- Essential Steps:
  - Average to 10-sec (from 1-sec)
  - Examination and Flagging (in plotms)
  - Calibration: flux density, bandpass, gain
    - delays absorbed by bandpass
  - Calibration transfer (to target)
  - Imaging (single field) of spectral cube
    - standard clean and multi-scale clean
  - Analysis : moments, spectral profiles



HC_3N moment-0 (color) and continuum (contours)

Use Case: RSRO Spectral Line

EVLA K-band Observations of massive young stellar objects in NGC6334-I

- 8 x 8 MHz sub-bands with 256 channels, RR only; also used referenced pointing: 10 minutes on source!!!!
- Test for RSRO project AB1346 (PI Crystal Brogan): “A Diagnostic K-band Survey of Massive Young Protostellar Objects” which will use 16 subbands

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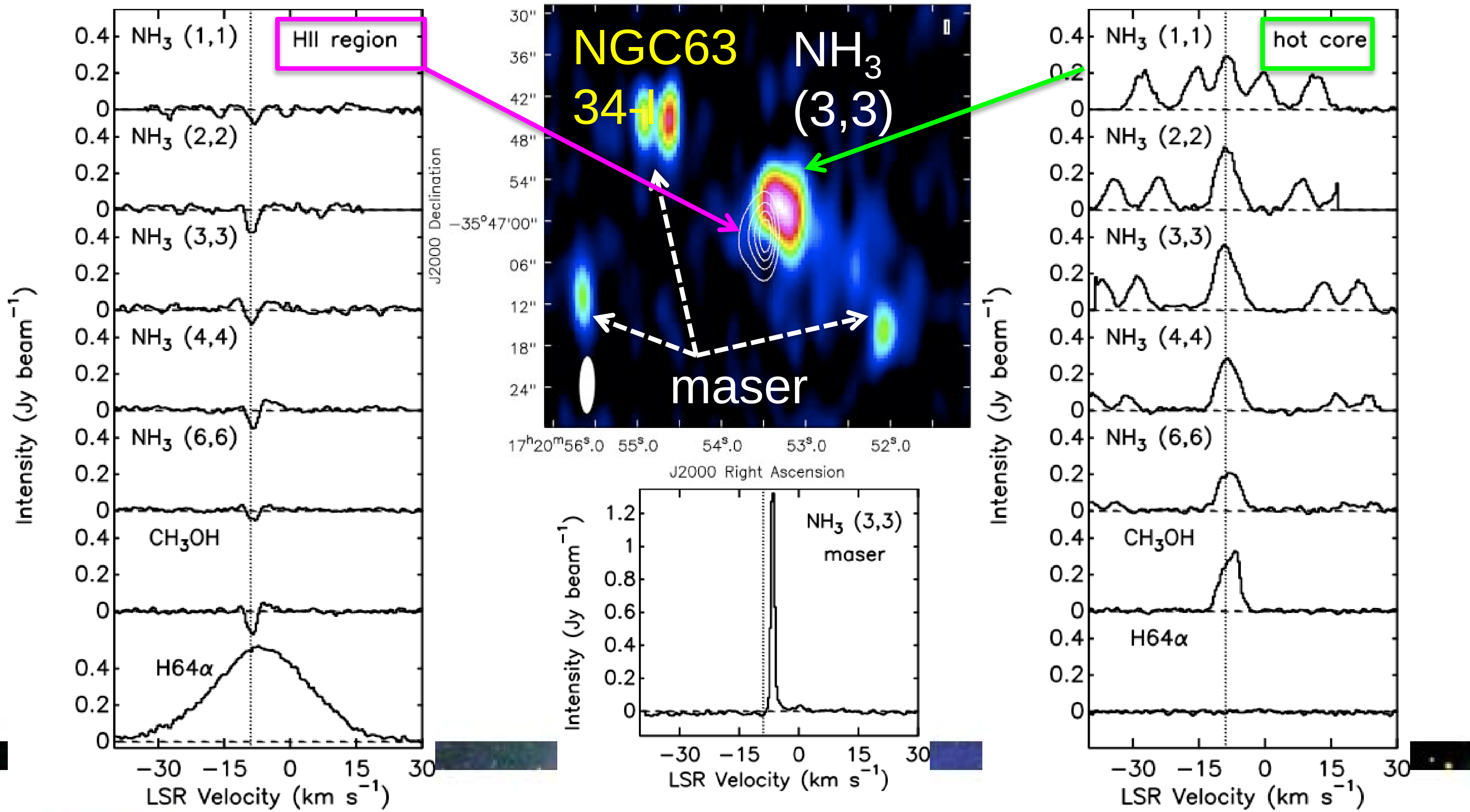
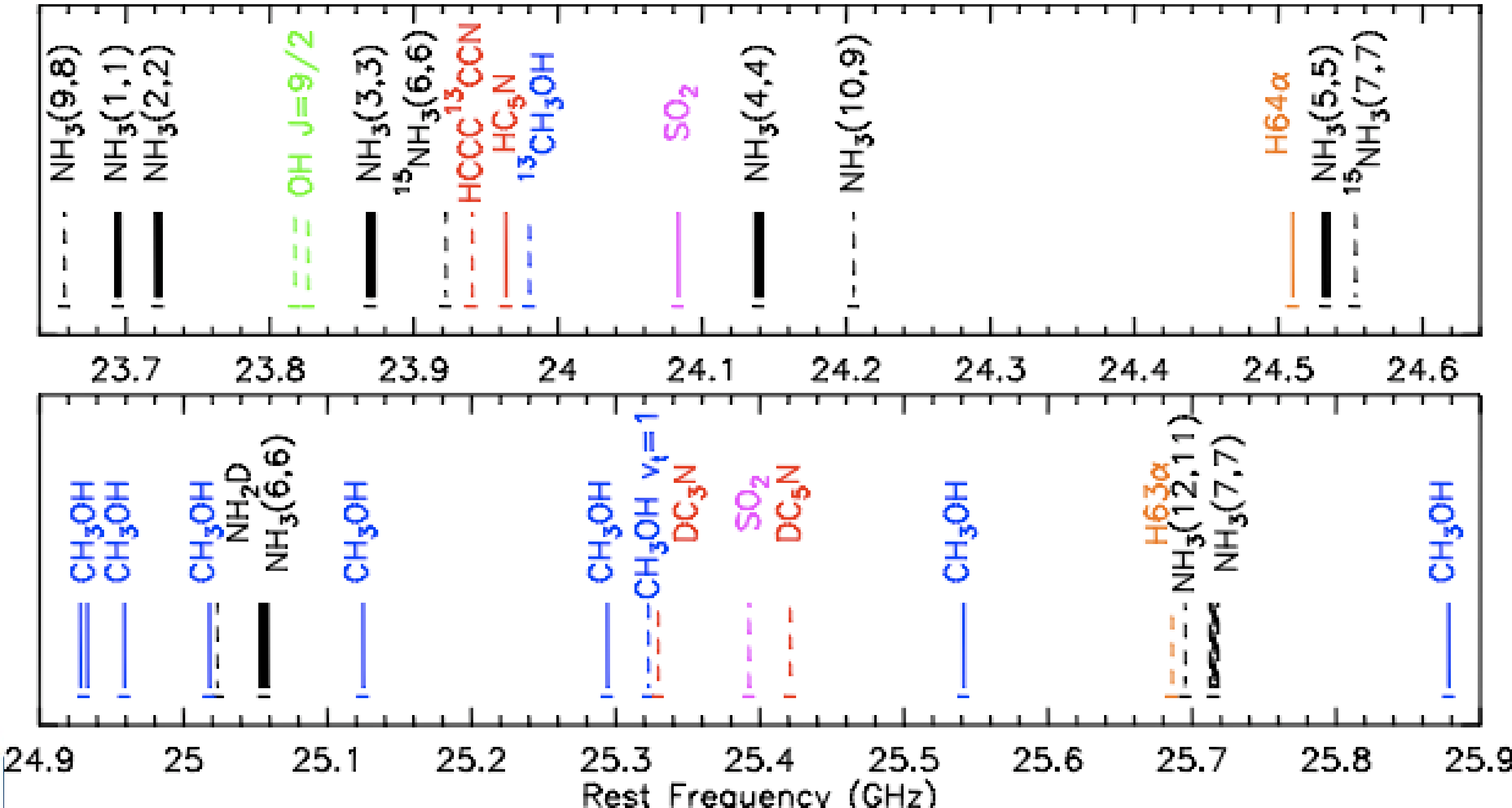
Use Case: RSRO Spectral Line

EVLA K-band Observations of massive young stellar objects in NGC6334-I



Use Case: RSRO Spectral Line

- RSRO (AB1346): A Diagnostic K-band Survey of 30 Massive Protostellar Objects



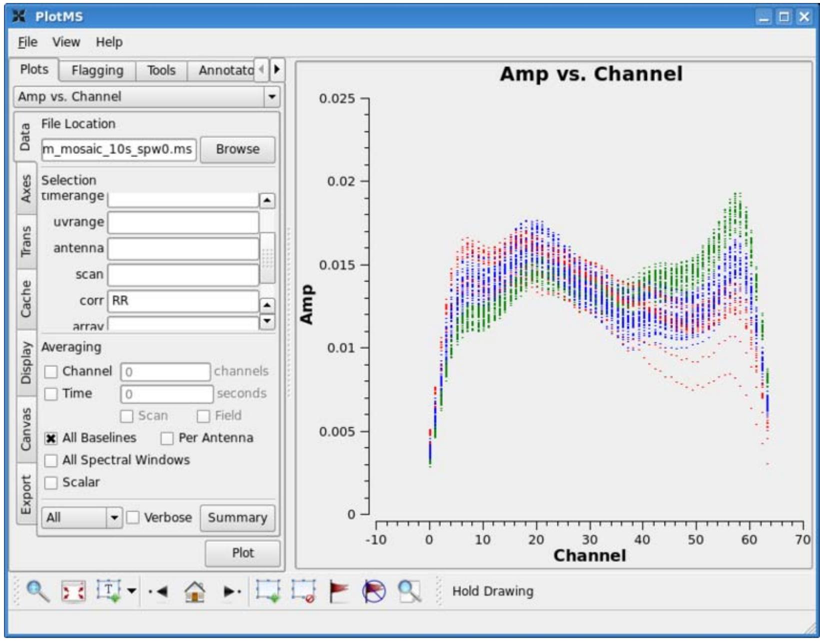
Use Case: RSRO Spectral Line

EVLA K-band Observations of massive young stellar objects in NGC6334-I

- 8 x 8 MHz sub-bands with 256 channels, RR only; also used referenced pointing: 10 minutes on source!!!!
- Test for RSRO project AB1346 (PI Crystal Brogan): "A Diagnostic K-band Survey of Massive Young Protostellar Objects" which will use 16 subbands
- In the "best case" scenario we will use 32 subbands (solid and dotted lines above) which includes a number of rare and Deuterated species
- In the "great case" scenario we will use 16 subbands (solid lines)
- Current test uses 8 of the sub-bands

Use Case: Basic Continuum Polarimetry

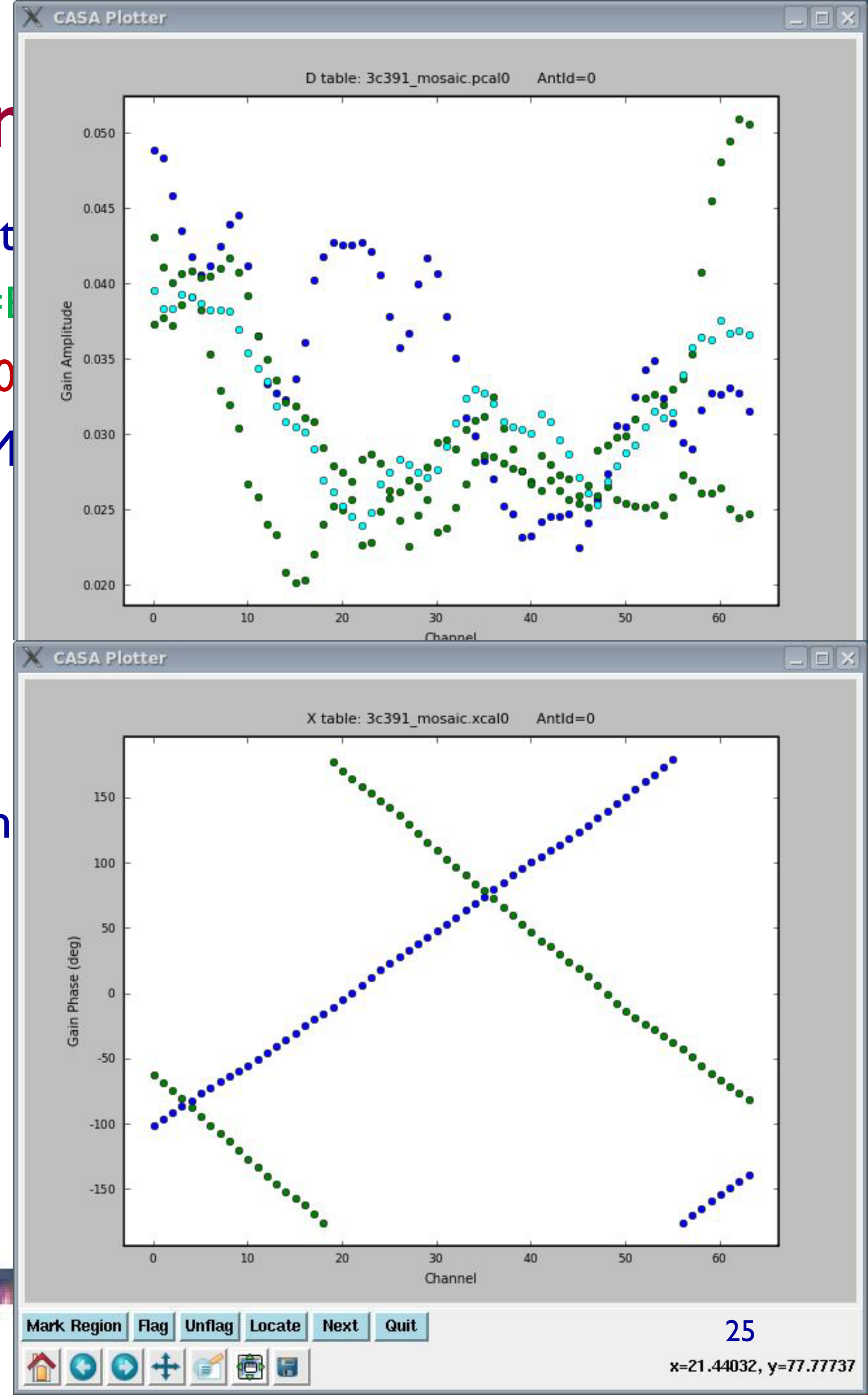
- Example Demo Science dataset: 3C391 at C-band
  http://casaguides.nrao.edu/index.php?title=EVLA_Continuum_Tutorial_3C391
- Dataset (OSRO-1, 24-Apr-2010) TDEM0001_sb1218006_1.55310.33439732639
  - 8hrs (40GB), 2 sub-bands x 64ch x 2MHz (4.54 and 7.44 GHz)
  - 7-field (hex-pattern) mosaic
- Essential Steps:
  - Average to 10-sec (from 1-sec)
  - Examination and Flagging (in *plotms*)
  - Calibration: flux density, bandpass, gain
    - delays absorbed by bandpass
  - Polarization Calibration
    - D-term (leakage) vs. frequency
    - R-L phase (angle) vs. frequency
  - Calibration transfer (to target)



Bandpass in *plotms* (amp vs. channel)

Use Case: Basic Contir

- Example Demo Science dataset: 3C391 at
    - http://casaguides.nrao.edu/index.php?title=I
- Dataset (OSRO-1, 24-Apr-2010) TDEM000
    - 8hrs (40GB), 2 sub-bands x 64ch x 2M
    - 7-field (hex-pattern) mosaic
- Essential Steps:
    - Average to 10-sec (from 1-sec)
    - Examination and Flagging (in *plotms*)
    - Calibration: flux density, bandpass, gain
        - delays absorbed by bandpass
    - Polarization Calibration
        - D-term (leakage) vs. frequency
        - R-L phase (angle) vs. frequency



Df solution (top) and Xf solution (bottom)

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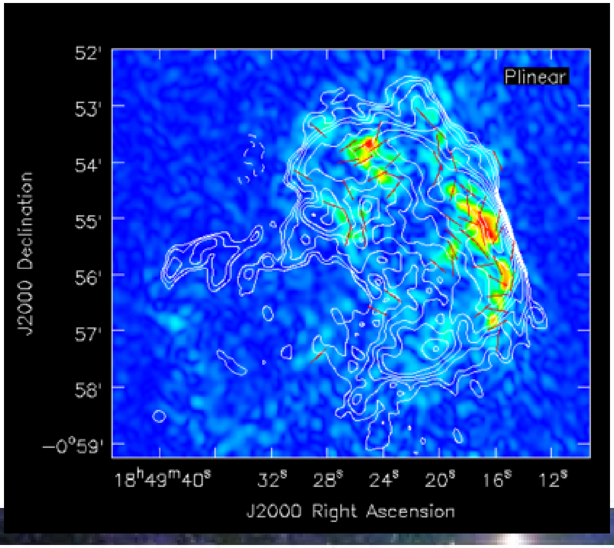
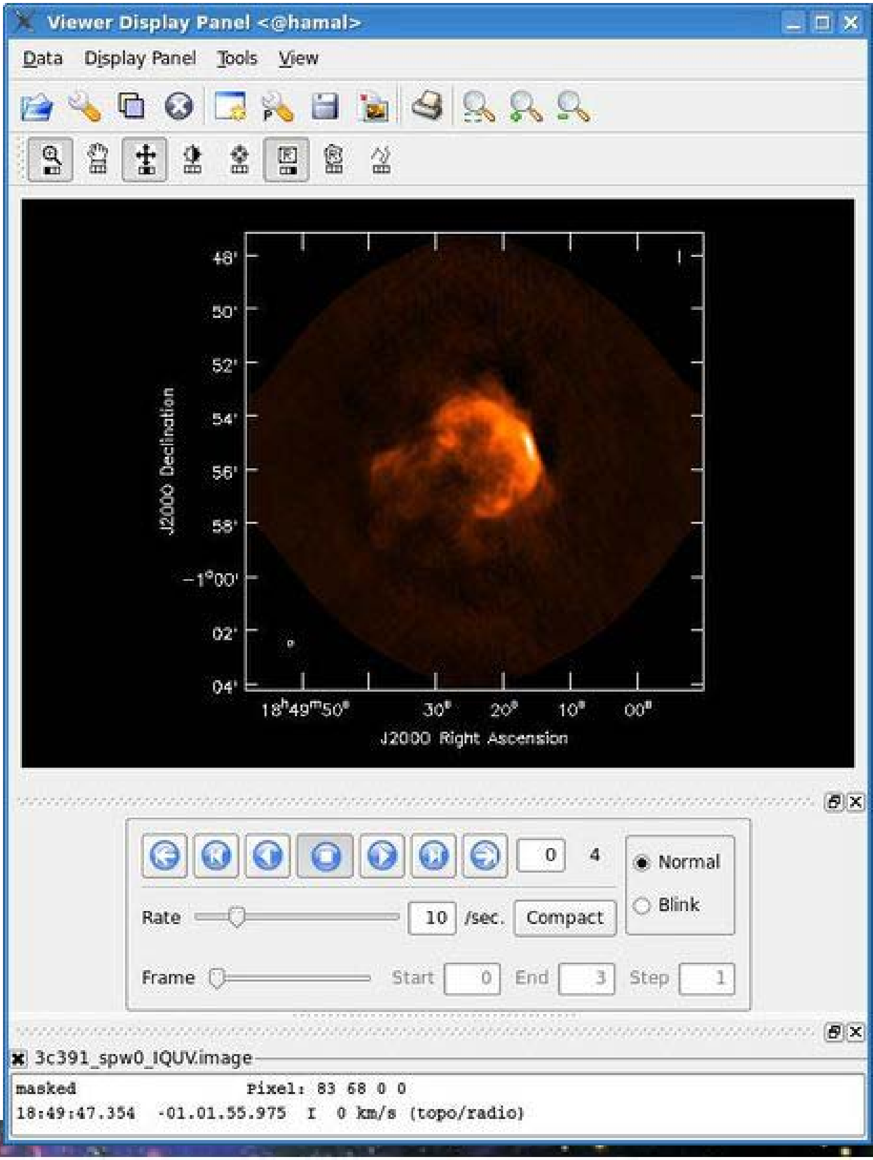
Use Case: Basic Continuum Polarimetry

- Essential Steps (continued):
  - Imaging (joint mosaic) MFS continuum
    - standard clean and multi-scale clean
    - IQUV imaging
  - Analysis : polarization
    - polarized intensity
    - polarization angle – 0.5atan(U/Q)





Key EVLA Development

- Priority – support of EVLA and ALMA commissioning needs
  - including Early Science, OSRO & RSRO
- Parallelization and cluster fine-tuning for imaging and flagging
  - use of EVLA cluster
- Evolving use and support of SDM
  - flagging tables & switched power (EVLA)
- Polarization calibration of linear feeds (ALMA, P/4-band EVLA)
- Improvements to interactive plotting & flagging in *plotms*
  - full incorporation of caltable plotting
  - support for switched power calibration & Tsys
- Improvements to "TV" based flagging in the *viewer*
  - on-the-fly spectral and time averaging
- Delay fitting & correction (incl. cross-hand, not global fringe-fitting)

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Key EVLA Development (continued)

- Planet tracking & models for use as resolved calibrators
- Use of atmospheric models (e.g. for optical depth)
- Calibration efficiency and usability improvements
  - use of source models without scratch column use
  - better management and mapping of calibration tables
- *Splatalogue* line-search capabilities and over-plotting
- Viewer improvements (especially for spectral line plotting, analysis)
- Imaging & deconvolution improvements:
  - mosaicing, high-dynamic range, wideband MFS + multi-scale
- Image analysis task improvements (spectral fitting, etc.)
  - current suite of analysis tasks is minimal, needs fleshing out
- Status Summary: CASA is handling current OSRO observing, RSRO D/C-config with some efficiency issues (data sizes), RSRO B/A-config will be more of a challenge (less averaging, big images)

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Challenges for EVLA processing

- Data rates and volumes
  - RSRO 75MB/s (2010-2011) → 1.6TB in 6hrs
- Wideband (1-8 GHz/pol)
  - large spectral cubes (thousands of channels)
  - multi-frequency synthesis (MFS) for continuum imaging
- Widefield (low-frequency single-field, high-frequency mosaicing)
  - "peeling" of bright sources in outer beam regions
  - direction-dependent corruption (polarized beam, ionosphere, pointing)
- High Dynamic Range imaging (10^4-10^7:1)
  - non-closing errors (e.g. due to polarization)
- Radio Frequency Interference (auto-flagging. correction)
- All of the above at the same time! <u>Avenues for mitigation:</u>
  - High-performance (cluster) computing and parallelization
  - New algorithms

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User Experiences

- Acceptance of CASA by AIPS & Miriad users has been slow
  - CASA focus has been for new users (e.g. Summer School)
  - young/new users seem to like it and catch on quickly
- AIPS is still supported, useable for most EVLA modes
  - used in commissioning & verification
  - new algorithm development (Greisen, Kogan, Cotton)
- CASA task interface
  - designed to be familiar to AIPS and Miriad users
  - full access to toolkit and use of Python (widely used & documented)
- Strengths & Weaknesses (real & perceived)
  - no known “fatal flaws” (see 2003 Technical Review)
  - lack of familiarity for veteran users (approach in different way)
  - its software! there are bugs, and currently gaps in functionality
    - working towards fulfilling user requirements (see documents)

Issues and Future Directions Summary

- CASA is now out of its “beta-testing” and into its use phase
  - being exercised daily for commissioning and science verification
  - growing user base (e.g. RSRO users)
  - focus is on EVLA and ALMA, but there are other interested users (SMA, CARMA, GMRT, e-MERLIN, other instruments)
- Focus shifting from filling gaps in functionality to “useability”
  - continually improving robustness and efficiency
  - hard to satisfy user preferences (e.g. interfaces, GUI look-and-feel)
- New Algorithms
  - must develop and implement new algorithms to enable the EVLA modes that make use of the main sensitivity gains (e.g. bandwidth)
- High Performance
  - must work efficiently in cluster environment for high data rate modes
  - defense in depth: MPI, OpenMP, simple task parallelization, I/O